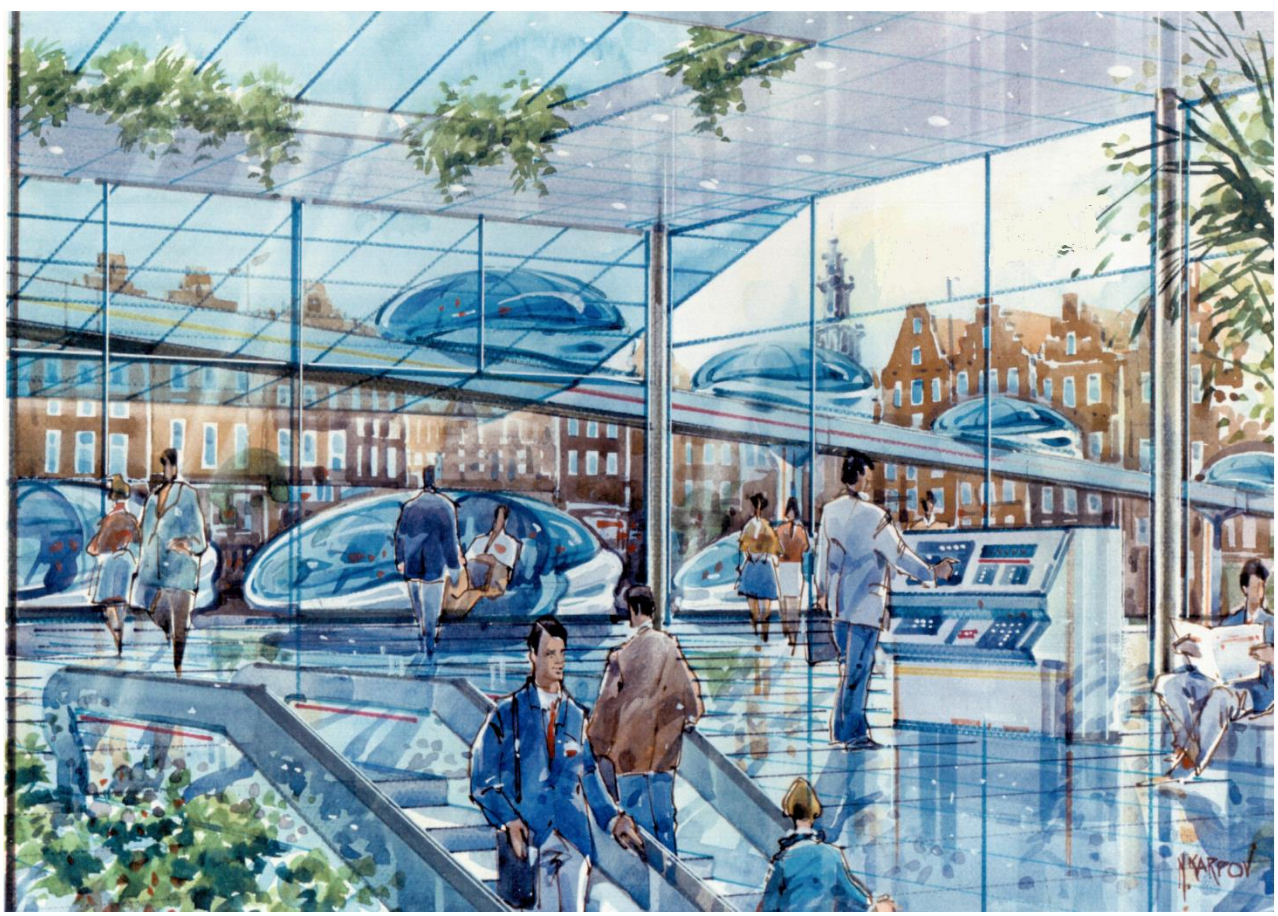
Contributions to the Development of Personal Rapid Transit

by

J. Edward Anderson

Volume I



Mission

To provide safe, reliable, and comfortable mobility while reducing congestion, air pollution, energy requirements, the need for oil, the land needed for transportation, and transportation costs.

Goal

To produce, install, and maintain the world's leading new transit system in a variety of expandable applications in a highly competitive worldwide market.

Values – Follow the Engineers' Creed:

- Give the utmost of performance,
- Participate in none but honest enterprise,
- Live and work according to the laws of man and the highest standards of professional conduct,
- Place service before profit, the honor and standing of the profession before personal advantage and the public welfare above all other considerations.

The title-page illustration was developed by Chipshol Forward NV, Amsterdam.

We now call our version of PRT an "Intelligent Transportation Network System" or *ITNS*. *ITNS* is a totally new form of public transportation designed to provide a high level of service safely and reliably over an urban area of any extent in all reasonable weather conditions without the need for a driver's license, and in a way that both maximizes ridership and minimizes cost, energy use, material use, land use, and noise. Being electrically operated it does not emit carbon dioxide or any other air pollutant, and requires no oil.

Dedication

This book is dedicated to members of the Advanced Transit Association and Citizens for Personal Rapid Transit who have attempted to educate decision makers on the advantages of installing High-Capacity Personal Rapid Transit in cities throughout our congested and troubled World.

"Many specialists agree on the need to give priority to public transportation. Yet some measures needed will not prove easily acceptable to society unless substantial improvements are made in the systems themselves, which in many cities force people to put up with undignified conditions due to crowding, inconvenience, infrequent service and lack of safety."

Pope Francis, in his Encyclical on the Environment

"Our greatest weakness lies in giving up. The most certain way to succeed is always to try just one more time." Thomas Edison

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THE VISION > An entirely new form of transit, combining elements of both personal taxi service and high-tech monorail.

THE TECHNOLOGY > A self-guided rail system, called the SkyWeb, ferrying passengers in three-person cars nonstop to their destination. Hop in a waiting car, say "Radisson" and it takes you there. Keeping the parts small enables the whole system to be elevated. Watch *Minority Report* on DVD and you'll get the basic idea.

WHAT COULD GO WRONG > The concept flies in the face of about a half-century of increasing dependency on automobiles, coupled with a trend of skepticism against big transit projects (witness the opposition to the Hiawatha Light Rail line). Officials acknowledge that credibility is the main hurdle, but counter that the SkyWeb system is cheaper than mass transit (a city-scale project would cost $90 million) and will pay for itself.

THE IDEA MAN > Edward Anderson, a former University of Minnesota professor who's been pursuing the idea since he read government studies of the concept in 1968. He hasn't seen *Minority Report*, by the way.

WHY IT MATTERS > Minnesota's highways are getting worse by the year. Officials say a city-scale SkyWeb system could carry 96 a day, lightening traffic on highways.

TAXI 2000

It's a great dream: personal comfort in a rapid transit system

THE BUZZ > It's hard not to smile at the company's world-of-tomorrow optimism, which extends to the "Tara" theme that plays on Taxi 2000's promotional video. But after years of skepticism, the company has enjoyed some momentum this year, with a prominent display at the State Fair, increased investor attention and interest from Duluth in building a system there. Anderson is also a finalist at this year's Tekne Awards.

Introduction

During the 1890's planners in Boston, New York, Philadelphia, Cleveland, and Chicago, experiencing worsening congestion, began to plan exclusive-guideway transit systems, either elevated or underground. Notwithstanding the expense of building systems that permitted heavy trains to run unimpeded by surface traffic, their need was great and they proceeded. These systems are still in operation as if no advance in service concept could be possible.

Fast forward to 1953 when two independent inventors, Donn Fichter and Ed Haltom, the former working in Chicago and the latter in Dallas, began considering the idea that if the large, heavy trains were replaced by many minimum-sized vehicles, the cost of the guideway could be substantially reduced. Moreover, because of developments in automatic control during World War II they believed that they could run these small cars without drivers, thus making the operating cost with small vehicles reasonable.

Fast forward to 1964 when the work of these two inventors as well as several others caught the attention of Congressman Henry Reuss of Milwaukee. He added a paragraph to the act that established the Urban Mass Transportation Administration (UMTA). It directed the new agency to invest in the new ideas. The result was 17 studies by major companies and research institutes that were published in 1968 in a report entitled *Tomorrow's Transportation*. Unfortunately, here in the United States, "Tomorrow's Transportation" is still tomorrow. A widely available summary of one of the studies was published in the July 1969 issue of *Scientific American*. One of the conclusions was that if the USA continued to advance public transportation by using only existing modes, congestion would continue to increase; but if the new systems called "Personal Rapid Transit" (PRT) were gradually deployed, congestion could be reduced.

Some people now comment that new driverless automobiles will make PRT obsolete. Not so! The main reason for PRT is to reduce congestion, and congestion cannot be reduced by using driverless automobiles on existing roadways where they will creep along with other traffic, often at a pace no faster than a fast walk. The need for PRT is as great as it has ever been, and I know that because of the number of officials who have told me that they want my system once it is tested full scale. The next major reasons PRT is needed are that 1) it can be designed to use energy very efficiently, 2) it does not pollute the air, 3) it will attract many more riders than conventional transit, and 4) it can in many applications be built and operated with no public subsidy – as a private business. Lack of air pollution and energy efficiency are now needed more than ever. Driverless automobiles can complement PRT by bringing people to and from stations.

I became aware of the idea of PRT in the fall of 1968 only a few months after *Tomorrow's Transportation* was released. Shortly later, UMTA released a request for proposals to universities inviting them to establish interdisciplinary research and training programs to study the application of new technology to urban transportation. I was at a point in my career where this was a very attractive possibility. I joined an interdisciplinary group of professors who submitted a proposal and won a grant that permitted us among other things to visit sites where work on PRT systems was underway. Three years later we ran a conference we called the "National Conference on Personal Rapid Transit." A year and a half later we ran a second conference, this time calling it "The 1973 International Conference on Personal Rapid Transit," and two and a half years later we ran a third conference with the same title updated to 1975. The first of these conferences won an award as the best conference put on by a University in the United States. Each of them produced a substantial body of information that is available in libraries. These conferences and subsequent work permitted us to become acquainted with the work of hundreds of engineers and planners who were working in almost every industrialized country on some form of PRT.

We learned that there was a large variety of systems called PRT while city planners with few exceptions had no budget to investigate them. That and resistance to something new turned many of them off to the entire idea of PRT. The New York City Transit Manager commented "I don't want any moon dust in my subway cars." The Apollo Moon Program was ending and there were many aerospace engineers and aerospace companies looking for alternatives. PRT was a logical alternative, and the field of PRT was soon filled with engineers including me who had no idea how difficult it would be to introduce a new mode of transportation in the urban environment. In the military environment fear causes countries to innovate as rapidly as possible, but in the urban environment fear of change produces the opposite reaction.

In December 1970, UMTA issued contracts for a so-called PRT system in Morgantown, West Virginia, to be operational by October 1972, just in time for the next presidential election. The vehicles would be built by Boeing in Seattle, Washington, the control system by Bendix in Ann Arbor, Michigan, and the guideway and stations by F. R. Harris in Stamford, Connecticut. The whole project would be managed by the Jet Propulsion Laboratory in Pasadena, California. In August 1971 JPL resigned from the project after learning that they would be only a "money pass-through" with no funds to do anything they were good at: Systems Engineering. An F. R. Harris manager told me that while thinking about the guideway design he asked an UMTA official how heavy the vehicles would be. He was told to assume that they would be as heavy as heavy rail cars. The fundamental idea behind PRT was to use the lightest possible vehicles in order to minimize the size and cost of the guideway. That idea was now blown and with it any chance of making a real breakthrough. Costs more than quadrupled and, notwithstanding an outstanding safety record, Congress was turned off.

My University of Minnesota group soon realized that the one company that was doing the job right was The Aerospace Corporation. They employed likely the best team of systems engineers in the world – chartered in 1960 to manage ballistic missile programs for the Air Force. Led by genus Vice President Dr. Jack Irving and notwithstanding a military-engineering background they did the systems engineering work needed at their own pace and developed what my group found was the best PRT system in the world. In 1973 we proposed with Dr. Irving to the Minnesota Legislature a test of his system at the Minnesota State Fair Grounds. In April 1974, the Minnesota State Legislature passed an Act that directed the Metropolitan Transit Commission to plan a real PRT system. This was like putting the fox in charge of the hen house. The MTC gave the contract to a company that, instead of using the Aerospace PRT System, used the large, heavy, expensive Morgantown system as the basis for the study, with the predicable result that "PRT" would be too expensive.

It became clearer and clearer as the 1970's wore on that a basic problem was that, notwithstanding the outstanding work of The Aerospace Corporation, there had been no comprehensive and widely available body of systems analysis that could show how best to design a PRT system and no means to teach such systems analysis to very many people. The Aerospace Corporation is a not-for-profit company that, by charter, cannot manufacturer. They would need government support to continue their work, but conventional transit managers lobbied sufficiently to destroy their continued involvement in PRT.

During the 1970's I became more and more involved with PRT planning and development, and as a professor in a research university could and did continue. In September 1981, after 13 years of involvement in PRT, I found a way via a Senior Mechanical Engineering Course to initiate the design of a new PRT system that would be built on the ideas developed by The Aerospace Corporation, but with newer technology that had been developed. I assigned the problem to about 15 senior mechanical engineering students during each of the three quarters of the academic year 1981-2. They plunged in with great enthusiasm and soon we had filed five patent applications. In June 1982 the University of Minnesota Patent Office gave me a grant of $100,000 to continue the work full time with two of my best graduate students. What happened after that is summarized in Chapter 4.

As Developed over decades, my PRT system, which I now call *ITNS*, possesses the following attributes:

- Off-line stations.
- Fully automatic control.
- Minimum-sized, minimum weight vehicles.
- Small, light-weight, generally elevated steel-truss guideways.
- Vehicles ride above guideway to minimize cost and maximize both rider comfort and speed range.
- Hierarchical, modular, asynchronous control to permit indefinite system expansion.
- Dual duplex computers for high dependability and safety.
- Accurate, dual position and speed sensors.
- Dual linear-induction-motor propulsion and braking for all-weather operation.
- Smooth running surfaces for a comfortable ride.
- High-pressure, rubber-tired wheels to minimize guideway cross section and weight, and to minimize road resistance and noise.
- Switching with no moving track parts to permit reliable, no-transfer travel in networks.
- Guideway support-posts separated by at least 90 ft (27 m) to meet planning requirements.
- Propulsive power from dual wayside sources for high system reliability.
- Adaptable to all renewable energy sources.
- Well lit, television-surveyed stations to insure passenger security.
- Nonstop trips with known companions or alone.
- Adequate speed, variable with application and location in a network.
- Vehicle movement only when trips are requested.
- Automatic empty-vehicle rerouting to fill stations.

- Planned & unplanned maintenance *within the system*.
- Full compliance with the Americans with Disabilities Act.

For the Riding Public, ITNS brings the following benefits:

- The system is easy for everyone to use. No driver's license needed.
- Vehicles wait for people, rather than people for vehicles.
- Travel is cost competitive.
- The trips are short, predictable, and nonstop.
- Average rush-period waiting less than a minute and off-peak waiting zero.
- Everyone will have a seat.
- The system is available at any hour and any day.
- The vehicles are heated, ventilated, and air conditioned.
- There is no crowding.
- There are no vehicle-to-vehicle transfers within the system.
- The ride is private and quiet.
- While riding, one can use a cell phone, text message, read, view scenery, meditate, etc.
- The chance of injury is extremely remote.
- Personal security is high.
- The ride is comfortable.
- There is space for luggage, a wheelchair, a baby carriage, or a bicycle.

For the Community, ITNS brings the following benefits:

- Energy use is very low.
- The system can use any kind of renewable energy.
- There is no direct air pollution. Being more than twice as energy efficient as the auto system and by using renewable energy, total air pollution will be reduced substantially.
- The system is attractive for many auto users, thus reducing congestion.
- Because every trip bypasses intermediate stations, stations can be spaced closer together without slowing the average speed, thus providing both increased access to the community and competitive trip times.
- Stations can be sized to demand, thus decreasing capital costs.
- **Land savings is huge** – 0.02% vs. 30-70% for the auto system, and less than 10% of right of way needed for surface-level rail. This is the key factor in the ability of *ITNS* to reduce congestion.
- As to accidents, no one can say that there will never be an accident, but the rate per hundred-million miles of travel will be less than one billionth of that experienced with autos.
- Seniors, currently marooned, will have much needed mobility and independence.
- *ITNS will augment and increase ridership on existing rail or bus systems.*
- By spreading the service among many lines and stations, there are no significant high-value targets for terrorists.

- Transit subsidies will be reduced.
- More livable high-density communities become possible.
- A pleasant ride is provided for commuting employees, thus permitting them to arrive at work rested and relaxed.
- More people-attracting parks and gardens become possible.
- Provides safe, swift movement of mail, goods and waste.
- Easier access to stores, clinics, offices and schools.
- Faster all-weather, inside-to-inside transportation.
- More efficient use of urban land.

Beginning in 2008 I started over. The purpose of this book is to describe that work as a basis for building *ITNS*.

In the first chapter I list all of the papers I have published on PRT topics. The second chapter gives some history of PRT. Chapter three is a brief summary of the fortunes of PRT in the United States. In the fourth chapter, as briefly as I could, I summarize the activities related to PRT in which I have been involved. In Chapter 5 I include a Position Paper I wrote about the UMTA R&D Program as a good introduction to how federal transit R&D was being conducted.

The sixth chapter initiates the process I used to arrive at what I consider to be the optimum PRT configuration: ***<u>Rules of Engineering Design</u>***. These rules can be summarized by the following advice:

1. **Thoroughly understand the <u>Problem</u> and the <u>Requirements</u> for solution.**
2. **Let the <u>System Requirements</u> dictate the technologies.**
3. **Identify all alternatives in all issues <u>without prejudice</u> and with <u>absolute objectivity</u>.**
4. **<u>Thoroughly analyze</u> all reasonable alternatives in each issue until it becomes clear which best meets all technical, social, and environmental requirements.**

A key point of these rules was summarized over 2000 years ago in the following statement:

"Therefore unattached ever
perform action that must be done;
For performing action without attachment
Man attains the highest."
The Bhagavad Gita

If all engineers, God Bless them, rigorously followed such rules, PRT would be much farther along than it is today. Following these rules is a hard, exacting process, and all too often the engineer either doesn't possess the necessary patience, is under time constraints beyond his control, or does not possess sufficient mathematical skills. The result has been one failure after another. In a presentation I gave at the 2009 Automated People Mover Conference, held in Atlanta, Georgia, I list 45 PRT systems that have faded away.

More often than not, during the 1970's PRT was sold on the basis its rider-friendly features: Minimum-wait travel in seated comfort directly from origin to destination. Opponents argued that these features were great, but would make the system so expensive that no one could purchase it. I realized that one had to approach the problem from the direction of cost minimization. Thus the paper that is the subject of Chapter 7: "Optimization of Transit System Characteristics." Its conclusion is that a search for system characteristics that minimize cost per passenger-mile are exactly the characteristics that provide the best service, the service provided by a real PRT system.

The paper of Chapter 7 and many others in this book were first published in the *Journal of Advanced Transportation*. Via the letter on the following page, I have permission to include them.

Chapter 8 gives a range of requirements and how they were met in the design of my PRT system, which I now call an "Intelligent Transportation Network System." I cannot claim that there are not more requirements, or that in subsequent pages of this book I have not used requirements that are not on this list.

Chapter 9 analyzes a series of major tradeoff issues that had to be settled once we had reached the conclusions stated at the end of Chapter 7.

Chapter 10, entitled "The Future of High-Capacity PRT" is a summary explanation of the process by which ITNS was designed and its characteristics. It is included as an introduction to the detailed work needed to actualize the system.

Chapter 11 gives a series of questions and answers about the PRT concept.

Chapter 12 gives a description of ITNS for the lay reader.

The rest of the book is divided into 12 tasks, each of which can be handled by an engineer with a specific and well-known area of competence, which will enable the production the necessary demonstration system a straightforward project that can be completed in a little over one year. The main subject of this book is the detailed analyses that have been required to bring ITNS to its present level of development – ready to build, and the instructions about how to do it. At this point we need a team of engineers to verify by computer analyses all aspects of the design, develop the necessary procurement documents needed to build the prototype system, guide the construction of the first full-scale demonstration, test it, and develop the plans needed for applications.

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The 12 tasks are

Task #1	Management & Systems Engineering
Task #2	Safety & Reliability
Task #3	The Cabin
Task #4	The Chassis
Task #5	The Guideway & Posts
Task #6	The Guideway Covers
Task #7	The Control System
Task #8	The Propulsion System
Task #9	Wayside Power
Task #10	The Station, Maintenance facility & Presentation room
Task #11	The Test Program
Task #12	Application Planning

Over the years, we have more often than not upset promoters of conventional transit by urging them to consider a system that they could not buy. The answer is to proceed as quietly and quickly as possible to demonstrate ITNS full-scale sufficiently that transit planners can recommend its purchase. We are dedicated to that task!

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Chapter 2. Basic Performance Relationships
Chapter 3. Transitions from Straight to Curved Guideways
Chapter 4. Performance Relationships for Specific Systems
Chapter 5. Cost Effectiveness
Chapter 6. Patronage Analysis
Chapter 7. Requirements for Safe Operation
Chapter 8. Life Cycle Cost and the Theory of Reliability Allocation
Chapter 9. Redundancy, Failure Modes and Effects, and Reliability Allocation
Chapter 10. Guideway Structures
Chapter 11. Design for Maximum Cost Effectiveness

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Chapter 2. The Evolution of Personal Rapid Transit

Abstract

The paper reviews the evolution of the PRT concept from its modern beginning in 1953. The early inventors, the projects, and the response of government are discussed. PRT activity diminished to almost nothing by 1980, but then revived strongly as a result of activity by the Northeastern Illinois Regional Transportation Authority. Their interest ignited enthusiastic activity on a growing front to the point that today one can truly say that the concept is coming of age.

2.1 Introduction

The evolution of Personal Rapid Transit (PRT) can be traced back to at least 1953. Some of the ideas embodied in PRT go back even to the last century, but were premature, briefly flowered and died. Since 1953 the evolution has been continuous, though fluctuating − continuous perhaps mainly because the concept of automatic control, essential to PRT, had been firmly established by the early 1950's; and fluctuating for reasons that had little or nothing to do with the technical feasibility of the idea or its potential value to urban society.

The development of automated urban transportation systems, among which PRT is considered to be the goal, has been a highly interactive process among a wide variety of professionals, politicians, and dedicated citizens. In examining the writings, it is clear that these people saw the need for a viable complement to the automobile, and they understood that such a complement could not be just more conventional transit. They were willing and able to invest freely of their own time and treasure to realize a dream.

Others, however, dreamed of a return to the glory days of the streetcar, the use of which had peaked in 1917 [1] and, due to preference for and availability of the automobile, declined in the 30 years thereafter as rapidly as it rose in the 30 years before. Many in the latter group saw that if the concept of PRT matured, the hope of return to the streetcar, even under a new name, would be gone forever. The resulting clash between the new and the old was severe and must be understood if the process of evolution of PRT is to be fully appreciated [2].

If PRT had advanced in a neutral environment, its evolution would have been far different. In fairness, however, one must add that some of the opposition to PRT came from people who genuinely thought it was not feasible for technical or other reasons. A full discussion of the opposition would require another paper [18].

An important part of the interest in PRT in the late 1960s and early 1970s in the United States was due to completion of the Apollo Moon Landing Program and the consequent need to find alternative government-funded projects, rather than a deep understanding of the need for alternative transit and the characteristics and requirements such systems would have to have to meet contemporary needs. In his budget speech to Congress in January 1972, in which he announced a federal

PRT development program, President Nixon said: "If we can send three men to the moon 200,000 miles away, we should be able to move 200,000 people to work three miles away." For a variety of institutional reasons, the later turned out to be much more difficult.

A successful PRT developer will examine every technical, social, and economic argument of its infeasibility, and must be satisfied that each and every argument is either wrong or implies assumptions about certain physical parameters that need not be made. Many parameters and physical alternatives must be examined in development of a PRT system. I once made a list of 46 categories of trade-off areas that need attention in design of a PRT system and the various alternatives that could be selected in each [20]. Upon calculating the number of possible combinations among these classes of alternatives, I found roughly ten quadrillion (10^{16}) possible PRT systems, only a few of which could be viable. It is not surprising therefore that many PRT development programs failed because of lack of understanding of PRT as a system within an urban environment serving real needs and meeting requirements of safety, security, dependability, and ride comfort. Successful development of PRT required a theory of transit to guide choices [3], which was not available in the early 1970s.

Even if one becomes convinced, as I have, that with certain carefully selected features there is a technically and economically feasible PRT system, its development is a much more demanding task than the invention and development of a device that you can put on a table, say a personal computer. The unit of sale of a PRT system is large, there must be a consensus among many people that it is worth the expenditure of substantial resources, it does not easily fit within the jurisdiction of an existing bureaucracy, the time horizon for return on investment is long, and it has no clear military application. While a state's fear of an external enemy compels the development of new military systems, a civil industry's fear of becoming irrelevant, real or not, causes its leaders to argue against the development of new systems that they perceive to be disruptive.

During the past four decades, several billion dollars-worth of work has been done on the development and application of automated forms of conventional rail or guideway transportation. This work was a necessary forerunner to PRT and has shown in many applications over decades that, notwithstanding a well-publicized 1972 failure of a BART train, automated transit works in daily practice and has been accepted by the public. While it seems that almost every investment analyst who was an adult in 1972 was aware of the BART control-system failure and subsequent accident, very few were aware of the accident-free operation of many automated systems such as the Lindenwold-Philadelphia line, the Tampa and SeaTac systems, the Duke University system, and many others that have run routinely for decades with no sensational events to report.

If these more or less conventional systems work, why the interest in PRT? Because the combination of small, private-party vehicles and nonstop trips collectively offer the possibility of a degree of cost reduction, service, and accessibility not achievable with conventional forms of automated transit, in which large, scheduled vehicles stop at all stations. Moreover, because it uses very little land, is quiet, and does not pollute the air, an optimized PRT system offers the possibility of design of cities of livable higher density; and, because a proper design also uses little energy and material, it has been referred to as an essential technology in a sustainable world. A PRT system that meets all of the needs and requirements is a substantial technical challenge, but one that a growing number of people have seen is worth the effort. [24]

In this paper I trace the more important early contributions to the development of PRT that, as chairman of the 1971, 1973, and 1975 International Conferences on PRT [4], I was privileged to study. As a Professor of Mechanical Engineering in a Research University (Minnesota), I had access to a much wider variety of programs than possible for someone in industry working on a specific PRT program. I was and am a participant, not a social historian; therefore, notwithstanding my efforts to the contrary, this discourse must be to a degree subjective. A full treatment of the topics would require many books. For the sake of brevity, I have left out events and developments I would rather have included, and apologize to those who may feel I did not do them justice. Since many things were happening simultaneously, the discussion necessarily departs somewhat from chronological order.

2.2 Early Beginnings in the United States

There is little question that the basic ideas embodied in the system now called PRT came from many sources. PRT is a natural idea that has been invented and reinvented to my knowledge at least a dozen times and quite likely many more. Quite often I hear from a person who claims to have conceived the major ideas and is surprised to learn that others had been thinking along similar lines. Each of the inventors discussed below I am quite sure independently invented the PRT concept in varying degrees of detail, and with no awareness of the work of other inventors. My hat is off to them. I am not one of them. I began to learn about PRT beginning in Fall 1968 from UMTA sponsored reports [5].

Donn Fichter. To my knowledge, the earliest PRT inventor is Donn Fichter, who is now retired from the New York State DOT. As a transportation graduate student in Chicago, he started in 1953 to think seriously about cities and their transportation needs, and made his first sketches of a system he called Veyar [6]. He gradually developed a total system concept, not only a hardware system but a system integrated into a city, and in 1964 published his ideas in a book [7] in which all of the essential ideas embodied in PRT are explained. Having an appreciation for the problems of introduction of a new transit system into the cityscape as well as the transportation needs of individuals, he strongly stressed the necessity for the smallest and lightest-weight cars and hence the smallest and lowest cost guideways possible. He designed his car for one person. Although Fichter did not initiate the development of a hardware system, his well-reasoned and thorough explanations had considerable influence on later developments.

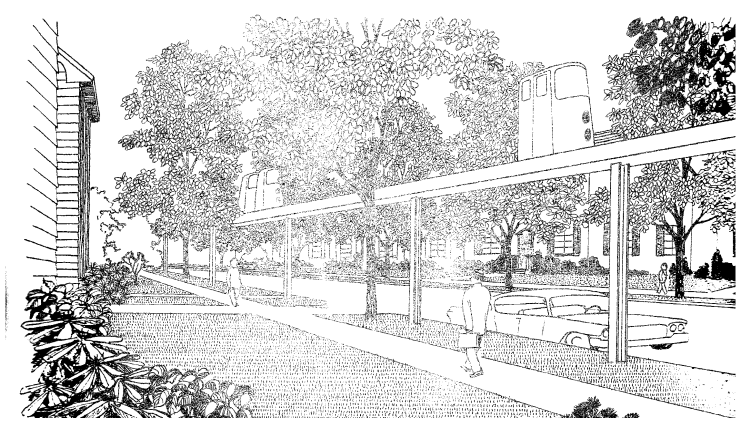

Figure 1. Donn Fichter's Veyar.

Monocab. Also in 1953, a Dallas contractor, Edward O. Haltom, was faced with the task of constructing a monorail system. Monorails are not new. One was built and operated in St. Paul, Minnesota in the 1880's. Another, called Meigs Elevated Railway, was tested in Boston in 1885. A third begin operation in Wuppertal, Germany, in 1902 and has been in continuous operation ever since as the backbone transit system of the city right through the two World Wars. A major difficulty with monorails of the conventional type, Haltom found, was that with the stations on the main line the requirement that vehicles be allowed sufficient time to stop at each station meant that the spacing between vehicles had to be so long that it was only possible to get 20 to 40 vehicles or trains per hour past a given point. This meant that, if the system was to carry enough people per hour to make the venture worthwhile, each vehicle had to have a capacity of several hundred people. To obtain this capacity large, heavy vehicle must be used and they must be trained. They therefore require large, heavy guideways. Haltom found that these large guideways not only drove costs outside the range of economic feasibility, but were so visually obtrusive that his project stalled.[1] Haltom reasoned that to reduce the guideway size and cost, he had to reduce vehicle weight substantially by using many small, automatically controlled vehicles running at close headways. The first version of his system, which he called Monocab, used six-passenger vehicles suspended from an overhead guideway, but it suffered the major disadvantage associated with most monorail systems—the switch. In his first version, switching required movement of the entire guideway. This was cumbersome, slow, unreliable, and limited the capacity of his system.

In the 1960s, Haltom sold his ideas to Vero, Inc. of Garland, Texas, at which time a new means of switching with no moving track parts was invented. A full-scale test track was built and operated at Vero in 1969. In 1971 Vero sold Monocab to Rohr Corporation. Rohr decided that a combination of magnetic suspension and linear induction propulsion was necessary [29] and developed and tested such a system on a test track in Chula Vista, California. The previous wheeled version, however, was demonstrated at Transpo72 at Dulles Airport (discussed below) and in 1973 was selected for installation in Las Vegas. A combination of factors including a 50% drop in the stock market in 1974 due to the oil crisis stopped the project. Boeing bought the patents from Rohr and continued to develop the system under UMTA's Advanced Group Rapid Transit (AGRT) program until that program was terminated in the 1980s.

Figure 2. Ed Haltom's Monocab.

Monocab had the smallest guideway of any of the PRT systems of the early 1970s, but its hanging vehicles required that the guideway be higher in the air than required for a bottom-supported system, which coupled with the required cantilevered posts increased visual impact and cost [30]. This countered the natural advantage of a hanging-vehicle system in curves. I believe, however,

[1] I am well aware that a Monorail Society still functions.

that diversion to an undeveloped combination of magnetic levitation and propulsion was the major factor that delayed and ultimately ended the program.

TTI, Inc. In the late 1950's and early 1960's, a group at General Motors Research Laboratories had been working on ground-effects machines for the Army. These were air-suspended vehicles that could run on a variety of surfaces, but with such low power on paved roads that air suspension appeared applicable to transit. Since an air-suspended vehicle made no direct contact with the roadway, a new type of motor was required that did not use wheels for traction. The logical choice was the linear induction motor (LIM), and thus the combination of air suspension and LIM propulsion was born. The development program was impeded at General Motors because of anti-trust laws that made it difficult for GM to be involved in development of transit systems. As a result, the air-cushion-vehicle (they called it Hovair) development group separated and formed a corporation they called Transportation Technology, Incorporated. TTI developed the idea into what became one of the leading candidate PRT systems. They carried their system to full-scale testing in Detroit in 1969 and in 1972 moved to Denver at which time they became a wholly owned subsidiary of Otis Elevator Company and demonstrated at Transpo72, which is discussed below. In Denver they constructed a second test track and participated in the AGRT program until its funds were withdrawn.

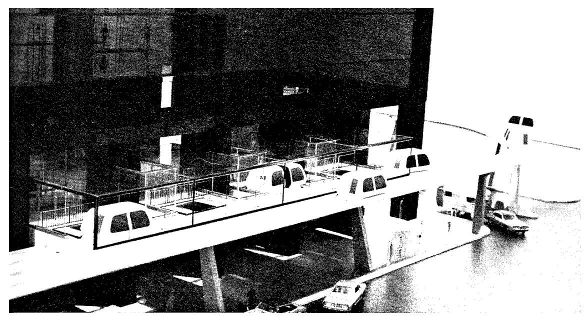

Figure 3. A model of the TTI PRT System.

An operating version of TTI's Hovair+LIM system has been in daily operation at Duke University Medical Center since the mid-1970s. The vehicles in the Duke system hold about ten standing passengers and shuttle between three points. The major problems with the TTI system were the visual impact and cost of the wide U-shaped guideway required to support an air-cushion vehicle, and the fact that it is a snow catcher, which made it unsuitable in northern climates. I also suspect that the lack during the 1970s of variable-frequency drives that markedly increase the efficiency of any induction motor must have been a contributing factor to their limited success. Otis has since sold several cable-drawn versions of their Hovair system.

Alden staRRcar. In 1960 William Alden, a graduate of the Harvard Business School, invented a system of small electric vehicles that could be driven from one's home to a guideway, then automatically on the guideway to a destination. This was quite possibly the earliest dual-mode-system proposal [25]. Alden called his system staRRcar, and formed a company called Alden Self-Transit Systems Corporation. Several years later it was realized that the development of a dual-mode system would be more difficult than a captive-vehicle PRT system, as a consequence of which the emphasis was shifted to wheeled captive vehicles driven by variable-speed hydraulic motors. Each vehicle had a seating capacity of six persons. Full-scale testing of staRRcar began on a test track in Bedford, Massachusetts in 1968 and the system later won a competition at Morgantown, which is discussed below.

An important feature of Alden's system was the invention of an on-board switch that made operation at short headway feasible. In 1968 they operated a 1/20th-scale model with ten vehicles and four off-line stations. The Alden system was essentially a series of cars, much like street vehicles, on a U-shaped guideway with power rails mounted on the inside surfaces of the U, making removal of snow by plowing impossible. Thus, the system required guideway heating, which on an annual basis in northern climates consumes several times as much energy as required to propel the vehicles. This operating-cost disadvantage plus the visual impact and cost of the guideways were factors that caused them to find no customers after Morgantown.

Uniflo. Another of the principal types of PRT had its beginnings in the mind of Lloyd Berggren in 1961 while he was working in the Planning Department of the Military Products Group at Honeywell, Inc. At that time Berggren's principal task was to try to develop ideas to diversify Honeywell's product line. He approached the problem of urban transportation from a system point of view by analyzing the weaknesses of present transport systems. He sought to lay down basic ideas that would enable a transport system to be competitive with the automobile, and thus arrived independently at all of the key features of PRT. He felt it was very important to keep the cost and weight of the vehicle to a minimum and thus felt it would be best to keep the motors in the track rather than on the vehicle.

Having a strong background in fluid-operated devices he saw how air jets could both suspend and propel the vehicles. This resulted in a very simple vehicle design—a passive people-carrying pod. All of the active propulsive and control components were in the track. Berggren's system had the advantage that electrical power is not required on board for propulsion and that a great deal of redundancy can be built into the control system. But it had the serious disadvantage that the vehicles had to be run in an enclosed tube, which ended up being 14 feet high and 6 feet wide—a considerable visual impact and expense. Berggren called his system Uniflo. He was able to obtain support to build a full-scale test track from Rosemont Engineering Company and later from Stone & Webster.

Jet Rail. Another idea that contains some of the concepts of PRT is the Jet Rail System, invented and designed by George Adams, who was president of Mobility Systems Control, Inc. of Los Angeles. At Love Field in Dallas, Texas, Braniff Airlines had wanted an automated system to carry people from a remote parking lot into the Braniff terminal. Braniff executives had been aware of the Monocab system, but felt based on rough estimates that it would be too expensive to be a candidate. They felt that a much less expensive system for that limited application could be built and George Adams showed them how. He designed, built, and in 1972 began to operate an overhead monorail system that looks very much like Monocab. It had Monocab's early difficulty in switching because the wheels that support the vehicle straddle an I-beam, so that the entire beam had to be moved to switch. Jet Rail was automatically controlled and demonstrated that a very lightweight guideway could be built and would adequately support the vehicles. A LIM version of Jet Rail was developed and has been marketed by Titan PRT Systems, Inc.

Urbmobile. In the early 1960's, a dual-mode concept called Urbmobile began to be developed by Morton O. Weinberg and Robert A. Wolf at Cornell Aeronautic Laboratories. This system made an important contribution to the development of PRT mainly because the Cornell people recognized the need for operation at headways down to one half to one second to get adequate capacity. Having strong backgrounds in the technology of automatic control, they attacked the problems directly and were able to show how it would be possible to operate vehicles safely at such short headways. The Urbmobile system was, however, never built.

M. I. T. In the mid 1960's a PRT concept was developed by a large senior-engineering-design task force at the Massachusetts Institute of Technology. A report was published called Project Metran, which embodied most of the basic ideas of PRT and influenced its development.

Bartells. While Robert J. Bartells was Director of Planning for the City of Hartford, Connecticut, he conceived of all of the basic ideas of PRT and, in 1962, explained them in a paper. The importance of Bartells' ideas is that they came from a planner who was faced with the practical problems of improving the mobility of people in a city. Bartells continued his interest in PRT as Professor of Planning at Syracuse University and later in retirement.

Kieffer. During the middle 1960's, Dr. Jarold A. Kieffer, while Head of the School of Public Affairs at the University of Oregon, was asked to advise the Governor of Oregon on transportation planning. He too wrestled with the problems of solving urban transportation problems with train systems and recognized that the costs were so great that not enough of such systems could be built to make a significant contribution in most cities to reducing the needs for automobiles. After having thought about these problems intensely for a period, he and his wife took a vacation at a ski resort. While there one glance at a cable-suspended ski lift caused all of the basic features of PRT to manifest in his mind. In 1967, he wrote a paper in which he described his concept of PRT. As a founding member of the Board of Directors of the Advanced Transit Association he has continued to provide essential leadership in the advancement of PRT, a kind of leadership made possible by his extensive experience in a variety of important positions in the federal government.

2.3 The Urban Mass Transportation Administration

The Act. Up to 1964, PRT activities were going on more or less independently. There were very few people in influential positions who had ever heard of the idea of automating horizontal transportation with small vehicles. One exception was Congressman Henry S. Reuss of Milwaukee, Wisconsin. Congressman Reuss had become aware of PRT and Dual Mode systems in the early 1960's and at that time gave speeches in which he urged political support for the development of new transit concepts. Because of his interest, he was assigned to a subcommittee that developed the Urban Mass Transportation Act of 1964. Through his efforts, a Section 6 was added to the Act entitled Research, Development, and Demonstration Projects. The key paragraph of that section read as follows:

> "The Secretary shall undertake a study and prepare a program of research, development, and demonstration of new systems of urban transportation that will carry people and goods within metropolitan areas speedily, safely, without polluting the air, and in a manner that will contribute to sound city planning. The program shall (1)

> concern itself with all aspects of new systems of urban transportation for metropolitan areas of various sizes, including technological, financial, economic, governmental, and social aspects; (2) take into account the most advanced available technologies and materials; and (3) provide national leadership to efforts of states, localities, private industry, universities, and foundations."

The HUD Studies. The work of the early inventors had finally produced an important political result! At that time the U. S. Department of Transportation did not exist and the Urban Mass Transportation Act therefore established the Urban Mass Transportation Administration as a unit of the Department of Housing and Urban Development. The new UMTA followed the directive of Congress and initiated a series of studies in 1966 to carry out Section 6 of the Act. Some 17 studies were authorized each at a level of $500,000, and became known as the HUD studies. The work was done mostly during 1967. The reports were finished in late 1967 and released in Spring 1968 while I was on an exchange visit to the Soviet Union working in an entirely different field, but almost daily experiencing a variety of mass transit systems.

The most influential of the HUD reports were these: 1) A study by Stanford Research Institute whose task was to develop on paper various new concepts from moving sidewalks to PRT to dual mode and to estimate their economic benefits for the United States; and 2) a study by the General Research Corporation of Santa Barbara. GRC's major task was to model alternative transport systems in actual cities to determine how they would perform compared to conventional systems. A team of 17 specialists in various fields chose Boston as a typical large transit-oriented city, Houston as a typical large auto-oriented city, Hartford as a typical small transit-oriented city, and Tucson as a typical small auto-oriented city. The results of these computer modeling studies strongly favored new transit systems. They showed that, with the projected population growth and growth of the use of automobiles, if only conventional transit systems were developed, the problems of cities would continue to worsen. Only by deploying personal transit systems would it be possible to reverse the direction of worsening congestion in our cities. The GRC study has been the most influential of the HUD studies for two reasons: The first is that the results were summarized in a very readable article in *Scientific American* [8]. This article has become a classic and has been the starting point for much more thinking about the problems of new transport technology. The second reason is that the GRC work convinced its chairman, Ben Alexander, of the importance of trying to create a national commitment to develop these new transport technologies. He talked to politicians and testified before congressional committees, in this way bringing PRT and Dual Mode more strongly into political thinking in Washington.

The HUD studies were summarized in a report, *Tomorrow's Transportation*, authored by William Merritt, who was at that time an UMTA official. The report was optimistic about the prospects for developing the new technologies in the United States, and influenced the start of a great deal of industrial work in the U. S. and elsewhere.

Then came an event that had unfortunate consequences for the development of PRT systems in the United States − a change of administration. The HUD studies were released only a few months before President Nixon's new administrators had warmed their chairs. It is far less important that the change was from Democrats to Republicans than that it was a change. Here was a new group of people heading UMTA that had no commitment, indeed no detailed understanding of the implications of the HUD studies. Moreover, R&D played a minor role in UMTA's agenda. Their main task was to prevent the collapse of existing transit systems in the United States and to do so by providing capital grants for the purchase of buses and rapid rail systems. The stage of development of the new systems was too early for them to make a contribution to immediate improvements, and the new administration wanted results prior to the 1972 elections. At the time UMTA was understaffed. When they received a flood of proposals from the 17 HUD-funded companies as well as from others for development of all kinds of new transit ideas, there was simply no way they could handle these proposals in an orderly manner. The reaction was to fail to consider any of them, which resulted in a great deal of frustration among people interested in new transit systems and a period of inaction at the Federal level.

In retrospect, it seems clear that placing both development of new systems and funding of existing systems in the same agency could only squeeze out the new systems. Existing systems had powerful lobbies at a time when federal money was abundant. The lobbyists were not about to be denied funds by competition from new ideas, and the lobbies for the new systems were relatively weak. If an agency responsible only for R&D in ground transportation had been established similar to the National Advisory Committee for Aeronautics, which was established by Congress in 1915 to study the problems of flight toward their practical solution, the evolution of PRT may have been more orderly, but because of the politics maybe not.

2.4 Activities in Other Countries

On various trips outside the United States I made many inquiries of developers of PRT and in the process sought to determine if any of the ideas were invented independently there. In every case I found that the stimulus came from contacts with U. S. inventors or later from study of the HUD reports. There were probably at least three reasons: 1) the impacts on the urban environment of large numbers of automobiles became a serious problem in the U. S. before it did in most other countries, 2) the frontier spirit that prevailed in the U. S. provided a climate of tolerance for mavericks rather than forcing them by social pressure to conform, and 3) during the 1950's, all of the other leading industrial nations were recovering from World War II.

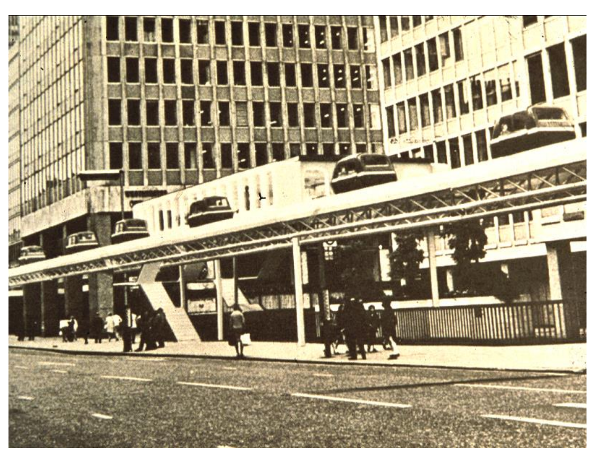

Figure 4. Cabtrack.

<u>Cabtrack.</u> The British Cabtrack System, a true PRT system, was initiated by activities of L. R. Blake, who then worked for Brush Electric Company. Blake had gone to the United States and examined the Alden staRRcar, Urbmobile and some other automated transit systems. In 1967, he wrote an article [9] in which he described his own synthesis of his findings into a system he felt was suitable for British cities and towns. He called his system "Autotaxi." Blake's work started as a private venture and was later sold to Brush Electric.

Brush executives later convinced the Minister of Transport to carry on the idea. A joint arrangement was made with a National Research and Development Board to fund 50% of the work of developing Cabtrack to the state of a test track. The total budget was £250,000.

The Royal Aircraft Establishment at Farnborough Hants had established an urban-transport group and was asked to study Autotaxi. They renamed it "Cabtrack." The first phase was a nine-month study with a comprehensive report issued in December 1968. As a second phase the RAE got an 18-month contract and then further contracts that culminated in testing of a one-fifth-scale model. The last report was issued in March 1974. The RAE work was the first comprehensive system study of PRT by a large government organization and considered not only technical development but extensive demand and layout analysis. They examined a wide variety of control schemes and became confident of operating at a minimum headway of 0.6 sec. A contract was awarded to Robert Matthew, Johnson-Marshall & Partners, a large British architectural firm, for a study of the integration of Cabtrack into a section of London. The results of that study were reported in May 1971 issues of the *Architects' Journal* and at the National Conference on PRT in Minneapolis in November 1971 [4]. It was the earliest serious study of the visual impact of overhead-guideway automated transit systems.

In early 1972, after a new election in Great Britain and the appointment of a new Minister of Environment, the Cabtrack program was stopped. I heard that the new Minister read of the Cabtrack program through the newspapers before he had any detailed briefing. His reaction was strongly negative and he refused to approve extensions of the program. The British Cabtrack program was the earliest serious development program in the world on high-capacity PRT and the final reports are still of great value both in methodology and results. It is a pity that they were never summarized in readily available book form.

<u>CVS.</u> The Computer-Controlled Vehicle System (CVS) is a one-second-headway, 2000-lb, four-passenger-vehicle PRT system developed in Japan beginning in 1968. Scale models were built, a 1000-vehicle network was simulated, and a full-scale test facility began operating in 1972 in a suburb of Tokyo with 4.8 km of guideway and 60 vehicles. Extensive planning and costing studies were done including one for Baltimore in the late 1970s. The CVS program was discontinued for a number of reasons. As an external observer, I became aware of the following: 1) The size, cost and visual impact of the guideway—three meters wide by about 1.8 meters deep; 2) problems of traction in wet and icy weather; 3) a rough ride; and 4) lack of understanding of how to obtain adequate capacity in stations by use of multiple berths and simultaneous loading.

Figure 5. CVS

The system was designed too quickly following the HUD studies and without adequate understanding of the elements required for success. The guideway was left as something that could be optimized later, but as time went on it became the millstone that sank the project. In 1983 a group of Japanese engineers sponsored by the Japanese government visited the United States in part to study progress in PRT. They recognized the need for guideway optimization, but by then the lack of a market for CVS as it stood was too much of a barrier for their top management to overcome. Unfavorable results are very difficult to overcome within a given organization.

Cabintaxi. In 1970, the German Ministry of Science and Technology became aware that two firms, Messerschmitt-Bölkow-Blohm (MBB) and DEMAG, had independently been working on concepts of PRT very similar to each other, each having been inspired by the HUD reports. As a result, the Ministry urged these firms to pool their resources and begin funding a joint venture DEMAG+MBB at a level of 50% of their total efforts. This gave industry much more incentive and the government much less need for detailed supervision than the U. S. practice of 100% federal funding of similar programs.

A thorough program of analysis of a variety of alternatives for suspension, switching, motor design, cabin size and track size led them to a configuration of three-passenger cabs, one set hanging under a beam and the other set supported above. The vehicles ran on solid rubber tires and were propelled by two-sided linear induction motors, one on each side of the vehicle, which permitted operation at headways as close as one second. Based on extensive study of control strategies, they selected an analog, asynchronous control system instead of digital synchronous or quasi-synchronous control, saying that while quasi-synchronous control is easier to simulate, asynchronous control is more flexible under practical conditions such as adjusting to speed changes and possible stoppages.

Full-scale testing began in May 1973 and by October 1974 the system was demonstrated successfully to the German press and to the Minister of Science and Technology. A large variety of tests on reliability, maintenance, and human factors were performed in preparation for offering the system for deployment in cities. Also the team undertook an ambitious planning program to study the deployment of Cabintaxi in Freiberg and Hagen. These studies convinced the team that the project could be successful and could be deployed in German cities.

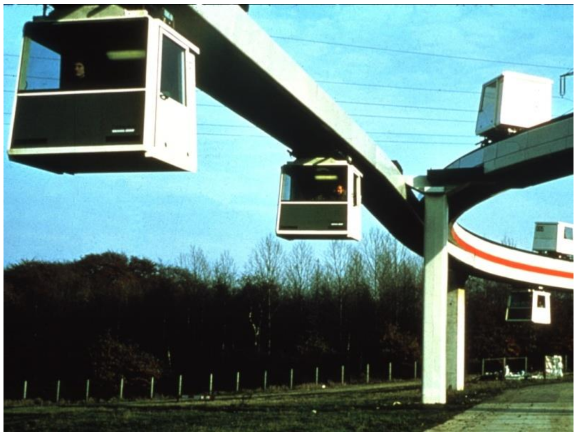

Figure 6. Cabinentaxi.

In 1975 at team from the Raytheon Missile Systems Division, to which I consulted, investigated several PRT development programs and decided to try to license Cabintaxi for deployment in the United States. That program came very close to succeeding but was canceled in July 1976 in favor of MSD's primary business, however, DEMAG+MBB continued to market in the United States, with me as their U. S. representative.

In the late 1970's Cabintaxi in both 3- and 12-passenger versions was tested in a comprehensive study funded by the State of Indiana of automated guideway transit systems for the Central Business District of Indianapolis, which considered AGT systems using 100, 60, 40, 20, 12 and 3 passenger vehicles. The total system cost per passenger-mile decreased directly with vehicle size and the system was strongly supported by a wide range of business, governmental, and civic organizations.

In the meantime, a program was underway in Germany to build a demonstration of the 12-passenger version of Cabintaxi in Hamburg. Due to an economic crisis in 1980 that required drastic cuts in expenditures, the German government withdrew support, yet continued marketing efforts have been undertaken in the United States. From today's perspective, it is most unfortunate that the Cabintaxi program was terminated in Germany because it could have shown that PRT works and could now be providing much improved transportation in many cities. The system is described in a comprehensive assessment report [10].

Aramis. This PRT system began with four-passenger vehicles running on rubber-tired wheels and propelled by a unique variable-reluctance motor. The ideas began in the mind of Frenchman Gerard Bardet, who started his work in 1967 with a budget of 10,000 Francs. In May 1970, the French aerospace firm Engins Matra bought the patents and began their own development work. In late 1970, Matra received its first contract on Aramis from the French agency DATAR. Full-scale testing of the vehicles began in April 1973 at Orly International Airport and by summer 1974 the first phase of proof testing of the basic concept was finished. In early 1974 Matra received a contract from the Paris Metro Authority to begin preparations for a public demonstration of Aramis in a suburb of Paris. The first phase of this program was to be a 16-month program to prove the safety and reliability of the system.

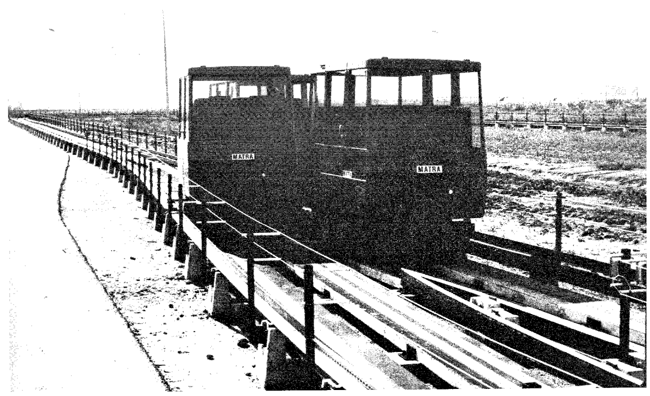

Figure 7. Aramis.

Aramis was unique among PRT systems in that the vehicles were to be electronically trained in platoons in which the vehicles were controlled to a separation of about 30 cm using ultrasonic and optical sensing. Any vehicle could be switched out of a platoon into a station by means of an in-vehicle switch and vehicles would leave stations between platoons and catch up to the last platooned vehicle. An important result of the Aramis program was demonstration that it was possible to attain rapid-rail capacities at stations by simultaneous loading and unloading of a series of vehicles. Aramis was designed to be a circumferential system around Paris, but, because of the platooning feature, was not well suited to network operation. Because braking was through wheels, it is quite possible that it was difficult to control the close spacing in wet weather. Later it was decided to increase vehicle capacity to ten, which was a serious mistake [11]. With ten-passenger vehicles, there are serious problems of personal security and virtually impossible station operations [11]. The Aramis PRT program is the only one to my knowledge that has been the subject of published sociological report [12].

Gothenburg. The leadership of the Gothenburg Transport Authority was stimulated by the British Cabtrack project. A transport study had been underway for Gothenburg and there was a strong belief that the solution could not be a subway because of very high costs, particularly because most of the sub-structure in Gothenburg is solid rock. A study was undertaken to plan a PRT system and a great deal of enthusiasm for the project developed. By March 1973, however, the Gothenburg authorities had reviewed enough of the international work on PRT to conclude that none of the systems were far enough along for early deployment. They chose, therefore, to extend their tram system for the time being and to wait and watch the developments in new technology. The work was significant in that it was sponsored by the city planning authority that, by making inquiries throughout the world, became very knowledgeable on new transit technology and showed that at least in one city the transit authority would be willing to consider new systems. Since 1990, interest in PRT in Sweden has revived with a series of studies sponsored by the Swedish Government that compare PRT very favorably with conventional transit [19], [26]. The Swedes have not liked to continue the name PRT and have instead coined the name “PodCar” for this technology.

Canada. In 1967 the Canadian Ministry of Transport sponsored a comparative study of transport alternatives for Canadian cities. The contract was awarded to Norman D. Lea and Associates of Toronto. They studied the future of Canadian cities if only conventional highway and transit technology was built and compared this with the future that could exist if PRT systems were to be developed. They didn't like the term PRT and instead used the term "Programmed Modules" to emphasize the use of the system for freight hauling as well as people movement. Their studies indicated that approximately half the revenue on a Programmed-Module system could come from freight movement. In a study of an automated network for Vancouver they concluded that if the system was used for freight movement as well as passenger movement a 50¢ fare would pay all of the costs. In about 1973, an Ontario provincial corporation was formed called Urban Transportation Development Corporation to develop a PRT system. Unfortunately, conventional rail people had too much influence over the project and turned it into 40-passenger steel-wheel, steel-rail vehicles propelled by linear induction motors. The guideway to support such large vehicles was large enough and expensive enough that the market for it has been limited.

2.4 The Aerospace Corporation

The Aerospace Corporation is a not-for-profit corporation established by the United States Air Force for the purpose of monitoring contracts on development of ballistic missile systems. In the 1960's, Aerospace employed about 3000 scientists and engineers in various areas of aerospace technology and had one of the finest collections of system-engineering talent in the entire world. In early 1968, its Board of Trustees wanted to try to determine how to make use of aerospace technology to solve urban problems.

A broad examination of such problems led by Aerospace Vice President Dr. Jack H. Irving led to the conclusion that the most promising direction for their efforts would be in development of high-capacity PRT based on many of the ideas contained in the HUD reports. They embarked on a very comprehensive program of systems analysis of the requirements for a PRT system and careful tradeoff analysis of components. They concluded that the problem of visual impact would be of prime importance in deploying the systems in cities and therefore chose a narrow, U-shaped guideway that permitted the vehicle's chassis to ride inside the beam with the cabin above. They chose to support the cars on two wheels in tandem. To reduce noise, increase reliability, reduce time of braking and acceleration, and make braking independent of the coefficient of friction, they chose to drive the vehicles with a pair of linear pulsed d. c. motors, which interacted with permanent magnets in the guideway. At the merge and diverge sections they used a no-moving-parts electromagnetic switch. These were new devices invented by Aerospace engineers and were tested in a one-tenth-scale model. The motor had the advantages that it could be controlled completely by solid-state circuitry and had an efficiency of about 88%.

During the period from 1968 to 1971, The Aerospace Corporation developed the entire system concept to a more advanced state than anyone else in the United States. By computer simulations they proved the feasibility of large PRT networks with many thousands of vehicles operating at headways as low as one sixth of a second at 60 mph. They performed economic and patronage analyses of PRT for Los Angeles and Tucson, Arizona, and lectured widely on the advantages of PRT. In the mid-1970s they summarized their work in a book [13].

Figure 8. The Aerospace Corporation PRT.

In 1973, a group at the University of Minnesota, called the Task Force on New Concepts in Urban Transportation that I coordinated proposed to the Minnesota State Legislature a test of the Aerospace PRT System at the Minnesota State Fair Grounds. In 1974, the Minnesota Legislature passed an act (S. F. No. 2703) that directed the development of a plan for an automated small-vehicle fixed-guideway system that would provide demand-activated origin-to-destination service. Aerospace submitted a strong bid, but, notwithstanding a Legislative mandate, the attraction of immediate capital grants for conventional systems prevented their selection by the Metropolitan Transit Commission.

Since The Aerospace Corporation is not-for-profit, it cannot manufacture. The Aerospace Board of Trustees felt, however, that the ideas were sufficiently important as a means of solving urban transportation problems that they urged the Department of Transportation to fund further studies related to high-capacity PRT (HCPRT). They also presented their ideas to the Office of Science and Technology (OST) in the Executive Office of the President where, during 1971, a group of 30 NASA system engineers were assisting in the development of a New Technologies Opportunities Program.

If The Aerospace Corporation had not entered the PRT field, I doubt if we would be talking about PRT today. Someday the world will recognize that they are owed a great debt of gratitude, unfortunately now after Dr. Jack Irving has passed away.

2.5 U. S. Government Involvement

Dr. Lawrence A. Goldmuntz, Director of Civilian Technology in OST, enthusiastically urged a program to develop PRT along the lines proposed by Aerospace, as a result of which such a program became the lead of a series of new technology initiatives to be developed, and was announced by President Nixon in a speech printed on the front page of the January 21, 1972 issue of the *New York Times*. UMTA was directed to divert $20,000,000 of its funds to development of a high-capacity PRT system, but the directive was ignored, following which OST asked NASA to prepare a PRT development program. By Fall 1972, DOT officials had been convinced to approve the program and to cooperate with NASA. But after the November 1972 presidential election, President Nixon replaced all of his appointed officials. Notwithstanding a "Memorandum-of-Understanding" party at NASA Huntsville, the NASA PRT program stalled within UMTA, while UMTA planned its own program.

On March 27, 1973 the new UMTA Administrator Frank Herringer announced his own HCPRT program with the following statement to the Transportation Appropriations Committee of the House of Representatives [14]: *"A DOT program leading to the development of a short, one-half to one-second headway, high-capacity PRT system will be initiated in fiscal year 1974."* [See the next page.] In contradistinction to frequent comments that PRT is useful only as a low-capacity circulator, Herringer also told Congress that "a high-capacity PRT could carry as many passengers as a rapid rail system for about one quarter the capital cost." He then directed his staff to prepare the required Request for Proposals.

Herringer's statement was backed up by studies by his R&D staff, a group of mostly former Aerospace engineers. Note the advances in computer performance in the 35 years since 1974: Computer memory per unit area has doubled every 18 months for at least 40 years, so in 35 years it has doubled over 23.3 times, giving an increase in memory of over $2^{23.3}$ or over ten million times. In regard to computer speeds, in 1990 a processor speed of about 100 kilobytes per second was common. Today 12 gigabytes per second is state-of-the-art. This is an improvement in speed of 120,000 to 1 only in the past 19 years. During the same period computer hardware reliability has increased by leaps and bounds. Similarly, computer design tools and software techniques needed to improve system reliability are orders of magnitude better than they were in 1974. Thus, in terms of computer power, what was considered feasible in 1974 is remarkably easy today, and there are many more engineers who understand the details. Arguments that high-capacity PRT can't work are obsolete.

As a result of marketing activities of the various companies that were developing PRT systems with private funds, interest in PRT had been growing in many U.S. cities. In September 1973, Denver citizens voted a one-half percent sales tax for a PRT system after experiencing some of the longest waits for gasoline in the country and after the characteristics of true PRT had been described in many articles in the Denver press. Six months later the Minnesota State Legislature passed an act, already mentioned, for a plan for a PRT system. Thus arguments made today that it was too early in the early 1970s for PRT in the United States have no validity.

The UMTA RFP for a high-capacity PRT system was ready to go with a press release in August 1974; however, a new UMTA Associate Administrator for R&D, George Pastor, was appointed. As a result of heavy lobbying from the conventional rail industry and from representatives of automated systems that saw no chance of recovering their investments if the UMTA program proceeded Pastor diverted the funds into an innocuous technology development program. Charles Broxmeyer, who was a manager in the UMTA R&D office was furious that the HCPRT program had been canceled. In fall 1974, he showed me the press release and told me that The Aerospace Corporation was to be the lead in the program and that my group at the University of Minnesota was to be involved. UMTA had already awarded us several important contracts in the areas of visual impacts, control and safety, all related to HCPRT.

Having come from aerospace engineering at Honeywell, it took me a while to realize that in civilian technology the bad can drive out the good. Urban transportation is a big business with many players having devoted their careers to it. New ideas threaten careers and businesses, as a consequence of which any change in modes of transportation, however promising, must be gradual. At a time when it had become possible to receive substantial federal grants for planning and building conventional transit systems and when businesses involved in transit did not see how they could be involved in the new systems, they opposed them. It became clear that federal money can be a curse as well as a blessing.

The above-mentioned GRC study (see p. 8) concluded very positively that if only conventional transit systems were to be deployed congestion would continue to worsen, as has been true, but if the new PRT systems could be deployed it would be possible to reduce congestion and to create much improved urban environments. Coming new into the field and armed with the GRC study, it seemed obvious to many of us that a serious development program on HCPRT needed to be a national priority.

In retrospect it is clear that such a program could be undertaken publically only when there would be a consensus among leaders that conventional transit cannot significantly improve the urban environment and cannot reduce congestion by a significant degree. The world may be reaching that point [15]. If undertaken by a government, an HCPRT program would have to be placed in an agency devoted to R&D, like NASA, which is led by career officials that are not replaced after every election and have no role in funding existing systems. Yet people in existing transit agencies and businesses must be kept informed of the new program and must be given opportunities to participate in a meaningful way.

Having come from aerospace engineering at Honeywell, it took me a while to realize that in civilian technology the bad can drive out the good. Urban transportation is a big business with many players having devoted their careers to it. New ideas threaten careers and businesses, as a consequence of which any change in modes of transportation, however promising, must be gradual. At a time when it had become possible to receive substantial federal grants for planning and building conventional transit systems and when businesses involved in transit did not see how they could be involved in the new systems, they opposed them. It became clear that federal money can be a curse as well as a blessing.

CURRENT OPTIMUM HEADWAY ON PRT SYSTEMS

Mr. CONTE. What is the present optimum headway capacity that has been developed for PRT's?

Mr. HERRINGER. The shortest headways demonstrated by a federally funded PRT development were realized at TRANSPO 1972. Both the Ford and Monocab systems were capable of 8 second headways. German and Japanese high capacity PRT developments, in the full scale prototype test phase, are aiming for minimum headways between one-half and 1 second.

TARGET FOR HIGH CAPACITY PRT DEVELOPMENT

Mr. CONTE. What areas are being investigated for purposes of increasing the capacity of PRT systems and how far in the future are the results and benefits?

Mr. HERRINGER. Higher capacity will significantly improve the cost effectiveness of PRT as an urban transportation choice. By increasing capacity, more revenue passengers can be carried on the expensive guideway investment, thus improving capital utilization. A useful measure of capital utilization in a transportation system is the system cost per lane mile divided by the passenger capacity in seats per lane mile per hour. This number is about $800 for a rapid rail system and approximately $200 for an advanced high-capacity PRT system. This means that a high-capacity PRT could carry as many passengers as a rapid rail system for about one quarter the capital cost. I would like to introduce the following table in the record to clarify these points:

[The following follows:]

CAPITAL COST COMPARISON BETWEEN PRT AND RAPID RAIL

System	Capacity (seats per lane hour)	Cost (millions per lane hour)	Cost (dollars per lane mile per seat per hour)
Washington Metro (648 seat trains, 120 s headways)	19,500	15.2	780
Dallas/Fort Worth "Airtrans" PRT (16 seat vehicles, 18 s headways)	3,200	2.6	812
Planned PRT development (12 seat vehicles, 3 s headways)	14,400	4.0	360
High-capacity PRT (4 seat vehicles ½ s headways)	28,800	6.0	208

The table indicates that shorter headways permit high-capacity operation with smaller vehicles, thus permitting essentially nonstop service at all times.

UMTA recognizes the advantages of shorter headways to achieve higher PRT capacities and better service. The planned PRT system development program (for possible application in Denver) will achieve headways in the 3-second range. This system will be available for urban deployment in approximately 3 years. A DOT program leading to the development of a short, one-half to one-second headway, high-capacity PRT system will be initiated in fiscal year 1974.

TSC'S AC PROPULSION SYSTEM

Mr. CONTE. What is the innovative a.c. propulsion system that TSC plans to develop and test?

2.6 Morgantown

In the late 1960's, Professor Samy Elias, Head of the Industrial Engineering Department at the University of West Virginia in Morgantown, had become aware of PRT systems and was aware that there were several PRT test tracks in operation in various parts of the United States. Morgantown is situated in a mountain valley along the Monongahela River. It was at that time a town of 20,000 people and the home of a State University with 20,000 students in three campuses in different parts of the city. The students were transported between campuses in buses that traversed the main street of Morgantown along with both town traffic and through traffic. All went through the center of the city and created congestion similar to that in a much larger city.

Professor Elias believed that a PRT system would be a logical solution to the movement of students between campuses and would be much less expensive than a conventional fixed-guideway system. With support from the University, the city, and the West Virginia Congressional Delegation, Elias was able to obtain $50,000 from UMTA for a comparative study of three different systems: Monocab, the Alden staRRcar, and Dashaveyor, a system not previously mentioned because with its in-track switching it was not suitable for PRT operation. The result was selection of the Alden staRRcar as the most suitable system for Morgantown. Political pressure from West Virginia was strong enough that the newly formed Department of Transportation and its Secretary John A. Volpe took seriously a follow-on proposal to proceed with plans for an operational system.
At that time, several of the companies involved in PRT development were saying that only about two years would be needed to build an urban demonstration from the state of development at that time. Close on the heels of Apollo success it was common for engineers to say: "We can do the difficult today and the impossible tomorrow." Unfortunately, non-engineers believed them. With the two-year period in mind, Volpe saw that it would be advantageous politically to have the system operating before the presidential election in November of 1972. A political deadline was therefore set. The system had to be in such a state of readiness by October 1972 that the President could ride it and use it as an important example of progress being made by his administration. Technical difficulties of meeting such a deadline were shoved aside.

Figure 9. The Morgantown “PRT” System.

Upon visiting the Alden Self-Transit Corporation, UMTA officials decided that they were far too small to be entrusted with a Federal Demonstration Program. They therefore asked Jet Propulsion Laboratory, a NASA lab in Pasadena, California, to be the system manager, and a contract with them was signed in December 1970. At the same time UMTA selected Boeing in Seattle to be the vehicle manufacturer, Bendix Company of Ann Arbor, Michigan, as the control system supplier, and F. R. Harris Engineering Company [31] of Stanford, Connecticut, to do design and construct the guideway, stations, and other fixed facilities. None of these firms had ever done anything similar and had much to learn, yet there was little time for learning. They had to make quick decisions.

JPL asked for funds to support a team of engineers to do the kind of systems analysis they had done in space programs, but UMTA allowed no time or budget for such analysis. They were to be only a “money pass through.” Consequently, JPL resigned from the program in August 1971 saying that “they could not maintain their reputation for technical excellence and be involved in such a program.”

In the great hurry mistakes were made that caused the system and its costs to grow by a factor of four, which was almost the only fact reported by the press. The result was a major black eye to PRT generally and a loss of confidence in PRT in Congress as well as in foreign governments. Yet the Morgantown system is still in continuous operation and was an important factor in convincing Gayle Franzen, Chairman of the Northeastern Illinois Regional Transportation Authority, to recommend to his Board a new PRT program in 1990.

2.7 Transpo72

UMTA decided to sponsor an international transportation exhibition at Dulles International Airport in May 1972. They called it "Transpo72." Exhibits of many companies on a wide range of transportation problems and solutions were to be presented and UMTA leaders decided that the development of PRT would be encouraged by exhibits of leading PRT systems. UMTA allotted $6,000,000 for this purpose to be split equally among four different PRT developers chosen from competitive bids, and it was expected that each company would match the funds they would receive. The successful bidders were TTI; Monocab; Dashaveyor, developer of a wheeled vehicle with an in-track switch; and Ford, a new entry. Ford called its system ACT for Automatically Controlled Transportation. Uniflo was to have been the fourth exhibitor so that UMTA could exhibit one LIM propelled vehicle, one air propelled vehicle, one hanging system, and one normal-looking wheeled vehicle; but the industrial might of Ford Motor Company prevailed, so that a second wheeled vehicle, but with an in-vehicle switch, was substituted.

The expectation of UMTA was that by exhibiting a minimum piece of guideway and one station, city leaders would obtain sufficient information and confidence to purchase one of these systems for installation under the UMTA capital-grant program. It was even said that the criterion for acceptance of one of these systems would be an application by a city for a capital grant. The time schedule given the companies to exhibit in May 1972 was, however, so short that there was no possibility of making any technical advances in the Transpo72 systems. Each developer had built and operated a full-scale test track on his own site and all that could be done was a slight bit of re-engineering.

Unfortunately, the developers were so busy improving their hardware that they paid inadequate attention to integrating their systems into communities. As a result, attendees at Transpo72 had little understanding of how these systems would be used, and the companies had a variety of ideas that tended to confuse non-technical planners and decision makers. As a result, Transpo72 did not produce the anticipated requests for capital grants.

A large number of cities, however, did request to be considered as sites for 100% federally funded demonstrations of the various systems, but none were ready to put any of their own money into such a system. One could not help but come away from Transpo72 feeling that the $6,000,000 invested could have been better spent in a more highly directed and carefully worked out systems development program. Apparently, however, notwithstanding a directive from the White House, UMTA did not believe that was their role. They saw their role rather in stimulating the private manufacturers to develop their own systems. They were of course subjected to a great deal of lobbying.

2.8 1974 to 1981

September 1974 was a turning point for PRT development. People interested in PRT could no longer get federal grants, yet the interest would not die because an unmet need existed and it was well understood by people working on PRT that the reason was not technical unfeasibility but turf protection. A third international PRT conference was held in Denver in September 1975 leading to a third volume of papers called PRT III [4], but attendance had peaked with the second conference in May 1973.

The organizing committee of the PRT conferences met at the Denver conference to develop a permanent organization, and in 1976 the Advanced Transit Association (ATRA) was formed. ATRA held a well-attended conference in Indianapolis in April 1978 and printed its proceedings, which form a valuable addition to the literature.

A major problem had been that a wide and confusing array of ideas had been advanced with insufficient underlying theory based on cost-effectiveness to help make selections among all the alternative features possible in designing a specific PRT system. Experience showed that a PRT system would not sell if it were only a marginal improvement in cost and performance over conventional light rail. When various developers, except for The Aerospace Corporation and the DEMAG+MBB team, were asked why they picked certain features, the answers were too often vague or entirely lacking. For example, a number of development organizations decided on four-passenger vehicles without giving anything but the most cursory discussion of the reasons for the selection and why it was better than some other number. Yet there are a variety of factors including safety, cost, capacity, traveling habits, and personal security that should enter such a decision and can enter only if a comprehensive understanding is attained [17].

After having worked at the Colorado Regional Transportation District on the largest study of transit alternatives ever attempted and then for a year and a half at Raytheon on a PRT development program, I had accumulated enough material to try to fill the need for underlying theory by writing a textbook [3], and have continued to update the material to the present time with papers published in the *Journal of Advanced Transportation* and elsewhere.

In the late 1970's, through vigorous efforts of two Indiana legislators, Dr. Ned Lamkin and Richard Doyle, the Indiana Assembly appropriated $300,000 for a study of automated transit in Indianapolis including PRT. This study has been mentioned above in the discussion of Cabintaxi. After the Cabintaxi program was terminated, my colleague Raymond MacDonald and I began thinking about a PRT system that would meet all of the requirements and criteria we had accumulated, but was yet to be developed.

2.9 1981 to 1990

I started such a development program in September 1981 at the University of Minnesota by assigning the project to my senior mechanical engineering design students. To avoid the serious and often fatal flaws of other systems, we realized that a successful PRT system had to be one that took advantage of all prior work. The University of Minnesota Task Force of the early 1970s, after extensive analysis of the requirements, concluded that the system closest to being right was the Aerospace PRT system. By 1981 it was clear that the technological advances that had occurred since the late 1960s could make it even better. By the spring of 1982, the ideas for the new system had developed to the point that patent applications were filed. In June 1982, the University of Minnesota Patent Office gave me a grant of $100,000 to work full-time for a year with two graduate students on the design and costing of the new system. As of the current date, all of those patents have expired, so the information is available and usable by anyone.

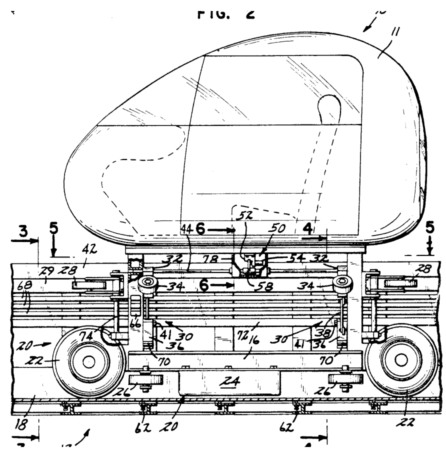

Figure 10. University of Minnesota PRT.

In June 1983, with the help of University of Minnesota officials, a company, later called Taxi 2000 Corporation, was formed to further the ideas. Early in 1984, Davy McKee Corporation of Chicago became interested and funded the development until mid-1985. In August 1986 I was attracted to Boston University and found that it was easier in Boston to assemble a team of competent engineers willing to devote substantial amounts of their own time to further the ideas. In 1988 ATRA published a report [16] of a broadly based Technical Committee on PRT that became a key factor in increasing the credibility of the PRT concept. With the endorsement of the ATRA study, and with the help of Raytheon executives, we were able to attract the interest of the leadership of the Chicago-Area Regional Transportation Authority (RTA), who had come to the important conclusion that they could not solve their transportation problems with just more roads and more conventional rail systems. They realized that they needed something new and in fact they had been mandated by the Illinois State Legislature to look at new systems.

2.10 The PRT Program of the Northeastern Illinois Regional Transportation Authority

The RTA's interest led them in April 1990 to release a request for proposals for a pair of $1,500,000 Phase I PRT design studies. Twelve proposals were received, and for Phase I two teams, Taxi 2000 Corporation with Stone & Webster as prime contractor and Intamin, A.G., were selected to develop parallel PRT designs. For Phase II, which started on October 1, 1993, the RTA selected the Taxi 2000 system with Raytheon Company as prime contractor to design, build and operate a test PRT system – intended to be a $40,000,000 program. One of many publications by the RTA to announce their initiative is shown on the following page.

Unfortunately, Raytheon set aside all of the prior work and decided that they could build a superior PRT system using engineers with no prior experience in PRT. Notwithstanding our strong protests, they built a test system with a guideway twice as wide and twice as deep as that which came out of the Stone & Webster study, a vehicle weight that had quadrupled, and a cost that more than tripled. Moreover, they made the mistake of abandoning the linear motor for conventional rotary motors [27]. The consequence was that in late 1998 the RTA Board set aside the issue of funding a Phase III demonstration in Rosemont, IL, and talked no more about PRT.

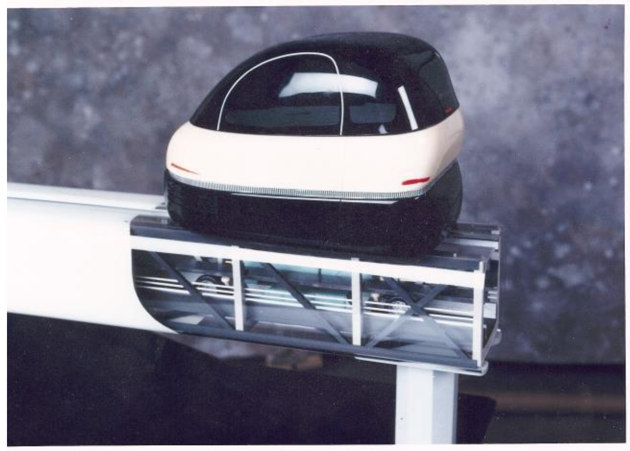

Figure 11. Going into Phase II.

A year later Raytheon announced that they abandoned the PRT business. This was tragic. In January 2000 Raytheon restored Taxi 2000's rights to its technology with a statement by one Raytheon manger: "Ed, taking my Raytheon hat off it would be a crime if you can't build your system." They knew they had erred. Some of them were ashamed. They suffered from the not too uncommon problems large companies have in managing new projects. Wise management at Lockheed-Martin understood the problem and solved it by establishing their famous "Skunk Works," which produced some remarkable new airplanes. Similarly, IBM got into personal computers by establishing a separate group far away from headquarters and devoted to make the PC a new line of business. The difference was in the degree to which the direct management of a new project thoroughly understood the need and was given unhindered control of the development process.

Figure 12. Coming out of Phase II.

THE FUTURE

"Traditional mass transportation responses have failed to meet mobility needs in areas of rapid development. As our suburban service areas approach gridlock, new answers must be found and new technologies examined."

Thomas J. McCracken, Jr.
RTA Chairman

The Regional Transportation Authority, (RTA) responding to its statutory obligation to pursue new and appropriate mass transit technologies for the Northeastern Illinois region, is designing an experimental transportation system to improve suburban mobility:

Personal Rapid Transit

Personal Rapid Transit (PRT) will provide an innovative addition to the existing family of mass transportation modes.

Personal Rapid Transit is well-suited to the needs of today's growing suburban activity centers. These areas have population and development densities that are too small and widely dispersed to support traditional rapid transit, but too large and concentrated to rely exclusively upon use of the automobile. PRT will provide much of the spontaneity, flexibility and privacy of the automobile, without suffering from and adding to ground-level congestion and pollution.

Personal Rapid Transit will offer:

- Small cars seating four passengers each.
- Wait-times of less than three minutes.
- On-demand service and fully-accessible off-line stations, permitting riders to proceed directly to their destinations without intermediate stops.
- Light-weight guideways which are unobtrusive and aesthetically pleasing.
- Fully-automated, computer-programmed travel.
- Maximum passenger safety.

Chicago Tribune 5-14-90

Getting personal with rapid transit

So here comes Gayle Franzen, chairman of the Regional Transportation Authority, with an idea so startling and futuristic in concept that it immediately was labeled as something out of Buck Rogers. It is, in fact, so wildly different from traditional transportation standards that Franzen and the RTA are absolutely correct in their determination to put it to a test.

It is personal rapid transit, a technological leap in line with the RTA's mission of exploring new ways of helping people get around. It recognizes the reality that the metropolitan area is beset by traffic congestion that eventually could cripple its economic growth. It recognizes that the traditional means of transportation are limited as solutions and that the suburbs are the testing ground for new answers.

Trains must operate on fixed schedules with little flexibility on century-old routes, and the cost of building new routes is prohibitive. Buses get caught in traffic, and—as Pace has discovered in its venturesome experiments—sometimes do not catch passengers. Cars. You know about cars. We have met the enemy and it is us, one by one, creeping in desperation.

Personal rapid transit is a means with a 21st Century difference. In simplest form, it is a procession of computer-operated small cars zipping along on lightweight, elevated guideways to individually chosen destinations. The cars hold from one to no more than five persons and can move at intervals of as few as five seconds. The use determines the schedule; whenever someone shows up to hop in, a car takes off.

The cars offer the personal privacy of an automobile without the disadvantages: traffic, pollution, danger, parking. The idea is to appeal to the psychology of drivers to wean them away from their automobiles as a means to supplement existing mass transit. And best of all, a system probably could be built at a small fraction of the cost of a traditional rail line.

The basic concept and technology have been around for years, and versions of the idea are already in operation. The difference with the RTA concept is scaling cars down to personal size, with the hope of someday building a first-in-the-world network on a huge scale.

The RTA is cautious about this, but as serious as money about giving it a try. It is prepared to award two $1.5 million contracts to mass transit and engineering firms to study the concept, using actual locations in three suburbs as models. If the studies pass the test of economic and technological feasibility, an experimental system of up to two miles would be built in one of the suburbs, concentrating on dense areas where great numbers of people move daily.

As one example, a system could link a Metra railroad station with an office or shopping complex.

The concept has brought refreshing whoops of delight from officials in several suburbs. It's enough to encourage the RTA to hope for a spirited competition among suburbs to be chosen for the experiment.

If the experiment actually happens and is successful, loosen the springs of imagination. The system could be replicated in locations throughout the suburbs, and in the grandest vision the guideways could be built in a vast network along existing, crowded highways and abandoned railroad rights-of-way—linking suburb to suburb and countless stops along the way.

Yes, it would look a lot like those scenes from Buck Rogers films—or "Star Trek." But that is the idea: to boldly go where no one has gone before, testing for the first time a new way of getting from here to there.

2.11 Post RTA

Surprisingly, perhaps, the collapse of the Chicago initiative did not discourage interest in PRT. Interest in PRT that had been expressed by the second largest transit organization in the United States via monthly newsletters, editorials and articles in the Chicago press (see the above Chicago Tribune editorial) could not be ignored. The RTA woke up many people to the potential of PRT. The first serious result was that using the earlier specifications in a comparative study with buses and light rail a 17-person steering committee serving SeaTac, Washington, voted unanimously in 1992 for PRT. Then the Swedish Transportation and Communications Research Board funded a series of studies of PRT in Swedish cities [19] that produced very positive results *if* the cost and visual impact of the system approximated the work of the Chicago Phase I PRT Design Project.

Figure 13. Vectus PRT in Uppsala.

Almost at the same time, due to the influence of Ray MacDonald, a Korean company WooBo became interested and performed a series of studies of PRT for their cities, which likely led to Posco's development of Vectus PRT. Also, at almost the same time the Internet began to be available to anyone who owned a personal computer so that publicity about the work exploded. New companies and individuals in many countries who had been working on various forms of PRT were represented at the International Conference on PRT and Other Emerging Transportation Systems, held in Minneapolis in November 1996, and at more recent conferences.

Cincinnati. In 1996 Dr. Chuck Roth of the Cincinnati Metropolitan Area got so interested in the Taxi 2000 system that he dropped what he was doing and spent almost full time during the next two years urging consideration of this system. In September 1998 a committee of 20 business and planning leaders supported by a businessmen's organization later called "The SkyLoop Committee" voted unanimously, I think it was, to select Taxi 2000 over about 50 other elevated systems as their preferred technology. Unfortunately, the Cincinnati Area Metropolitan Planning Organization had leaned strongly in favor of a conventional surface-level rail system (called "Light" Rail), and had sufficient political strength to postpone any serious consideration of PRT of any type.

State Fair. Interest from Cincinnati was sufficient to enable Taxi 2000 Corporation, when I was its CEO, to raise about $800,000 to design, build and demonstrate one automated, linear-induction-motor propelled, three-passenger vehicle that operated on a 60-ft length of guideway. It ran flawlessly for thousands of rides during the 2003 Minnesota State Fair. Citizens for PRT assisted in more ways than I know by providing displays and people to manage the crowds and answer questions. A reporter asked me: "What was the most surprising thing about it?" After a moment of thought, knowing that it worked technically exactly as designed, I said that the most surprising thing to me was the thrill people got out of riding only 40 feet. I could only imagine the reaction to riding around the loop of the first pilot system and subsequent applications. Seeing a comprehensive display of what it would be like to live in a city served by PRT and appreciating the way concerns about PRT would be treated produced an overwhelmingly positive reaction.

Figure 14. Taxi 2000 at State Fair.

What happened to us after that, though, was awful. A clash of interests caused three board members including me to resign from Taxi 2000 Corporation in January 2005 and to go on to form PRT International, LLC. I had the satisfaction, at least, that the Chicago RTA project, made possible by work at the University of Minnesota, was the catalyst for a great deal of activity around the world today. PRT now seems unstoppable!

2.12 Today

As a result of publicity from the Chicago PRT project, operational PRT systems are under test at Heathrow International Airport and in the Masdar project in Abu Dhabi, and a test PRT system is in operation in Uppsala, Sweden. In September 2009 plans to install PRT systems were announced for four Swedish cities: Stockholm, Södertälje, Umeå, and Uppsala; and in the South Korean city Suncheon. New conferences on PRT or Pod Cars as well as the APM Conferences have been held and more are planned. Clearly, PRT is coming of age. I gave a paper entitled "Overcoming Headway Limitations in PRT Systems" at the 2009 Pod Car Conference in Malmö, Sweden.

Figure 15. ULTra at Heathrow.

On August 31, 2009 the City of San Jose, California, released a request for proposals to Federally Funded Research and Development Centers to find a Center qualified and willing to work with them to identify which of the 25 PRT systems currently on their list they should plan for and deploy. The selection is to be made in December. This is the most significant action by any American city related to PRT since the Chicago RTA initiative of 1990. I am very hopeful that the Federal Center will do a thorough and objective job. May the truly best PRT system win! On October 4, 2009 the *Boston Sunday Globe* published an article by Rebecca Tuhus-Dubrow entitled "Invasion of the Pod Car: The dream of personal rapid transit picks up speed." This is the first article on PRT by a writer and published by a major American newspaper in more than a decade. New information is coming so rapidly now that I can only refer the reader for the latest news to http://kinetic.seattle.wa.us/prt/, the best independent webpage on PRT.

With concern about too much CO_2 released into the atmosphere as well as other atmospheric pollutants, increasing prices of oil, ever increasing congestion, retiring baby boomers, and economic hard times there is today far more evidence than in 1974 that these new systems are needed, should be developed, and can be developed. Designs that meet the requirements of low cost, acceptable visual impact, and adequate all-weather safety and reliability appear to have a bright future. These are only a few of the requirements. In my basic non-technical paper [24], which I update from time to time, I list some 37 design requirements and 18 design criteria.

2.13 What have we learned?

During over 50 years of experience in PRT development and planning, some things have been learned that should be of benefit to future PRT designers. PRT development is a challenging interdisciplinary task that cannot be taken casually. It should not be undertaken without deep understanding of the interrelated features of the system, the urban environment in which it would be deployed, and the institutional factors that enter. Inadequate designs have provided fodder for

PRT critics, and if such designs represented all that is possible, I would agree with them; however, these critics have never come up with a single valid reason that optimized high-capacity PRT should not be developed. I recommend that the engineers and managers in any new PRT program follow a rigorous set of rules of design such as I have outlined [20]. I hope other experienced designers will add to them.

A successful PRT development program requires at least the following:

- Leadership that understands the engineering science behind PRT, its relationship to the transportation problem in quantitative detail, the various PRT development programs and their successes and failures, the concerns of citizens and planners, customer needs, and the institutional problems that have hindered development of PRT. This experience can be acquired through involvement in site-specific planning projects in which all of the practical considerations concerning the installation of such a system are considered. Currently there is a substantial body of literature on all of these aspects of PRT.

- A strong, disciplined, and continuous commitment to weight and cost control.

- Use of proven components when such components are available, but willingness to develop new components when necessary.

- Commercially realistic performance specifications.

- A commitment to careful system optimization of components.

- Willingness to consider unconventional guideway designs to obtain adequate stiffness with minimum guideway size and cost [29]. Almost every PRT program that has failed has failed due to lack of attention to guideway design requirements.

- Sufficient training at the beginning of the design process to enable engineers to avoid pitfalls by having thought about them in advance when errors can be easily corrected and before committing to specific hardware solutions.

PRT developers need to recognize that once PRT matures, it is “just” one more civil work, albeit a badly needed one. In the long run PRT technology will be similar to bridge technology, or the technology to build any other civil work. It will be taught in Universities and companies will win contracts to plan, build, and operate PRT systems based on their management and technical strength and skill. PRT development will proceed much more rapidly if those involved can learn to work cooperatively. Consider the Automobile Manufacturers Association.

Today cities all over the world have serious infrastructure problems coupled with declining budgets. Trying to solve these problems in old ways is an exercise in futility [22, 23]. Governments must learn to encourage innovation in the civil sector just as they have in the military. Our future depends on it!

On April 27, 2009 the Obama Administration issued a Funding Opportunity Announcement, the first paragraph of which says:

"This is the first solicitation for the Advanced Research Projects Agency – Energy (ARPA-E). ARPA-E is a new organization within the Department of Energy (DOE), created specifically to foster research and development (R&D) of *transformational* energy-related technologies. Transformational technologies are by definition technologies that *disrupt the status quo*. They are not merely better than current technologies, they are significantly better. Often, a technology is considered transformational when it so outperforms current approaches that it causes an industry to shift its technology base to the new technology. The Nation needs transformational energy-related technologies to overcome the threats posed by climate change and energy security, arising from its reliance on traditional uses of fossil fuels and the dominant use of oil in transportation." (Emphasis added.)

PRT is a *transformational* technology. It will indeed be *disruptive*, but in a very positive way. We watch to see if the Obama Administration can carry through its mandate for change.

For information about the author's work and PRT generally see the following web pages:

www.advancedtransit.org, www.cprt.org, www.acprt.org
http://kinetic.seattle.wa.us/prt
http://faculty.washington.edu/jbs/itrans
http://gettherefast.org

2.14 Evolution of this Paper

The first version of this paper was written in 1974, the second in 1982, the third in 1996 as a paper to be presented to the 1996 International Conference on PRT and Other Emerging Transportation Systems, a fourth in 2008 and a fifth in 2009.

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Chapter 3. The Fortunes of PRT in the United States

The Urban Mass Transportation Act of the United States Congress, which was approved in 1964, included a Section 6 entitled Research, Development, and Demonstration Projects. The key paragraph of that section read as follows:

> "The Secretary shall undertake a study and prepare a program of research, development, and demonstration of new systems of urban transportation that will carry people and goods within metropolitan areas speedily, safely, without polluting the air, and in a manner that will contribute to sound city planning. The program shall (1) concern itself with all aspects of new systems of urban transportation for metropolitan areas of various sizes, including technological, financial, economic, governmental, and social aspects; (2) take into account the most advanced available technologies and materials; and (3) provide national leadership to efforts of states, localities, private industry, universities, and foundations."

This Act led to a series of 17 studies by research institutes and corporations that led in 1968 to a 100-page summary report entitled *Tomorrow's Transportation: New Systems for the Urban Future*. The report defined the system called Personal Rapid Transit (PRT), which consists of fully automated minimum-weight vehicles operating between off-line stations on special, minimum-sized guideways. A summary paper on the work of General Research Corporation of Santa Barbara on the Act was published in the July 1969 issue of *Scientific American*. The authors concluded that if only conventional transit were to be used, congestion would steadily worsen, but if PRT systems were gradually introduced, congestion could be contained.

The studies resulted in a plethora of interest from all over the industrialized world, but with such a diverse range of ideas that planners became confused and many refused to consider any of the new ideas. While ground work had been laid, much needed to be done to sort through the various concepts and to develop theory that would assist in selecting among a huge array of possible alternative system features. In 1978 I published a book *Transit Systems Theory,* and in the following decades advanced the ideas to over 1500 pages of system and component analyses.

I became aware of the federal work on PRT in 1968 and soon, with 15 colleagues, received a grant of $50,000 from the Minnesota State Legislature "for the development and planning of a demonstration project for an advanced form of public transportation." After several years of study, site visits to a half dozen groups involved in PRT research, and our own research, we proposed to demonstrate the PRT system then under development by The Aerospace Corporation of El Segundo, California, at the Minnesota State Fair Grounds. With substantial assistance from the University of Minnesota's Department of Conferences, we held and I chaired Conferences on PRT in 1971, 1973, and 1975, which produced 156 papers by 226 authors in three volumes that can be found in many libraries. The staff of the newly formed

Urban Mass Transportation Administration (UMTA) contributed some of the published papers and participated in the Planning Committee. Additional conferences sponsored by UMTA and by the Advanced Transit Association, which was formed following the 1975 conference, added significantly to the literature base.

Yet here we are in 2016 finding that, while almost all of the PRT system concepts came from the United States, PRT systems are now in operation in England, United Arab Emirates, and South Korea, but not in the U. S., notwithstanding substantial interest expressed by leaders in dozens of potential applications, mostly but not entirely in the United States. The automated transit system that operates in Morgantown, West Virginia, is called PRT but uses 20-passenger vehicles. It safety record has been outstanding and has contributed importantly to the viability of automatic control in urban transportation; but, mainly because of use of vehicles that are much too heavy, its cost overrun discouraged Congress. Many planners have stated to me that before they decide to acquire a PRT system they must first see the new cost-effective PRT system demonstrated, and the challenge has been to find the funds to do so.

Notwithstanding marked advances in aviation, telecommunication and other fields, almost the only methods of urban transportation now in operation use concepts that go back well over a century. As a result, we are mired in traffic jams. We have no choice but to breathe foul air. We worry about civilization's influence on the climate. We are captive to the price of oil. We are concerned with the lack of equity in our society because of the large number of people who cannot or should not drive. We witness an appalling number of people killed and injured in auto accidents. We worry about urban sprawl.

We are today optimistic that we will find private funds to demonstrate what we believe to be the most promising ideas, but that has not yet occurred. A likely reason is that since the 1980s, largely as a result of failure of federal demonstration programs, our federal government stopped investing in new systems of urban transportation while states had become accustomed to looking to federal leadership.

For decades a relatively small number of engineers, planners and public citizens have understood in increasing detail that marked improvements in urban transportation require some form of PRT. Short of teleportation it is the logical result of searches for the ultimate solution. Many PRT systems have been proposed, unfortunately almost all hurriedly designed and flawed in one way or another to the point that many planners and public officials believe that the promise of the new mode has faded. Nonetheless, results of decades of work on the technology and planning of PRT have convinced my colleagues and me that *optimally system-engineered PRT* holds great promise for our future. In many applications we have found that such a system will pay all of its costs out of revenues from passengers, freight hauling, and focused advertising. Moreover, by requiring only a small fraction of one percent of the urban land area, significant congestion mitigation becomes practical. A federal official has called our version of PRT "an essential technology for a sustainable world."

Chapter 4. My Involvement in the Development of PRT

- 1968-69: I joined an interdisciplinary team of professors in a program to bring new technology into urban transportation.
- 1970-1974: I coordinated a University of Minnesota Task Force on New Concepts in Urban Transportation, an interdisciplinary team of 15 professors from engineering, architecture, urban planning, economics, sociology, psychology, and public affairs. We became immersed in PRT concepts.
- 1971: Formed, chaired, and published proceedings of the National Conference on Personal Rapid Transit – 28 papers. Here is the Forward to proceedings:

FOREWORD

The President's State of the Union Message presented to Congress January 20, 1972, committed this Nation to a substantial goal for personal rapid transit.

> "... our outstanding capabilities in space technology should be used to help the Department of Transportation develop better mass transportation systems. As has been said so often in the last 2 years, a nation that can send three people across 240,000 miles of space to the moon should also be able to send 240,000 people 3 miles across a city to work."

The supporting budget message to Congress, transmitted on January 24, requested a doubling of the Urban Mass Transportation Administration's research, development and demonstration program from $62 million in 1972 to $115 million in 1973.

This Presidential commitment and request to the Congress is a recognition of the need for and technological opportunity in personal rapid transit. It is a testimony to the pioneering efforts of many people ... some of whom are represented in this historic volume. It is now necessary for all segments of our society to respond to the President's initiative with imagination, thoughtfulness and energy.

Community planners and environmentalists should understand the implications of this new technology and should help guide its development into channels that will be welcomed by the people served. Technologists certainly understand that no Presidential commitment will sustain a transit system that is so expensive as to force the continued use of less satisfactory but also less epxensive transit modes. If technology can only offer a 70¢ per passenger mile system having the requisite safety, reliability, environmental and service requirements, the future of personal mass transit will be dim. If, on the other hand, we are sufficiently clever to develop a 7¢ per passenger mile system the future for this technology is bright indeed. The editors of this volume deserves the thanks of the personal rapid transit community for their role in organizing the first national conference and for making available to the transit community the excellent work reported in this document.

February 2, 1972

Dr. Lawrence A. Goldmuntz
Executive Office of the President
Office of Science and Technology
Washington, D.C. 20506

- 1971-3: With a $50,000 grant from the Minnesota Legislature, developed a proposal to demonstrate The Aerospace Corporation PRT in Minnesota. Delivered to the Legislature.
- 1972: President Nixon announced a High-Capacity PRT program in his State of the Union Address, but his own DOT ignored it. A long struggle ensued leading to the NASA Advanced PRT Program. I was invited to Chair an Oversight Committee.
- 1973: UMTA announced to Congress: "A DOT Program leading to the development of a short, one-half to one-second headway, high-capacity PRT system will be initiated in fiscal year 1974." It was lobbied to death by the conventional transit industry and was dead by September 1974.

- 1973: Formed, chaired, and published proceedings of the 1973 International Conference on Personal Rapid Transit, Minneapolis – 77 papers. Forward to Proceedings:

FOREWORD

Mass transit is in deep trouble and despite their good intentions, some of transit's best friends appear bent on making matters worse. These transit advocates are obsessed by the assumption that the automobile's cost, comfort, and convenience will not be matched by public transit. This unnecessarily pessimistic assumption has led many of our transit planners down blind alleys from which we are only now beginning to escape.

Today mass transit carries a tiny fraction of the market--less than five percent of all urban trips--and its share continues to decline. One group of transit pessimists has simply given up all hope of substantially improving this market picture. Instead they have tried to turn our attention, and all our resources, to the worthy but limited task of furnishing service to those without cars and to those dwindling numbers still commuting to work in the central city. This group would be thrilled with a market share approaching ten percent.

A second group of transit pessimists has adopted a strategy designed to limit use of the automobile. This group looks to government to force imposition of the same traditional mass transit systems that have failed again and again to attract significant ridership on their own merits. These pessimists are asking the federal government to pay the cost of their multi-billion dollar traditional systems, to pick up the huge operating subsidy tab, and to impose tough limitations on the use of the automobile. The only problem is it won't work. This strategy is reminiscent of that employed by the horse and buggy industries around the turn of the century. It failed seventy years ago and the prospects for suceess today seem little improved. The public is not likely to accept being forced back into a substantially inferior mode of travel, but it might accept some limits on autos if attractive alternatives are available.

A much more positive strategy for tackling the transit ridership problem is outlined in this collection of articles. The authors start by discarding the pessimist's assumption of inferiority. They turn their attention instead to the task of defining and developing a reasonably competitive alternative to the automobile. Readers can judge for themselves just how far they have come in meeting this objective.

There is still some distance to go, but I believe the evidence is substantial that they are finally on the right track. Hopefully this volume will encourage the pessimists among us to raise their expectations concerning the future role of transit in our cities. No miracles are promised, but it offers hope of a real transit choice, rather than obsolete systems or more motor cars.

Bill Frenzel
Member of Congress
Third District, Minnesota

- 1974: The Minnesota State Legislature passed S.F. No. 2703 Chapter No. 573, an Act directing the MTC "to plan an automated small vehicle fixed guideway system." There were two bidders: The Aerospace Corporation and a consulting firm that wished the idea of PRT would go away. The MTC picked the latter, who used the much-to-expensive Morgantown system as the model, which showed as would be expected that if that were PRT, it would be too expensive.
- 1974-5: Consulted for the Colorado Regional Transportation District on the largest study of transit alternatives performed in the USA after Denver citizens had been told that PRT would be the major option. PRT ended up being too early for the transit industry, and I left for Raytheon.
- 1975: Formed and chaired the 1975 International Conference on Personal Rapid Transit, held in Denver – 60 papers.
- 1975-6: Consulted for Raytheon Company Transportation Group, Bedford, Massachusetts on program to develop PRT. At the last minute the needed funds were diverted to a proposal for a new air-to-air missile.

- 1976: Helped organize and was voted first President of the Advanced Transit Association.
- 1976-77: Developed and published the textbook *Transit Systems Theory,* Lexington Books, D. C. Heath and Company, 1978.
- 1977-1979: Consulted for DEMAG+MBB as U.S. Representative for Cabintaxi PRT until that program was canceled by a new administration that diverted the funds to other programs.
- 1978-1980: Consulted for the State of Indiana on planning for PRT in Indianapolis based on Cabintaxi PRT System via Anderson-MacDonald, Inc.
- 1981: Initiated design of a new High-Capacity PRT system at the University of Minnesota.
- 1982: Filed 5 patents on the new system. A U of MN $100,000 patent development grant permitted me with two graduate students to work full time on PRT for a year.
- 1982: Indianapolis leaders met with University of Minnesota administrators. They had been immersed in PRT with me for 9 years but U of MN administrators were new to PRT. Was like oil and water. Cooperation collapsed. Terrible loss.
- 1983: Formed Automated Transportation Systems, Inc. to develop the new system with enough funds to permit my students and me to work full time on PRT for one more year.
- 1984: Dr. John Silber, President of Boston University invited me to join BU Faculty, but at that point I could not abandon the University of Minnesota.
- 1984-5: Worked full time with Davy McKee Corporation in Chicago to develop system specifications, costs, and program plans. They invested about $700,000 but parent Davy Corporation was not in a condition to invest.
- 1985: We were close to a deal with a Madison, WI, developer, but it collapsed because of a management problem.
- 1986: Stuart Watson, grandson of IBM Founder, took over our company and named it Taxi 2000 Corporation. Later in that year he resigned to form a new company to absorb T2C, making me CEO of T2C. Prospects in Minnesota were not favorable so I accepted a position as Professor of Aerospace and Mechanical Engineering at Boston University.
- 1986-9: At Boston University, I formed a Boston-Area industry team to further develop the system and to do application studies in cooperation with Raytheon Company. Led in May 1989 to interest of Chicago Regional Transportation Authority.
- 1987-9: Worked with Harvard Graduate School of Design on several city-development projects using PRT.
- 1989: Visited by Manager of Parks Operations Research, Disney Florida, who described many applications of my system in Disney World. Last of many questions: "Who will build it?" not answerable then.
- 1990-1991: Participated in $1.5 million PRT design study for the Chicago RTA led by Stone & Webster. The RTA published a glowingly positive monthly newsletter called "PRT UpDate."
- 1992: Presentations I gave at SeaTac and Tacoma, WA, resulted in a $300,000 study of PRT for Seattle-Tacoma International Airport. Although the consultant quadrupled our costs, we were selected unanimously by a 17-person steering committee over busses and light rail.

- 1993-5: Consulted for Raytheon Company on their PRT design program for RTA that led to a test track of cars and guideway much too large and too expensive to be practical. Our concerns were ignored.
- 1994-5: Returned to Minnesota and accepted an invitation to give a two-week course on PRT at Chalmers University, Gothenburg, Sweden.
- 1995-7: Consulted for Korean company Woo Bo on a PRT development program.
- 1996: U of MN Dept. of Parking and Transportation told me they need my system on campus. I develop a simulation of a PRT system to connect West Bank Campus to East Bank. Many discussions about PRT for the University continued over 14 months.
- 1996: Chaired conference on PRT and related technologies, held in Minneapolis.
- 1997: I was invited to give a presentation to the Transportation Advisory Board of the Metropolitan Council. They were very interested and ask Metro Council staff to gather questions for a second meeting, which was held on October 9. Again great interest. Two days later no more discussion about PRT. Was the same year a request was being prepared for presentation to the Legislature for $100M for the Hiawatha Light Rail system.
- 1997-8: Work with Cincinnati Advanced Elevated Rail Committee resulted in their selection of my PRT system over 50 other elevated rail proposals. Was rejected by the Metropolitan Planning Organization because no demonstration system had been built.
- 1998: RTA dropped consideration of Raytheon PRT program because of excessive cost.
- 1998-9: Worked on application of my system to Mayo Clinic with cooperation from the Clinic and the Rochester Public Works Department. Laid out an application from the main Clinic building to St. Mary's Hospital. Engaged consultant to assist. New Clinic contact declined further interest because we had not demonstrated full scale.
- 1997-9: Worked with a company formed to introduce American technology in Turkey. Mayor of Ankara announced on TV that my system would be installed in Ankara. The program died for complex reasons.
- 2000: Lockheed Martin Missile Systems Division in Orlando became interested. After a full day meeting at their office, Sr. VP Dr. Harold Cates accompanied me on week-long visit to five potential applications, but the LM Board declined to proceed.
- 2000-2002: Raised $800,000 from friends to design, build and operate one automated, LIM-propelled PRT vehicle running on 60-ft guideway.
- 2003: Exhibited system at Minnesota State Fair where several thousand people were given rides with no failures, after which we were visited by the Minneapolis Mayor, Council and staff. All they talked about was where to put our system, but there was no follow-up.
- 2004: The Taxi 2000 Board of Directors, with my enthusiastic concurrence as its Chairman and CEO, determined the need to find a new CEO to assist us in finding the funds needed to build a full-scale demonstration system. The new CEO created an environment such that two other Directors and I called for an election of a new Board of Directors. A terrible fight ensued.
- 2005: I resigned from Taxi 2000 Corporation and continued further development and marketing of an improved version of my system, which I now call ITNS.
- 2007: Law suit with Taxi 2000 was settled favorably, leaving me free to continue work on PRT.

- 2008: Following a presentation to Disney Imagineering, Glendale, CA, Disney wanted to consider ITNS for their Anaheim Theme Park, but we would need to build a demonstration system first.
- 2008: Flew to Nashville to meet with two transit planners with the Vanderbilt University Medical School. Need was great, but we needed first to demonstrate our system full scale.
- 2009: Together with MTS Systems Corporation we submitted a proposal to ARPA-E, the U. S. Energy Department's equivalence to the Defense Department's ARPA, but got no response.
- 2009: I gave a paper "How to Design a PRT Guideway" at the Automated People Mover Conference in Atlanta.
- 2009: MnDOT held a forum on PRT in Rochester, MN. I was thanked publically for my work on PRT by the MnDOT Commissioner Tom Sorel and State Senator Gen Olson.
- 2009: I gave a paper "Overcoming Headway Limitations in PRT" at the PodCar Conference in Mölmo, Sweden.
- 2010: MnDOT held a Workshop on PRT at the University of Minnesota. PRT interest was later blocked by LRT interests in the Minnesota Legislature.
- 2011: Mayor of Rochester, MN, asked "when will Ed's PRT system be ready."
- 2012: Executive Director of MSP stated that he needed ITNS to bring people to the airport.
- 2012: Winnipeg interest in ITNS began.
- 2013: At the end of August, I was so certain that we had been funded that I took my wife out to dinner to celebrate. A few days later I learned that the investment source did not come through.
- 2014: Winnipeg Mayor wrote a letter stating that he would purchase a $300M ITNS once it was tested. Again, the investor did not come through.
- 2015: With conditions, an investment firm will provide $30,000,000 for our demonstration program once we have obtained a Standby Letter of Credit for $3,000,000 and a place to put our demonstration system.
- 2016: We approach MTS Systems Corporation and received, after 2 weeks investigation, a turn-down.

Chapter 5. A Position Paper

A Position Paper

THE

URBAN MASS TRANSPORTATION ADMINISTRATION'S

PROGRAM OF DEVELOPMENT AND DEPLOYMENT

OF

AUTOMATED GUIDEWAY TRANSIT

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INTRODUCTION

Several private initiatives to develop automated guideway transit (AGT) systems began to appear in the United States in the early 1960's. The motivation then was--and still is--the judgment that these "AGT" systems could provide a substantially higher level of urban transportation service for substantially lower cost. There was naturally much disagreement over the specific features of these systems, and of course, many people doubted that they would ever provide a significant contribution to public transit.

In 1966, Congress formed the Urban Mass Transportation Administration and gave it responsibility for development of new types of transit systems. But the vast majority of UMTA's activity was pointed toward distribution of federal transit funds to existing transit systems to prevent their continued decline. Most of the professionals in the transit community were understandably so busy with problems of operating, expanding or deploying conventional systems that they had little or no patience with new systems and new service concepts. As it had been decades since any new type of transit system had been deployed, few people within the industry thought at all in terms of development or deployment of new systems. There was no institutional structure related to new systems, there was no consensus that adequate transit service could not be provided by expanding and up-dating existing systems, and the increasing subsidies removed incentives for fundamental change. Nevertheless, an influential group of people felt that transit suppliers could do most of the necessary research and development on existing systems and that it was the government's business to get on with the task of development of new systems.

In the early 1970's, the "new-system" view seemed to some extent to prevail in UMTA's Office of Research and Development, but there was no real

<u>system</u> view either in terms of the level of service that ought to be provided or in terms of optimization of the physical hardware needed to reach a particular service level. In late 1970, in response to political pressure from West Virginia, UMTA let contracts for construction of the Morgantown AGT system. In 1971, they funded four companies $1.5 million each to set up AGT demonstrations at Transpo '72, Dulles International Airport, in hopes that that would stimulate cities to procure systems. In these actions, no patience with systems analysis was apparent. Things had to be built right away.

The results of Transpo '72 were disappointing. About 18 months later, Las Vegas announced that they had selected the Rohr Monocab AGT system, but the order did not materialize. While a few systems were ordered for airports and zoos, no urban area ordered an AGT system. Pressure increased for UMTA to stimulate the market, and in mid 1975 UMTA announced the Downtown People Mover Program. (DPM was a new name for the simplest types of AGT.) Cleveland, St. Paul, Los Angeles and Houston were selected for deployments in late 1976. But in 1977 the new Cleveland mayor refused the DPM funds, saying the system would be too expensive and too disruptive; and, in May 1979, the Minnesota House of Representatives voted against the St. Paul People Mover. These actions provide motivation for a review of UMTA efforts to develop AGT.

In the following paragraph, the Morgantown program is reviewed. Next, the most advanced UMTA AGT development program is shown to have serious problems, and finally the Downtown People Mover Program is shown to have been flawed from its inception. It is concluded that UMTA initiatives to develop and encourage development of new transit systems are failures. UMTA has neither developed nor absorbed the transit systems theory needed to guide the development of new systems. UMTA has not taken advantage of modern systems development techniques and procedures. UMTA has not developed a broad concept of transit service toward which new systems development programs can be aimed. Instead of facilitating the process of development of new systems, UMTA has inhibited that process. It is time to reconsider how civil research and development in the national interest should be done. A concept analogous to the agricultural experiment stations is suggested.

THE MORGANTOWN PROGRAM

The contracts for the Morgantown AGT program were awarded in December 1970 and stipulated that the first vehicles had to be running in October 1972. The prime contractor for the system was the Jet Propulsion Laboratory and the vehicles were to be manufactured by Boeing. Neither had had experience in the field of AGT. By contrast, it takes approximately seven years for a new airplane design to move from concept to flight test in companies in which there are experts in all phases of aeronautical engineering. No comparable theoretical or experimental background was available to guide the development of the Morgantown AGT system. The result was a system substantially overdesigned from the original concept of the Alden Starrcar System upon which it was based. The totally unrealistic 20-month development schedule led to a four-to-one cost overrun, thus producing a great deal of disillusionment with the whole field of AGT.

People in positions of influence, but with little knowledge of the details of the Morgantown Program, became convinced that the failure of Morgantown was somehow a failure of automation, a failure of modern technology. It became conventional wisdom that the answer was to move toward simpler systems in future deployments. But the best of modern technology never had a chance. The failure of Morgantown was not the failure of technical sophistication but the failure to understand the process of development of new systems. Instead of funding Morgantown, UMTA should have proposed a ten-year development program with all the required phases: systems and planning analysis, economic analysis, trade-off development and analysis, component design and testing, subsystem testing, more analysis, full-scale system testing and public demonstration, thorough socio-economic assessment, and only then, deployment in a city. Ample time should have been scheduled for possible changes in direction as a result of unforeseen findings. But there was no commitment to such a process. The pressures to deploy an existing but under-developed system were too strong. Perhaps landing of men on the moon made people overconfident and impatient. Whatever the reason, we have suffered for it. The Morgantown program did little to advance transit technology.

THE ADVANCED GROUP RAPID TRANSIT PROGRAM

The AGRT Program is UMTA's most advanced initiative in the AGT field. It may be thought to be a long-term system program of the type described above. Unfortunately, it is not. The reasons are: 1) that it is based upon system configurations (one an advanced version of Morgantown) that were settled upon long ago without the detailed systems analysis needed to determine optimum configurations; and 2) that basic system parameters (headway and vehicle size) were given in advance rather than as variables to be determined by analysis.

Three illustrations of the difficulties will suffice:

1) The vehicle size of 12 seated passengers was chosen together with off-line stations and networks of upwards of 200 stations without the benefit of detailed operational simulations. Subsequent simulations of similar configurations performed in the Colorado Regional Transportation District's large-scale study of transit alternatives produced the following result[1]:

> "The overall conclusion is that either an on-line, all-stop system, or an HCPRT (high-capacity personal rapid transit) system with nonstop, single-party, origin-to-destination service are promising alternatives, whereas the intermediate headway systems (including GRT) offer little, if any, improvement in service over a simple on-line, all-stop system. A system such as the high-performance PRT (now AGRT) with 12-passenger vehicles might be desirable, if operated as an HCPRT during the off-peak, and used to provide multi-party, nonstop, origin-to-destination (or origin-to-transfer station) service during the peak periods."

Unfortunately the waiting time for the latter type of group service concept quickly becomes too long to be practical as the system grows. The problem became apparent when the vehicle and passenger flows through stations were simulated. The above results mean that AGRT may not be a workable concept, except in systems with very few stations, and at best, the concept is not operationally efficient. This result has been available since early 1975 and is known to some UMTA people. Unfortunately, by picking the vehicle size in advance they locked themselves into an ineffective configuration, but to change it would require major redirection of the whole program. Because of Morgantown, it may have been felt that Congress would not tolerate a new major blunder. Thus, the AGRT program goes on, perhaps with the hope that the internal contradiction will be resolved later.

2) The guideways of the principal configurations are wide U-shaped troughs with the power rails attached to one side. Figure 2.2 from Report No. DOT-TSC-OST-77-54 (included with this paper) shows that UMTA views this configuration as the only one worth considering. Yet, UMTA's own research[2] shows that the U-shaped trough configuration has had serious and possible insurmountable winter weather problems. That this should be the case is immediately obvious to many people who live in northern climates. Snow must be melted from the whole width and length of the guideway by means of energy-consuming heaters imbedded in the concrete, the power rails ice up, and thermal cycling

of the reinforced concrete guideway is likely to produce cracks in the surface and eventually may lead to its disintegration. Moreover, a two-way configuration is 15 or more feet wide, it takes a significant strip of land, it is costly to build into a city streetscape, and it has a large visual impact.

The only substantive justification given for the U-shaped trough guideway is that, in emergencies, it permits people to escape from the vehicles onto the guideway. But considering winter weather, elderly and handicapped people, and exposed high-voltage power rails, such an escape method is inappropriate. There is a better approach to this problem.[3] It needs to be examined in a total system context in which probabilities of various failure modes are estimated and potentially serious failures are corrected by redesign. Only then can the most economical and effective escape methods be devised. One, for example, is the use of simple carriages attached to the side of the guideway and normally stored at the stations. All of these matters need to have been considered before selecting the guideway configuration.

3) The operational headway is limited to three seconds. Such a limitation is technically necessary if the vehicles use propulsion and braking through the wheels but not if linear electric propulsion and braking is used. The significance of the limitation on headway is that it provides too severe a limitation on capacity in large systems. If the system were to remain small, comparable to a downtown people mover, there is no problem, but if there is interest in expansion, as there almost always is, it may become capacity limited. By choosing linear electric propulsion and braking, and by choosing one of a number of continuous position sensing systems, an arbitrary headway limitation is avoided, and the system does not have to be rebuilt at great cost if it is expanded. Again, systems analysis shows the advantage of the choice and would have led to a configuration different from those selected

for AGRT. The question of headway is one of the most controversial in AGT development, and can be settled only through understanding of transit systems theory. See References 4 and 5.

The conclusion is that, by use of unsubstantiated intuition in parameter and configuration selection, wrong technical choices are made and the resulting systems will have serious economic, functional and service limitations.

THE DOWNTOWN PEOPLE MOVER PROGRAM

On May 24, 1979, the Minnesota House of Representatives voted 103 to 26 against the St. Paul DPM System, thus denying support for ten percent of the capital costs by the State of Minnesota. Unless a revised proposal can be made for less than half of the projected $90 million capital cost or another source of funds is found, the project is dead.

The project was defeated in a two-and-one-half hour debate on the floor of the Minnesota House mainly because the line and station configuration was not perceived to provide a significant service. Too many of the trips could be taken by walking, particularly through the skyway system. The comment that the people mover didn't go anywhere was constantly raised. Because of the topography, it could not be well connected to peripheral parking. Unfortunately, the UMTA procurement process required that the approximate route configuration be selected hurriedly during the proposal period (May 1976) before an adequate process of analysis and community involvement could be carried out, and did not permit anything but minor deviations. An important additional factor in the defeat was derived from the data of the Preliminary Engineering (PE) study, and from a Charles River Associates (CRA) review of the PE study for the Twin Cities Metropolitan Council. In a nutshell, the CRA study showed that the present worth of a 40-year stream of benefits calculated was only of the order of $60 million, whereas similar analysis showed that the present worth of the operating and maintenance costs over the same period were of the order of $100 million. Thus the $18 million local share of the capital cost was only the tip of the iceburg. Moreover, to make the patronage estimate valid, $60 million worth of fringe parking ramps would have to have been constructed and, according to CRA, these ramps would have operated at an annual deficit of up to $2 million.

The financial and planning analysis of the St. Paul DPM was based on a so-called "baseline" configuration: a two-way, U-shaped concrete trough guideway configuration 27 feet wide, upon which 33-passenger vehicles moved between on-line stations. Although this was to be a simple configuration, the consultants at one time showed 18 switch crossovers for the purpose of handling failed vehicles. UMTA insisted that the baseline procurement process was necessary in order that none of the so-called "proven" systems would be ruled out of competition. The alternative of a design competition in which suppliers would participate and explain the characteristics of their specific systems was not considered. Much emphasis was placed by UMTA on the idea that the system chosen for deployment would be one that was technically proven, by which they meant that that system had operated in some form in public service. This idea was repeated many times in St. Paul even though UMTA's own report on winter operations[2] indicated, as mentioned in the above discussion of AGRT, that the suppliers of systems that resembled the baseline configuration were having great difficulties with winter operation. As the St. Paul DPM Task Force became aware of the problem of winter operation, they modified the illustrations used in public information to a narrow guideway system and told people that the baseline system was only the most expensive of a number of alternatives and was chosen to obtain a high estimate of the costs. By the time they realized the difficulty (it should have been clarified to them by UMTA) it was too late to do anything else. By providing financial and physical data on the "baseline" system only, there was no opportunity to learn if a more cost effective, narrow guideway system, possibly with a different line and station configuration, would have been accepted. An unnecessarily rigid procurement process, the difficulties of which should have been debated, caused a great deal of wasted effort.

The recommendation to Congress to institute the DPM Program developed out of a 1975 study of the Office of Technology Assessment. As a member of the economic panel of that study, this author had no opportunity to debate the concept of the DPM Program. From the economic viewpoint, it could not have been justified. Indeed, the DPM program had been conceived in part as a result of complaints that an UMTA policy, which required that all capital grant applications be preceded by an economic alternatives analysis, prevented new systems from being selected. Instead of resolving to mount a program to develop an AGT system that could win an alternatives analysis, a decision was made as part of the DPM Program to waive the alternatives analysis. It was not difficult in 1975 to show that the type of DPM typified by the baseline configuration would be too expensive. The St. Paul study's ratio of costs to benefits well above one merely provides confirmation of a result of rather simple analysis. The St. Paul system was estimated to cost a little less than $40 million per two-way mile and the maximum flow past a point computed from the patronage analysis was less than 1500 people per hour. Characteristics like these could have been estimated roughly during the time of inception of the DPM Program and would have contributed to understanding of the economic problem. The fact that they were not considered indicates a profound indifference to the need for economic viability in AGT. Moreover, during the large-scale alternatives analysis conducted in Denver in 1974-1975 citizens groups had completely rejected the wide, two-way, concrete guideway--just the kind of configuration that formed the basis of the

DPM Program. This information, readily available at the time, was ignored. The DPM Program, unfortunately, was from its inception fated to parallel the Morgantown experience. It originated from a desire to build systems as soon as possible, and lacked understanding of the socioeconomic consequences of the technology.

A SEARCH FOR COST EFFECTIVE AND TECHNICALLY SOUND AGT

The question of developing a technically sound AGT system that would provide a substantially higher level of service than possible with conventional transit for minimum cost has occupied the attention of many people during the last quarter century. These efforts have led many inventors independently to some version of the basic concept now referred to as personal rapid transit. Unfortunately, the term personal rapid transit (PRT) is used to describe the Morgantown system and other non-optimum configurations thus rendering it all but useless without modifiers. The original concept is, therefore, often referred to as "true PRT" or, as mentioned on page 5, HCPRT. The latter designation was used to describe an UMTA "true PRT" program that was cancelled in August 1974. The HCPRT program had received an appropriation from Congress in 1973 and the detailed request for proposals had been prepared. At the time of cancellation and diversion of the funds, no hearings of any kind were held. Nonetheless, UMTA now has documented information on two true PRT systems, The Aerospace Corporation system[6] and the German Cabintaxi system.[7] The Aerospace Corporation system is also now described in a book[4] and many other forms of PRT as well as planning for them are described in the series of books PRT[8], PRT II[9] and PRT III.[10]

By analysis of the work of many investigators, it is possible to set down some basic concepts of cost-effective AGT. By "cost-effective AGT" is meant

AGT systems in which the ratio of annualized capital cost plus annual operating and maintenance costs to annual patronage, i.e., the total cost per trip is minimum. The author has developed concepts of cost-effective AGT in Transit Systems Theory[5] and in summary form in a slide presentation.[11] The results are obtained by seeking step by step to minimize total system cost. They are summarized as follows:

1) The most expensive element of an AGT system is the guideway and its support structure. Three basic factors determine its capital and operating cost: the shape of the cross section, the weight per unit length of the vehicles, and the provision or lack of provision for standing passengers. Analysis of bending, torsional and vibratory loading leads to an understanding of these factors. The optimum cross section is a deep, narrow beam with a width roughly one third the depth. The vehicles must therefore be designed to fit the guideway and not vice versa. The required guideway weight per unit length needed to support the vehicles is directly proportional to the vehicle weight per unit length. The vehicle weight per unit length is minimized if small vehicles permitting only seated passengers are used. Minimizing guideway and vehicle weight per unit length minimizes the size and cost of the support structures, minimizes right-of-way requirements, makes possible prefabrication and quick erection of the guideway, and minimizes vibrations associated with vehicles entering buildings. The resultant narrow guideway minimizes costs of winter operations and visual impact. Proper selection of the configuration can eliminate the need for guideway heating.

2) Regardless of vehicle capacity, the cost of the entire fleet of vehicles is minimized if the average trip time is minimized. The trip time is minimized if every trip is on-demand and nonstop so that vehicles wait at stations a minimum of time and do not make intermediate stops, and if the passengers are seated

so that comfortable speed changes occur as rapidly as possible. But, on-demand, nonstop service can be provided only if small vehicles are used. Thus, it is seen that the use of small vehicles leads to minimization of both the fleet cost and the guideway cost. On-demand, nonstop service is possible only if the stations are off line. But, with small vehicles, off-line stations are necessary if the capacity is to be adequate. Fortunately, if narrow guideways are used, the cost of off-line stations is less than the cost of the much longer and larger stations required with on-line-station systems. The surprising result is that cost minimization leads to the best service that can be provided--nonstop, on-demand service with a seat; and, with such service, a passenger travels with others by choice, not by necessity. A further advantage of a minimum-cost system is that, for a given cost, the service area covered is maximized.

3) If linear electric motors are used for propulsion and braking, adequate capacity can be maintained in all weather conditions because the coefficient of friction of the track does not affect propulsion and braking, and because the response time of braking can be made sufficiently short to not restrict capacity. On the other hand, if rotory motors and wheel brakes are used, larger vehicles are required for a given capacity because close spacing between vehicles cannot be maintained in all weather conditions. Hence the costs increase and the service deteriorates.

4) Power rails must be covered to minimize problems of ice formation and consequent service disruptions during severe winter weather.

5) To provide adequate service availability to the public, all critical on-board subsystems such as motors, controllers and brakes must be redundant and failure monitored, and a control strategy must be developed to permit rapid removal of failed vehicles.

6) Switching must be accomplished using mechancial moving parts in the vehicle only and not in the track. Moving track switch parts do not respond rapidly enough to remove headway limitations and require extremely high reliability. The consequent longer headway means larger vehicles for given capacity, higher guideway cost, and poorer service.

7) Controllers must be designed to sense continuously the position of the vehicle ahead regardless of its operating condition. Such controllers permit safe operation at minimum headway. Therefore, they permit the use of vehicles of minimum size and hence, minimize system cost.

8) The vehicles must be designed to protect the passengers in the unlikely event of a collision. This is possible with small, personal vehicles because of their low kinetic energy, but not with large vehicles.

9) Strategies for rescuing passengers from non-movable failed vehicles must be developed in a manner other than requiring passengers to walk on the guideway. Such a development requires understanding of the probabilities of various kinds of failures.

By careful selection of line and station locations, an AGT system designed according to the above principles operates in a cost effective manner in a small loop, in a large network, or in intermediate configurations. In small loops, however, the advantage of the off-line station is minimal but increases with system size. Likewise, in a small system, say with fewer than a dozen stations, the advantage of nonstop, on-demand service is operationally minimal but increases with system size. But, by beginning with optimal subsystems, the guideways and stations fit much more easily into the city and the network can be expanded to provide additional service without modification of the guideways or vehicles. The line configurations could be similar to those used with rail transit systems but, because of substantially lower unit costs, need not be so restricted. It is often stated that true PRT systems are effective only in large, city-wide networks. While large networks become practical and provide much better transit service, they are by no means necessary for cost effectiveness.

Energy use is minimized with a cost-optimal system. Construction energy is minimized because both guideway and vehicle-fleet weight are minimized. Operational energy is minimized because the use of on-demand, nonstop service permits satisfaction of a given demand with minimum vehicle movement. For the same reasons, operational costs are minimized.

Service in a cost-optimal AGT system is nonstop, on-demand (short wait in the rush period) at all hours, <u>private</u> with one's own traveling companions and not with strangers, and permits seating of all passengers. Wheel chairs and luggage can be accommodated. It is remarkable that such service--the best that can be provided--is not a luxury, but must be provided to minimize capital and operating costs. This is perhaps one of the features of "true PRT" most difficult to understand. One expects that economy implies discomfort. Surprisingly, mass movement of people in cities is markedly more expensive. Personal service permits use of a much lower cost guideway structure which permits the construction of many more stations for a given cost. (Compared with conventional rail, The Aerospace Corporation found that roughly twenty times as many stations can be included for a given cost.[4]) The service implications of use of cost optimal systems is therefore considerable.

Many transit analysts have difficulty understanding why the operating and maintenance costs will not be much higher with many small vehicles rather than a few large ones. One answer is to examine the detailed cost information provided in References 4, 6 and 7. Another answer is to note: 1) that with a larger number of smaller vehicles, maintenance operations can be more easily routinized and automated, and 2) that large vehicles are more difficult and expensive to handle than small vehicles. But intuition provides only a little help, one must examine the data.

A common question about the small-vehicle system relates to complexity: With all the problems seen in development of larger vehicle systems, will not the problems multiply with development of smaller, more sophisticated vehicle systems? If the cost-optimal system is developed in the manner of the Morgantown system, the answer certainly is yes. There is no question that development of a cost-optimal system requires excellent engineering and excellent management, and it must be preceded by understanding of basic transit systems theory. Without proper theoretical understanding, choices will appear to be based on subjective preference rather than on analysis. In this circumstance, an engineering team will be reduced to arguing over every point. The layman has difficulty understanding the importance of proper training of engineers placed in a specific task. For a specialized task such as discussed here, engineers need more knowledge than is obtained in a typical engineering curriculum. Without such additional knowledge, costly errors are inevitable. A small-vehicle system must be cleanly designed if it is to minimize cost. It must be subject to detailed failure modes and effects analysis early in the design program, and it must be designed to be fault tolerant. The program must not be subject to unrealistic time schedules. Only then can the resulting system provide genuinely improved public service.

Except for a brief period in 1973, there has never been an opportunity except in a most perfunctory way to engage UMTA in point/counterpoint discussion on the characteristics of true PRT. UMTA has never sponsored planning studies in which true PRT could be compared with conventional or large-vehicle AGT systems. Thus, statements UMTA makes concerning comparison of true PRT with other modes are based on unsupported intuition and not upon analysis. Consider this illustration: In the fall of 1978, during an UMTA-sponsored study of socio-economics of AGT, a study team visited Atlanta to obtain citizen information on various AGT systems, allegedly including PRT. They showed the citizen groups pictures of four-to-ten passenger automated vehicles and asked if they would ride them. The answer was that they would prefer larger vehicles because they would feel more secure. Nothing at all was said about the concept of private-party service. On this basis, the PRT option was recommended to be dropped from the study. This is typical of attempts to discredit the concept of true PRT. The concept is assigned characteristics it does not possess (in this case riding with strangers) and it is dismissed on the basis of those bogus characteristics. UMTA could clear the air a great deal simply by revealing the basis of its statements about the true PRT concept and permitting these statements to be commented upon by people who understand the concept. Many of UMTA's objections may be based on genuine misunderstandings.

Urging that the concept of true PRT be given a hearing has often produced the response that the advocates of such a hearing want everything else stopped and converted to work on true PRT. This is another of many exaggerations that have been made. Of course, work on other systems must continue, but there is a great deal of evidence that true PRT ought to be placed on the agenda. More fundamentally, what ought to be considered is the search for cost and energy optimal AGT systems. There is much evidence that that search has led to the form of true PRT described above. But all of the features of an optimal system cannot be verified without the detailed analysis and experimentation that seems now to be fundable only through governments. If true PRT were to be accepted more and more widely in an open society, it could be accepted only if it were indeed superior to other alternatives. The public will benefit from an opportunity to find that out.

THE GERMAN EXPERIENCE IN AGT DEVELOPMENT

West Germany has a cabinet-level ministry devoted to research and technology development. They are sponsoring development of three AGT systems as well as a high-speed, intercity, magnetically levitated transport system. All of these programs are long range and contain all of the steps of analysis and experimentation needed to create significant advances in the state of the art. There is no rush to deploy systems before they are ready or without thorough socio-economic analysis. One of these systems, C-Bahn, is in its ninth year of development. A loop C-Bahn system is to be constructed in Hamburg beginning in 1980. The next system, H-Bahn, is in full-scale testing in Erlangen and will probably be deployed in Erlangen; and the newest, M-Bahn, is to be built into the Hanover exhibition grounds in the near future. All of these systems will provide remarkable improvements in both cost and service over the baseline type of system described above in the discussion of the DPM Program. From many conversations with German engineers working on new and conventional transit technology over the past eight years, it is very apparent to this author that the above programs would not have been possible without the support of a ministry devoted to research and development in the national interest.

THE INSTITUTIONAL STRUCTURE OF TRANSIT RESEARCH

Trying to get an institution to do something it does not want to do is not productive. It is rather more productive to examine the institutional and decision-making structure in transit research in the United States to see if it can be improved. The results may also apply to other areas of civil research and development.

UMTA policies have been a failure not only in development of AGT but in development of Transbus.[12] Why? Is it possible for the government to lead development of innovations, or can the government only follow and regulate what exists? In military technology, the government is the buyer and the fear that the enemy will develop a superior technology is always a driving force to continual technology development and improvement. In civil technology the corresponding driving force is the market place; and for government it is, at least in word, the improvement of the public welfare. The microelectronics industry is a prime example of how civil technology works when there is little government interference. Unfortunately, it is difficult to motivate government bureaucracies along similar lines. Indeed, if AGT became too inexpensive, there would be no need of government financing of capital grants at all--government would work itself out of a job. An example of lack of concern for economics is found in UMTA's insistence on wide guideways apparently mainly because of the requirement for escape from failed vehicles. No effort to solve this problem in a cost-effective way through comprehensive systems analysis has been evident. Lacking the incentive of profits, government imposes a design configuration based on simplistic intuitive processes rather than on detailed analysis.

There is a great deal of technical talent in the United States. Our country has traditionally been a land of "Yankee ingenuity" where private inventors develop and market ideas based on resources they can obtain. Perhaps because of dominance of the automobile, transit systems development has apparently gone beyond the stage in which it can be financed privately. But, running counter to the trend, Walt Disney Corporation and Universal Mobility, Inc. both construct transit systems under private financing, albeit for special circumstances, and PRT Systems, Inc. seems about to do so too, all for substantially less per mile than UMTA-backed systems. Is there not strength through this kind of diversity? Is it not better to let the best ideas emerge in free competition? Instead of performing all physical and financial planning on a single "baseline" system and then requiring that a decision be made on the basis of that limited information, would it not have been better to expose decision makers directly to independently developed plans of a variety of suppliers?

Use of the concept of government financing of new transit alternatives through an agency primarily devoted to other matters has been a failure. The effort has been much more inhibiting than facilitating. UMTA was established in a period in which the standard solution to every public problem seemed to be a new government agency. Many people are beginning to doubt the wisdom of such a practice. Many people are beginning to think that government bureaucracies have become too large, too numerous and too ineffective. To government bureaucrats looking at problems in urban transit in 235 cities, these problems must appear staggeringly difficult--they are difficult enough in one city. To cope, bureaucrats may have to oversimplify. Government bureaucrats are usually influenced most by people they see the most. Being human, they may begin to think that the general public consensus is the consensus of the people they see. But nothing could be farther from the truth. As in St. Paul, the public sentiment rises up only when necessary to kill an illfounded proposal.

Certainly, industries need to be regulated. Technologies can no longer be developed without regard to unintended and negative side effects. The Office of Technology Assessment and other means for technology assessment are absolutely necessary in the complex, interrelated world in which we live. But just as it is essential to assess, regulate and possibly restrict the development of technologies, it is equally important to innovate in constructive directions in many civil areas. Regulators do not tend to be innovators nor innovators regulators, and when the job of innovation is given to a primarily regulating agency one can be quite certain that few if any innovations will result. If UMTA had been established when stagecoaches were dominant, the history of recent years would suggest that the lobbying efforts of then dominant stagecoach manufacturers and operators would have been able to prevent anything but improvements in stagecoaches. Now when large-vehicle transit is dominant, it is perhaps not surprising that an innovation as different as the concept described in the previous section is strongly resisted. Yet, such an innovation is needed. The problems of innovation in public transit are developed in depth by Dr. C. G. Burke in a forthcoming book (Lexington Books, 1979).

AN ALTERNATIVE

If the UMTA research, development and deployment office did not exist during the past decade, one can scarcely imagine that the AGT development situation would be worse. The hope of federal grants has dampened private initiative. Where federal grants have been forthcoming, they have been for systems far too expensive to fund privately or by municipalities. Instead of encouraging development of the fundamentals of new systems, UMTA has tended to inhibit consideration of anything but certain existing systems.

An ideal would seem perhaps to be a mechanism for public support of research and development through a number of independent agencies, say engineering experiment stations analogous to the agricultural experiment stations. Each of these stations would receive block grants from the federal government, and each would be totally independent of the others. Development of technology in universities would be done cooperatively with industry to make it relevant, and the industries involved would have to contribute, say, 20 percent of the costs so that they would be motivated to work only on potentially profitable projects. As a consequence, the present detailed federal monitoring would not be necessary to assure that the funds were wisely spent. No central federal agency would be authorized to approve specific projects, but the experiment stations would be subject to federal audit of finances and operations. Regulatory agencies such as safety agencies would be invited to comment on specific designs but would not be authorized to approve designs until they had to be certified for use. Technology assessments would be made by independent organizations, but the experiment stations would have resources needed to challenge the findings.

The need for innovations in civil technology is too urgent to drift along present paths. Frank, open discussion of failures and potentialities is badly needed.

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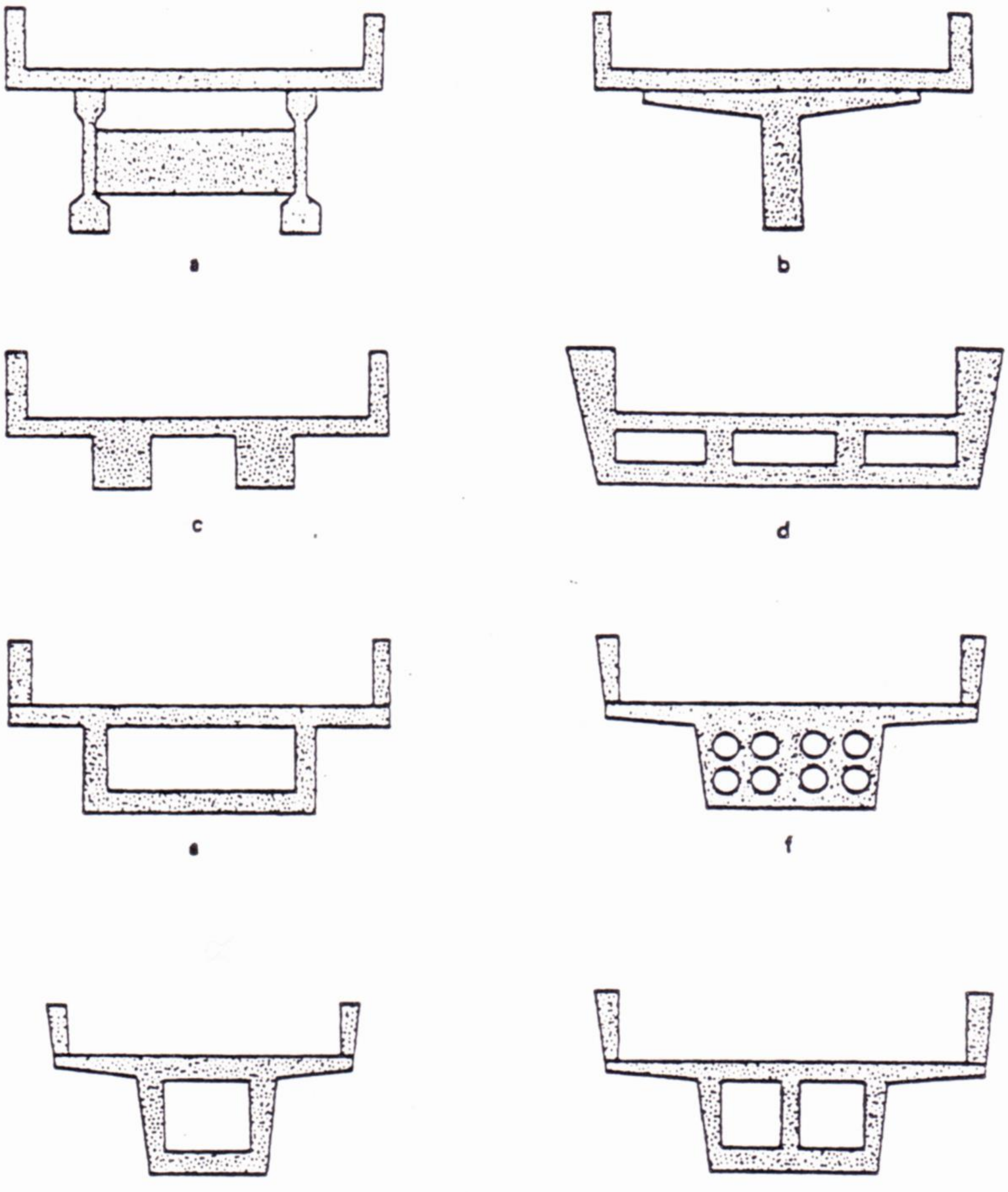

FIGURE 2.2: SUPERSTRUCTURE GUIDEWAY CONFIGURATIONS

2-10

(From Report No. DOT-TSC-OST-77-54, Elevated Guideway Cost-Ride Quality Studies for Group Rapid Transit Systems.)

Chapter 6. Rules of Engineering Design

1. Consider the system to be designed as a field of Requirements and Characteristics. It is easy for an engineer, and all too common, to jump right into specific designs before thoroughly understanding all of the requirements that relate the subject system to its environment. To make genuine progress, it is absolutely necessary to take the time to study the problem for which an engineering solution is desired in as broad an interdisciplinary context as it requires. This means understanding and documenting all of the desired performance, environmental, social, and economic requirements. By the "field of characteristics" I mean all of the alternative system characteristics. One characteristic of a transit system, for example, is suspension. A vehicle could be suspended on wheels, air cushions, magnetic fields, or sled runners. The decision as to which is most suitable requires a "trade-off" analysis, which is resolved to best meet the requirements. Detailed study of the requirements must lead to a quantitative set of criteria that will guide the design.

2. Identify all trade-off issues. Suspension as a characteristic or trade-off issue in transit design is mentioned above. We found 47 trade-off issues in transit design, which certainly is not an exhaustive list. Each issue must be considered carefully in any new design. By considering such issues explicitly with the criteria firmly in mind, the task of design is clarified and organized.

3. Without prejudice, identify all reasonable alternatives within each trade-off issue. By rushing into details too quickly, practical alternatives are often overlooked; someone else finds them and develops a superior design. Perhaps more important is that the designer who has not examined alternatives carefully before committing to a design cannot defend the design rationally and then becomes emotionally "locked in" to one approach as others point out superior alternatives. All too often such a designer causes more harm than good in advancing the design of a new system.

4. Study each alternative until the choice is clear, rational and optimal. This is hard work and is where the use of engineering science and mathematics enters. If not done rationally the design may have fatal flaws. Such a process creates designs that are difficult or impossible to better, which is the objective of a good design engineer.

5. Let the system requirements dictate the technologies. I have observed cases in which the designer had become fascinated with a certain component or technique and proceeded to design his system around it. In every one of these cases the resulting system failed to meet the system requirements and was discarded.

6. Seek and listen *humbly* to comments from any-one who will listen. By explaining ideas and listening to comments, you clarify them. A difficulty many engineers have is failing to listen humbly, particularly to an outsider. Arrogance is disastrous to good design. A good designer must be humble – a rare attribute.

7. Seek advice from the best experts available in every specialty area. It should be obvious that none of us can know the details of every specialty required, yet there is often an innate desire to try to develop the design ourselves. The best design will take advantage of the best information available anywhere, from anyone. A large portion of an engineer's work involves searching for information developed by others. In the age of the Internet, this is much easier.

8. Consult with manufacturing engineers at every stage of design. In the United States, particularly, all too many design offices have left manufacturing considerations to the end of the design process. Managers who grade manufacturing engineers lower than design engineers inform the able engineer where to concentrate. The Japanese practice of including the manufacturing engineer in every stage of the design process led to superior products that often took most of the market share.

9. Recognize that while emotion is a fundament-al driving force in human behavior, emotion must not select alternatives. Emotional commitment is vital for any human being to enter fully into a task, but it must be set aside when making design decisions. A good design engineer must be free of emotional "hang-ups" that inhibit making use of all information available. The engineer must calmly sort through the pros and cons of each approach before recommending a solution and must be willing to accept someone else's idea when objective analysis shows it to be superior. Too few engineers have a deep understanding of the subconscious factors that motivate and direct thinking. Yet it is necessary for the engineer to put the ego in the background when making design decisions. The following verse from The Bhagavad Gita, written over 2500 years ago, applies today!

"Therefore unattached ever
Perform action that must be done;
For performing action without
Attachment
Man attains the highest."

10. Recognize and avoid NIH (Not Invented Here). I worked for eight years in the Honeywell Aeronautical Division's Research Department in Minneapolis. Honeywell management established a design and production group in Clearwater, Florida, partly for the purpose of commercializing systems and components developed in Aero Research. It was found time and again that after designs management wanted commercialized were sent to Clearwater they were changed for the worse. As a result, a management policy was implemented that required that whenever a project went from Minneapolis to Clearwater, the engineers that developed it went with it to supervise the detail-design process through production.

NIH is joked about, but it can destroy the profitability of a design office. The motivating drives that produce it must be understood and controlled. The human emotion that says "we can do it better than you can" is okay if it is controlled, but when it prevents an engineering office from making good use of ideas developed elsewhere, as is all too often the case, it is destructive. I witnessed a case in which this attitude resulted in the collapse of a promising industry, from which it has taken decades to recover.

11. Consider the overall economic implications of each design decision. This requires good market and economic analysis to parallel design analysis. A design is successful if it wins in a highly competitive market, and it can do so only by taking economics into account at every step. Unfortunately, cost and economic analysis are not part of most engineering curricula so too many graduate engineers are unprepared and must learn these subjects after graduation, if they ever do.

12. Minimize the number of moving parts. I have noticed that some engineers become fascinated with extremely complex designs, but they too often are subject to more failures and end up with higher life-cycle cost. Examine carefully the function of each part.

13. Consider the consequences of failure in every design decision. It is easy to design something if failures are not considered. A good design requires that the best engineers perform careful failure-modes-and-effects analysis as a fundamental part of the design process. It cannot be just something tacked on at the end, as is too often the case.

14. Use commercially available components wherever practical. I have mentioned that the temptation to "design it yourself" is strong, but it is expensive and does not take into account that a design engineer cannot be a specialist in very many areas of engineering. There are of course times when a commercially available component just will not do, but such a decision should be made only after commercially available components are considered very carefully.

15. Design for function. Sounds obvious, but is too often overlooked. A Japanese engineer reduced the

cost of a magnetron for a microwave oven from over $500 as developed by an American engineering firm to under $5 by asking himself what the magnetron is really supposed to do. I reduced the design of an instrument from 90 parts to 19 by asking: What was the real function of the device? The new design passed a much tougher vibration specification than the previous one and led to complete domination of its market.

16. Analyze thoroughly. It is much cheaper to correct designs through analysis than after hardware is built. Analysis is hard, exacting work. Most engineers do not have sufficient mathematical background to do such work well and thus blunder along from one inadequate design to another. This "garage-shop" approach has initiated many designs, for example the bicycle and the automobile, but modern aircraft and automotive design requires a great deal of analysis corroborated by experiment. Design of a truly cost-effective, high-performance transit system requires the best of modern engineering analysis.

JEA (right) with Raytheon Marketing Vice President

Chapter 7. Optimization of Transit-System Characteristics

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The transit industry is facing declining ridership and increasing costs with no apparent end in sight. This paper takes the view that totally new solutions are needed. The approach is to examine the equation for total cost of a transit system per passenger-mile to determine how to configure a new system to minimize this quantity. Term-by-term analysis leads to derivation of a consistent set of optimum characteristic: Guideway costs are minimized by distributing the load in very small capsules. The fleet cost is minimized by increasing the average speed without increasing the cruising speed by use of offline stations, which in turn minimize energy use by permitting nonstop trips. Maintenance costs are minimized by designing a very light-weight, automated vehicle with very few moving parts. While this general configuration has been known for several decades, it has not been generally recognized that it can be derived by minimization of system costs, and that cost minimization is obtained simultaneously with service maximization. While a great deal of controversy surrounded this concept a decade ago, advances in technology make it fully practical now.

Introduction

The aim of the transit-system designer should be to choose the characteristics of his system in such a way that the life-cycle cost per passenger-mile is minimum subject to constraints on performance, safety, dependability, environmental impacts, etc. As federal capital grants decline in both percentage and amount, interest has increased in this important problem of cost effectiveness. Pushkarev (1982), based on a comprehensive study of American rail systems, concluded that the field needs a new, narrow-guideway, low-cost transit system that does not require snow melting, i.e., a much more cost-effective system.

The problem has rightly been approached by trying to shave cost of acquisition and support of more-or-less conventional systems. I have for many years tried to look at the problem from a fundamental view, Anderson (1978), (1979), (1981), aimed at clarifying the characteristics of a transit system, optimum in the sense described above. The purpose of this paper is to update and consolidate my research on transit-system optimization and to further clarify the selection of characteristics of a new, optimum transit system.

The Equation for Cost per Passenger-Mile

In Appendix A I have derived a general equation for the cost per passenger-mile of any transit system in two different ways, and in a form useful for general systems analysis. This derivation is a modification of the derivation given in Anderson (1981). The results are presented in equations (A-3), (A-4), and (A-5*)* in terms of fixed costs and variable costs. These equations are not repeated here because it is essential for the serious reader to follow the derivation if the results are to be fully understood.

Note that the fixed costs are independent of the number of passenger-miles traveled, and the variable costs are proportional to the number of passenger-miles traveled. If the variable costs per passenger-mile, denoted by ***VC****,* are greater than can be borne by a reasonable fare per passenger-mile, the system will have to be subsidized at all levels of patronage, represented by the term ***PM/YR/LMI*** (passenger-miles per year per lane mile). If the annualized fixed-facility costs per lane mile, represented by ***FC***, are high, then, as is well understood, the patronage level must also be high to bring the total cost per passenger-mile to a reasonable level.

In the following paragraphs, each of the terms in the equation for cost per passenger-mile is analyzed in terms of the system characteristics required to minimize the total cost per passenger-mile. Many inventors have attempted such cost minimization by more or less intuitive approaches, the result of which has been a number of sub-optimal systems. The approach through study of the cost equations can bring together all of the pieces of analysis and determine if, by minimizing one term, another term doesn't increase by a larger amount.

Fixed Costs per Year per Lane-Mile

The cost per year is the annual payment on the total cost. The ratio of the annual payment to the total cost is the annualization factor

$$\boldsymbol{A} = \frac{\mathbf{i}}{1 - (1+ \mathbf{i})^{-\mathbf{n}}}$$

where **i** is the interest rate and **n** is the lifetime of the equipment. The derivation of this equation can be found in any text on engineering economics. A little analysis shows that if the equipment is paid off in less than **n** years, the present value of the sum of the payments at a given interest rate is the same as if it is paid off in **n** years; therefore, it is logical to take **n** as the lifetime of the equipment. Much debate has occurred in the economic literature over what value to use for **i** for public-sector expenditures, but currently a value of 0.07 is reasonable. Using this value, we have

n, yrs.	5	10	15	20	30	40
A	0.244	0.142	0.110	0.094	0.081	0.075

The lifetime of fixed transit facilities is usually taken as about 30 years, and it is seen that there is only a small economic advantage to longer life.

Minimum fixed cost per lane-mile is attained for a transit system if the way is shared with road traffic, in which case, because transit carries only 3% of the urban passenger-miles in the United States (UMTA 1983) the way is paid for by highway taxes. In many cases, using a shared roadway is the only practical economic alternative; however, then the speed is very slow during rush periods and there are many accidents. For example, from UMTA (1983), the average number of collisions per million vehicle-miles for the average U.S. streetcar is 180, and the corresponding number for nine U.S. rail rapid transit systems is only 3.6, a ratio of 50:1. The fact that the exclusive-guideway rail rapid transit systems usually operate in trains only partially explains this large ratio. For reasons of speed and safety, exclusive guideways are used when they can be justified. I take as my objective, therefore, the reduction of the cost of these systems, but without losing sight of the need to compare them with mixed-traffic systems.

The most important factor in the cost of the roadway or guideway of a transit system is the weight of the vehicles it must carry. According to Pushkarev (1982), the damage to roads has been found to be proportional to the fourth power of the weight of the vehicles carried. The cost of a transit guideway similarly increases with the weight of the vehicles, with the power relationship dependent on cross sectional shape and other factors. The important point is that guideway cost increases as vehicle weight increases. This leads to a fundamental idea that has been expressed by many people in many ways: if the capacity of a transit vehicle can be split up into smaller units so that the load is distributed in smaller increments over the guideway, the required guideway weight per unit of length and the corresponding cost per unit of length reduce. Typical guideways for elevated rapid rail systems weigh in the neighborhood of 2000 pounds per foot. By using the above simple principle, we have found a way to reduce the guideway weight to only 100 pounds per foot. Heavier guideways not only cost more directly, they require larger equipment in manufacture and erection and more space, all of which add to the cost.

Based on guideway costs alone, the use of smaller vehicles traveling at shorter headways is a trend to be encouraged. Some analysts have argued that once the headway is down to one or two minutes, there is no point in reducing it further. Their analysis is based on the effect of reducing headway on reducing waiting time and hence on increasing patronage. The effect is very small. But a headway of one minute at say 30 miles per hour corresponds to a nose-to-nose vehicle spacing of half a mile. To obtain a line capacity equivalent to, say, two freeway lanes of automobile traffic, roughly 4000 people per hour, at one minute headways requires an average of 67 people per vehicle or train. If this capacity could be provided in units 1/60th as large, traveling at nose-to-nose spacings of 44 feet, the loading on the guideway is substantially reduced, and so is its cost. This is a principle that has been advocated by many people over the past 30 years — the question is how to achieve it practically. The main objective of headway reduction, at this point in the analysis, is guideway cost reduction, not reduced waiting time.

Other design choices affect the weight and cost of the guideway:

1. Standing vs. seated passengers. If the vehicles are designed to permit adult passengers to stand, they must be higher and wider than if they are designed for seated passengers. Several analyses, including my own, show that the requirement of standing passengers roughly doubles the weight per unit of length of the guideway. Standing-passenger vehicles require that the fore-and-aft and lateral accelerations be restricted to about one-eighth of gravity, whereas, if all adult passengers are seated, these values can be doubled. The result is reduction in curve radii of a factor of two, which is often critical in engineering the system into a city without tearing down buildings. A third factor favoring the smaller cross-section of seated-passenger vehicles is air drag reduction. This has not been a major factor in large trains that stop frequently, but becomes more important as the vehicle size reduces.

2. Optimum cross section. As shown in Anderson (1978), there is always an optimum cross section that minimizes the weight and cost of a guideway per unit of length. The optimum is a narrow, deep beam. To make use of this fact of structural theory requires, however, that the vehicle be designed to fit the requirements of the guideway, and not vice versa, as has so often been the case. The narrow beam also has the advantage of being the smallest in visual impact and the easiest to engineer into the city.

3. Hanging vs. supported vehicles. Some inventors who have appreciated the obvious advantages of narrow-beam guideways have assumed that the vehicle must hang from the guideway. The main cost increase if this is done comes from the requirement for a certain clearance for road traffic. If the vehicles hang from the guideway, it must be roughly eight feet higher from the ground than if the vehicles ride on top. Moreover, the hanging vehicle requires that the guideway support post must be cantilevered. Analysis shows that the lateral bending moment at the root of the support posts due to maximum cross winds and vehicle weight is roughly twice as large if a hanging-vehicle configuration is used.

4. Guideway heating. Pushkarev (1982) makes a particular point of the large increase in operating cost that result in climates in which ice and snow are present in guideway transit systems that require snow melting. Because of the use of electric power rails to provide power to the vehicles, it is impractical to remove snow by mechanical means without damaging these rails. Therefore, heaters have been embedded into the guideways to melt snow. Unfortunately, the amount of energy required to remove snow in this manner is greatly increased (80 calories per gram).

The answer is not in cleverer methods of removing snow, but in the development of a configuration that requires very little if any snow removal. This is more difficult in supported-vehicle systems than in hanging-vehicle systems, but, because of the higher foundation costs of the latter, is worthy of serious attention in the configuration design.

A final factor in the fixed costs per lane-mile is the requirement for land. This is often neglected because public land is used, and taking the land is then not a direct cost. Yet, with light rail transit (LRT) systems operating on city streets, the required width for a two-way system is about 27 feet. The main purpose of LRT is to penetrate the downtown during the rush periods, when the automobile traffic is the heaviest. Fixed costs will then be increased by the need to construct multi-story parking structures to replace on-street parking. Minimization of land-condemnation requirements and costs is compatible with the use of minimum-width guideways.

This section can be summarized with the observation that the trend in designing minimum-cost-guideway transit systems should be toward the smallest practical vehicles, designed for seated passengers only, riding on top of optimum-cross-section guideways that require no heating. Use of very small vehicles requires automation, and we will show that the need for cost reduction in guideways is a more important reason for moving toward automation than the reduction of operating costs.

Stations

Station costs increase with the size and number of vehicles that must be accommodated at one time, and with the amount of space required for waiting passengers. Smaller vehicles operating at closer headways reduce the required platform length as well as the passenger wait time, thus reducing the space required for waiting passengers. Maximum station throughput is attained by using a platooning operating procedure, such as described by Dais and York (1973). As an example of the station platform length reduction possible, Anderson (1980) showed that the maximum station flow during the busiest hours at the busiest station of the Philadelphia Lindenwold rapid rail system could be handled by three-passenger vehicles in a platooning operation using nine station berths. The present system uses eight-car trains, requiring a platform about 560 feet long. A nine-berth station for three-passenger, automated vehicles would be 81 feet long, a ratio of 6.9:1. Moreover, the required line headway for the small vehicle system would be 1.14 seconds.

The costs of the guideways of a transit system can be considered the economic drag on the system, whereas the stations are the economic generators. The more stops that are added, the greater is the accessibility to the system and hence the greater the potential patronage. The problem with conventional transit systems is that adding stations slows the average speed because it increases the number of stops per trip. This is the fundamental dilemma of on-line-station transit systems: high speed is attained with wide station spacing and hence poor access; yet good access requires close station spacing, which results in low average speed. People do not ride the system either because it is too slow or because they can't get to it conveniently. The answer is a new configuration using off-line stations. This is not new, but has been considered for over 30 years. The reason for off-line stations primarily is not capacity, as widely assumed, but speed. Adequate capacity can be obtained by the above-mentioned platooning operational procedure, but adequate speed requires that the trip bypass intermediate stations. Use of nonstop trips permits saving of the kinetic energy that is lost each time the vehicle stops and provides remarkable improvements in service.

Freed of the speed limitation on station spacing, we are able to consider the economics of adding stations without loss of patronage due to speed reduction. The problem is solved mathematically in Appendix B, in which a criterion is derived to show whether or not adding a station increases or decreases the total cost per passenger-mile. In the example shown, substantially smaller station spacing would be economical if adding stations does not reduce the average trip speed.

Vehicle Cost Characteristics

The variable cost term in equation (A-3), ***VC***, is composed of two terms, given in equation (A-5). The first term is related to vehicle capital costs, and the second to operating and maintenance costs. In this section, I consider the numerator of the first term. The factors involved are the manufacturing cost of a vehicle per place, the associated support-service capital costs, the lifetime of the equipment, and the size of the maintenance float.

On page 98 of Anderson (1978), I plotted data from the Lea Transit Compendium showing that the quoted capital cost of transit vehicles per unit of capacity or per place is not dependent on vehicle capacity. In particular, there is no economy of scale in going to larger vehicles. In these considerations, the capacity is not the number of seats, but the manufacturer's quoted design capacity including standees. To update this information, I give some more recent information taken from Thompson (1982) in Table 1. By comparison, in the data shown in Anderson (1978) the Morgantown system gave the highest cost per place, and was about three times the average of the 28 other systems shown. The Fairlane system is clearly very much out of line in Table 1. According to industrial sources, a

Table 1. Economic Data on Automated Guideway Transit Systems

System	Total Cost per Lane-Mile	Vehicle Capacity, Places	Vehicle Cost per Place	O&M Cost per Place-Mile, ¢	Average Speed, mph
Airtrans	$7,240,000	40	$9,300	4.3	10
Atlanta	29,900,000	80	10,200	4.4	13
Busch Gardens	5,300,000	96	6,700	8.8	11
Disney World	21,420,000	20	8,300	1.5	5
Fairlane	15,300,000	24	23,700	45.6	10
Houston	16,100,000	36	5,900	26.1	6
King's Dominion	4,100,000	96	6,100	0.9	6
Miami	29,000,000	99	2,900	1.5	17
Minnesota Zoo	7,000,000	94	10,400	32.1	7
Morgantown	18,300,000	21	14,000	8.7	17
Orlando	19,200,000	100	7,050	2.2	21
Seattle-Tacoma	30,500,000	102	6,300	1.6	9
Tampa	16,100,000	100	5,240	2.6	9

Source: Thompson (1982)

180-passenger LRT vehicle currently costs about $1,000,000 or about $5600 per place. A 60-passenger city bus costs about $150,000 or $2500 per place. By comparison, contemporary modestly priced automobiles cost in the range of $2000 per place and the job-shop price quote on a new three-passenger automated vehicle I have been working on is about $7600 per place. A chart in Anderson (1980) shows that the weight per place of transit vehicles is also remarkably in the same range. Thus, transit vehicles cost roughly in the same range per pound regardless of their size, and this cost is substantially higher than the corresponding cost of automobiles.

Large transit vehicles are manufactured in low quantities; it takes large shops in which to make them, and large cranes to move them. Smaller vehicles can take greater advantage of higher production techniques. They can be made in smaller shops and with lighter, cheaper equipment to move them around. Longer transit vehicles have longer wheelbases, which require heavier support beams, which increase the weight and cost per unit of length. The important point is that if a designer has low cost as an objective, he can design a transit vehicle in the same range of cost per place regardless of size and in spite of the fact that there are more motors, wheels, etc.

In the discussion of guideway cost, the cost advantage in the use of small vehicles was shown. A response could have been, on intuitive grounds, that that may be true but that it would increase the cost of the vehicle fleet if the same total capacity were attained using small vehicles. The above data show that that is not the case. Indeed, for reasons discussed below, the vehicle cost per passenger-mile is actually decreased if small vehicles are used.

Less data are available on the corresponding ***SMA*** cost per place, i.e., the cost for storage, maintenance and administration. The first of these is related to the storage volume, which should be roughly the same for a given number of places. The second is related to the maintenance float. The term ***TV/OV*** in equation (A-5) is the ratio of the total fleet to the rush-period operating fleet. From UMTA (1983), the Section 15 Data Report, this ratio for the average U.S. city bus system is 1.32, for streetcars 2.07, and for rapid rail systems 1.31. If ***TV/0V*** can be reduced, a double cost advantage accrues: fewer vehicles need be purchased, and less maintenance space and cost are required to service them. Small, lightweight vehicles have the advantage that it is easier to over-design bearings, wheels, etc. for longer life. In an exclusive-guideway system, it is possible to reduce damage because there are no potholes. By modular design, the mean time to restore service of a vehicle can be reduced by replacing the faulty part, returning the vehicle to service and repairing it separately. Larger vehicles are harder to handle in a maintenance shop, which contributes to lengthening the time to restore service. We estimate that with available techniques of modular design and available technology, it should be possible to reduce the quantity ***TV/OV*** to about 1.02 for an exclusive-guideway, small-vehicle, automated transit fleet, particularly if care is taken in the design of the guideway to remove all causes of sharp bumps.

Peak-Period Average Speed

The component of total cost per passenger-mile due to the capital cost of the vehicle fleet is inversely proportional to the peak-period average speed. The number of vehicles required is determined by the peak-period flow of people per unit of time, and for example, would be cut in half if the peak-period average speed can be doubled. Mathematically, these facts can be seen by studying equations (A-5) and (A-7). The average speed was discussed in the above section on "Stations" in terms of the reduction in ridership if the average speed is reduced. Here speed enters the analysis in terms of the number of vehicles required.

The average speed depends on the distance between stops, D_s; the line speed, V_L; the dwell time at stops to load and unload passengers, t_D; and the comfort rates of acceleration, **a**, and jerk, **J**. It is given by the well-known equation Anderson, (1978):

$$V_{av} = \frac{D_s}{D_s/V_L + V_L/a + a/J + t_D}$$

$$= \frac{V_L}{1 + V_L T_{ex}/D_s} \qquad (1)$$

in which

$$T_{ex} = V_L/a + a/J + t_D \tag{2}$$

is the excess time associated with each stop.

Note that if the length $V_L T_{ex}$ is small compared with D_s the average speed is close to the line speed. Consider an example with conventional transit vehicles, which permit standing passengers. The acceleration, a, can be no larger than about 4 ft/sec^2 and a/J can be taken as about one second. Assume a line speed V_L of 30 mph or 44 ft/sec and t_D = 20 sec. Then T_{ex} = 32 sec. and $V_L T_{ex}$ = 1408 ft. or 0.27 miles. If the line speed were increased to, say, 40 mph in an attempt to increase the average speed, $V_L T_{ex}$ = 0.40 miles, thus making the increase in V_{av} less than proportional to V_L.

To provide adequate access to the community, transit operators like to permit their buses or streetcars to stop at least every two to four blocks, i.e., every one-eighth to one-quarter mile. In these cases, using the above numbers, which are typical, equation (1) shows that the average speed can be only one-third to one-half of the line speed, or 10 to 15 mph. According to APTA (1981), the average speeds of U.S. transit systems are:

	Bus	Light Rail	Heavy Rail
Average Speed, mph	11.8	9.6	19.8

Note also the range of average speeds of the systems listed in Table 1.

Because of the use of exclusive guideways and wider station spacings, the average speed of the heavy rail systems is almost double that of systems that operate in mixed traffic. For example, if V_L = 40 mph and t_D = 30 seconds, equation (1) shows that an average speed of 19.8 mph is attained if the distance between stops is one-half mile.

A problem with the above data is that it is not clear if it refers to daily average speeds or peak-hour average speeds. During the peak period, the non-exclusive-way systems are slowed the most by other traffic, and during this period, the vehicles stop most frequently and the dwell times are the longest. I have observed many times dwell times of streetcars and heavy rail trains during peak-load periods well above a minute. With t_D = one minute, V_L = 30 mph, and D_s = 0.25 mile, V_{av} = 8.8 mph.

It is clear that increasing the rush-period average speed is, according to equation (A-5), important in reducing the cost of the vehicle fleet, if such an increase doesn't in itself cause some other increase in capital or operating cost associated with increased speed, such as the need for larger motors or greater energy use. The answer does not lie in a brute-force approach but in a configuration change. The best that can be done is to configure the system so that the trip is nonstop at uniform speed with minimum station dwell time. The former is achieved by use of off-line stations and the latter by use of one-party vehicles. Both of these conclusions, arrived at independently from the conclusions of the preceding paragraphs, are compatible with them. As has been mentioned, the use of nonstop trips at uniform speed markedly decreases energy use. This was shown by Anderson (1981).

With nonstop trips in single-party vehicles permitting only seated passengers, we can let $\boldsymbol{a}$ = 8 ft/ sec^2 and $\boldsymbol{t_D}$ = 10 sec. Then, with a line speed of 30 mph and an average trip length of two miles, equation (1) gives $\boldsymbol{V_{av}}$ = 28.1 mph, almost three times the average speed of bus and streetcar systems. Thus, the factor of speed alone reduces the fleet cost of an optimum system to roughly one-third that of a conventional system.

The Ratio of Yearly to Peak-Hour Travel

Because the number of vehicles required in a transit system is proportional to the peak-period flow, the vehicle capital cost per passenger-mile is independent of the total flow of passengers, but is inversely proportional to the ratio of yearly to peak-hour travel. This is shown in equation (A-5). The latter quantity can conveniently be expressed as the product of two ratios: the number of peak-hour equivalents of travel per week-day, ***PK-HR/DAY***, and the number of week-day equivalents of travel per year, ***DAYS/YR***.

Table 2. The Ratio of Weekday Travel to Peak-Hour Travel by Several Modes

Mode	***PK-HR/DAY***
Suburban Taxi	12.2
Suburban Auto	11.4
Manhattan Buses	10.0
Walking to and from Manhattan Apartments	9.3
New Haven Buses	8.3
Stamford Buses	7.9
Hartford Buses	6.5

Manhattan Rapid Rail	6.0
Canadian Bus System	5.0
Manhattan Commuter Rail	4.2
Common U.S. Bus System	3.3

Source. Pushkarev and Zupan (1977)

Some observed values of ***PK-HR/DAY***, taken from Pushkarev and Zupan (1977), are listed in Table 2. The most highly peaked travel occurs in the Common U. S. Bus System, which evidently is used almost wholly for work trips. Since it is very expensive to operate such a system in the off-peak periods, the time between buses must be cut back sharply then, thus markedly decreasing the attractiveness of off-peak service. Note, from Appendix C, that the ratio ***PK-HR/DAY*** for the Lindenwold-Philadelphia commuter line is t_D/t_h = 1/0.252 = 4.0, very close to the corresponding value for the Manhattan system.

The values in Table 2 for the Canadian and U. S. bus systems are taken from comments of Pushkarev and Zupan (1977) at the end of their Chapter 4. These values indicate that it is more common for bus systems to be used almost wholly for the work trip. As the transit service becomes better for a larger portion of the day in transit-oriented cities, ***PK-HR/DAY*** increases, and except for the Manhattan bus system, is highest for demand-responsive modes. Because a very large portion of people living on Manhattan Island are transit dependent, its ratio of daily to peak-hour travel is typical of demand-responsive modes.

The characteristics of a minimum-cost transit system, as have been emerging from this analysis, provides virtually no-wait, nonstop, private service in seated comfort 24 hours per day. This means of travel is available when needed, as is the case with walking or automobiles and to a lesser extent with taxis. As a result of these characteristics, in the economic tabulations given later in this paper we take for the optimum system a value ***PK-HR/DAY*** = 11.5.

For the value of yearly to weekday travel, ***DAYS/YR***, Pushkarev (1982) uses 280. This includes 256 weekdays per year plus 22 percent of the remaining 109 weekend days and holidays. The service of the optimum system should attract a considerably larger portion of the weekend and holiday travel. The actual value will vary and must be determined from experiments not yet possible, but for the tabulations, I assume that a reasonable value includes as weekend and holiday travel 50 percent of weekday travel. Then ***DAYS/YR*** = 256 + 0.5(109) = 310.

Average Load Factor

The load factor is the ratio of the number of passengers per vehicle to the vehicle capacity. Equation (A-5) shows that the peak-period average load factor enters into the denominator of the expression for vehicle capital cost per passenger-mile, and the daily average load factor enters into the denominator of the expression for O&M cost per passenger-mile. If other factors are not worsened in the process, it is clearly desirable to configure the system so that these two load factors will be as large as possible. It is not practical to do this by changing the behavior of people. This has been tried as "ride sharing" during periods of energy shortages with marginal success, and requires people to suffer inconveniences. It is better to try to change the physical configuration of the system so that the load factor will naturally be higher.

Appendix C shows how the peak-period average load factor relates to the daily average load factor for scheduled systems and that these two quantities will be about the same in fully demand-responsive systems. In particular, equation (C-9) shows that the ratio of peak load factor to daily load factor for scheduled systems is

$$LF_{pk}/LF_{av} = \frac{\Sigma\, t_i / c_i}{PK\text{-}HR/DAY} \qquad (3)$$

The numerator of equation (3) is dependent on the schedule used. If vehicles were to operate on the same schedule day and night, which would be required to provide the same level of service, the numerator of equation (3) would be 24. In the systems used as examples in Appendix C, this factor is in the range of 13 to 14. To drive down costs, this factor must be reduced, but to increase service, it must be increased. Using values of ***PK-HR/DAY*** given in Table 2, we can find the ratio of peak to average load factor. It is seen that this ratio usually falls between two and four, with an average close to three. For the Twin City Area bus system, we found that this ratio is about 3.3.

Daily average load factors can be found from the UMTA Section 15 Report (1982) by dividing passenger-miles per year by capacity-miles per year. The results are

Motor Bus	0.223
Rapid Rail	0.110
Streetcar	0.187
Demand-Responsive Systems	0.141

The demand-responsive systems are manually driven dial-a-bus systems. As shown in Table 3, they average about 13 places per vehicle or only about 1.8 persons per vehicle—close to the average for the automobile.

Optimization requires reconfiguring the system so that $\boldsymbol{LF_{pk}}$ and $\boldsymbol{LF_{av}}$ are as high as possible. To be consistent with conclusions reached in connection with minimization of guideway and vehicle-fleet costs, we want to see if this can be done with small, automated vehicles. From the above data on demand-responsive systems and the discussion at the end of Appendix C, it is seen that the two load factors will be the largest if the size of the vehicle corresponds to the size of groups of people traveling together by choice. Moreover, with very small vehicles the peak- and daily-average load factors should be about the same.

The load factors are obviously the largest if the vehicle holds only one person; however, this is not socially acceptable. If the vehicle holds two persons, it is still a bit small to carry one person and much luggage, groceries, etc., and may not be able to accommodate a wheelchair. Also, if an odd number of people are traveling together, one of them must be isolated in a single vehicle – a socially awkward practice. If the vehicle holds three persons in side-by-side seating, none of the above problems is serious. Also, as shown by Kuzmyak (1981) and Ryan (1983), typically about 95 percent of the trips in urban areas are taken with one, two or three people traveling together. If the vehicle has four seats, it is too wide for side-by-side seating; therefore, designers of such vehicles have used two-forward and two-backward seating. Unfortunately the vehicle is then longer, which reduces capacity somewhat, and it is more difficult to provide for the ultimate safety of the passengers in a collision, however unlikely it may be. With the three-passenger, side-by-side seating, a padded dash and airbag can easily be used for ultimate protection. For these reasons, the three-passenger vehicle is the best choice if the vehicles have no paid drivers. In purchasing a private automobile, other considerations, such as the desire to use the vehicle for long trips and the occasional use for more than three people, enter the decision calculus. In a public system, where the trip is relatively short and where another vehicle is easily available, the advantage of more than three seats is lost.

Counting empty vehicles recirculating to pick up passengers in a three-passenger vehicle system, computer simulations and studies using the method of Anderson (1982) have shown that the fleet average vehicle occupancy will be roughly one person, giving $\boldsymbol{LF_{pk}} = \boldsymbol{LF_{av}} = 0.33$.

Table 3. Operating and Maintenance Costs per Place-Mile

	Vehicle Capacity	*O&M COST PER PLACE-MILE, ¢*
Automobiles		
Large	6	3.2
Intermediate	6	2.9
Compact	5	3.1
Subcompact	4	3.6
Conventional Transit		
Rapid Rail	203	2.2
Streetcar	116	5.1
Trolley Bus	75	5.2
Motor Bus	67	4.7
Dial-a-Bus	13	12.6
Automated Transit		
Fairlane	24	45.6
Houston	21	26.1
Morgantown	20	8.7
Airtrans	40	4.3
Westinghouse	96	2.9
Disney	4	1.5
ATS PRT	3	2.6

Sources: Automobiles: FHWA (I 982)

Conventional Transit: UMTA (1982)

Automated Transit: Thompson (1982)

ATS Alpha: Company Data

Operating and Maintenance Costs per Place-Mile

Table 3 lists O&M costs per place-mile for a variety of urban transportation systems. The capacity of the conventional transit systems is taken as the total number of capacity-miles of U.S. transit systems divided by the total number of car-miles. Note that the conventional transit systems have paid operators, whereas operator wages are, of course, not included in the auto costs. The general similarity of these costs on a per-place-mile basis is remarkable considering, for example, that 203 intermediate-automobile places have about 17 times as many wheels and motors as one rapid-rail car. Of the vehicles using paid drivers, dial-a-bus systems have the highest O&M costs per place-mile because the wages of the drivers are amortized over the fewest places; yet, if the driver wage rate were the same as for motor buses, the O&M cost per place-mile for dial-a-bus systems would almost double. Manually driven vehicles requiring paid drivers must be large to amortize the driver wages over a reasonable number of passengers. If there is no paid driver it is clear from the general trend of the data that there is no inherent advantage to large vehicles-indeed, large vehicles have the disadvantage of providing poorer service.

The O&M cost experience of the early automated-transit systems, however, varies widely on a per-place-mile basis. While the source of the data does not explain why the Fairlane and Houston systems are so far out of line with the rest of the data, the data do not show that vehicle size is the explanation. The high values for the Fairlane and Morgantown systems are partly explained by their location in cold-winter environments and their need for snow melting. Pushkarev (1982) stresses the cost deficiency of systems like this that use wide guideways. The cost given for Westinghouse is the weighted average of five airport systems operating either in warm climates or underground.

If the first three automated systems listed were thought to be representative of what can be done with automation, it would have to be concluded that automation is a failure in terms of lowering operating costs. Clearly, one must be careful in designing automated systems if cost reduction is the goal. The expensive systems are, however, relatively low-use systems and Thompson (1982) lists the weighted average O&M cost per place-mile of 15 systems as 4.2 cents, about ten percent less than for the conventional motor bus.

The last automated system listed is a system I designed but have not yet operated. I estimated the O&M cost per vehicle-mile of a three-passenger automated vehicle, with special design features aimed at cost minimization, by computing the energy required (see Anderson (1981)), and the cost of worn-out part replacement, cleaning, maintenance labor, and general and administrative costs. Instead of trying to defend these numbers, which will be considered speculative until test data are available, I will explain why I think they are reasonable in a careful design: the vehicle uses linear induction motors driven by commercially proven variable-frequency drives, a no-moving-parts propulsion and braking system markedly simpler than that of an internal combustion engine, transmission, drive train and braking system for an automobile. Wheels are used for vertical and lateral support in a guideway that does not require guideway heating. With a very lightweight vehicle design, the load-support bearings operate at loadings so light that the supplier's experience indicates that they will last the ten-year projected lifetime of the vehicle. Data on the required frequency of tire replacement are obtained from experience with similar loadings in similar environments. Data on vehicle-cleaning costs are obtained from consultation with car-wash operators. The wheels run on smooth steel surfaces with no potholes, no salt, in the shade of the guideway, under conditions of excellent ventilation. Compared with the environment an automobile operates in and the comparative complexity of its suspension and drive train, we believe that our estimate of 2.6 cents per place-mile, or 7.9 cents per passenger-mile, is high.

Passenger-Miles per Year per Lane-Mile

Equation (A-3) shows that the fixed costs of a transit system per passenger-mile are inversely proportional to the patronage in terms of the number of passenger-miles per year per lane-mile, ***PM/YR/LMI***. Table 4 shows, along with other data, the 1982 values of **PM/YR/LMI** for American rail systems. The ratio of the largest to the smallest value for both heavy rail and streetcar systems is about seven; consequently, for given fixed cost per lane-mile, the economic viability of these systems varies in the same proportion. Recent estimates for two new heavy rail systems, one in operation and one planned, are as follows:

City	Fixed Costs, $M/LMI	PM/YR/LMI	Fixed Costs per Pass-Mi, $
Baltimore	49.8	2,360,000	2.15
Houston	57.7	13,250,000	0.44

In computing the last column, a value of the amortization factor ***A*** = 0.102 was used.

The system found to minimize guideway and vehicle-fleet costs is a novel fixed-guideway system using three-passenger vehicles operating under automatic control. There has been much debate over whether or not economically significant travel can be attained in such systems at practical time headways. Therefore, in Appendix D I have derived the relationship between ***PM/YR/LMI*** and the peak-hour time headway. A number of investigators including Irving (1978) and Anderson (1978) have shown how to configure a small-vehicle automated system so that a line headway of one-half second can be attained. If that flow occurs in rush-period travel where all of the vehicles in the busiest direction are occupied with, say, 1.3 persons per vehicle, then, using the numerical values given in Appendix D we find that ***PM/YR/LMI*** = 33,368,400. From Table 4 we can see that even if this value is discounted by a substantial amount, there are many applications in which current flows can be handled by the small-vehicle, optimum system.

For many analysts, the so-called "brick-wall" emergency-stopping criterion is inviolable. For a speed of 30 mph this criterion corresponds to a time headway for a small-vehicle system of about two seconds (Anderson (1978)). Using this criterion, the maximum value of ***PM/YR/LMI*** is over 8,000,000. Consideration of Table 4.shows that there are many applications in which the small-vehicle system can handle the traffic with no controversy. Indeed, early applications requiring only a few miles of track cannot approach such values of ***PM/YR/LMI***. Thus, there is plenty of time to obtain the necessary experimental data to determine the ultimate limit of the small-vehicle system before committing to it.

Along a given corridor or in a given portion of an urban area, it is intuitively obvious and has been shown by experience that improved service increases ridership on a transit system and that cost increases decrease ridership. The remarkable consequence of the process of optimization developed in this paper is that, in every case, reconfiguration of the system to lower an element of cost led to improved service, so that, as has been described, the service is available with little or no wait on a 24-hour basis, nonstop, fast, comfortable and private. Moreover, the economics of use of off-line stations is such that substantially closer station spacings and hence greater access to the community are practical. Studies such as those of Golob and Dobson (1974) show that such features will make the demand for service higher. How much higher can be answered in fact only by experience.

As an example, consider the possible increase in ridership due to decreased trip time. Using the well-established logit mode-split model, the ratio of use of two modes in which the only difference is that one gives a trip time shorter by the time Δt compared to the other is $e^{(\alpha \Delta t)}$. Consider a typical urban transit trip of length three miles. A typical bus speed would be 11 mph, and as discussed above, the small-vehicle, off-line-station system could average 28 mph. Using these values, Δt = 10 minutes. The value of α used by consultants (see, for example, Anderson (1976)) is roughly 0.3. In this case $e^{(\alpha \Delta t)} = e^3 = 20$. The new mode virtually replaces the old, and may even be competitive with the auto.

Table 4. American Heavy Rail and Streetcar Systems.

City	Ave. Speed, mph	Ave. Age of Fleet, yrs.	*TV/OV*	*PM/YR/LMI*
Heavy Rail Systems				
New York City	15.4	19.9	1.28	48,600,000
Washington, D. C.	19.9	4.2	1.18	21,000,000
Chicago	25.6	19.1	1.25	12,900,000
Philadelphia	15.4	31.9	1.64	10,300,000
Atlanta	21.9	1.3	2.36	8,790,000
San Francisco	27.4	7.7	1.43	8,480,000
Boston	22.0	18.9	1.55	7,720,000
Cleveland	23.7	22.6	1.35	6,700,000
Camden	29.0	29.0	1.67	
Streetcar Systems				
Cleveland	15.8	15.8	1.28	5,100,000
San Francisco	11.5	11.5	2.17	4,530,000
New Orleans	8.7	8.7	1.75	2,970,000
Newark	14.6	14.6	1.63	2,260,000
Pittsburgh	11.8	11.8	1.51	2,010,000
Philadelphia	9.0	9.0	1.64	1,220,000
Boston	15.2	15.2	4.24	744,000

Source: UMTA Section 15 Report (1983)

A final and very important consideration is that the small-vehicle system using off-line stations is very suited to freight movement, whereas conventional transit has not been found to be so. Inconvenience and security problems have required separate freight movement. There has been little work on freight movement, but I was able to estimate (Anderson (1974)) that the potential for freight trips in urban areas in units about the size of the small vehicle derived in this paper is about the same as the number of passenger trips. It is important to note that these trips can be made in the off-peak periods, thus, from equation (D-4), they might double ***PM/YR/LMI*** by doubling the ratio of trips per year to trips per peak hour without decreasing the rush hour time headway. Some of the freight trips, for example for mail, can be handled by passenger vehicles, and some will require special freight vehicles. The vehicles could be pallets designed so that various freight containers could be clamped to them.

Data Synthesis

Up to now, I have examined each term of equation (A-4) and equation (A-5) to determine how to configure the system so that the cost per passenger-mile for both capital equipment and operation is minimized. Now it is necessary to combine all of the results by considering specific representative examples of the conventional systems and comparing them with an optimized system. I have worked on this problem for many years at the University of Minnesota and have developed a system in which each characteristic and each parameter has been carefully chosen to minimize the cost per passenger-mile. My colleagues and I have gone to potential suppliers and subcontractors to obtain estimates of the costs of all subsystems as well as all phases of site engineering, installation, and operation. Our system is a version of personal rapid transit we call "ATS Alpha" and its characteristics are listed in the fourth column of Table 5 in comparison with representative numbers for the three most common conventional modes of transit.

The fixed facility cost listed in Table 5 for light rail transit (LRT) is the average of systems under construction in Pittsburgh, Toronto, Calgary, Portland and Vancouver taken from a paper by Cervero (1984). The estimated cost of the Buffalo LRT system, $42.4M per lane-mile, was not included because most of this system is tunneled, making it more representative of rail rapid transit (RRT). The corresponding value for RRT is the average of the costs of the Baltimore and Houston systems, given above. The current estimated cost of the Los Angeles system of $93.5M per lane-mile, another tunneled system, was not averaged in. The reader can of course make his own calculations for particular systems. The fixed-facility cost of ATS Alpha is a job-shop price and does not reflect further cost reduction possible with use of modern production techniques.

No fixed-facility costs are included for bus systems. All of these costs are assumed to be included in the term SMA (storage, maintenance and administration) in equation (A-5), since these costs are assumed to be proportional to the fleet size. While bus operators generally do not pay costs of road construction and repair except through fuel taxes, bus weight per axle is considerably higher than auto weight and on many roads is applied much more frequently than the weight of an occasional large truck. As already mentioned, Pushkarev (1982) refers to Federal Highway Administration data showing that the damage to roads is proportional to the fourth power of the weight per axle. Since road taxes do not follow this power law, it is not correct to assume no cost for the roadway for bus systems. Unfortunately, I am aware of no data that would permit the required value of roadway costs for bus systems to be computed. The bus costs must be viewed with this uncertainty in mind.

Table 5. Economic Analysis of Transit Alternatives

	Bus	LRT	RRT	ATS Alpha
Fixed-Facility Cost per Lane-Mile	0	\$12.9M	\$53.8M	\$4.5M
Interest Rate per Year	10%	10%	10%	10%
Fixed Equipment Lifetime, years	–	30	30	30
FC	0	\$1.37M	\$5.71M	\$0.45M
Vehicle + SMA Cost per Place	\$3,023	\$8,620	\$5,488	\$7,670
Vehicle Lifetime	15	20	20	10
TV/OV	1.32	2.07	1.31	1.02
Peak-Hour Average Speed, mph	11.8	9.6	19.8	28.0
Average Load Factor	0.223	0.187	0.110	0.33
$\sum t_i/c_i$	14	13	12	–
Peak Load Factor	0.69	0.49	0.29	0.33
PK-HR/DAY	4.5	5.0	4.5	11.5
DAYS/YR	280	280	280	310
Vehicle Cost per Passenger-Mile	5.1 ¢	32.1¢	11.5 ¢	3.9 ¢
O&M Cost per Place-Mile	4.7 ¢	5.1 ¢	2.2¢	2.6 ¢
O&M Cost per Passenger-Mile	21.1 ¢	27.3 ¢	20.0 ¢	7.9 ¢
VC	26.2 ¢	59.4 ¢	31.5 ¢	11.8 ¢
Representative **PM/YR/LMI**	1M	2.3M	10M	4M
Total Cost per Passenger-Mile	26.2¢	\$1.19	88.6¢	23.1¢

Vehicle cost data were determined from industrial sources. A bus was assumed to cost $165,000, an LRT vehicle $935,000, and an RRT vehicle $1,000,000. The capacities were taken from Table 3. The SMA cost is taken as $50 per square foot and proportional to the plan area of the vehicle. The ratio of total number of vehicles to the number in operation in the peak period (***TV/OV***), the peak-period average speed, the daily average load factor and the O&M cost per place-mile for bus, LRT and RRT are U.S. national averages.

Equation (3) shows that

$$LF_{pk}PK\text{-}HR/DAY = LF_{av}\sum t_i/c_i \tag{4}$$

The left side of this equation appears in equation (A-5). For scheduled systems, this quantity is more easily estimated from its equivalent on the right side since the only additional information required is the schedule. In Table 5, the summation term is estimated taking into account Appendix C and comments of Pushkarev and Zupan (1977). Unfortunately I do not have the schedule information needed to compute the national average of this term. Consistent values of LF_{pk} and ***PK-HR/DAY*** are listed for interest for the conventional systems, but for the ATS Alpha system the listed values are used directly to compute the vehicle cost per passenger-mile.

The components of the variable cost per passenger-mile are the vehicle cost and the O&M cost. Note that in all but LRT the vehicle-cost component is relatively small. The high value of vehicle cost for LRT is not due to any one factor, but to worse values of almost all factors in the equation for vehicle cost. For the other systems, further reduction in the vehicle cost component would have only minor impact on ***VC.*** Major cost reduction must come from finding ways either to reduce the O&M cost or to increase the daily average load factor.

With the quantities ***FC*** and ***VC*** known, equation (A-3) shows that the total cost per passenger-mile can be found for a given value of passenger-miles per year per lane-mile. In Table 5, I list representative values of this quantity. The values for LRT and RRT are median values from Table 4. The value for bus systems is the value for the Twin Cities Area bus system in the highest-use corridor. The value for ATS Alpha is the value we found from a patronage analysis of such a system designed to serve as a circulation system in downtown Indianapolis**,** and is more than the value needed to make the Alpha system cheaper than the bus.

Much of conventional wisdom is that it is worthwhile to spend large amounts for capital equipment in order to lower operating costs. The remarkable fact shown in Table 5 is that the huge expenditure for capital costs for LRT and RRT provides no significant reduction in O&M costs and results in higher variable costs. Only by reconfiguring the system in the optimum ways is it possible to lower the variable costs significantly. This is shown dramatically in Figure 1 where the data of Table 5 are substituted into equation (A-6) to give the surplus to the operator per year per lane-mile. Use of a fare per mile in Figure 1 does not imply a recommendation of fare policy. The fare could be flat with the indicated averages. A typical current bus fare is $0.75 with an average trip length of three miles, or \$0.25 per mile. If the goods-movement potential of the optimized system is considered, it is seen from Figure 1 how increasing ***PM/YR/LMI*** improves the surplus, whereas if patronage increases on conventional systems, the deficit increases.

Conclusions

In this paper, I have shown how the equation for cost per passenger-mile for any transit system can be used to discover the system characteristics required to minimize the cost per passenger-mile. The result is a new, but long-discussed configuration using automated vehicles of minimum practical size and weight operating on demand and nonstop between off-line stations in a network of narrow-beam guideways that don't require snow melting. This is well known as a personal rapid transit (PRT) system, but has special features not common to all systems called PRT, features that probably could not be fully understood without a comprehensive framework of analysis.

The remarkable fact is that the process of cost reduction leads to a system that provides the best possible service: A private, comfortable, fast, nonstop, virtually no-wait trip at any time of the day or night. The system is also ideal from the community standpoint: it takes very little land, and properly configured produces inherently very little noise, vibration and air pollution and is extremely energy efficient. Most of these characteristics of an optimum PRT system have been known to some people for a long time, but very few people have realized that service maximization could accompany cost minimization.

The analysis shows that automation alone does not necessarily lead to cost reduction, indeed study of the data of Table I in the context of the analysis framework shows that most of the presently operating automated systems reduce costs very little if at all. The requirement for automation drops out of the present analysis, not primarily to reduce waiting time at stations as is commonly assumed, but to reduce the cost of the guideway by permitting the practical distribution of the passenger capacity among small capsules operating at short headways. That guideway cost minimization by use of very small vehicles also permits minimization of the vehicle-fleet cost and much improved service is a happy coincidence.

The present paper provides an analysis framework in which future transit systems can be designed. Questions of control, safety and dependability are not addressed in this paper. These questions have, however, been addressed in considerable detail in UMTA research programs, by research in other countries, by Irving (1978), Anderson (1978), and by many others. Advances in the design of linear induction motors, variable-frequency solid-state drives, microprocessors and the application of microelectronics to fields such as materials handling have paved the way for the practical introduction of transit systems optimized by the means developed. Even the heatedly debated question of the practical minimum time headway need not interfere with these developments because it has been shown that there are many applications, very economical in today's terms, in which the minimum required headway is well outside the range of controversy. By building optimum systems, the minimum headway and other features can be demonstrated.

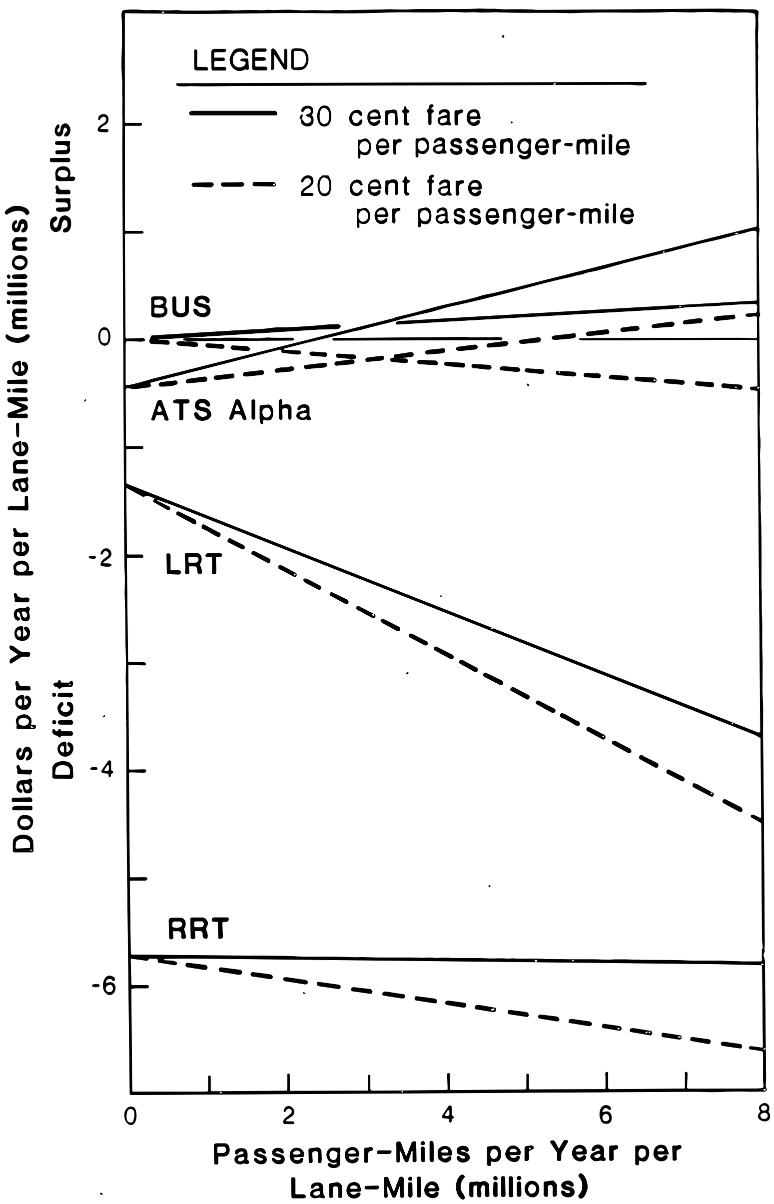

Figure 1. The Surplus or Deficit per Year per Lane-Mile of Representative Transit Systems.

Appendix A

Derivation of Cost Equations for Transit Systems Analysis

For Systems analysis, it is useful to express the equation for the total transit system cost per passenger-mile in the following form:

$$\textit{COST/PASS-MILE} = \frac{[\textit{LANE COST} + N_s\,(\textit{STATION COST})]/\ \textit{YR/LMI}}{\textit{PM/ YR/LMI}}$$

$$+ \frac{(\textit{STORAGE} + \textit{MAINT} + \textit{ADM. CAPITAL COST})/\ \textit{YR/VEH}}{\textit{PM/ YR/ VEH}}$$

$$+ \frac{\textit{VEH COST/ YR/ VEH}}{\textit{PM/ YR/ VEH}}$$

$$+ \frac{\textit{O\&M COST/ PLACE-MI}}{\textit{PASS/ PLACE}} \qquad \text{(A-1)}$$

in which the following abbreviations are used:

PASS = Passenger

N_s = Number of stations in system

YR = Year

LMI = Lane-Mile

PM = Passenger-miles

VEH = Number of vehicles

The first term on the right side of equation (A-1) includes all of the fixed-facility costs associated with the guideway or "lane" including power distribution and fixed elements of the control system and the total cost of the stations. The total cost of these facilities is "annualized" to give cost per year by multiplying the total cost by the factor

$$\frac{i}{1 - (1 + i)^{-n}} \qquad \text{(A-2)}$$

in which $\boldsymbol{i}$ is the annual rate of interest, i.e., the cost of borrowing money; and $\boldsymbol{n}$ is the period over which the money borrowed to pay for the fixed facilities is paid, usually taken as the life-time of the facilities. The derivation of equation (A-2) may be found in any textbook on engineering economics.

The first term in equation (A-1) is normalized with respect to the number of lane-miles in the system because this is an obvious and useful basis upon which to compare various transit systems.

The second term in equation (A-1) is normalized with respect to the number of vehicles in the system because the facilities required for storage, maintenance and administration are more in proportion to the number of vehicles than the number of miles of track or guideway. Dividing the numerator and denominator of the first term by the number of lane-miles and the second by the number of vehicles could be considered arbitrary, but it is useful for systems analysis.

The third term is the capital cost of the vehicle fleet per passenger-mile. For parallelism we write ***VEH COST/VEH*** for the cost of one vehicle. Again, the annualized cost of a vehicle is found by multiplying by expression (A-2) using for $\boldsymbol{n}$ the lifetime of a vehicle in years.

The fourth term is the operating and maintenance cost of the system per passenger-mile. In comparing systems, it is useful to work in terms of the **O&M *COST/PLACE-MI*** because this term is only weakly related to number of people riding the vehicles. The **O&M** cost per place-mile is the **O&M** cost per vehicle-mile divided by the capacity of the vehicle, i.e., the number of places per vehicle. The term **PASS/PLACE** is the daily average load factor, which is related to the sociology of riding, the kind of service provided, and distribution of travel within the transit-system area.

Now consider the quantity ***PM/YR/VEH*** in the second and third terms of equation (A-1). This is the number of passenger-miles of travel in the transit system per year divided by the number of vehicles in the system. The number of passenger-miles per year can be expressed as the number of passenger-miles during the average weekday peak hour multiplied by the ratio of yearly to peak-hour travel. Thus

PM/YR/VEH = (PM/PK-HR/VEH)(PK-HR/DAY)(DAYS/YR)

in which ***PK-HR/DAY*** is the ratio of weekday travel to peak-hour travel, and ***DAYS/YR*** is the ratio of yearly travel to weekday travel. But

PM/ PK-HR/ VEH = (PASS/ VEH) (VEH-MI / PK-HR/ VEH)

in which ***PASS/VEH*** is the average vehicle occupancy during the peak period. If all of the vehicles in the fleet were in operation during the weekday peak period, the term ***VEH-MI/PK-HR/VEH*** is simply the average speed. However, the total fleet must be larger than the fleet actually operating during the peak period because some of the vehicles will be under repair. Therefore, define ***TV/OV*** as the ratio of the total fleet to the peak-period operating fleet.

The average peak period speed, $\boldsymbol{V_{pk}}$ is

$$VEH\text{-}MI/PK\text{-}HR/OPERATING\ VEH$$

Therefore

$$VEH\text{-}MI\ /\ PK\text{-}HR\ /\ VEH = V_{pk}/(TV/OV)$$

Combining the above expressions, we see that

$$PM/YR/VEH = \frac{(PASS\ /VEH)V_{pk}(PK\text{-}HR/\ DAY)(DAYS/YR)}{TV/OV}$$

Now divide the numerator and denominator of the second and third terms of equation (A-1) by the number of places per vehicle. Then in an abbreviated notation, these terms can be written in the form

$$\frac{(TV/OV)(SMA\ COST + VEHCOST)/PLACE/YR}{LF_{pk}V_{pk}(PK\text{-}HR\ /DAY)(DAYS/\ YR)}$$

in which

$LF_{pk} = (PASS/\ VEH)/(PLACES/\ VEH)$ is the peak-period load factor,

and

V_{pk} = is the average vehicle speed during the peak period.

Note that these terms apply to the peak period because the size of the vehicle fleet is determined by peak-period requirements.

Equation A-1 can now be expressed in the form

$$COST/PASS\text{-}MILE = \frac{FC}{PM/\ YR/LMI} + VC \tag{A-3}$$

in which

$$FC = [LANE\ COST + N_s\ (STATION\ COST)]/\ YR/LMI \tag{A-4}$$

and

$$VC = \frac{(TV/OV)(VEH + SMA\ COST/PLACE/YR)}{V_{pk}LF_{pk}(PK\text{-}HR/\ DAY)(DAYS/\ YR)} + \frac{O\&M\ COST/PLACE\text{-}MI}{LF_{av}} \tag{A-5}$$

where LF_{av} the daily average load factor.

In the above expression, ***FC*** is the fixed cost, which is independent of the ridership. The cost for vehicles, vehicle-related facilities, and operation and maintenance per year are proportional to the ridership; therefore these costs, on a per-passenger-mile basis, represented as the variable cost ***VC,*** are independent of ridership.

The surplus to the transit operator (or its negative, the deficit) is the revenue minus the total cost. On an annual, per lane-mile basis, we have

$$\textit{SURPLUS / YR/LMI} = \textit{(FARE/PM - COST/PM)(PM/ YR/LMI)}$$

$$= \textit{(FARE/PM- VC)(PM/ YR/LMI) - FC} \qquad \text{(A-6)}$$

in which equation (A-3) has been substituted and ***FARE/PM*** is the fare per passenger-mile. This does not imply a recommendation that a fare per passenger-mile be charged but that the variable costs per trip are proportional to the length of the trip.

The term ***VEH COST/ PASS-MI*** in equation (A-1) can also be expressed as

$$\frac{\textit{(COST OF ONE VEH/ YR)(TOTAL NUMBER OF VEH)}}{\textit{PM/ YR}} \qquad \text{(A-7)}$$

But, from Appendix C,

$$\textit{TOTAL NUMBER OF VEH} = (TV/OV)t_hL_t/C_vLF_{pk}V_{pk}$$

Also

$$PM/YR = t_h(\textit{PK-HRS/DAY})(\textit{DAYS/ YR})L_t$$

By substituting these two expressions into equation (A-7), the quantity t_h,L_t, the number of passenger-miles per peak hour, cancels out and the corresponding expression in equation (A-5) is obtained.

Appendix B

The Economics of Adding a Station

From equation (A-3), we can write the cost per passenger-mile in the alternate form

$$\boldsymbol{COST/PASS\text{-}MI = \frac{(N_sSC + LC)/YR}{PM/\ YR} + VC} \qquad \text{(B-1)}$$

in which

$\boldsymbol{SC}$ = the acquisition cost of one station

$\boldsymbol{LC}$ = the acquisition cost of the guideway and its associated equipment

$\boldsymbol{PM/YR}$ = Passenger-miles per year.

If one station is added to the system, $\boldsymbol{N_s}$ becomes $\boldsymbol{N_s + 1}$ and $\boldsymbol{PM/YR}$ increases by the increment $\boldsymbol{\Delta PM/YR}$. Thus the change in total cost per passenger-mile is

$$\boldsymbol{\Delta C/PM = \frac{(N_s + 1)SC + LC}{PM + \Delta PM} - \frac{N_sSC + LC}{PM}}$$

in which the $\boldsymbol{/YR}$ designation is not necessary. The cost per passenger-mile decreases if a station is added if the first of the above terms is less than the second. Thus, $\boldsymbol{C/\ PM}$ decreases if

$$\boldsymbol{[(N_s + 1)SC + LC]PM < (N_sSC + LC)(PM + \Delta PM)}$$

or if

$$\boldsymbol{SCPM < (N_sSC + LC)\ \Delta PM}$$

By rearranging, the criterion for cost reduction by adding a station becomes

$$\boldsymbol{\frac{\Delta PM}{PM/N_s} > \frac{1}{1 + LC/N_sSC}} \qquad \text{(B-2)}$$

Equation (B-2) shows that the cost per passenger-mile for capital and operation, i.e., the total cost, will decrease if a station is added if the incremental increase in ridership in the system as a fraction of the ridership per station is greater than a fraction which is always less than one. That fraction depends on the ratio of line cost to station cost.

Based on data accumulated by Thompson (1982), the ratio $\boldsymbol{LC/N_sSC}$ for 13 operating automated guideway transit systems ranges from 2.29 to 29.08, with an average of 9.73. Thus for a system with this average value, the cost per passenger-mile will decrease if one station is added if

$$\boldsymbol{\frac{\Delta PM}{PM/N_s}} > \frac{1}{1+9.73} = 0.093$$

In words, if the additional system ridership due to adding a station is greater than 9.3% of the average ridership per station before the new station was added, the system cost per passenger-mile will decrease if the station is added.

This quantifies the self-evident economic advantage of adding stations. Conventional transit systems, however, face a dilemma because adding stations at which every vehicle must stop reduces the average speed. While having a new location from which and to which trips can be taken would increase ridership, the reduced average speed and hence increased trip time reduces ridership. A transit system in which every trip is nonstop from origin to destination preserves a high average speed regardless of how many stations are added, and hence does not counter the advantage of increased access.

Appendix C

The Daily Average Load Factor in Transit Systems

The daily average load factor, designated as LF_{av}, can be computed from the following equation:

$$LF_{av} = \frac{PASSENGER - MILES/DAY}{PLACE - MILES/DAY} = \frac{t_d L_t}{PMPD} \tag{C-1}$$

in which

t_d = trips per day

L_t = average trip length

$PMPD$ = place-miles per day = C_v(vehicle-miles/day)

C_v = vehicle design capacity

Consider a transit system that operates on schedule, with varying time head-ways throughout the day. Let the day be divided into time intervals during which the time headway is uniform. and designate the **i-th** of such time intervals as t_i. Let the number of vehicles operating during the **i-th** time interval be N_i, the time headway be T_i, and the average speed of the vehicles be V_i. Then

$$PMPD = C_v \sum_i V_i t_i N_i \tag{C-2}$$

in which $\sum_i$ indicates the sum over all periods t_i during a single weekday.

Let L be the total one-way length of the transit lines, i.e., the number of lane-miles. The average distance between vehicles during the **i-th** time interval is $V_i T_i$. Therefore,

$$N_i = \frac{L}{V_i T_i} \quad \text{(C-3)}$$

Substituting equation (C-3) into equation (C-2),

$$PMPD = C_v L \textstyle\sum_i t_i / T_i \quad \text{(C-4)}$$

During the peak-flow period of the day, $T_i = T_{pk}$ is chosen so that there are enough vehicles or trains to meet the demand. The number of vehicles needed during the peak period is

$$N_{pk} = \frac{\text{peak number of people riding vehicles at one time}}{\text{Average number of people per vehicle}}$$

$$= \frac{\text{(trips per peak-hour)(average trip time in hours)}}{P_{Vpk}}$$

in which

P_{Vpk} = average number of people per vehicle during the peak period.

Let

t_h = trips per peak-hour[1] and note that

L_t / V_{pk} = average trip time.

Then

$$N_{pk} = \frac{t_h L_t}{P_{Vpk} V_{pk}} = \frac{L}{T_{pk}} \text{ from Equation (C-3).}$$

Hence,

$$L/T_{pk} = t_h L_t / P_{Vpk} \quad \text{(C-5)}$$

Let

$$T_i = c_i T_{pk} \quad \text{(C-6)}$$

where c_i is a ratio larger than or equal to one.

Substitute equation (C-6) and then equation (C-5) into equation (C-4) and let

$$LF_{pk} = P_{Vpk} / C_v \quad \text{(C-7)}$$

denote the peak-period load factor. Then, equation (C-4) becomes

$$PMPD = (t_h T_t / L F_{pk}) \textstyle\sum t_i / c_i \quad \text{(C-8)}$$

Finally, substitute this expression into equation (C-1). The result is

$$LF_{av} = LF_{pk} / (t_h/t_d) \sum t_i / c_i \qquad \text{(C-9)}$$

Note that t_d / t_h, is the factor ***PK-HR/DAY***, defined in Appendix A, so that t_d/t_h is the fraction of the daily travel that occurs in the peak hour. A number of values of this parameter are given by Pushkarev (1977) for various kinds of urban transportation (see Table 2).

I have been able to obtain specific values of the parameters in equation (C-9) in several cases. For example, from time-table, passenger-flow and train-size data for the Lindenwold-Philadelphia rapid rail line, a typical suburb-to-downtown system, I found that LF_{pk} = 0.35, t_h/t_d = 0.252, and $\sum t_i/c_i$ = 13.3. Substituting into equation (C-9**),** LF_{av} = 0.104.

I was able to find similar data for the St. Paul Downtown People Mover during its planning stage. This is, of course, a very different kind of transit system, a downtown circulator. The plan was to operate vehicles from 6 am to 6 PM at 2-minute headways, from 6 PM to 9 PM at 4-minute headways, from 9 PM to midnight at 6-minute headways, and not at all from midnight to 6 am. With this schedule

$$\sum t_i/c_i = 12/1 + 3/2 + 3/3 = 14.5 \text{ hours}$$

From the passenger-flow data, we found that for this 40-passenger-vehicle system, LF_{pk} = 0.49 and that t_h/t_d = 0.19. With these parameters, equation (C-9) gives F_{av} = 0.178.

For a completely demand-responsive transit system, in which each vehicle is occupied by one party of people traveling together as in a private automobile, the average vehicle occupancy can be expected to be close to that of an automobile. Indeed, by charging a fare per vehicle instead of per person, there is an incentive for voluntary group riding that may increase vehicle occupancy. On the other hand, because empty vehicles must be recirculated in a public transit system, the average vehicle occupancy counting empty vehicles decreases. Studies such as those by Kuzmyak (1981) and Ryan (1983) show that the daily average vehicle occupancy of automobiles is in the range of 1.5 persons per vehicle, whereas the peak-period vehicle occupancy drops to the range of 1.2 persons per vehicle. Considering that about one-third of the vehicles in a demand-responsive transit system will be recirculating empties, but that a fare per person would be charged, we assume for our calculations average vehicle occupancy of one person per vehicle throughout the day. Using three-passenger vehicles to increase the load factor, the load factor is then assumed to be LF_{av} = 0.33.

Accumulating the above results, we have

	LF_{pk}	LF_{av}
Lindenwold-Philadelphia Rail Transit	0.35	0.104
St. Paul Downtown People Mover	0.49	0.178
Demand-Responsive System with Three-Passenger Vehicles	0.33	0.33

Appendix D

Passenger-Miles per Year per Lane-Mile vs. Average Headway

The quantity ***PM/YR/LMI*** in equation (A-3) can be related to average time headway in the following way:

$$\textbf{\textit{PM/YR/LMI}} = \frac{\textbf{\textit{(PASSENGERS/YR)(AVE TRIP LENGTH)}}}{\textbf{\textit{LANE MILES}}} \tag{D-1}$$

which is the definition of ***PM/YR/LMI.***

From equation (C-5) the quantity

$$\frac{\textbf{\textit{AVE TRIP LENGTH}}}{\textbf{\textit{LANE MILES}}} = \frac{\textbf{\textit{PASS/ VEH, PK-HR}}}{\textbf{\textit{(PASS/ PK-HR)(PK-HR AVE TIME HEADWAY)}}} \tag{D-2}$$

But

$$\textbf{\textit{PASSENGERS/ YR = (PASS/ PK-HR)(PK-HR/DAY)(DAYS/ YR)}} \tag{D-3}$$

Substituting equations (D-2) and (D-3) into equation (D-1) gives

$$\textbf{\textit{PM/YR/LMI}} = \frac{\textbf{\textit{(PASS/VEH, PK-HR)(PK-HR/ DAY)(DAYS/YR)}}}{\textbf{\textit{PK-HR AVE TIME HEADWAY, hrs}}} \tag{D-4}$$

For general numerical orientation with respect to equation (D-4), consider the following cases:

	Motor Bus	Rapid Rail Transit	Personal Rapid Transit
PASS/VEH, PK-HR	40	300	1
PK-HR/DAY	6.5	5	11.5
DAYS/YR	280	280	310
PM/YR/LMI	$2(10)^6$	$2(10)^6$	$2(10)^6$
PK-HR AVE TIME HEADWAY	2.2 min	12.6 min	6.4 sec

In the above table, the numerator values on the right side of equation (D-4) are chosen as representative values based on considerations given in the text of this paper. The value of 300 passengers per vehicle for rail rapid transit is really per train, and the corresponding time headway is between trains. The corresponding value for PRT assumes 1.5 passengers per occupied vehicle with one third of the vehicles empty and recirculating to pick up passengers. For comparative purposes, the value of 2,000,000 passenger-miles per year per lane-mile is used in all cases. This value is generally high for bus systems, but, as shown in Table 4, is low for rail systems.

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Chapter 8. System Requirements

	Requirement	How Requirement is Met
1	The system must be designed for a substantially higher level of safety than existing people-moving systems in terms of incidents per billion miles.	By use of components of proven reliability and as few of them as practical. By use of dual duplex computers wherever computers are needed.
2	The possibility of injury due to collisions with the guideway posts or falling trees must be extremely rare.	If street vehicles could collide with the guideway posts they must be either placed on concrete pedestals or highway barriers must protect them. If a tree large enough to damage the guideway might fall on the guideway, either the guideway must be relocated or the tree must be cabled back.
3	Adequate ride comfort. This seems obvious, but a number of the PRT developers neglected ride comfort until it was too late. Ride comfort requires not only designing to given maximum steady-state jerk and acceleration but to meeting ISO criteria on acceptable acceleration vs. frequency. Moreover, the design must take into account motion sickness as vehicles bank in curves.	By rolling curved angle running surfaces to be smooth within a given criterion. By designing all curves to keep lateral jerk and acceleration at planned speeds to be within accepted ride comfort standards. By designing so that fore-aft jerk and acceleration lie within accepted standards. There are no standards on motion sickness, but the Swedish railroad experience is a guide.
4	The design must be compatible with the American Disabilities Act.	The vehicles must be able to accommodate a wheelchair with an attendant. The station ticketing and boarding procedure must permit the system to be used by visual and hearing impaired persons.
5	The design must permit straightforward manufacturability and installation.	Design for simplicity and consult manufacturing engineers in every phase of development.
6	Minimum size, weight and capital cost.	These factors are fundamental to PRT design. What I found is that the minimum weight guideway cross section, taking into account maximum vertical loads and maximum lateral wind loads, is a little narrower than deep. The Aerospace Corporation first reached this conclusion and also observed that this structurally optimum design would give the least visual impact, i.e., the smallest shadow. These features are achieved • by use of a vertical chassis, which permits a minimum width guideway; • by supporting the vehicle on high-pressure pneumatic tires or airless tires with similar characteristics. Wheels minimizes the contact area and hence the guideway width, and • by use of a steel truss guideway structure, which minimizes weight and cost.

7	Minimum practical operating cost.	By eliminating intermediate stops, the system requires less than half the vehicle-miles of travel than required by scheduled, all-stop systems, and minimizes the energy required to supply kinetic energy of motion. Use of smooth metallic running surfaces minimizes road drag. Careful attention to streamlining minimizes air drag. By designing the variable frequency drives to minimize the current requirement at each speed minimizes electrical-power losses.
8	The switching concept must be straightforward, easily explained, and one of the first items to clarify while developing the configuration.	A switch arm on the vehicle that rotates around a longitudinal axis fulfills this requirement. By designing it so that the force applied during switching passes through the center of the switch rotational axis makes the switch bi-stable.
9	Span. Planning studies have shown that the guideway should be designed for spans of up to 27 meters (90 ft). Longer spans needed to cross rivers or major highways will use cable-stayed suspension-bridge technology.	By use of a minimum-weight, steel, truss structure the guideway loads are minimized, which permits maximum span.
10	The guideway and its manufacturability must be designed to accommodate hills and valleys as well as horizontal curves.	Use a steel truss guideway with round-tube stringers for easy bending into curves.
11	Weather protection. The system will need to operate in rain, snow, ice, dust, and salt spray, i.e. in a general outdoor environment with temperatures ranging from -40°F to +130°F. Some designers concluded that this required that the vehicles hang from the guideway; however, I found a number of reasons to prefer placing the vehicles on top of the guideway.	Attach composite covers to the sides and over the top of the steel-truss guideway leaving a slot only 3 inches wide for the chassis to pass through. These covers prevent ice accumulation on the power rails, they shield the tires from the sun, they minimize differential thermal expansion, and they provide electromagnetic and noise shielding.
12	Guideway heating. The guideway must be designed so that under winter conditions, guideway heating will not be necessary.	The design described in the previous item satisfies the need to eliminate guideway heating.
13	Resistance to maximum wind load. Codes vary from city to city, so thinking in terms of hurricane winds I designed for 240 km/hr (150 mph) cross winds. I did not design for tornado winds, which can go well over 320 km/hr (200 mph) because it would be cheaper to replace failed sections than to build the entire system to withstand such a highly improbable load.	Build the covers with curve radii at the top and bottom of 1/6th the height of the guideway to reduce the side drag coefficient to about 0.6. Design the posts and foundations for the maximum side load.
14	Resistance to earthquake loads. If an earthquake causes the earth to shear horizontally, as has happened, no design will prevent failure. The most common earthquake	The lighter the guideway the easier it will be for the foundations and posts to resist a side inertia load. The truss guideway is the lightest possible. In an

	load translates to a horizontal acceleration. In the 1994 Los Angeles earthquake, horizontal loads up to 1.6 g were detected.	earthquake zone, the post foundations will be designed to absorb the shock of an earthquake load.
15	The system design must permit competitive operating speeds.	The maximum comfortable operating speed is proportional to the natural frequency of the guideway, which is maximized by using a light-weight truss structure.
16	The guideway must be easy to erect, change, expand or remove. The guideway sections must be designed so that the system can be expanded by taking out a straight section and substituting a switch section.	The light-weight truss structure minimizes the cost of erection, change, or removal. The end configuration of each section is designed to facilitate assembly and removal.
17	The system must be designed so that it can be expanded indefinitely in a straightforward way.	Use of wayside power provided via power rails permits trips of any length.
18	The guideway design must be such that slope discontinuities at posts are eliminated.	Careful attention to the guideway joints has enabled design of joints that eliminate slope discontinuities, which would result in unacceptable bumps.
19	Access for maintenance. I visited the H-Bahn test system in Düsseldorf in 1974. The cars hung from an inverted U-shaped steel-plate guideway. There were power rails and communication lines on the inside of the guideway but no way to reach them. One had to assume that they would never require maintenance, which is an unacceptable assumption.	By hinging the covers at the bottom and by use of quick fasteners at the top, they can be swung down in sections to reach the guideway interior for any maintenance task, however improbable it will be.
20	Relief of thermal stresses. Except at noon, the sun will shine on one side of the guideway, with the other side in the shade, thus causing one side to expand more than the other. In some cases this has caused structural failure.	The use of covers over the steel truss will enable a nearly uniform internal temperature, thus eliminating the problem of differential thermal expansion.
21	The power rails must be shielded from the winter-night sky. Some PRT systems operate their vehicles with on-board batteries, so for them this is not a problem. However, on-board batteries add weight and must contain enough energy for the worst conditions of wind, grade, and trip length, which increase as the system expands; so it is better to pick up wayside power via sliding contacts. On clear winter nights heat radiates to a very cold space and as a consequence frost often forms on metallic surfaces. In the Airtrans system, which was installed at the Dallas-Ft. Worth Airport in 1972, it was found that on clear winter nights enough frost formed on the power rails that they had to be sprayed with ethylene glycol as a temporary expedient before starting the system each morning. Later they installed heaters in the power rails.	The covers eliminate this problem.

	A similar problem was discovered in the elevated guideway system installed at the Minnesota Zoo. In systems such as Cabintaxi in which the power rails were covered, frost formation was never a problem.	
22	The design must provide adequate torsional stiffness.	Torsional rigid is increased to an adequate level by clamping the guideway to the posts via a special bracket and by use of tube stringers.
23	Design to liberalize the required post-settling tolerance.	Design for shims to be placed at the bottom of the guideway posts. Design the joint between guideway sections to eliminate slope discontinuities.
24	High natural frequency to obtain maximum speed. This is not as important a consideration as I once thought it was, but all else being equal higher natural frequency is better.	Use a minimum-weight guideway, i.e., a truss to give the highest natural frequency.
25	Lightning protection.	Ground the guideway at the posts, and provide a ground path from each vehicle to the guideway via the power rails.
26	It must be very difficult if not impossible for anyone to be electrocuted by the system.	The covers, with only a 3-inch-wide slot at the top, make electrocution virtually impossible.
27	Space for communication wires. Wireless communication may be practical, but is more likely to be subject to interference. Moreover, the system would likely have to lease the frequencies it needs, which would be prohibitively expensive.	Design space for installation of a leaky cable for communications between the vehicle and the guideway. Nothing special need be done with the truss guideway to do this.
28	Minimize electromagnetic interference. The U. S. Federal Communications Commission requires that any new element in a community not interfere with existing electronic devices. The motors or drives on a PRT vehicle may emit electromagnetic noise and the communications system may be subject to electromagnetic noise.	Apply a thin layer of aluminum to the inside of the guideway covers to provide the needed electromagnetic shielding.
29	Minimize potential for vandalism or sabotage.	Use as narrow as practical a slot at the bottom of the guideway covers. The narrow gap at the top of the guideway minimizes the chance of a foreign object being thrown in. Provide adequate lighting and video monitoring in stations. Design the station-guideway interface to make it very difficult to get out on the guideway.
30	There must be no producers of vibration or noise.	All of the parts must be firmly attached. Vibration tests during the design phase must be performed.
31	Provision must be made to prevent corrosion.	All of the steel parts of the guideway must be coated with a zinc-based paint used for outdoor steel structures.

32	There must be no place for water to accumulate.	Design the bottom portion of the covers to slope downward toward the center.
34	It must be difficult if not impossible to walk on the guideway unless walkways are provided.	Design the top portion of the guideway covers to slope downward towards the sides. Moreover, the cover need not have sufficient strength to support a person. Design the stations so that walking out onto the guideway will be virtually impossible.
35	Thought must be given to providing for damping.	The connection between guideway sections while transferring shear is accomplished by inserting tubes inside the main stringers. The material used between the tubes will provide damping.
36	Curved and branching sections are more difficult than straight sections; therefore it is prudent to think through first a design in which the many required curved, merge, and diverge sections will be easy to fabricate.	The truss guideway configuration, the basic element of which is a series of transverse U-frames, can be assembled and welded in a computer-operated fixture, which permits curves of any configuration to be fabricated readily.
37	Design the system for 50-year life.	The corrosion-resistant coating, such as a zinc-based paint should be specified for 50-year life.
		These requirements provide a series of features that will be embedded in the system.

Chapter 9. Major Tradeoffs leading to ITNS

9.1 How does Dual Mode Compare with Personal Rapid Transit?

Advocates for improving urban transportation can be divided into the following six groups:

1. Advocates of conventional rail systems. For example, organizations of people dedicated to bringing the streetcar back.

2. Advocates for conventional bus or rail systems because nothing else is proven and there is no visible mechanism for proving better systems. This includes many public officials who have become convinced both that transit is needed and that they should work to obtain federal grants to build it.

3. Advocates of a network of small guideways on which small automated vehicles operate exclusively on the guideways, i.e. the vehicles are captive to the guideway. Optimally designed, such a system is expected to have much lower cost per mile and much higher attractiveness to riders than conventional rail. Such a system has been called personal rapid transit or PRT.

4. Advocates of an automated network of guideways that can accept street vehicles, i.e., a dual-mode system. http://faculty.washington.edu/jbs/itrans/ includes a series of papers on dual mode.

5. Advocates of automated highways such as tested near San Diego during the 1990's.

6. Advocates of an automobile-only society.

This paper compares the middle two options among the spectrum listed above. The system of group #3 will be referred to hereinafter as "Single Mode" or SM. The system of group #4 is called "Dual Mode" or DM. DM has the advantage over SM for auto drivers that the same vehicle may be taken for any trip, just as occurs now with one's own automobile. DM has an advantage over conventional freeways in that automation is expected to substantially increase the throughput of a lane. In many respects, DM is much like the system envisioned by group #5 – an Intelligent Vehicle Highway System – except that special narrower guideways could be used for the automated guideway portion of the trip. Thus DM is expected to both decrease the cost of additional lanes and to increase their throughput. Since the automobile system in typical U. S. cities attracts about 95.4% of the urban trips[2] a percentage improvement of the throughput of the highway system will have far greater impact on congestion mitigation than the same percentage improvement of transit. SM advocates can't dispute that, but argue that SM is a transit system that will permit a major increase in transit ridership and with it major reductions in petroleum use, greenhouse gas emissions, and congestion.

There are important differences between DM and SM that need to be studied carefully before committing to one or the other. The differences should be clarified in the broadest sense taking into account economic, environmental, and social considerations. In examining the differences,

[2] C. Kenneth Orski, *Innovation* Briefs, Nov/Dec 2006.

the reader will likely be aware that I long ago committed to developing SM rather than DM, so my analysis must be viewed very critically, which I welcome warmly.

The following DM concepts have been considered:

1. The basic DM concept is one in which ordinary automobiles or buses are equipped with automatic control systems that permit them to operate automatically on a guideway. This would be similar, and perhaps identical, to those tested on a freeway near San Diego during the 1990s, except that a special, narrower guideway designed for autos only could be used. Since conventional highways are designed for trucks currently having gross weights up to 80,000 lb, whereas an automobile-only guideway could be designed for vehicles weighing a maximum of perhaps 5000 lb, the weight, cost, and size of this special guideway would be substantially less than a freeway lane; however, such a guideway would be substantially larger and more expensive than one that can be and has been[3] designed to accommodate captive vehicles.

2. In order to avoid both the cost of equipping a private automobile with the necessary automatic controls and the need for inspection upon entry to the DM guideway, some have suggested that the guideway be equipped with pallets on which private automobiles could be attached. The attachment device must be rapid and extremely reliable. If it is not rapid, i.e., secured in one or two seconds, the throughput at the entry points will be unreasonably compromised. If the mechanism were to detach while underway, the auto could fall off the guideway, kill the driver and possible pedestrians below – a catastrophic failure mode. Can a quick acting device be developed that would be so reliable that it could be accepted in this kind of service? Assuming that the necessarily almost perfect reliability can be attained day in and day out over many years is quite a risk – quite possibly an unacceptable risk.

3. In a third type of DM, to minimize the size and cost of the guideways, the street vehicle would be designed specially to attach to a narrow guideway. In this case, to make use of the guideway, the user would be required to purchase a special vehicle – a vehicle of a style and features that may not otherwise have been selected.

DM does not come without disadvantages, a discussion of which follows.

- Envision the process of getting an auto from the street onto the guideway. At a conference on Dual Mode Transportation held in Washington, D. C. in 1975[4] both Ford and General Motors brought for display models of DM stations showing the on and off ramps needed to permit autos to enter and exit the guideway as well as a loading platform for those who do not drive. With their ramps, these stations clearly could be seen to be much more expensive and land consuming than SM stations, which reduced enthusiasm for DM.

- Maintenance of DM vehicles would be done privately, just as takes place with autos today, so the condition of vehicles entering the guideway would be much more difficult to determine than would be possible in a SM system in which the condition of the vehicles can be monitored

[3] J. E. Anderson, "The Structural Properties of a PRT Guideway," available from the author upon request.
[4] Dual Mode Transportation, Special Report 170, Transportation Research Board, Washington, D.C. 1976.

and maintenance can be controlled.

- At each point of entry to the guideway, DM vehicles will pass an inspection station one at a time and then enter the guideway. This minimizes the throughput of the entry point. In a SM system vehicles can be batch loaded, which permits the station throughput to increase with the number of loading berths.[5]

- DM vehicles will have to be inspected carefully before entering the guideway. If the inspection time is only a second or two, throughput is barely compromised; however, if the inspection time is say 10 seconds, the throughput at each entry point will often be unacceptable.

- Because DM vehicles must be designed for both the street and the guideway, they will be heavier, longer, and more expensive than SM vehicles. Street vehicles must be designed to meet all federal safety standards, including design for side collisions and rollovers, whereas SM vehicles captive to a guideway do not.

- The requirement for operation on the street limits flexibility in design of a minimum size, minimum cost guideway. Moreover, since guideway cost will be proportional to vehicle weight per unit of length, a DM guideway will cost substantially more than an optimally designed SM guideway[6]and will possess correspondingly greater visual impact.

- Since DM vehicles of the first and third types given above would be more expensive than regular automobiles, they would be purchased near the beginning of DM operation only by the subset of wealthy people interested in experimenting with new ideas.

- A question then arises: How much guideway would have to be built before even a wealthy person would purchase a DM vehicle? At least in early stages the return on investment would be unattractive to private investors; therefore taxes would have to pay for installation of the guideway, a guideway that only the wealthy could in early stages afford to use. There has been much debate on this question related to requirement for payment for use of high-occupancy lanes on freeways. This debate will be much more contentious when it comes to paying for a whole system of guideways that early on could be used only by the rich.

- Because road vehicles are the intended primary users, DM will be of little use to those who can't or choose not to drive. If, however, a political decision directs that transit users must also benefit from a DM system, guideway would have to be designed to accommodate both SM and DM vehicles. But, since DM vehicles would be longer than SM vehicles, the stations would be longer and hence more expensive than in a SM system.
- In downtown areas, DM vehicles cannot always be permitted to enter the street system because congestion could then back up onto the guideway, so some DM advocates suggest that there simply be no off-ramps in the downtown area. Instead, some sort of automated vehicle storage (parking) and retrieval (valet) would occur at downtown stations. Otherwise the downtown network would operate identically with SM, but with bulkier guideways and longer

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[5] Irving, J. H., Bernstein, H., Olson, C. L., and Buyan, J. *Fundamentals of Personal Rapid Transit,* Lexington Books, D. C. Heath and Company, Lexington, MA, 1978, Section 3.2. See also Section 1.6 for a discussion of DM.

[6] For example see the paper cited in footnote #2.

stations.

- DM vehicles would be stored like conventional autos, sitting unused all day, whereas a SM vehicle is ready for the next trip as soon as one is completed, thus not taking up parking space. Studies have shown that one SM vehicle could serve dozens of trips during the day, giving a great economy in the cost of the vehicle fleet.

- The time required to retrieve a DM vehicle at the end of the work day will be much longer than the time to wait for the next SM vehicle. Moreover, if the DM vehicle is called in advance and the driver is delayed, the vehicle would have to be recirculated, thus adding to congestion on the guideway.

- Because the driver of a DM vehicle might not mind driving say two to three miles to an entry point, DM designers usually speak in terms of only a minimal guideway network being needed. While saving on guideways, this feature would render use of the system marginal for those who do not drive.

- With wider spacings between guideways, DM will have fewer loading and unloading points. If the DM system were to be able to attract even as many trips as SM, each station or loading point would have to have a higher maximum throughput than possible with a SM station, but as mentioned an SM station can have substantially higher maximum throughput than possible in DM stations. To have as much capacity as SM, and taking into account the small capacity of a DM entry point, DM would have to have many more entry points per mile than SM, yet because of their complexity, size, and cost DM proponents recommend fewer entry points.

- I have discovered some 32 criteria for guideway design[7]. Developing a DM guideway that will meet all of these criteria has not been demonstrated. Every DM guideway design I have thus far seen has had serious problems.

- DM has been shown[8] to be unable to attract more riders than SM.

- Because of the combination of public and private assets, assigning legal responsibility for accidents would be more complex for DM than SM.

- For DM to begin as intended – a system of special DM guideways serving a fleet of privately owned especially equipped automobiles – it would seem have to start from Day 1 as a regional system covering a metropolitan area. DM could of course start experimentally with one DM guideway and with a fleet of DM cars leased from the builder of the DM guideway to perhaps randomly selected individuals who would use the DM guideway and report on the experiences. On the other hand, SM can start as a small system serving a special application such as an office park, a theme park, etc. It would seem then that the resources, education, and approvals needed to initiate SM are vastly less than needed for DM. Starting small likely means working at first with a single client and being able to prove the system in daily practice

[7] See the paper of footnote #2.

[8] Irving, J. H., Bernstein, H., Olson, C. L., and Buyan, J. *Fundamentals of Personal Rapid Transit,* Lexington Books, D. C. Heath and Company, Lexington, MA, 1978, page 25.

quickly – proof that will be needed before the system can be extended to a metropolitan area. SM can and should be designed so that it can be expanded in both extent and speed.[9]

- DM suffers from the attempt to combine two different functions, and as a result fails to excel at either.

Urban Planning Implications of DM vs. SM

In SM one either walks or rides a street vehicle from home to a station, and at the destination (job, store, school, restaurant, theater, stadium, etc.) one would walk a short distance, probably no farther than from a parking ramp into a building. Once a trip on SM is completed the vehicle is instantly available for the next trip. In the central city, SM guideways could be placed a quarter to a half mile apart. For its posts and stations, SM will occupy a tiny fraction of the urban land – about 0.02%. Moreover, with an optimally designed guideway, visual impact will be small and more land could be devoted to gardens and parks.

Because

- the system cost of optimally designed SM will be about 25% of the cost of conventional surface rail and the stations of SM can be placed typically at half the spacing of conventional rail stations without sacrificing trip speed, about eight times as much land can be placed within walking distance of stations with SM as with an urban rail system;
- there is little or no waiting for an SM vehicle;
- SM vehicles will be available any time of day or night; and
- the trip is nonstop and therefore in many cases faster than an auto trip;

a much larger fraction of trips will be attracted to SM than to conventional transit. With livable higher density, many more of the longer trips will be taken by SM and many more of the shorter trips by walking and bicycling. For these reasons SM would make possible higher density, more energy-efficient, less polluting communities that in some cases could become auto-free zones.

DM does not answer the legitimate criticism of the auto system that everyone in an urban area should have equal access to transportation. In a DM system one boards a private DM vehicle at home and proceeds perhaps one to three miles away to a DM guideway, then perhaps ten to fifteen miles[10] on the guideway to the destination, where the driver must search for a parking spot just as occurs today. The private DM vehicle then sits all day in that parking spot taking up valuable space and is of no use to anyone. Improvement in land use is therefore minimal. DM does not answer the legitimate criticism that the auto system promotes urban sprawl, with the encroachment of the auto on rural land possibly already past the point of sustainability. Due to DM being an extension of the current highway system through automation, its effect would be the same as adding more highway lanes. It will exacerbate already unsustainable land use patterns.

[9] J. E. Anderson, "High-Capacity Personal Rapid Transit,."
[10] Unless the trip is at least this long, it will be difficult to justify the cost of a DM vehicle and the guideway toll.

Many of us envision a future in which energy will be much more expensive and the continual encroachment of the auto on farm land will result one day in too little land for agriculture and recreation. A conflict manifests between those who envision the future pretty much as it is today and those of us who envision the changes that can be expected to occur on a finite earth as more and more people grasp for fewer resources.

Concluding Remarks

There is nothing in the remarks I have made that would indicate that DM is not feasible. I only conclude that on a per-mile basis DM will be much more expensive than SM and that the capacity of DM will be disappointing. DM advocates counter by proposing that their guideways can be much farther apart so that the overall cost would be less. A problem those of us who try to advance either DM or SM have in the United States is that many of the assumptions or arguments have not been studied recently in sufficient detail through interdisciplinary studies of the type sponsored by our federal government 40 years ago in the 1967 HUD studies. In the meantime, we in the USA look on with envy at the extensive studies of PRT done during the 1990s in Sweden and now being done for English cities. A few public officials in the U. S. have remarked recently that something more than conventional highways and conventional rail is needed, but they virtually never say what. With too little knowledge, and usually no mandate to innovate, to say "what" may make them look foolish so they advocate nothing new, not even the kind of studies needed. But then, who would do the studies? Past experience has shown that government can obtain pretty much any result it wants by determining who will do the studies. All too often government officials have in advance certain conclusions in mind based on their prejudices and constituencies.

The conventional wisdom holds that only the market place will shake out the best ideas. But the market place can and often is distorted too by prejudices and constituencies and rarely for the long term benefit of the population as a whole. In the United States the large companies wait for a market to appear, which cannot appear without proven hardware, which cannot be fully proven without financial support, which cannot be forthcoming without specific proof of a market. Notwithstanding past failures, we remain convinced through increasingly detailed study that the elements of success are at hand and will be manifested through the right kind of education. The European social democracies, commonly considered – at least from the American corporate perspective – to be less business-friendly, have nonetheless revealed themselves better able to foster transport innovation as a public policy, and offer an apparently welcoming environment for innovating enterprises. Here in the USA we struggle along as we do, each working and hoping to find a funding source that can convert dreams into reality. The problem is of sufficient importance that we continue the search.

There are two classes of people interested in improving urban transportation. One class consists of those in the stands cheering for any improvement. The second class consists of a much smaller number of people in the arena trying to design and build a new system. They must get specific. By some process they must decide to do one thing rather than another. How that is done is extremely important. There are a great many factors that must be considered in designing a new system of urban transportation, which cannot be fully understood without detailed involvement in planning studies, which are necessary to understand all of the requirements and criteria. After watching the failure of a number of potential new transit systems, I developed out of my experience in mechanical engineering design and in teaching of mechanical engineering design a set of fifteen rules. I included them in my paper "The Future of High-Capacity Personal Rapid Transit," which can be found on several web sites, and I have recently released them to a number of friends in a paper entitled "15 Rules of Engineering Design." After I get sufficient feedback, I want to try to get them published. I would welcome others to add to these rules and then perhaps we could publish them either with a number of authors or under a suitable pen name. I believe that understanding and applying such rules is one of the essential elements of success in many fields including engineering.

Acknowledgements

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9.2 The Tradeoff between Supported vs. Hanging Vehicles

One of the most difficult tradeoffs in the design of PRT systems is the choice between use of supported or hanging vehicles, i.e., Supported-Vehicle Systems (SVS) or Hanging-Vehicle Systems (HVS). During the 1970s, the DEMAG+MBB group solved this problem by developing a guideway that permits one set of vehicles to ride above the guideway and another set that ride below. In my textbook[11] I examined the tradeoff between systems using one-way guideways and two-way, above-below guideways, and found that the cost per passenger-mile of the one-way system was somewhat lower. The two-way system reduces circuity[12] while riding the system, but to make the use of larger, two-way guideways economical, the lines must be spread farther apart, which results in longer walking distances, which add more to the trip time than the two-way system reduces it. The two-way guideway had about twice the bulk of the one-way guideway, which increases visual impact and increased cost. I thus concluded that it is better to concentrate on one-way-guideway systems.

Another very important tradeoff is the type of suspension selected. The alternatives that have been considered are air cushion, magnetic levitation (maglev), and wheels. Among these, the use of high-pressure tires running on smooth surfaces permits the most compact guideway design, which means less cost and less visual impact. I have discussed this tradeoff in more detail elsewhere, but for this discussion I assume wheeled suspension. While advocates of maglev regard wheeled suspension as old fashion and while maglev has a mystique to it, I have seen no maglev idea that will result in a system of lower cost per passenger mile than a properly designed

[11] *Transit Systems Theory*, Lexington Books, 1978 (available on www.advancedtransit.org), Figure 5-8.
[12] The ratio of distance along the guideway to the direct-line distance.

wheeled system. In our design, the wheels are used for suspension only. With no braking through the wheels and with the wheels running in the shade on a smooth surface, the tires will last much longer than automobile tires. In system engineering, one must start with overall system requirements and pick components on that basis. Generally a study of maglev literature shows that the proponents start with a fixed component concept and try to design a system around it. This very seldom works.

First consider the advantages of running vehicles above a guideway:

1. Visual impact. There must always be a specified clearance between the ground and an obstruction above – either the bottom of the guideway of an SVS or the bottom of the vehicles in an HVS. Thus the guideway of an HVS must be at a higher elevation by the height of the vehicles, and the support posts must be offset from the guideway by a sufficient distance to permit the vehicles to pass and thus at the top must have a horizontal arm that connects to the top of the guideway. Such a structure has substantially more visual impact than a SVS.
2. Cost for posts and foundations. Simple calculations show that the maximum bending moment at the foundations of HVS posts due to the combination of a maximum cross wind on a higher guideway and the offset of the posts with respect to the guideway is about twice the maximum bending moment at the foundation of SVS posts. The cost for posts and foundations for an HVS will therefore be about twice that for a SVS.

3. Ease of Switching. Simplification of switching is one of the most important considerations in the design of a PRT system. In an SVS the path through each of the merges and diverges is continuous. In a HVS there must be an arm extending down from a chassis inside the guideway to support the vehicle and, with gravity always acting downward, the support structures for the wheels cannot be continuous. There must of necessity be a mechanism to unload one set of wheels as the vehicle passes across the slot in a merge or diverge section of guideway. This is one more mechanism that can fail. In an SVS no such mechanism is needed.

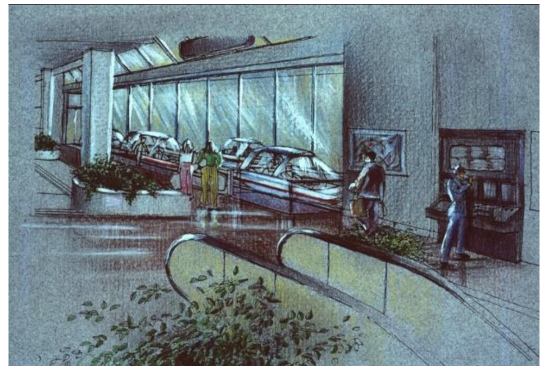
4. Guideway natural frequency. In an SVS, the guideway can be clamped to posts directly underneath[13] whereas in an HVS the guideway must be attached to horizontal arms that connect to vertical posts set alongside the guideway. Thus the attachment points in an HVS will be more flexible than in an SVS, which results in a guideway natural frequency lower by a factor up to 2.27, and the natural frequency is a strong function of the flexibility of the attachment points. Lower natural frequency results in a lower critical speed, which is the maximum speed that meets the ride-comfort criterion.[14] To achieve higher

[13] This was first suggested on page 219 of Irving, J. H., Bernstein, H., Olson, C. L., and Buyan, J. *Fundamentals of Personal Rapid Transit,* Lexington Books, D. C. Heath and Company, Lexington, MA, 1978.

[14] *Transit Systems Theory*, Lexington Books, 1978 (available on www.advancedtransit.org), Section 10.5.

cruising speeds, the HVS guideway will have to be substantially stiffer and more expensive than the SVS guideway.

5. Rider feeling of security. In the DEMAG+MBB PRT program, mentioned above, both supported and hanging vehicles were deployed and many people rode both above and below the guideway. This gave the development team an opportunity to quiz the riders as to their preference. The result was that more people felt secure seeing the guideway underneath them rather than above.



6. Vehicle weight. In an SVS, the strength requirements of the vehicle cabins relate mostly to people loads. In an HVS the cabin shell must also be designed to support its weight, thus resulting in a somewhat heavier cabin. Increased weight results in slightly increased cost.

7. Underground sections. Occasionally it is necessary to place a PRT system underground. In this case the guideway of an SVS can be laid directly on the ground, which results in savings in the weight of the guideway structure. With an HVS the underground guideway must be designed for the same vehicle loading as in the above-ground case.

8. Sections of Guideway within Buildings. When a section of guideway is placed inside a building, with SVS the guideway would have to be placed below the station floor, which would require special construction that would not be necessary with HVS. This gives HVS a cost advantage in buildings but a cost disadvantage everywhere else.

Now consider the advantages of the HVS.

1. Winter weather. In an HVS the guideway is completely covered on top, which results in zero concern about snow and ice, even though some can be blown upward into it. In an SVS, special considerations must be given to the entry of snow and ice. In my PRT design, the guideway is covered except for a slot only 3 inches wide at the top, and it is opened at the bottom. A special plow has been designed that will take any residual snow from the running surfaces and toss it down a 6-inch-wide slot between them.

2. Torsion in curves. This problem is of sufficient importance that I have developed a detailed analysis of it, which is included as Appendix A. In short, while intuitively this appears to be a deciding factor in favor of an HVS, more careful study shows that the advantage of the HVS guideway is small and negative when considering the guideway natural frequency.

3. Requirement for super-elevation. To minimize curve radii the guideway of an SVS must often be super-elevated in curves, which increases the complexity and possibly the cost of manufacture. With an HVS, the vehicle can be permitted to swing as they round the curve up to an angle about twice that permissible with an SVS, thus eliminating the need for super-elevation. The swing of course must be damped to prevent the vehicle from rocking side by side, and that increases complexity. **There is, however, a problem with too large a bank or super-elevation angle that was uncovered in operation of the Swedish and British tilt trains: Their cars ride on tilting bogies, which permits them to bank in curves, thus permitting curves of fixed radii to be traversed at higher speed. It was found, however, that enough people got seasick in riding such trains that the maximum speed had to be reduced substantially over the desired speed. This problem will also be a factor in the design of PRT systems, which will limit the maximum bank angle and thus the advantage of using large bank angles to minimize curve radii, or with given curve radii to maximize speed.**

Conclusion

Study of the above factors caused me to opt for the SVS, and I have seen nothing over the past two decades to alter that conclusion.

Appendix: Torsion in Curved Guideway due to Supported vs. Hanging Vehicles

Consider a vehicle composed of a cabin of weight W_{cabin} and a chassis of weight $W_{chassis}$ moving at speed V over a curved guideway with distance L between support posts measured along the guideway. This geometry is depicted in Figure A-1. The guideway is designed so that the radius of curvature at the center of the cabin is

$$R = \frac{V^2}{A_H}. \tag{1}$$

where A_H is the centripetal acceleration given by

$$A_H = g\tan\phi + \frac{A_l}{\cos\phi} \tag{2}$$

in which ϕ is the super-elevation or bank angle and A_l is the acceptable lateral acceleration felt by the passengers. With supported vehicles, we specify $\phi = 10^o$ and $A_l = 0.2g$, which gives

$A_H = 0.379g$. With hanging vehicles it is usual to take ϕ large enough so that $A_l = 0$. If ϕ is increased enough so that A_H has the same value as with supported vehicles, then ϕ increases to 20.78^0. So we assume that R has the same value for both supported and hanging vehicles.

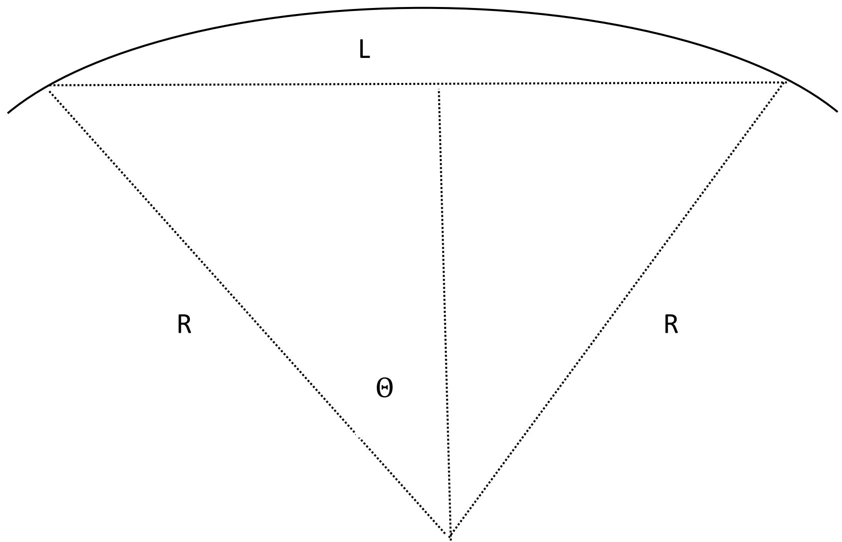


Figure A-1. Vehicle moving on curved guideway half way between support posts.

Let Θ be the angle in Figure A-1 measured from the center of curvature between a line directed to one of the posts and a line half way between the posts. Then

$$\Theta = \frac{L}{2R_g}, \tag{3}$$

where R_g is the radius of the centerline of the guideway, which differs slightly from the radius calculated from equation (1). The distance between a point midway between two posts at the center of the guideway and a straight line connection a pair of posts is

$$d = R_g\left(1-\cos\Theta\right) = R_g\left[1-\cos\left(\frac{L}{2R_g}\right)\right] \tag{4}$$

From Figure A-2, the mass center of the cabin of the vehicle is displaced from the mass center of the guideway, but the mass center of the chassis is close to the center of twist of the guideway.

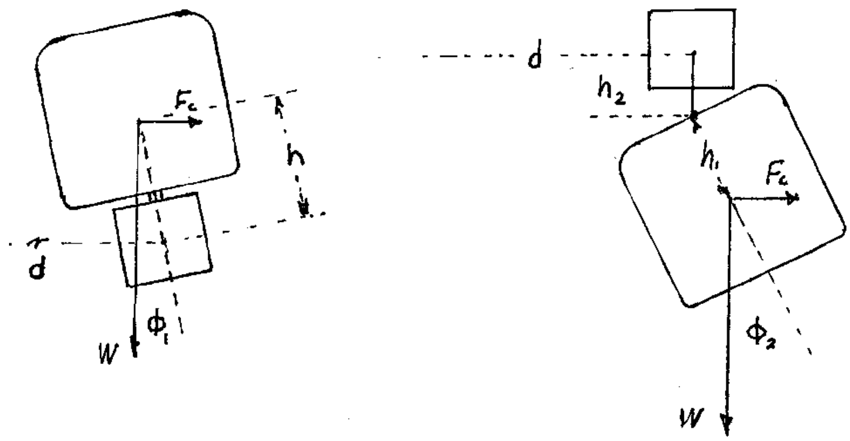


Figure A-2. Centrifugal torque of supported or hanging vehicles

<u>Consider the supported vehicle.</u> In such a system the guideway will be superelevated at an angle shown in Figure A-2 as ϕ_1. If the torsional moment at each post due to the moving vehicle is designated by T_s then from Figure A-2

$$T_s = \frac{1}{2}\cos\Theta\left\{W_{chassis}d_s + W_{cabin}\left[d_s - h\sin\phi_1 + \frac{\left(g\tan\phi_1 + A_l/\cos\phi_1\right)}{g}h\cos\phi_1\right]\right\}$$
$$= \frac{1}{2}\cos\Theta\left(Wd_s + W_{cabin}h\frac{A_l}{g}\right)$$

(5)

in which $d_s = d$ in equation (4) with

$$R_g = \frac{V^2}{A_H} + h\sin\phi_1 \qquad (6)$$

Also

$$W = W_{chassis} + W_{cabin} \qquad (7)$$

<u>Consider the hanging vehicle</u>. If the torsional moment at each post is designated by T_h then from Figure A-2

$$T_h = \frac{1}{2}\cos\Theta\left\{W_{chassis}d_h + W_{cabin}\left[d_h + h_1\sin\phi_2 - \frac{g\tan\phi_2}{g}\left(h_2 + h_1\cos\phi_2\right)\right]\right\}$$
$$= \frac{1}{2}\cos\Theta\left(Wd_h - W_{cabin}h_2\tan\phi_2\right) \qquad (8)$$

in which in equation (4)

$$R_g = \frac{V^2}{A_H} - h_1 \sin\phi_2 \tag{9}$$

Thus, the ratio of torsional moments is

$$\frac{T_s}{T_h} = \frac{d_s + \frac{W_{cabin}}{W} h \frac{A_l}{g}}{d_h - \frac{W_{cabin}}{W} h_2 \tan\phi_2} \tag{10}$$

The torsional moment ratio has been calculated from equation (10) in an Excel spread sheet with the following results:

Ratio of Torsion at Posts due to Supported to Hanging Vehicles

g =	9.80665	m/s^2			
Speed =	30	mph	or	13.41	m/s
Post Spacing =	90	ft	or	27.432	M
Phi, supported =	12.00	deg	or	0.20944	Radian
Al, supported =	0.20	g's	or	1.96133	m/s^2
AH =	0.4170	g's	or	4.0896	m/s^2
R =	144.3	ft	or	43.98	M
Phi, hanging =	22.64	deg	or	0.3951	radian

	Supported	Hanging		
h =	1	n/a	m	
h1 =	n/a	1	m	
h2 =	n/a	0.6	m	
Rg =	44.19	43.59	m	
d =	2.112	2.140	m	
Wcabin/W =	0.5	0.7		
Torsion factor =	2.212	1.965		
Torsion ratio =				1.126

Torsion Ratio:

Speed, mph ->	20	30	40
Post spacing, ft			
60	1.108	1.336	1.750
90	1.032	1.126	1.258

Natural Frequency of the Guideway

If the vehicles are supported above the guideway, the guideway can be clamped to the posts, whereas if the vehicles hang from the guideway, the support posts must be placed at one side with a horizontal member extending from each post to the top of and to support the guideway. Because of the limited torsional rigidity that can practically be built into such support structures, the joints at the posts behave much more nearly like simple supports.

From Marks' Standard Handbook for Mechanical Engineers, 10th Edition, page 3-73 the natural frequency of a beam clamped at both ends is $1.506^2 = 2.268$ times the natural frequency of a simply supported beam of the same properties. Moreover, the natural frequency of any beam increases as the square root of the moment of inertia, which means that to double the natural frequency it is necessary to quadruple the beam's moment of inertia. Compared with a clamped beam then, to achieve the same natural frequency, a simply-supported beam must have a moment of inertia $1.506^4 = 5.144$ times the moment of inertia of a beam clamped at both ends. The ratio of moments of inertial required to achieve the same natural frequency in a hanging-vehicle system relative to a supported-vehicle system will not be quite as large as in this idealized case, but it is sufficiently large that it becomes clear that the hanging-vehicle system will necessarily have a natural frequency substantially lower than can be achieved in a supported-vehicle system in which the guideway is clamped to the posts.

Some Properties of the ITNS Guideway

From the ITNS paper "The Structural Properties of a PRT Guideway," pages 11 and 12, the following data is found:

Table A-1. Some Properties of the ITNS Guideway

	1	2	Ratio 2/1
Stringer wall thickness, in	0.233	0.315	1.35
Tube weight, lb/ft	9.4	12.4	1.32
Weight of 4 tubes, lb/ft	37.6	49.6	1.32
Guideway weight, lb/ft	149	162	1.09
Twist angle, degrees	7.6	6.1	0.80

Torsional stiffness			1.25
Vertical moment of inertia, in^4	2894	3451	1.19

Discussion

It is seen from Table A-1 that the torsional stiffness increase that results from increasing the weight of the guideway by about 8% is about 25%, which, from the numerical results given, is close to the increase in torsional stiffness in the supported guideway needed to equal the torsional stiffness of the hanging guideway. But this increased torsional stiffness increases the vertical moment of inertia by only 19%, which would increase the natural frequency in bending by only $1.19^{1/2} = 1.09$ or 9 %, whereas to increase the natural frequency of a hanging-vehicle guideway to that of the supported-vehicle guideway the moment of inertial would have to be increased by a factor close to 5, which is impractical. Thus, one price of the hanging-vehicle guideway is an inherently lower natural frequency, which, from Section 18 of the paper "The Structural Properties of a PRT Guideway," means a critical speed lower than that of a supported-vehicle guideway by a factor of almost $5^{1/2}$ or over 2, or to a critical speed of no more than about 35 mph.

9.3 Magnetic Levitation vs. Wheeled PRT

Magnetic levitation or maglev is an alternative approach to vehicle suspension. Instead of wheels, magnetic force counteracts gravity. This approach is particularly useful at very high speeds when wheels cannot resist centrifugal forces.

There are two basic types of magnetic levitation or maglev: **magnetic attraction and magnetic repulsion**. Attraction can be accomplished with room-temperature magnets but is unstable so that it requires high-gain electronic servo mechanisms to maintain the gap between the guideway and the vehicle. Repulsion has required much higher magnetic fields that can be attained using super-cooled coils, which require use of liquid helium, which is not practical in a small vehicle, but it is stable. Some very powerful room-temperature magnets may change this situation at some point.

Use of magnetic attraction has in several designs led to the configuration shown below in the left-hand sketch, in which vehicle elements wrap around and underneath a guideway element so that the vehicle can be lifted by an attractive force, but this means that the vehicle can't switch without moving the whole guideway, which is not practical for short-headway systems. With the short headways needed for PRT the configuration must be turned around to that shown below in the right-hand sketch. But in a diverge or merge section, if the vehicle is, for example, to switch to the right, the left hand levitation surface disappears and must be replaced by some other means of levitation. By whatever means used, that left side of the vehicle must be supported from below if the vehicles run above the guideway. This could be by repulsive maglev limited to only switch sections, with the superconducting means at wayside, or it could be by wheels. Similar sketches for hanging systems will show similar problems.

Even if the maglev developers create a workable, switchable configuration, either attractive or repulsive, what is its advantage over wheels? The critical advantage of maglev occurs at very high speeds, typically over 200 mph where the friction of steel wheels on steel rails becomes inadequate. This is not a problem at urban speeds.

The maglev configurations I have seen use linear synchronous motors (LSM) for propulsion. The advantage of the LSM is that the propulsive power is at wayside so that sliding contacts are not needed. Sliding contacts cause excessive arcing at very high speeds, which then quickly wears out the power rail. This is not a problem at urban speeds.

The LSM requires windings in the guideway, which must be partitioned so that each separate winding controls one vehicle. Thus the number of these windings required per mile is inversely proportional to the minimum headway. Each of these windings must be controlled by its own electronic package. One LSM expert admitted that that means for PRT one winding about every 20 feet or 264 per mile or 2640 in ten miles, etc., which means that the minimum headway is fixed once and for all – once built there can be no experimentation with smaller headways. Imagine then that because these electronic packages occasionally fail, they must be replaced by a maintenance person who would need to run out to some section of guideway in any kind of weather at any time of day or night. With Linear Induction Motors (LIM) all such repairs or replacements occur in a maintenance shop. The LSM experts say that the mean time to failure of each electronic package is long, but how long? If you have thousands of them, the failure frequency in a system will be high and thus the maintenance cost for replacement will be high.

I have yet to see a practical maglev-LSM PRT configuration, and even if a practical configuration is discovered and developed, it will have high costs for wayside windings and electronic devices. So what is wrong with wheels, other than that they have been used for thousands of years? If LIMs are used for propulsion the main support tires need be used only for suspension. They can be smooth and the running surface can be smooth. The 80-psi tires I use result in very low road resistance. In my configuration no thrust is applied through the wheels either for acceleration or for braking, so wear is minimum. Emergency braking is applied via separate shoes that on extremely rare occasions[15] would press down on the guideway, and they are tested every time the vehicle stops because they are used also as a parking brake. Wheel bearings may fail, but how often? Today, we rarely hear of a bearing failure in an automobile even though their environment is much rougher. With very light-weight vehicles, bearings can be over-designed for long life with little penalty.

[15] "Failure Modes and Effects," internal paper.

In my configuration the wheels operate in the most benign environment possible – smooth running surfaces always away from the sun, with no chuck holes or curbs to run over, and no acceleration or braking through the wheels. What about blowouts or flats? The lifetime of tires in our benign environment will be very long compared with automobile tires, which now typically survive for at least 60,000 mi. Moreover, it is likely that we can use the new Michelin airless tire that provides the cushioning and sound-deadening effect of pneumatic tires without any chance of going flat. One imagined advantage of maglev is a smoother ride. But in practical experience, maglev follows every perturbation in the guideway as closely as rubber-tired wheels. A final very important point is that, because wheel contact requires a very small width, we can design a much more compact, lower-cost guideway with wheels than with maglev, and the guideway is the most expensive component in the system. Unlike maglev, wheels require no energy input to support the load.

My opinion about the tradeoff between maglev and wheels is based on these facts. Moreover, with wheeled support, I am ready to go into production immediately and can get into operation in much less time than would be possible with maglev. Maglev was designed for very high speed, on-line-station systems, which require long headways. Scaling such systems down to urban speeds is a solution looking for a problem.

9.4. Propulsion that depends on Friction vs. Independent of Friction

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Safe Design of Personal Rapid Transit Systems

The safety of personal rapid transit systems involves careful attention to all features of the design such as the use of a hierarchy of fault-tolerant redundant control systems, bi-stable fail-safe switching, back-up power supplies, vehicle and passenger protection, and attention to the interaction of people with the system. Safety, together with reliability and adequate capacity, must be achieved while making the system economically attractive, hence techniques to achieve these goals at minimum life-cycle cost are primary in PRT design. Building on theory of safe, reliable, environmentally acceptable, and cost-effective design of PRT systems developed during the 1970s, in 1981 the author and his colleagues initiated design of a new PRT system. The paper describes the relevant features of the new system and principles of safe design incorporated into it.

Introduction

Following a decade of apparent dormancy, the concept of Personal Rapid Transit (PRT) has gained attention largely because of two parallel $1,500,000 studies of PRT sponsored by the Northern Illinois Regional Transportation Authority (RTA). These studies are expected to lead to a demonstration PRT system in a suburb of Chicago in about four years. The development of PRT had continued "behind-the-scenes" throughout the 1980s and a study of PRT by the Advanced Transit Association [1988] influenced the RTA decision to proceed.

PRT can be derived from a system form of the equation for cost per passenger per unit of distance [Anderson, 1984]. The major cost element of an exclusive-guideway transit system is the guideway itself. Many factors lead to minimization of its cost, the main one being the mass of the vehicles. Based on a study of dynamic loading of guideways [Snyder, Wormley, Richardson, 1975], the ratio of the mass per unit length of small-vehicle to large-vehicle guideways is much smaller than would have been calculated based on static considerations alone. From analysis of data on many transit systems, it was found [Anderson, 1984] that transit vehicle cost per unit of (design) capacity is not noticeably dependent on capacity, which led to the conclusion that, for a given number of riders, the size of the fleet, and hence its cost, will be minimum if the average speed is a maximum. The highest average speed requires that there be no intermediate stops, which is possible with small vehicles, off-line stations, and automatic control. Similar analysis of operating and maintenance (O&M) costs shows that O&M cost per unit of capacity per unit of distance is markedly independent of vehicle size, which led to the conclusion that the O&M cost per year is inversely proportional to daily average load factor. Study of daily average load factors in various systems showed a marked increase if the service is demand-responsive rather than scheduled. But demand-responsive service is exactly what is provided if the stations are off-line, because vehicles can wait to provide service, like taxis, rather than having the passengers wait for the vehicles. *The exact factors that fundamentally minimize the cost of a transit system also provide the best service.*

For these reasons the concept of PRT will become a common form of public transportation once it is understood how such a system can provide safe, secure, dependable, environmentally sound, and adequate-capacity service at minimum cost. The safe design of PRT was discussed extensively at the Second International Conference on PRT [Anderson and Romig, 1974]. In this paper, following a description of safety-relevant features of HCPRT [Anderson, 1988], the factors involved in design for maximum safety with adequate capacity and the means for achieving them today are discussed.

Description of the System

Performance Goals

The fundamental goal of the HCPRT program has been to design a PRT system that will not be unnecessarily limited in capacity, speed or ability to grow indefinitely. Safety and dependability cannot be compromised in meeting the goal. Planning studies have shown that early PRT systems will need a headway capability in the range of two to four seconds, but that as the system grows, a headway capability down to a range of one-half second is desirable. Much work has convinced us that half-second headway will also be practical, but will require very careful attention to all matters of safety.

The Switch

Because a fully developed PRT system has many switches, two per station and others for line-to-line merges and diverges, an adequate switch design is the most fundamental element in the development of a safe and reliable PRT system. The two initial tradeoffs are between an in-track switch and an in-vehicle switch. From the viewpoint of safety, with in-track switching there must be enough time headway between vehicles so that 1) the switch can be thrown from the opposite position, 2) its position can be assured to be locked in the correct position and verified, and 3) the vehicle can be stopped well before hitting the switch if verification does not occur. The time headway that must be allowed for stopping is approximately the line speed divided by the braking acceleration. This number, in practical cases, is large enough by itself to severely limit the safe time headway. Estimates vary in detail but a minimum headway in the range of 8 to 12 seconds is as low as would be safe. With in-vehicle switching, there is no comparable limit.

An in-vehicle switch could be electromagnetic or mechanical. For reasons of safety, electromagnetic switches have required a mechanical backup, which if it meets all criteria may as well be the primary switch, unless the life-cycle cost of an electromagnetic-mechanical combination is lower. At present, the switch is mechanical. It is very conservatively designed and cannot disengage in a diverging section of guideway. Such a switch must be designed so that it is bi-stable, so that there is no position in which it can impale on any track part, so that it is naturally held in position in merge and diverge sections, and so that maintenance personnel can move it manually in an emergency. These criteria led to a switch consisting of wheeled arms rotating about a longitudinal axis, constrained by a spring to make it bi-stable, and configured so that the line of force of the engaged switch passes through the center of the support bearing. Switch rails in the guideway are flared at both ends to permit smooth engagement and disengagement in presence of side winds.

The Guideway

Adequate guideway design is the foundation of a successful PRT system. The design is constrained mainly by the requirements of switching, ride-comfort and cost, although in total it must meet over two dozen criteria, which I accumulated from analysis of all of the AGT systems of the 1970s. After the switch tradeoff was made, the next key tradeoff was the location of the vehicle with respect to the guideway. Designs have been developed for top-mounted, side-mounted, and bottom-mounted vehicles. Provided that we could solve the problems of winter weather, we found seven reasons to prefer top-mounted vehicles, the most important of which relate to the post and foundation size, the natural frequency in bending and torsion, the ease of switching, and visual impact.

Interwoven in the decision process was also the tradeoff of suspension type: wheels, air, or magnetic fields. While magnetic suspension has well-advertised advantages at very high speeds, these advantages disappear at urban speeds when compared with rubber-tired wheels. Air suspension requires too much area, while the criteria of economy and visual impact dictate a minimum cross section. We concluded that the vehicle should be supported on firm, cushion-tired wheels, and, considering the requirements of switching and cost minimization, concluded with The Aerospace Corporation PRT group [Irving, 1978] that the guideway should be a U-shaped configuration as narrow as practical with a vertically oriented chassis inside, and the passenger cabin on top. Polyurethane-tired wheels provide lateral support.

To minimize weight and cost, and to provide access for maintenance, the guideway is a truss structure fabricated to ordinary structural tolerances. To obtain adequate stiffness in torsion and bending, each truss is bolted firmly to a specially-designed moment-carrying bracket at the top of a post, and the joint, required for thermal expansion, is close to the point of zero bending moment in a clamped beam. Overlap angles provide continuity while allowing for thermal expansion. The running surfaces are adjustable with respect to the truss with the joint overlapping the guideway joint enough so that any slope discontinuity is eliminated even if a post should settle. Guideway covers provide protection against ice and snow, electromagnetic shielding, reduced lateral wind force, an external appearance independent of structural characteristics, and prevent differential solar heating from distorting the guideway.

Propulsion and Braking

To achieve high capacity safely and to minimize maintenance costs, propulsion and braking is provided through linear electric motors. There are two basic types: synchronous and induction. While linear synchronous motors have higher efficiency, they require track segmentation, which raises the complexity and cost of the guideway. Today, linear induction motors (LIMs) are more suitable than they were in the 1970s because they can be driven from amply small variable-frequency electronic drives. By selecting the frequency at each speed to minimize current, the efficiency is up to 60 percent and the motors provide braking right to a stop. The motors receive power from 600-volt DC power rails through sliding contacts. To provide safety and continuity of service during power interruptions, either wayside battery banks or motor-generator sets, or both can be provided.

The Vehicle

The vehicle configuration followed directly once the switch and guideway were determined. The HCPRT vehicle has a vertically oriented chassis inside the guideway with the passenger cabin firmly attached at the top. With three-abreast seating and all passengers seated, all requirements for safety are met. A wheel-chaired person and one attendant are accommodated. Heating and air conditioning are provided, with the mechanical components in the chassis. For reasons of safety, the electric power provided in the cabin is at 24 volts only.

The Control System

The control system can operate either quasi-synchronously or asynchronously [Irving, 1978]. The difference in performance appears slight and the final decision will be made on the basis of complexity of the central controller, capacity and station wait time. Microprocessors aboard the vehicles permit maneuvering within ride-comfort and power limits with only a speed or maneuver signal provided from wayside, throw the switch based on a wayside command, monitor various functions for failures, perform a predetermined action if a specific failure occurs, provide two-way communication with the passengers, and operate the door lock, parking brake, and other secondary functions.

Zone controllers (ZC) provide a continuous speed signal to the vehicles in its zone, watch for and react to anomalous behavior, reduce the speed to a safe value when necessary, and provide switch commands. At a predetermined point in advance of each diverge section of the guideway, the ZC interrogates each vehicle for its destination. The ZC, containing the switch command for every station, looks up the appropriate command and transmits it to the vehicle. By linking the ZCs to the a central computer through fiber-optic lines, the switch commands can be revised based on traffic conditions, thus providing dynamic rerouting to specific detail not possible with automobile traffic. A station controller commands and monitors all actions involving passenger flow in its station. For safety, commands to vehicles are transmitted only through the ZC.

A central computer provides optimum rerouting of empty vehicles, adjusts the line speed for weather conditions, monitors the flow into stations and at merge points to either delay passengers in origin stations or reroute traffic as needed, computes system dependability [Anderson, 1992], and gathers data on system operations. It is common to suppose that the software requirements for such a system are immense, but careful study has shown that they can be quite modest.

Principles of Safe and High-Capacity Design in PRT

Minimize the Probability and Consequences of Failures

1. Minimize the number of moving parts. The vehicle has four main support wheels, eight lateral stabilization wheels, four switch wheels, and four LIM-bogie wheels. The LIM propulsion and braking system has no moving parts. The only other moving parts are the switch arm, the parking brake and the doors.

2. Minimize the stress on all parts, particularly on the moving parts. Because of the small size of a PRT vehicle, there is little cost penalty in over-design of tires, bearings, axles and other components to keep the stresses in the range in which the chances of wheel, axle or bearing failure is virtually nil. In general, the stresses in a body due to its weight are directly proportional to linear dimension of the body. Therefore, if the body is scaled down, its weight-induced stresses reduce in direct proportion to size. This principal was first stated by Galileo in his *Dialogues Concerning Two New Sciences* (1632).

3. Minimize the opportunity for unusual forces on the vehicles. The vehicles ride on smooth tires on smooth steel surfaces in a protected, well ventilated guideway away from the heat and ultra-violet radiation of the sun, away from ice formation on critical parts, away from opportunities for debris to land on the running surfaces, and away from broken road surfaces.

4. Minimize the effects of severe weather. The wheels that support the vehicles run inside of a U-shaped guideway covered on the sides and top except for a 3-in-wide slot through which the chassis passes. The bottom is open to permit rain, snow and ice to fall through. With this design, relatively little snow and ice can enter the guideway to interfere with operations, and that small

amount can be easily removed from critical surfaces. By careful shaping of the covers, the lateral wind force is reduced by a factor of more than two.

5. Minimize thermal stresses due to day-night and seasonal temperature variations. The expansion joints described above virtually eliminate thermal stresses. By suitably selecting the emissivity of the covers, they permit the sides of the steel guideway structure to equilibrate at nearly the same temperature, thus preventing warpage.

6. Minimize the possibility of overheating in the electrical systems. Electric currents and critical temperatures are monitored continuously with appropriate responses programmed into the computers. Careful attention to heat transfer from the LIMs and drives provide further protection.

7. Use fault tolerance and managed redundancy where possible to minimize the consequences of failures. All computer systems in HCPRT have these features. Ticket machines in the stations are duplicated.

8. Minimize the chance and consequence of fire aboard a vehicle. No high-voltage equipment is placed in the vehicle body. All construction is of noncombustible material. Temperatures at critical points are monitored and currents are shut off if the temperature exceeds a specified limit. Vehicles will be cleaned as frequently as needed to remove debris left by passengers.

9. Minimize the probability of damage due to vandalism. Because of the narrow slot on top of the guideway, not only is ice and snow kept out, but, because the slot is over five meters above ground, it is very difficult to inject an object large enough to do any damage. Object and ice deflectors in front of the wheels will keep small objects from harming the vehicles. Stations will be clean, well lit, and monitored by standard television-monitoring systems. Infrared sensors are used to warn operators of the presence of people during the night.

10. Minimize the possibility of externally induced failure. In places in which it is likely that a truck may hit a support post, the usual procedure will be to place a highway barrier around it, yet the guideway and post design has taken into account the possibility of a post being knocked out.

Time Headway and the Linear Induction Motor

Design for safety at high capacity relates to the time headway achievable safely and dependably, and how the minimum safe headway depends on selection of certain components. The linear induction motor is a key component of a safe, high-capacity PRT system, and has been proven in numerous applications. From the standpoint of safety, its main advantage is in rapid, reliable, all-weather braking. The LIM is also advantageous because of its simplicity, which leads to low operating and maintenance costs.

The argument can be seen from the following equation for minimum time headway [Anderson, 1978].

$$T_{\min} = \frac{L}{V} + t_c + k\frac{V}{2}\left(\frac{1}{a_e} - \frac{1}{a_f}\right) \qquad (1)$$

The first term is the time required for a vehicle of length L traveling at a velocity V to travel one vehicle length. It is the minimum possible headway. The second term t_c is the time required to detect a malfunction and apply the brakes. The third term is proportional to the available stopping distance after the brakes are fully applied divided by the cruising speed V. a_e is the emergency braking rate and a_f is the failure braking rate. $k = 1$ is a dimensionless number included to increase safety.

To appreciate the fundamentals of the question of minimum headway, consider some numerical values. For the HCPRT vehicle, L = 3 m and V = 48 kph. Therefore

$$\frac{L}{V} = 0.224 \text{ sec.}$$

Consider t_c. It is the sum of the time interval between failure occurrence and braking initiation, and the time required to fully apply the brakes. In an automobile, the time to react to an emergency depends on human reaction time. Under automation, the time interval needed to detect the failure and to begin applying the brakes depends on the characteristics of the control system. In a PRT system designed for maximum throughput, it is necessary for the zone controller to be able to sense the position of each vehicle at any point, i. e., vehicle-position data must be continuously available. The first part of t_c is about 0.1 sec plus the much smaller time for the computer to react. The second part of t_c must be as short as practical with current technology. With electromagnetic braking, this time is the inductive time constant of the motor, which is of the order of 10 msec. For a state-of-the-art PRT system, I therefore estimate

$$t_c = 0.12 \text{ sec.}$$

Consider the third term in equation (1). From this term, the value of the LIM used as a brake becomes more apparent. The term a_e must be as high as practical. If all passengers are seated, simple experiments show that a 0.5g deceleration will not throw a passenger out of the seat. If passengers are standing, even half this acceleration is too much, so one of the requirements of PRT safety is that the vehicle be designed for all passengers seated. If braking is through wheels, a_e depends on the coefficient of friction. It is necessary to assume the worst conditions. These would be a wet or snowy day in which the vehicle is going downhill in a tail wind [Diamant, 1974]. Moreover, it must be assumed that the vehicle ahead may fail by locking its brakes on a dry section of guideway. To minimize headway safely, it is necessary that braking deceleration be controlled to the same value regardless of weather. LIMs used for braking satisfy these requirements since they provide reliable braking independent of friction, whereas braking through wheels does not.

The value of a_f used in equation (1) should be the maximum that can conceivably occur. With wheel braking, it must be assumed that the brakes could suddenly lock while the vehicle is on dry pavement. There must be sufficient tread on the tires and the running surface must be sufficiently rough to make the coefficient of friction as high as practical. In this case $a_f \approx 0.9g$. If the vehicle is propelled by linear induction motors, it can also be braked by the same devices and both the tires and the running surface can be smooth, which results in lower tire noise, less tire wear, and much lower friction. A locked bearing, however rare, then cannot cause the vehicle to stop as fast as a_e, in which case the sum

$$t_c + k\frac{V}{2}\left(\frac{1}{a_e} - \frac{1}{a_f}\right)$$

can become negative.

It is necessary to look for all ways a vehicle can stop quickly and to assess their probability. The diverge section of the guideway must be examined carefully. If the in-vehicle switch were to disengage in a diverge section, the vehicle could impale on the diverge junction. Prevention requires that the designer insure that the switch cannot disengage and that it is sufficiently strong so that it will not break under the most extreme conditions.

Control

The HCPRT control system is designed with safety as its first priority. The critical maneuvers that it must perform repeatedly and flawlessly every day of the year are

- Merging from a station into main-line traffic;
- Merging of traffic on two main lines; and
- Deceleration into a station.

The elements of control-system design for safe operation are:

- Simplicity in software architecture so that software is as easy as possible to write and check. Separate functions have been listed above, the software for each of which must be programmed and checked using the latest protocols for development of reliable operational software [Shulmeyer, 1990].

- Use of checked and managed redundancy in critical functions [Anderson, 1978]. Today, fault-tolerant computers are commercially available for a variety of critical applications in which a failure of a computer could produce serious consequences. These computers have built in tests and alternative paths in case of failure. A pair of fault-tolerant computers should be used aboard each vehicle, with one as a hot standby arranged to take over if the other fails. Computers used for zone control, station control and central control should be similarly configured. Speed and position sensors should be redundant. In HCPRT there is a pair of

LIMs and variable-frequency drives, either of which can keep the vehicle moving according to commands except under reduced speed in the most extreme conditions such as high wind or grade.

- Clearly defined failure-management strategies. Every possible failure must be considered and a strategy developed for reacting to it in a fail-safe manner. For example, in HCPRT each vehicle's control system is configured so that the lack of an active speed signal from wayside at each check interval produces a command to slow to a predetermined default speed if the speed signal is not received.

Ultimate Passenger Protection

Every precaution must be taken in design of the control system to prevent collisions, but in no transportation system can it be assumed that no collision could ever occur. The prudent path is to design to minimize the consequences. If all passengers are seated, it is possible to protect them if there should be a collision. With all passengers seated, the design goal for PRT can and should be that no system failure can cause passenger injury. The problem is simpler than in protection of automobile passengers because there can be no head-on collisions, direct side collisions, or roll-overs, because the vehicles are of uniform size and mass with bumpers at the same location, because the speeds are closely controlled by the system, and because more adequate bumpers can be used than common in automobiles [Garrard, Caudill, Rushfeldt, 1976].

Injury prevention in a collision requires the right combination of three lengths: the length of a shock-absorbing bumper, the throw distance between the passenger and a padded surface, and the deflection of the padded surface [Anderson, 1978]. An air bag functions as a means to substantially reduce the throw distance and to increase the deflection of a padded surface, both of which reduce the probability of injury. Passenger protection also requires that the vehicle structure not intrude into the passenger compartment during a collision, which of course is more of a problem in high-speed collisions.

The kinetic energy that must be absorbed during the collision between two similar vehicles is half the kinetic energy of one of the vehicles. If the stroke of a shock-absorbing bumper is S, the deceleration during collision is a, and the relative speed is V_c, then, equating the kinetic energy to the work of the shock absorber

$$\frac{mV_c^2}{4} = maS \quad or \quad V_c = 2\sqrt{aS}$$

Reasonable values of S and a are 0.1m and 10g, respectively, which gives V_c = 6.26 m/s. This means that, for a relative collision speed up to 6.26 m/s, all of the kinetic energy can be absorbed in the shock absorber. It was found that a hydraulic shock absorber with a 0.1m stroke and an energy-absorption rating suitable for a vehicle of the mass of a reasonably designed PRT vehicle was commercially available at a mass of only 13 kg; however, as the vehicle mass increases, the size of such a shock absorber quickly becomes prohibitive, which means either that the shock absorber must be longer or the collision energy must be absorbed in crushing the vehicle. With a throw distance similar to the distance of the occupant of an automobile to a padded dashboard, it is relatively simple to protect passengers if V_c = 7.5 m/sec. Careful attention to collision-energy management in a crushing vehicle body plus the use of an air bag provides protection at V_c = 15 m/sec.

Station Features

Safety in PRT stations involves protection against falling off the station platform, being hit by a vehicle, and assault. The problem of falling off the platform is no different than in conventional transit and could, if desired, be protected against by suitable barriers. While most conventional transit systems have open platforms, automatic doors can be placed in front of each boarding position, but of course with the penalty of lower reliability and greater cost. Warning sounds may be sufficient. The problem of assault is most often mentioned. PRT systems should have television monitors with infrared devices to warn monitoring personnel of a person in the station in non-busy periods. Experience at the Morgantown, West Virginia "PRT" System showed that the existence of such devices markedly reduces perverse incidences. The station areas must be well lit and must be designed to have no corners where an assailant can hid.

Conclusions

Careful attention to the design of all elements of a PRT system can result in a level of safety possibly higher than can be attained in large-vehicle transit systems. This conclusion is counterintuitive to many transit professionals and requires proof through extensive testing and demonstration, the success of which can bring marked cost reductions and service improvements in public transportation. Recent advances in computer hardware and software make the difference from the 1970s, but the PRT designer will have to demonstrate that he has not overlooked safety as a primary requirement in any portion of his design.

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9.5 LIMs vs. LSMs for PRT

Advantages of LIMs for PRT:

- Short-headway, continuous control – no blocks.
- With digital encoders, adequate precision.
- Very small air-gap (3 mm) practical.
- Electronics on-board and in stations minimize maintenance cost.
- Ease of providing two independent LIMs & VFDs.
- Permits smooth rails and smooth guideways for minimum road resistance.
- No degradation of safety in rain or snow.
- Adequate drainage.
- Minimum size, minimum cost guideway.

Disadvantages of LIMs for PRT:

- Lower efficiency than LSMs
- Requires separate devices for power supply, communication, and propulsion

Questions about LSMs for PRT:

- Electronic packages in the guideway?
  - Every 20 ft?
  - What is MTBF?
  - What is the replacement frequency per mile?
  - What is the labor cost?
- What would a simulation of close-headway merging show?
- What would the guideway configuration look like?
  - Would the guideway configuration meet the criteria?
  - What would be the guideway cost per mile?
  - What would be the guideway dimensions?
  - How would drainage be handled?
- What would be the system cost per passenger-mi?
  - How would it compare with a LIM system?

At the 11th International Conference on Automated People Movers, held in Vienna, Austria, on April 22-25, 2007. Dr. Richard Thornton, the foremost expert on LSMs, gave a paper entitled "Maglev Personal Rapid Transit," in which he gave the cost of his LSM guideway components as high as our entire guideway. Subsequently he talked only of about 20-passenger GRT.

9.6 LIMs in Vehicles vs. LIMs in Guideway

We compare the cost of a PRT system using LIMs for propulsion in which the LIMs are in either the vehicles or in the guideway. Let

W_{LIM} = weight of one LIM.
W_{VFD} = weight of one LIM drive.
C_{LIM} = cost of one LIM
C_{VFD} = cost of one LIM drive
D_{veh} = Average distance between vehicles in operation, ft
D_{min} = Distance between vehicles for determining the guideway maximum load, ft
D_{LIM} = Distance between LIMs in guideway, ft

LIMs in guideway:

LIM guideway loading per unit length: W_{LIM}/D_{LIM}
Number of LIMs required per mile: $5280/ D_{LIM}$
Cost of LIMs per mile: $(C_{LIM} + C_{VFD})(5280/ D_{LIM})$

LIMs in vehicles:

LIM guideway loading per unit length: $2(W_{LIM} + W_{VFD})/D_{min}$
Number of LIMs required per mile: $2(5280)/ D_{veh}$
Cost of LIMs per mile: $(C_{LIM} + C_{VFD})(5280/ D_{veh})$
Cost of power rails per mile: \$14.60(5280) = \$77,100
Extra energy per vehicle-mile to carry LIMs and VFDs on board = 0.073 kW-hr[16]
Extra energy per year to carry LIMs and VFDs on board = 0.073 kW-hr × 80,000 mi/yr = 5840 kW-hr/yr.
Annual cost of this extra energy per vehicle = 5840(\$0.07) = \$409.
Annual cost of this extra energy per mile of system = \$409(5280)/ D_{veh}

Let A be the annualization factor, 7% from the OMB web page.
If the cost of LIMs on board vs. LIMs in the guideway is the same we get

$$[A(C_{LIM} + C_{VFD} + \$77,100) + \$409](5280)/ D_{veh} = A(C_{LIM} + C_{VFD})(5280/ D_{LIM})$$
$$D_{veh} = [A(C_{LIM} + C_{VFD} + \$77,100) + \$409]\, D_{LIM}/ A(C_{LIM} + C_{VFD})$$
$$= [A(C_{LIM} + C_{VFD}) + \$5810]\, D_{LIM}/ A(C_{LIM} + C_{VFD})$$

or
$$D_{veh} = [1+\$5810/ (0.07)(C_{LIM} + C_{VFD})]\, D_{LIM}$$

Assume C_{LIM} = \$4900 and C_{VFD} = \$4800. Then

[16] From "What determines transit energy use?"

$$D_{veh} = [1+\$5810/\ \$679]\ D_{LIM} = 8.6\ D_{LIM}$$

But $D_{LIM} \approx 5$ft. Therefore $D_{veh} = 43$ ft or 5280/43 = 123 vehicles per mile, which is higher than the maximum number of vehicles per mile. Therefore, on this basis the system cost is lower if the LIMs and VFDs are in the vehicles.

Is there a difference in the maximum guideway loading due to LIMs? If we consider the maximum guideway loading to be loaded vehicles nose-to-tail on the guideway then the load would be equal if the vehicles were 2(5 ft) = 10 ft apart. This is very close to the specified loading, which means that the basic guideway weight needed to support the load would be about the same in the two cases. The weight of power rails is not enough to make much difference.

We therefore conclude that the system cost will be lower if the LIMs are in the vehicles rather than in the guideway. One difference that we have not considered is the weight of the VFDs. If the LIMs are in the vehicles then so are the VFDs, but if the LIMs are in the guideway, the VFDs need not be in the guideway but could be placed in or on the posts, in which case their weight would not add to guideway weight. But with LIMs in the guideway and VFDs at the posts, much wiring must be added for them to reach each LIM, and in case of repair, a maintenance person would have to go out to the guideway to reach the LIMs, whereas if the LIMs and VFDs are in the vehicles, they will be maintained in a maintenance shop, which is less costly.

9.7 Power source on board vs. power source at wayside

On-board power can be provided through batteries, which are being manufactured in increasingly higher energy densities. However it takes time to charge them, which means that every vehicle must spend the charge time out of service. ULTra personnel have said that their lithium-ion batteries can be charged in only one minute, but that is long enough that the vehicle must in some way be taken out of service if it is not interfere with service. Moreover, a vehicle powered by on-board batteries must be limited in speed and range. I calculated many years ago that to take into account high winds and emergencies the on-board batteries should be charged with about seven times the energy required for an average trip. Lithium batteries are relatively light but each vehicle must carry its weight during every trip.

To provide power from wayside, it is necessary to mount power rails inside the guideway, which is an extra expense but a minor one, and wayside power can be provided by redundant means in any quantity from any source including renewable sources.

Conclusion: Use wayside power.

9.8 Synchronous vs. Quasi-synchronous vs. Asynchronous Control

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Control of Personal Rapid Transit Systems

Abstract

The problem of precise longitudinal control of vehicles to follow predetermined time-varying speeds and positions has been solved. To control vehicles to the required close headway of at least 0.5 sec, the control philosophy is different from but no less rigorous than that of railroad practice. A PRT system can be designed with as good a safety record as any existing transit system and, because of the ease of adequate passenger protection, quite likely much better. The basis for the control of a fleet of PRT vehicles of arbitrary size is a complete set of maneuver equations. The author's conclusion is that the preferred control strategy is one that could be called an "asynchronous point follower." Such a strategy requires no clock synchronization, is flexible in the face of all unusual conditions, permits the maximum possible throughput, requires a minimum of maneuvering and uses a minimum of software. Since each vehicle is controlled independently, there is no string instability. Since the wayside zone controllers have in their memory exactly the same maneuver equations as the on-board computers, accurate safety monitoring is practical. To obtain sufficiently high reliability, careful failure modes and effects analysis must be a key part of the design process, and the control computers must be checked redundant.

Introduction

The problem of closed-loop automatic longitudinal control of a single vehicle constrained to follow a guideway at a specified time-varying speed and position within adequate accuracy has been solved by several investigators [1, 2], and analytical equations for the required speed and position gains have been derived. The architecture of checked redundant microprocessor control for automated transit vehicles has been developed and has been shown to be able to achieve a safety record as good or better than a modern rapid rail system [3]. The major challenge in PRT control has been to control a large fleet of vehicles operating at fractional-second headway and merging and diverging in and out of stations and between separate branches in a network of guideways with an acceptable level of safety, comfort, and dependability, while meeting other essential criteria. A great deal of work has been done on this problem over the past few decades. Much of the published work can be found in conference proceedings [4, 5, 6], in papers referenced in those proceedings, and in results of the Urban Mass Transportation Administration's Advanced Group Rapid Transit Program [7, 8]. While the AGRT system was designed for 3-sec headway, much of the work is directly applicable to PRT. Together with the work of The Aerospace Corporation PRT Program [9] and the DEMAG+MBB Cabintaxi PRT Program [10], one can obtain an excellent perspective on the field.

In a short paper, it is not possible to describe any appreciable portion of this work, but it is more useful to give a synthesis of conclusions reached concerning the means of controlling a PRT system, which have been built on the shoulders of prior investigators. I first discuss the criteria any PRT control system must meet. Then, it is necessary to discuss the problem of safe achievement of adequately low time headway between vehicles and how the safety philosophy must differ from standard railroad practice. Next is a discussion of strategies of control of many vehicles in a network. With this background, the next topics are the information that must be available on board the vehicles and at various wayside points, the sensing and communication requirements, and the mathematics involved. I do not discuss lateral control because, in most PRT systems, wheels running against lateral surfaces achieve it passively.

Control Criteria

Line and Station Throughput

Analysis of PRT networks in many applications has shown that fractional-second headways are both needed and attainable. The 1974 UMTA Administrator Frank Herringer, in testimony before a committee of the Congress of the United States, said: "A DOT program leading to the development of a short, one-half to one-second headway, high-capacity PRT system will be initiated in fiscal year 1974 [11]." This statement was a result of consensus among workers in the PRT field in consultation with the Research and Development staff of UMTA on the need and practicality of headways as low as 0.5 sec. Off-line stations must be designed to meet expected input and output flows, and the system must be designed to prevent excessive congestion at merge points and destination stations.

Safety

A PRT system must provide a level of safety in terms of injuries per 100 million miles at least as good as a modern rapid rail system [3], and preferably better because the improvements provided by PRT in all areas must be good enough to justify the development cost. To achieve this level of safety, the on-board and wayside computers must be checked redundant.

Dependability

The term "dependability" is less often used than "availability," which is measurable in conventional transit systems as the percentage of trains that arrive at stations when expected. The quantity dependability, which is the ratio of person-hours not delayed to the number of person-hours of operation, is a more meaningful criteria and, in PRT, can be easily measured and updated trip by trip by a central computer [12]. In a recent PRT program, it was specified that the undependability (1 - dependability) should be no more than 3 person-hrs of delay per 1000 person-hrs of operation. From our analysis, if the safety criterion is met, the undependability will be at least an order of magnitude less.

Ride Comfort

Longitudinal maneuvers must be performed in such a way that International Standards Organization ride comfort standards on acceleration as a function of frequency are met. As to maneuvers, the National Maglev Initiative Office set the most recent federal standards on ride comfort that would be applicable to vehicles in which all passengers are seated. They restrict acceleration to 0.2 g and jerk to 0.25 g/s in normal operation. The maximum emergency-braking deceleration depends on whether or not passenger constraints are provided. If not, the criterion must be that the passenger not slide off the seat in an emergency stop.

Changing Conditions

The control system must be able to reduce cruising speed in high winds and must be able to cope with any unusual situation, such as a stopped vehicle, that would require vehicles to slow down or stop away from a station.

Dead-Vehicle Detection

There must be a means to detect a dead vehicle on the guideway, however remote that possibility may be. In Section 5, it is stated that the vehicles must transmit their speeds and positions at frequent intervals to a wayside computer – a zone controller. If the zone controller suddenly does not receive the expected signal, it must be programmed to remove the speed signal for all vehicles in that link and transmit this information to the next upstream zone controller. Each vehicle's control system is configured to command reduction in speed to creep speed[17] if the zone controller's speed signal is not received. Magnetic detectors are placed at specified intervals along the guideway to inform the zone controller of passage of a vehicle. Thus, if a vehicle passes one of these markers and not the next, the location of the dead vehicle is approximately known. Then, as discussed at the end of Section 3.2, because the passengers are seated and can be protected and the vehicle can be protected by appropriately designed shock-absorbing bumpers [13], a creeping vehicle can be permitted to advance until it soft engages with the dead vehicle, whereupon the position of the dead vehicle becomes known and an appropriate failure strategy can be engaged.

Interchange Flexibility

The simplest interchange is a Y, with either two lines entering and one exiting or vice versa. Such an interchange gives the least visual impact at any one point, but it requires that vehicles first merge, then diverge, which creates a bottleneck after a merge. Desiring to obtain maximum possible throughput, The Aerospace Corporation [9] used two-in, two-out, multilevel interchanges, which permit vehicles to diverge first and then merge. With such interchanges, the input and output capacity of the lines is the same, hence the worst that can happen is that a vehicle may have to be diverted from the direction it would normally go. Thus the control system does not have to be concerned with sending too much traffic along a particular line. If Y-interchanges are used, control is more complex and is discussed below. Since Y-interchanges are often necessary, the control system must permit them.

Vandalism and Sabotage

A system in which the control functions are distributed and the wayside computers are protected, for example in safe rooms under the stations, will be less susceptible to damage than a system in which a central computer plays an essential role. To minimize the consequences of failures of any kind, distributed control is also preferred. The required central-computer functions should be such that the worst that can happen if it fails is that the system will operate less efficiently.

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[17]A finite creep speed permits normal vehicles ahead of the failed vehicle to move safely to the next zone, reduces anxiety, and with seated passengers is safe.

Modularity

The control units should be easily exchangeable so that down time is minimized.

Expandability

The control system should be designed for easy expansion of the system.

Principles of Safe, High-Capacity PRT

The Headway Equation

The minimum safe spacing between vehicles is the longest emergency stopping distance minus the shortest failure stopping distance. It is given by the equation

$$H_{\min} = Vt_c + \frac{V^2}{2}\left(\frac{1}{A_e} - \frac{1}{A_f}\right) \tag{1}$$

in which V is the line speed, t_c is the time constant for brake actuation, A_e is the minimum emergency braking deceleration, and A_f is the maximum failure deceleration. Strictly speaking there should be a term added involving the rates of change of deceleration (jerk), but the emergency jerk can be made high enough so that jerk does not add to H_{min}. If L is the length of the vehicle, the minimum time headway, using equation (1), is

$$T_{\min} = \frac{L + H_{\min}}{V} = \frac{L}{V} + t_c + \frac{V}{2}\left(\frac{1}{A_e} - \frac{1}{A_f}\right) \tag{2}$$

Equation (2) shows first that PRT vehicles should be as short as possible. With careful design, a length of 2.6 m is practical. A typical operating speed is 13 m/s, in which case the first term in T_{min} is 0.2 sec. Boeing work [14] showed that vehicles can transmit their speeds and positions as frequently as once every 40 msec. To command emergency braking requires two such transmissions. The braking time constant, once a signal is received must be very short. With the right technology, 100 msec is practical. Therefore, with some extra allowance, assume t_c = 0.2 sec. If the minimum line headway is to be 0.5 sec, the third term in equation (2) can thus be no more than 0.1 sec – practically zero. This means that *in a fractional-second-headway PRT system, the design must be such that the minimum emergency deceleration must be as high as the maximum reasonably possible failure deceleration.*

The most recent indication of the practicality of close-headway control is an announcement by the National Automated Highway System Consortium [15] that in about a year "10 specially outfitted Buick LeSabres will take part in the first test of an automated highway." A companion article on the same page says that these 200-inch long autos will operate at a spacing of only 6 feet at "50-plus miles an hour." This works out to a time headway of 0.309 sec. At 30 mph the headway would be 0.515 sec.

Departures from Railroad Practice

In railroad practice, trains may be so long that the first term in equation (2) may be several times the term $V/2A_e$. Also, at grade level, it is easiest for some foreign object or another train to quite suddenly appear ahead. In the worst case the train ahead theoretically stops instantly, in which case the fourth term in equation (2) is zero. Relative to the size of the term L/V, this is not a severe assumption and is conservative. In railroad practice it is standard to design for the so-called "brick-wall" stop in which A_f is infinite.

A railroad block control system depends in emergency situations on a vital relay that virtually never fails. Its failure is likely to cause a collision, but such a failure is so rare that it is assumed never to occur. What is implied is that the probability that the vital relay fails when it is needed is so low that it is acceptable. There is no other choice. *In any moving system the simultaneous occurrence of two very improbable major failures may set up the conditions for a collision.*

In simple terms, in railroad practice the philosophy is that if one train is to stop instantaneously, the train behind must be able to stop in a distance short enough to avoid a collision. In PRT, the philosophy must and can be that if one vehicle stops instantaneously, someone is already killed. Therefore, one must and can design the system so that, barring a calamitous external event, it is "impossible" for one vehicle to stop instantaneously. Just as in railroad practice, "impossible" has the meaning stated in the paragraph above.

This failure philosophy requires careful analysis of every circumstance in which a sudden stop could theoretically occur. There are only two: 1) Something falls off a vehicle or a foreign object appears that wedges the vehicle in the guideway and causes it to stop very quickly, and 2) a collision with the junction point of a diverge. Making the first of these possibilities acceptably remote requires careful design and an inspection procedure that frequently assures that nothing is coming loose. Experience with road vehicles gives a feeling for the possible frequency of such an occurrence, which almost never happens to a well maintained vehicle. By more detailed analysis than possible here it can be shown that by proper design a diverge collision will require two simultaneous highly improbable failures plus a rare "Act of God" event.

If there are many vehicles on a guideway, there are two additional possibilities for a sudden stop. One is a runaway vehicle entering a station and failing to stop before colliding with a standing vehicle, and the other is a merge collision. By use of checked-redundant vehicle control such as developed by Boeing [8], it is practical to design the control system in such a way that the mean time between over-speed failures continuing to a station collision is at least a million years. It can be shown that a merge collision would require two such failures in very close proximity in space and time, which places its MTBF in a range more remote than the estimated life of the universe.

In a PRT system designed as indicated above, there are no sudden stops; however, there may be on-board failures that require emergency braking. Equation (2) shows that to achieve safe fractional-second headway, one vehicle cannot be permitted to stop quicker than the vehicle behind. This requires closely controlled, constant-deceleration braking regardless of the condition of the guideway, which rules out systems that rely on braking through wheels because in rainy or snowy weather the coefficient of friction may vary along the guideway. This is the safety-related argument for the use of linear electric motors.[18] It may be noted that it is quite likely best to decelerate at the normal rate if an on-board failure is detected. Trying to decelerate too rapidly may cause more problems than it solves.

The final factor in the difference between PRT and railroad practice is that PRT vehicles are light enough so that reasonably sized bumpers can absorb a great deal if not all of the collision energy, and all passengers are seated. By using data from auto safety practice, a PRT vehicle therefore can and should be designed so that even a collision need not cause injuries [13].

Control Strategy

General Considerations

Adequately tight control of the speed profile can be attained by using proportional plus integral (P+I) control based on tachometer feedback. A vehicle must be able to perform any one of the following maneuvers:

Speed change from given speed and acceleration to new speed
Slip given distance forward or backward from line speed
Slip given distance from acceleration maneuver
Slip given distance from slip maneuver
Advance given distance in station from rest or from deceleration maneuver
Emergency stop

Code must be written so that the time-varying speed and position profiles of any of these maneuvers with any set of desired parameters can be calculated in the on-board computer and used as com-

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[18]Another important reason for use of linear electric motors (with an appropriate guideway design) is to eliminate the need for guideway heating.

mands to the controller. If during each computational or time-multiplexing interval a wayside zone controller transmits a speed signal to all vehicles in its domain and at certain command points can transmit to a specific vehicle a maneuver command with a parameter (the desired speed, distance to slip, etc.), the vehicle has all the information it needs to perform the maneuver. Moreover, by calculating the speed profile in parallel, the zone controller has all of the information it needs to monitor the execution of the maneuver. If a vehicle moving at line speed moves away from the desired time varying position, the integral portion of the P+I controller corrects the position. If the tachometer drifts, as it will, magnetic markers along the guideway provide the basis for correcting the tachometer constant, and, by commanding a slip maneuver, the time-varying position. If the speed of the vehicle at a certain time is in error in excess of a preset amount, the zone controller assumes a fault and removes the speed signal from its domain. The vehicle controller is programmed to command creep speed if it does not receive the speed signal, so any failure causes a safe reaction.

We now have a system in which the vehicles each closely and reliably follow commanded speed profiles and are simultaneously monitored for failures by wayside zone controllers. Upon this basis it is possible to describe the maneuvers needed to operate the system. This discussion is based on extensive experience with a PRT-network simulation. We first consider the progress of an occupied vehicle from the point a passenger group enter to the point that they arrive at their destination, then we consider movement of empty vehicles.

Movement of an Occupied Vehicle

Let's join a group traveling together to the same destination by choice. We either have a magnetically coded ticket with the destination recorded on it because we take the same trip every day, or we must approach a ticket machine to punch in a destination, pay a fare, and receive a ticket. With a valid ticket we approach the forward-most available vehicle in a line of vehicles and insert the ticket into a stanchion in front of the stopped and ready vehicle. This action flashes the origin and destination station to a central computer which has in its memory the estimated arrival times of all vehicles moving through the system. If our vehicle is expected to arrive at its destination station at a time when the station is full and cannot receive another vehicle, we are informed that we must wait a specified time before we can try again. Generally this will be a very small time and the central computer will prioritize the unfulfilled demands for service.

When the ticket can be accepted, the station computer so informs us, causes our vehicle's door to open, and transfers the memory of the destination to the on-board computer. We enter our vehicle, sit down and when ready one of us presses a "GO" button. Thereupon the door is automatically locked. If our vehicle is not in the forward-most loading berth, it must wait until the vehicle or vehicles ahead move out. If it cannot yet be commanded to line speed because an opening is not yet available, it is commanded to advance as far forward as possible.

The station zone controller meanwhile is examining the flow passing the station for an opening. By zone-controller supervision the vehicles on the main line are maintained at separations at or greater than the minimum separation permitted by equation (1). Note that there need at this point be no synchronization. If there is no traffic on the main line a vehicle can be commanded to accelerate to line speed at any time it is ready. As traffic on the main line builds up, say with the approach of the morning rush hour, vehicles pass stations at any spacing down to the minimum allowed.

To create an opening for our vehicle, the zone controller may command a mainline vehicle too close ahead to slip ahead if possible and a mainline vehicle behind to slip behind at the moment it commands our vehicle to line speed. If slipping of the mainline vehicle behind would cause the headway between it and the vehicle behind it to fall below the minimum, the zone controller would within a few milliseconds cause that vehicle to slip too, and so on upstream. If there would be too much slipping of upstream vehicles or if the slipping of downstream vehicles has propagated into the station area, our vehicle would wait until there is an acceptable opportunity to accelerate out of the station.

When an opening appears, our vehicle is commanded to accelerate out of the station, either from rest or from a station-advance maneuver. While our vehicle is accelerating, a vehicle ahead may be caused to slip because of a conflict at a downstream merge point. If that happens and if our vehicle would reach line speed too close behind the vehicle ahead after it is through slipping, our vehicle is commanded to slip the necessary amount while accelerating and, if necessary, the main-line vehicles behind it will be commanded to slip by the amount needed to maintain minimum headway.

Next, suppose our vehicle approaches a line-to-line merge point. As it passes a command point at a predetermined location upstream of the merge junction, the cognizant wayside zone controller, having in its memory the positions, speeds and slip maneuver data for each vehicle within this merge zone, gives a maneuver command needed to resolve any conflict. If the vehicle ahead on the other branch of the merge is too close, the zone controller commands it to slip ahead if possible[19], or if not, it commands our vehicle to slip back. If our vehicle is commanded to slip back it may slip into the headway domain of the vehicle behind on the same leg of the merge, in which case that vehicle and possibly vehicles behind it are commanded simultaneously to slip necessary amounts. Since our vehicle may thus already be slipping when passing the command point, the on-board maneuver algorithm is designed so that it can cause additional slip of a slipping vehicle. Such operations have been found by simulation to be completely stable.

After passing the merge point, suppose our vehicle next approaches a diverge point. At a predetermined command point upstream of the diverge, the cognizant zone controller requests our destination, which is transmitted through a transmission medium to the zone controller. The diverge zone controller has in its memory a switch table giving the left or right switch command for each station in the network from that diverge point. By fiber optic line, the central computer can transmit revised switch tables to various diverge-point zone controllers every few seconds if necessary to avoid excessive congestion in certain downstream links. The zone controller transmits the right or left switch command to our vehicle, which then acts on the command.

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[19]Slipping ahead is practical only if the minimum line headway is less than about one second. Otherwise the maximum travel distance to slip is excessive.

Next suppose our vehicle approaches a station. As soon as it has passed a merge or diverge point, it is handed off to a new zone controller that asks for and receives its destination. If this station is not our destination, the zone controller commands our vehicle to switch in the direction opposite the station off-line guideway. If this station is our destination, the zone controller does not give a switch command immediately but waits until our vehicle reaches a switch command point at the farthest downstream point at which the switch can, with a tolerance, be safely thrown. The wait is necessary because the station may have been full when our vehicle first entered the domain of the cognizant zone controller, but the last position in the waiting queue on the station off-line guideway may have cleared a few moments later.

When our vehicle reaches its destination station's switch command point, the zone controller commands it to switch in the direction of the station if there is an available berth, and if not commands it to switch away from the station. If the zone controller commands our vehicle to switch into the station, it assigns it a berth so that the next vehicle will find that this berth is reserved. Our vehicle switches if necessary and continues forward at line speed to a deceleration command point. At this point, if one or more positions down- stream of the assigned berth have cleared, a new farther-forward position is assigned, the old one is cleared, and our vehicle is commanded to decelerate along a speed profile that first reduces the speed to a predesignated station speed and then moves the vehicle forward, usually at station speed, until it must decelerate at the comfort rate to stop at the assigned position. If, at any time during the deceleration maneuver, the zone controller has advanced a vehicle out of the position or positions ahead of the assigned position, it reassigns our vehicle to the forward-most empty or to-be-empty position and revised the deceleration maneuver accordingly.

If our vehicle must stop at one of the waiting positions upstream of the station unloading and loading berths, it waits until the zone controller can command it to advance into a loading berth. If, any time during the station-advance maneuver, the berth ahead of the previously assigned berth clears, the station-advance maneuver is revised to dock our vehicle at the new forward-most free berth. When our vehicle stops, the door is either opened by a passenger or by an automatic device.

The reader may note that some PRT designers have proposed that there be separate loading and unloading platforms. This doubles the station length, reduces the throughput, and with the small passenger groups characteristic of PRT it does not significantly reduce the time required for unloading then loading.

Synchronous, Quasi-synchronous and Asynchronous Control

In the early 1970s, the discussion of PRT control virtually always started with a discussion of the relative merits of synchronous, quasi-synchronous, or asynchronous control. In a purely synchronous control system, a vehicle that is ready to leave a station waits until it has a confirmed reservation through every merge point and at the destination before being dispatched. Such a system was discarded because it is inflexible in a slow-down or stoppage on the main line; and, if the number of merges that must be negotiated exceeds three or four, the wait time becomes excessive [18]. The quasi-synchronous system was therefore proposed to permit vehicles to maneuver to resolve merge conflicts.

In his book [9] Dr. Jack Irving, while advocating quasi-synchronous control, commented that the essential point is that a wayside computer command and monitor maneuvers, just as described above. Until reaching a merge point, there is no need to synchronize the flow, and to do so in advance results in more maneuvering than necessary. As in the scheme described in the above paragraphs, whenever a vehicle arrives at the merge command point, if there is an approaching conflict, a merge-point zone controller either commands the conflicting downstream vehicle on the other leg of the merge to slip ahead if possible, or if not to slip the vehicle that has just arrived at the command point back. There is no need at merges to synchronize with specific clock times. We have also found that the described strategy requires less software than quasi-synchronicity.

Such a scheme is asynchronous except for the technicality of having to synchronize merging of certain vehicles with respect to one vehicle, but not with respect to a clock. In the 1970s, asynchronous control usually implied car following, in which each vehicle is controlled based on the position and sometimes the speed of the next downstream vehicle [1]. As pointed out above and by Dr. Irving, car following is not necessary. It complicates the control problem and is difficult for the necessary wayside monitor because the monitor does not know independently the profile of the maneuver. In the terminology used in the 1970s, the system we prefer could be called an "asynchronous point follower."

Movement of Empty Vehicles

During the night when there is little or no traffic on the system, most of the vehicles are stored at strategically located storage barns and the rest are stored at stations so that, as in elevator service, passengers don't need to wait anxiously on deserted platforms, but instead vehicles that are ready to leave immediately wait for passengers. The number of vehicles required to wait at each station must be determined by an operational study.

As passengers start arriving at stations, the waiting empty vehicles are used up and more must be ordered. Based on operational experience, a flow of empty vehicles can be started in anticipation of passengers. In any case, once the number of vehicles in a station that have not been given destinations plus the number within a specified time of arrival is less than the number of passengers waiting, the station computer signals to the central computer via fiber-optic line that it needs an empty vehicle. Other stations will have surplus empty vehicles either because there are no passengers at the station and there are more vehicles in or approaching the station than the specified minimum, or because the flow of occupied vehicles in and approaching the station exceeds the flow of passenger groups entering the station from the street. In the latter case, it will sometimes be necessary to dispatch an empty vehicle while a passenger group is approaching it in order to permit occupied vehicles to enter the station and unload. In this case, the passenger group will be informed by computer voice that another vehicle will be docking in a few seconds. As soon as a station has a surplus vehicle its computer so informs the central computer and dispatches the surplus vehicle to the next station.

When an empty vehicle reaches the switch command point of a station, if the station does not need an empty vehicle its computer waves it off to the next station. If this station could use an empty vehicle, it would like to call this one in, but there may be a greater need for it at a downstream station. So, the central computer, having a knowledge of the number of empty and occupied vehicles in each link in the network and of the number and wait time of passenger groups waiting at each station, has the basis for determining whether each station should accept or wave off needed empty vehicles. Since the situation is updated every few seconds, no passenger group need wait much more than at other stations. The average wait time can be reduced by increasing the number of empty vehicles in the network, but at the expense of increased congestion and system cost.

The major decision points for distribution of empty vehicles are the diverge points. Here, as already mentioned, the central computer, with knowledge of the whole system, can, by fiber-optic link, direct left or right switch commands for the next empty vehicle. Such frequent updating of empty-vehicle commands at the last possible moment is a far easier problem to solve than the general transport problem.

Information Transfer

With the above described control strategy, the information that must be fed to the vehicle computer is the vehicle's actual speed and position; the cruising speed, which could be a function of wind or position in the guideway; and, at certain command points, the number of a maneuver with a parameter. The information required by each wayside zone controller is all vehicle positions and speeds in its domain including hand-off of the state of each vehicle as it enters its zone, and any information about anomalies. The information needed by the central computer is the stations at which there are surpluses or deficits of empty vehicles, the number of empty and occupied vehicles in each link, the destinations of and the departure times of all vehicles commanded to leave stations, the arrival times, the distance each vehicle has traveled, the distance traveled at which each vehicle is due for maintenance or cleaning, the location of and data on any faults in the system, and the weather conditions.

To perform the required data transfer there must be a continuous and noise resistant means for data transfer between vehicles and zone controllers, such as the three-wire communication line developed by Boeing [14, 16], a series of magnet markers to signal passage of vehicles, and fiber-optic links between the central controller and all zone controllers. At predetermined intervals

(Boeing used 40 msec), each vehicle must transmit to the cognizant zone controller its vehicle number, speed, position, destination on call from the zone controller, and any data about faults. The wayside zone controller must be able to transmit to all vehicles in its domain a continuous cruise-speed signal, and it must be able to transmit parameterized maneuver commands and switch commands to specific vehicles when needed.

For position and speed sensing, Boeing engineers [17] found that incremental wheel-angle encoders with a resolution of 0.04 foot per pulse were sufficient as the basis for computing both. Position measurement consisted only of counting pulses, but the calculation of speed was "considerably more complex and, to a large extent, dictated the Programmable Digital Vehicle Control System configuration" they selected. The vehicle must also be equipped with sensors to detect the magnetic markers and to transmit to and receive data from the communications line.

Mathematics

Maneuver equations

Parameterized equations are needed for all of the maneuvers required to run a PRT system as described. This is not an easy task, but once the algebra is worked out, as we have done, it is available forever. The equations can easily be programmed into the memory of the on-board and wayside computers, which then permits accurate control and monitoring of each vehicle with a minimum of data transfer.

Curved-Guideway Equations

In the above discussion, reference was made to the location of certain command points. Determination of the positions of all such points requires a complete understanding of the equations of curved guideways and their use in minimization of off-line guideway lengths and distances between branch points.

Empty-Vehicle Movement

A general scheme of the points and times in the system where empty vehicles are to be redirected has been given and the use of decision algorithms has been suggested. In relatively small systems, these are quite simple, but the challenge is to optimize such algorithms as the network grows. Some good work [9] has been done on this problem, but more is needed.

Conclusions

Analysis, simulation and hardware experience has shown that the problem of precise longitudinal control of vehicles to follow predetermined time-varying speeds and positions has been solved. To control vehicles to the required close headway of at least 0.5 sec, the control philosophy is different from but no less rigorous than that of railroad practice. Available results show that a PRT system can be designed with as good a safety record as any existing transit system and, because of the ease of adequate passenger protection, quite likely better.

With maneuver equations derived in easily programmable form, one has the basis for the control of a fleet of PRT vehicles of arbitrary size. The author's conclusion is then that the preferred control strategy is one that could be called an "asynchronous point follower." Such a system requires no clock synchronization, is flexible in the face of all unusual conditions, permits the maximum possible throughput, requires a minimum of maneuvering, and a minimum of software. Since each vehicle is controlled independently, there is no string instability. Since the wayside zone controllers have in their memory exactly the same maneuver equations as the on-board computers, accurate safety monitoring is practical. To obtain sufficiently high reliability, careful failure modes and effects analysis must be a key part of the design process, and the control computers must be checked redundant. Work of the federal Advanced Group Rapid Transit Program showed a decade ago how that can be done in a very satisfactory manner.

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9.9 Why Synchronous Control is not a Good Idea

Journal of Advanced Transportation, 30:3(1996):1-3.

Synchronous or Clear-Path Control in Personal Rapid Transit Systems

An equation is derived for the ratio of the expected value of the maximum possible station flow to average line flow in a personal rapid transit or dual-mode system using fully synchronous control. It is shown that such a system is impractical except in very small networks.

In a synchronously controlled PRT system a vehicle waits at an origin station until the path through all merges to the destination is clear. The system then reserves this path for the specific vehicle in question, which then proceeds without any maneuvers directly to the destination. Such a scheme was proposed in the late 1960s for the automated transit system deployed in Morgantown, West Virginia. Because of its inflexibility in face of failure of any vehicle to maintain its path, interest declined, but the clear-path idea has emerged again on the Transit Alternatives mailing list on Internet. It is thus worthwhile to show why, by estimating the wait time for an origin-to-destination reservation, fully synchronous systems are not practical except in very small networks.

Let f be the average rush-period line flow in vehicles per second in a PRT system, let h be the minimum time headway in seconds, and let m be the number of merge points to be passed on an average trip including the merge from station to line. Then, $1/h$ is the number of moving slots passing any point on the main line per second, and the quantity fh is the average fraction of line slots occupied by vehicles. Thus the probability of finding an empty slot at any instant of time is $1 - fh$.

To find a clear path, it is necessary to find m slots at the time a vehicle is ready to leave a station. The probability of such an event is the probability of the simultaneous occurrence of m independent events, which is the product of the probabilities of the individual events. Thus, the probability of finding a clear path at any time is

$$(1 - fh)^m . \qquad (1)$$

If the search is repeated n times, the probability of finding a clear path is n times the probabilities of the individual events. If there is to be a 50-50 chance of attaining a clear path in n tries, its probability of occurrence must be one half. Thus, set

$$n(1 - fh)^m = \frac{1}{2}$$

or

$$n = \frac{1}{2(1 - fh)^m} \qquad (2)$$

If at any moment a clear path is not attained, it is necessary to wait h seconds to try again. Thus, the expected wait time is nh or

$$T_{wait} = \frac{h}{2\left(1 - fh\right)^m} \tag{3}$$

In dimensionless terms, the quantity $\left(1/T_{wait}\right)/f$ is the ratio of the maximum station flow, restricted by the need to wait for a clear path, to the average line flow. Thus

$$\frac{1/T_{wait}}{f} = \frac{2\left(1 - fh\right)^m}{fh}. \tag{4}$$

Equation (4) is plotted in Figure 1 with fh, the average line-slot occupancy ratio, as the abscissa, for a range of values of m. For economic viability in a PRT system, it is necessary to be able to operate at values of the average line-slot occupancy ratio up to about one half. To obtain sufficient throughput at the largest stations, it is necessary that the ratio of maximum station flow to maximum line flow be at least a quarter. From Figure 1, it is seen therefore that if clear-path control is to be practical, there should be no more than an average of four merges, including station-to-line merges.

The idea, sometimes advanced, of a large PRT network using clear-path or synchronous control is seen to be completely impractical.

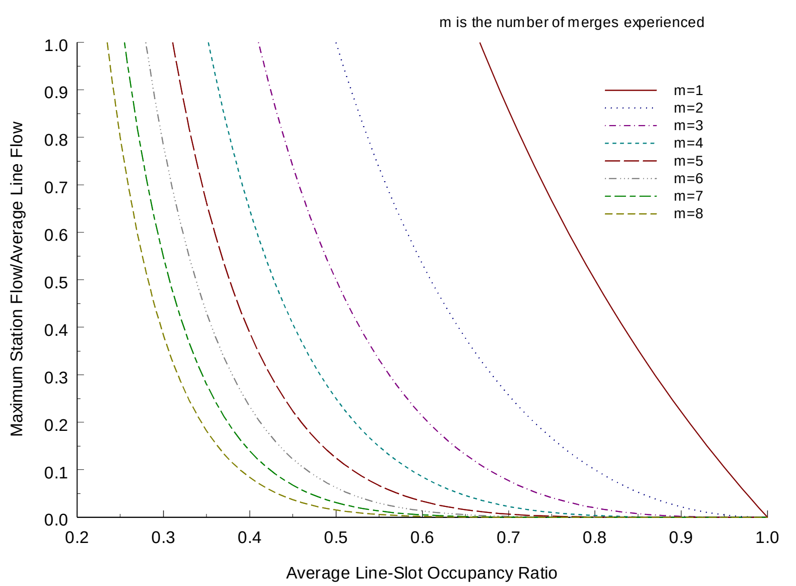


Figure 1. Performance of a PRT System Using Synchronous Control.

9.10 The Minimum-Weight Guideway

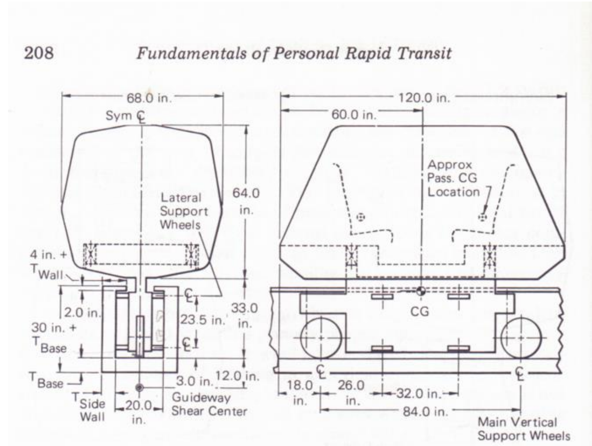


Fig. 7-4. PRT Vehicle/Guideway Geometry

The guideway of any PRT system is the most expensive component of the system. It is thus necessary to determine how to minimize guideway cost. I took the drawing shown here from The Aerospace Corporation 1978 book *Fundamentals of Personal Rapid Transit.* On their page 207 they said "Because of the greater mechanical simplicity of the overriding concept (vehicle above guideway), its inherently greater safety, and the lower cost and improved aesthetics of the guideway, we chose this concept (Fig. 7-4) for more detailed study. In Chapter 10 of my book *Transit Systems Theory*, thinking at the time about the German Cabintaxi guideway, I showed that based on bending stress, the minimum-cost guideway has a width less than the depth and hence less than the vehicle width. Further analysis, reported in this book under Task 5, I show that the guideway width needed to withstand the maximum crosswind is less than the depth and hence less than the vehicle width. This bit of systems analysis shows that to minimum both cost and visual impact, it is necessary to design the vehicle to fit an optimum guideway rather than, as often happened, to design the guideway to fit a conventional-looking vehicle. The fact that The Aerospace Corporation opted, as shown in the above Fig. 7-4, for a vertical chassis gave me the courage to try an unorthodox chassis configuration, and I have never regretted that decision.

9.11 Two vs. four lower side wheels

Offset of the Lower Rear Wheel on the Chassis

Reference: "Control and Simulation of ITNS," an internal paper.

When our vehicle passes through a portion of the guideway that is in transition to a super-elevated turn, the positions of the contact points of a pair of upper side wheels and a pair of lower side wheels cannot all lie in one plane since only three points define a plane. Thus, there will be a twisting moment applied to the chassis as the vehicle traverses the transition section of guideway. The purpose of this analysis is to determine how far out of the plane formed by three side-wheel contact points the fourth contact point will be, i.e., the offset of the 4^{th} wheel, and thus the extent to which this is a problem if we use four side wheels, two upper and two lower on each side, which reduce the loads on the lower side wheels.

Consider the cross section of the guideway to be a U-shaped section defined by four points. Let there be a fixed reference frame with its origin at the midpoint of the bottom of the U at the beginning of the transition. Let the *x* axis be in the direction of motion at the start of a transition to a super-elevated turn, the *y* axis be horizontal, perpendicular to the *x* axis, and positive to the left. Let the *z* axis be vertical and positive upward. In this right-handed orthogonal reference frame, the coordinates of the four side-wheel contact points in the U section at $x = 0$ are

$$x_1 = 0, \quad y_1 = -\frac{1}{2}w, \quad z_1 = 0$$
$$x_2 = 0, \quad y_2 = \frac{1}{2}w, \quad z_2 = 0$$
$$x_3 = 0, \quad y_3 = -\frac{1}{2}w, \quad z_3 = h$$
$$x_4 = 0, \quad y_4 = \frac{1}{2}w, \quad z_4 = h$$

in which *w* is the distance between the left and right contact points and *h* is the vertical distance between the upper and lower contact points.

In the transition region to the maximum superelevation angle $\phi_{\max}$ the coordinates of the center-line of the guideway are

$$x \cong s, \quad y = \frac{J}{6V^3}x^3, \quad z = 0.$$

In these equations J is the lateral jerk, V is the speed, and we take into account that the direction change is small. At a point $s \cong x$, the slope θ_s and bank angle ϕ_s of the guideway are

$$\theta_s = \frac{J}{2V^3}x^2, \quad \phi_s = \phi_{\max}\frac{x}{s_{\max}}, \text{ where } s_{\max} = Vt_J, \text{ where } t_J \text{ is greater of } \frac{A_c}{J}, \frac{\phi_{\max}}{\dot{\phi}_{\max}}$$ [20]

in which A_c is the comfort horizontal acceleration and we let the super-elevation angle increase linearly from 0 to its maximum value. The coordinates of the four points of the U-frame at position x are

[20] With $\phi = 6^o$ $A_c = g(tan\phi + 0.2/cos\phi) = 0.306g$ and $J = 0.25g$. Therefore $\frac{A_c}{J} = 1.225\ sec.$ $\frac{\phi_{max}}{\dot{\phi}} = \frac{6^o}{5^o/sec} = 1.2sec$ which is less than $\frac{A_c}{J}$ at 6° but greater for larger values.

$$x_{1_s} = x + \frac{1}{2}w\theta_s = x + \frac{wJ}{4V^3}x^2, \quad y_{1_s} = \frac{J}{6V^3}x^3 - \frac{1}{2}w, \quad z_{1_s} = \frac{w\phi_{\max}}{2s_{\max}}x$$

$$x_{2_s} = x - \frac{1}{2}w\theta_s = x - \frac{wJ}{4V^3}x^2, \quad y_{2_s} = \frac{J}{6V^3}x^3 + \frac{1}{2}w, \quad z_{2_s} = -\frac{w\phi_{\max}}{2s_{\max}}x$$

$$x_{3_s} = x + \frac{1}{2}w\theta_s = x + \frac{wJ}{4V^3}x^2, \quad y_{3_s} = \frac{J}{6V^3}x^3 - \frac{1}{2}w, \quad z_{3_s} = \frac{w\phi_{\max}}{2s_{\max}}x + h$$

$$x_{4_s} = x - \frac{1}{2}w\theta_s = x - \frac{wJ}{4V^3}x^2, \quad y_{4_s} = \frac{J}{6V^3}x^3 + \frac{1}{2}w, \quad z_{4_s} = -\frac{w\phi_{\max}}{2s_{\max}}x + h$$

Consider two sets of these points with the upper pair of wheels separated by the distance $\Delta x = L$, where L is the distance between the upper front and upper back side-wheel contact points. The lower rear wheel is forward of the upper wheel by a distance D and the lower front wheel is behind the upper front wheel by the distance D. Since the centrifugal force on the chassis pushes it to the right, i.e., into the wheels 1 and 3, define a plane by three points on the right side of the chassis. Two of these points are at the forward and rear upper positions 3 separated by the distance L and the third is at the forward lower position 1. We want to determine how far the rear position 1 is from the plane thus defined. These four points on the right side, 3f, 3r, 1f, and 1r, can be represented as vectors from the origin of the x, y, z reference frame, with corresponding unit vectors $\hat{\imath}, \hat{\jmath}, \hat{k}$. Thus

$$\hat{V}_{3f} = \left(x + \frac{wJ}{4V^3}x^2\right)\hat{\imath} + \left(\frac{J}{6V^3}x^3 - \frac{1}{2}w\right)\hat{\jmath} + \left(\frac{w\phi_{max}}{2s_{max}}x + h\right)\hat{k}$$

$$\hat{V}_{3r} = \left(x - L + \frac{wJ}{4V^3}(x-L)^2\right)\hat{\imath} + \left(\frac{J}{6V^3}(x-L)^3 - \frac{1}{2}w\right)\hat{\jmath} + \left(\frac{w\phi_{max}}{2s_{max}}(x-L) + h\right)\hat{k}$$

$$\hat{V}_{1f} = \left(x - D + \frac{wJ}{4V^3}(x-D)^2\right)\hat{\imath} + \left(\frac{J}{6V^3}(x-D)^3 - \frac{1}{2}w\right)\hat{\jmath} + \left(\frac{w\phi_{max}}{2s_{max}}(x-D)\right)\hat{k}$$

$$\hat{V}_{1r} = \left(x - L + D + \frac{wJ}{4V^3}(x-L+D)^2\right)\hat{\imath} + \left(\frac{J}{6V^3}(x-L+D)^3 - \frac{1}{2}w\right)\hat{\jmath} + \left(\frac{w\phi_{max}}{2s_{max}}(x-L+D)\right)\hat{k}$$

The vector from point 3f to point 3r is

$$\Delta\vec{V}_{33} = \hat{V}_{3f} - \hat{V}_{3r} = \left(L + \frac{wJL}{4V^3}(2x-L)\right)\hat{\imath} + \frac{JL}{6V^3}(3x^2 - 3xL + L^2)\hat{\jmath} + \frac{w\phi_{max}}{2s_{max}}L\hat{k}$$
$$= p_3\hat{\imath} + q_3\hat{\jmath} + r_3\hat{k}$$

The vector from point 3f to point 1f is

$$
\begin{aligned}
\Delta\vec{V}_{31} = \hat{V}_{3f} - \hat{V}_{1f} &= D\left\{\left[1 + \frac{wJ}{4V^3}(2x - D)\right]\hat{\imath} + \frac{J}{6V^3}(3x^2 - 3xD + D^2)\hat{\jmath} + \left(\frac{h}{D} + \frac{w\phi_{max}}{2s_{max}}\right)\hat{k}\right\} \\
&= p_1\hat{\imath} + q_1\hat{\jmath} + r_1\hat{k}
\end{aligned}
$$

The cross product of these last two vectors is a vector perpendicular to the plane 3f, 1f, 3r. Thus

$$
\Delta\vec{V}_{33} \times \Delta\vec{V}_{31} = (q_3r_1 - q_1r_3)\hat{\imath} + (p_1r_3 - p_3r_1)\hat{\jmath} + (p_3q_1 - p_1q_3)\hat{k}
$$

Thus, the unit vector perpendicular to the plane 3f, 1f, 3r is

$$
\hat{\imath}_p = \frac{\left[(q_3r_1 - q_1r_3)\hat{\imath} + (p_1r_3 - p_3r_1)\hat{\jmath} + (p_3q_1 - p_1q_3)\hat{k}\right]}{\sqrt{(q_3r_1 - q_1r_3)^2 + (p_1r_3 - p_3r_1)^2 + (p_3q_1 - p_1q_3)^2}}
$$

The vector from point 3r to 1r is

$$
\begin{aligned}
\Delta\vec{V}_{31r} &= \hat{V}_{3r} - \hat{V}_{1r} \\
&= -D\left[1 + \frac{wJ}{4V^3}(2(x - L) + D)\right]\hat{\imath} - \frac{JD}{6V^3}[3(x - L)(x - L + D) + D^2]\hat{\jmath} \\
&\quad + (h - D)\hat{k} \\
&= p_{1r}\hat{\imath} + q_{1r}\hat{\jmath} + r_{1r}\hat{k}
\end{aligned}
$$

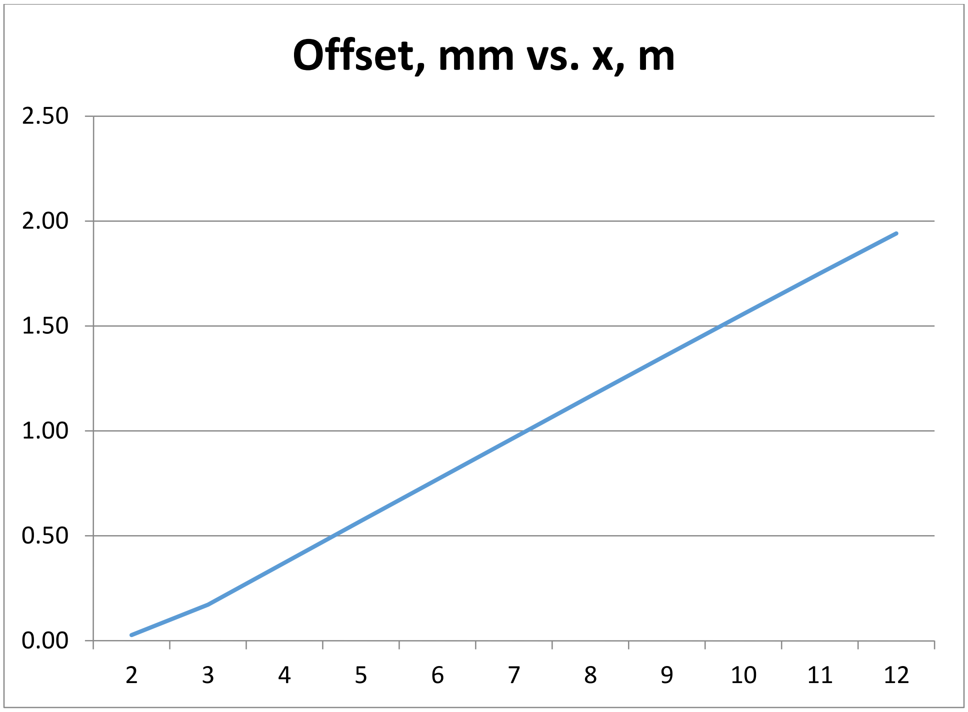
The dot product of $\hat{\imath}_p$ and $\Delta\vec{V}_{31r}$ is the desired offset of the lower right rear tire from the 3f, 1f, 3r plane. Thus

$$
Offset = \hat{\imath}_p \cdot \hat{V}_{1r} = \frac{[p_{1r}(q_3r_1 - q_1r_3) + q_{1r}(p_1r_3 - p_3r_1) + r_{1r}(p_3q_1 - p_1q_3)]}{\sqrt{(q_3r_1 - q_1r_3)^2 + (p_1r_3 - p_3r_1)^2 + (p_3q_1 - p_1q_3)^2}}
$$

Results were calculated for the Offset in mm in an Excel spreadsheet with the results shown graphically on the next page.

Conclusion

With the Offset less than 2 mm, occurring only for a fraction of a second and the deflection taken up by the side tires, use of pairs of lower side tires at both front and back of the chassis, which substantially reduces and balances the loads on the side tires, is preferable.



9.12 Comparison of the weight per unit length of a pipe guideway with a truss guideway

Compare two guideways under the same loading, the same span, and the same end conditions. Then the deflection is inversely proportional to the moment of inertia, and the maximum stress is proportional to c/I where c is the distance from the neutral axis to the outer fiber and I is the moment of inertial. Thus of two guideways with the same moment of inertia the one with the lowest value of c will have the lowest maximum bending stress. It is reasonable to assume that using a pipe as the major structural element will give the smallest value of c. Therefore we should compare the two guideways on the basis of I only. For a round hollow pipe the moment of inertia is

$$I = \frac{\pi}{64}\left(OD^4 - ID^4\right) \tag{1}$$

In which OD is the outside diameter and ID is the inside diameter. Then the wall thickness is

$$t = \frac{1}{2}\left(OD - ID\right). \tag{2}$$

The cross sectional area of the pipe is

$$A = \frac{\pi}{4}\left(OD^2 - ID^2\right) \tag{3}$$

Let the OD of the pipe be given and let I be the value for a truss guideway with which we wish to compare the pipe guideway. Then from equation (1)

$$ID = \left(OD^4 - \frac{64}{\pi} I \right)^{1/4} \tag{4}$$

which enables us to calculate the wall thickness from equation (2). We must look up the next larger wall thickness for the given OD from a table such as given in the *Manual of Steel Construction*, American Institute of Steel Construction, 3rd Ed, 2001. With the moment of inertia I calculated for a truss guideway designed to support a load of 200 lb/ft, I calculate the weight of the entire guideway including the running surfaces to be 125 lb/ft.

Using the above formulas and tabular data I calculated the following properties of a round pipe in the table on the following page. We see that for a 20" OD pipe, the weight of the pipe alone is 296.4/125 = 2.37 times as heavy as the entire truss structure including its running surfaces. To the round pipe must be added all of the running surfaces. Without data on the weight of these surfaces, one cannot calculate the total weight of the pipe guideway.

Properties of Round Pipe

	20" pipe	30" pipe	Units
Moment of inertia =	3682	3682	in^4
Outside Diameter =	20	30	in
Inside Diameter =	17.074	29.280	in
Wall thickness =	1.463	0.360	in
Nominal wall thickness of a standard size =	1.5	0.5	in
Cross sectional area of standard size =	87.18	46.34	in^2
Moment of inertia with standard wall thickness =	3754.15	5042.21	in^4
Weight per ft (calculated) =	297.11	157.92	lb/ft
Weight per ft (from table) =	296.4	NA	lb/ft
Density of steel =	0.284	0.284	lb/in^3

Journal of Advanced Transportation, 20:2(1986):97-105.

9.13 Automated Transit Vehicle Size Considerations

Synthesis of cost-effective transit alternatives using automated vehicles requires consideration of a wide range of factors that are moot in determination of the optimum size of manually driven vehicles where the need to amortize driver wages dominates the economics. Discussions of many of these factors have appeared in previous papers. This article brings them together into consideration of one specific system characteristic: the optimum automated-transit-vehicle size.

Introduction

The current and projected economic situation requires that more cost-effective solutions to human needs be found. Public transportation, a fundamental need of urban society, is struggling with increasing deficits largely as a result of commitment to a service concept introduced over a century ago -- slow, tedious, stop-start travel necessitated by the need to use large vehicles in order to amortize the wages of drivers over as many trips as possible. Even the relatively new automated people movers by and large do nothing but replace the driver with automation—the service concept is still the same.

Automation, however, permits reconsideration of the entire service concept. Many persons have tried to do this but success up to now has been sparse. In this article, I bring together a range of factors that enter into optimization for maximum cost effectiveness of one fundamental characteristic: the size of the vehicles. Information is now available to do this much more completely than was possible a decade ago.

The dominant factor in determining the size of a manually operated transit vehicle is driver wages per passenger. Even with 60-passenger buses, almost 80 percent of the operating costs of a bus fleet go to driver wages, and if the buses were much smaller, the cost of driver wages per passenger carried would be prohibitive except in special circumstances in which the average vehicle occupancy or load factor can be kept very high. If the vehicles do not require drivers, the optimum vehicle size is governed by the following factors:

1. Guideway cost per unit length
2. Vehicle-fleet capital cost
3. Vehicle-fleet operating and maintenance cost
4. Station and network operations
5. Personal security
6. Service
7. Social requirements
8. Line-capacity requirements
9. Safety
10. Dependability

In this article, each of these factors is considered, the author's conclusions are given and factors that enter into determination of the seat width are discussed.

Guideway Cost per Unit Length

The guideway size and weight is fundamentally dependent on the vehicle weight. Data (Anderson, 1978) on a large number of transit systems shows that the guideway weight per unit of length increases quite markedly with vehicle capacity. Whereas guideways carrying 40 to 100 passenger vehicles typically weigh in the range of 2000 to 3000 pounds per foot. I have found it practical to reduce the weight of the guideway of a three-passenger-vehicle system to 140 pounds per *foot.* To minimize guideway cost, size and weight it is therefore necessary to use the smallest practical size of vehicle.

Vehicle Fleet Capital Cost

Using the smallest practical vehicle size makes sense only if the cost of a fleet needed to move a given number of people does not thereby increase enough to cancel out the reduction in guideway cost. The acquisition cost per unit of capacity and weight per unit of capacity of transit vehicles are in the same range regardless of the vehicle size (Anderson, 1978, 1980); i.e., for a given person-carrying capacity of a fleet of transit vehicles, the cost of the fleet is independent of vehicle size, and depends roughly only on fleet capacity and weight per unit of capacity, which is independent of vehicle capacity.

The required fleet capacity is proportional to the average time a vehicle is committed to a trip. If the trip time is cut in half, i.e., the average trip speed is doubled, only half as much fleet capacity is needed to meet a given demand, and the cost of the vehicle fleet is cut in half. Average speed can be increased in two ways: by increasing the maximum speed; and by increasing the distance between stops. Increasing maximum speed, however, requires larger motors, more kinetic energy, higher air drag and a stiffer guideway, all causing costs to increase. In a transit system in which the stops are on line, increasing the distance between stops decreases the access to the system and hence the ridership.

The distance between stops is maximized without sacrificing access by placing the stops on bypass tracks and making each trip nonstop. This is of course the principal of the freeway. Nonstop travel is practical if each trip is taken by only one small party of people traveling together, thus implying very small vehicles. Vehicles of such a size that they would have to toad multiple parties would in general have to wait too long to load, thus increasing the average time a vehicle is committed to one trip. This is one of the reasons carpooling is not popular.

To minimize the dead weight of vehicle per person carried, and hence the fleet cost, the vehicle size must conform to the traveling habits of the public. Ryan (1983) shows that about 95 percent of urban trips are taken by one, two or three people traveling together. Typical rush-hour auto occupancy rates are about 1.2 people per vehicle. Vehicles therefore need be no larger than required for about three persons. The decision to buy a larger automobile is governed by occasional-use considerations. In the type of transit system envisioned here, however, a larger group can easily take two vehicles, which would be only a few seconds apart.

Vehicle Fleet Operating and Maintenance Costs

Anderson (1984) showed that the O&M cost per place-mile (O&M cost per vehicle-mile divided by vehicle capacity) of transit systems is remarkably independent of vehicle size. The use of small vehicles therefore does not increase the O&M cost of a vehicle fleet of a given capacity.

The O&M cost per passenger-mile is of more interest, and is obtained by dividing the O&M cost per place-mile by the average number of passengers per place or load factor. Load factor depends both on vehicle size and on the kind of service provided: scheduled or demand-responsive.

Conventional large-vehicle transit systems must run vehicles on schedule, picking up and leaving people off on fixed routes regardless of the number of people per vehicle. In off-peak periods, vehicle frequency must decrease, causing further decline in the load factor. With scheduled service, dairy load factors average up to about 0.20 (Anderson, 1984).

If private-party vehicles are used with off-line stations, the service can be completely demand responsive, in which case the load factor of moving vehicles remains high throughout the day. In typical private-party, demand-responsive systems one finds from computer simulations that about one third of the vehicles in operation are empty and are recirculating to replenish stations that have shortages of vehicles. By charging a fare per vehicle instead of per person, it is reasonable to assume an average of 1.5 persons per occupied vehicle, giving a fleet average of one person per vehicle. The smaller the vehicle, the larger the daily average load factor. With a vehicle designed for three or four persons, a daily load factor of 0.33 to 0.25 is attained. Since this is higher than the daily load factor attained by scheduled systems, the O&M cost per passenger-mile is lower for demand-responsive, private-party vehicles designed for three or four persons.

Station and Network Operations

Involvement in many planning exercises has shown me that in almost every realistic application a network including several branches would be preferable if the cost were sufficiently low and the system could switch operationally. Assume in this case that the concept of off-line stations is accepted, but that the system is to use vehicles of capacity say eight to twelve seats intended for multiple parties. If there is more than one possible route through a network, then, because a vehicle that arrives at a station generally has people aboard headed to certain other stations, each vehicle must be committed to a specific route that includes those stations. Consequently the boarding patron must wait for a vehicle committed to the route that includes his destination station. If there are n loops in a network, the number of routes is approximately $n(n+1)/2$. If, for example, there are four loops, the number of routes is about ten. In this case, one would on the average wait for one vehicle in ten. Some routes, however, will have less demand than others; therefore, to increase the average load factor the frequency along some routes must decrease. Examples show that either the waiting time quickly becomes prohibitive or the average load factor drops so low that any advantage of larger vehicles is lost.

Johnson (1976) showed that with off-line stations, it is not practical to predict in advance of a vehicle switching into a station at which berth the vehicle will dock. Therefore, with multiple-group-sized vehicles committed to specific routes, one must wait near the center of the station platform and watch for the vehicle committed to the desired route and the berth 10 which it is headed. To keep the system moving, the vehicle dwell time must be kept to a minimum, therefore potential patrons will have a very small amount of time to reach the desired vehicle before the door closes. With a system of more than two or three loops, the problem for the boarding passenger becomes impractical for all but the most agile and alert persons. Vehicles of more than the size required for a small private party are therefore not practical in any but the smallest systems. Even in these smallest systems, however, the above cost analysis shows that use of the smallest vehicles will lower capital and operating costs.

Personal Security

Multiple-party driverless vehicles open the possibility of undesirable parties boarding at the origin station or at intermediate stations. While this kind of service is accepted in conventional transit systems, but only by the small portion of the population who regularly ride these systems, it is perceived to be much more of a problem in small, driverless vehicles. In this respect, vehicles used by only one party at a time are strongly preferable.

Service

The best possible service involves minimum wait at any time of day or night, no transfers, nonstop trips, a seat for everyone, and privacy. Such service requires very small vehicles operating nonstop between off-line stations in a network. This is exactly the kind of service that has been shown to minimize cost.

Social Considerations

A vehicle designed for one normal-sized person will be too small for large persons and prevents couples from enjoying each other's company.

A vehicle designed for two normal-sized persons poses a problem for three persons traveling together: one of them must separate and ride alone — a situation that is sometimes socially awkward. Moreover, a two-person vehicle is too tight for a small family and provides room for only a small amount of luggage.

As mentioned above, a vehicle designed for three normal-sized adults accommodates about 95 percent of the trips taken in an urban area, i.e., about 95 percent of the trips involve one, two or three persons traveling together. Such a vehicle could also accommodate a mother, a father and two or three small children. Increasing the vehicle size to say four persons would accommodate only a fraction of the remaining four percent of the trips. Since the trip is only a few to ten or fifteen minutes long, the problem of a larger group splitting up into two successive vehicles that would leave and arrive only seconds apart is minor and corresponds to common use of taxis and automobiles.

Line-Capacity Requirements

Use of small vehicles would of course not be practical if it were not possible to build in sufficient capacity. The capacity or maximum throughput obtainable safely has been shown by Irving (1978) and Anderson (1978) to be strongly dependent on the type of propulsion and braking system used. If propulsion and braking are through wheels, then traction depends on the coefficient of friction between the tires and the roadway.

In an extreme but possible case assume that a rainstorm has just subsided, and that the guideway is drying out. One must assume the possibility that the brakes on the vehicle ahead have locked while it is on a dry surface, but that the vehicle behind is on a wet surface. Kinematical analysis shows that the minimum safe separation distance in this case corresponds to a headway of several seconds. In the early 1970s, the Urban Mass Transportation Administration was willing to assume in the Advanced Group Rapid Transit program a minimum headway of three seconds, corresponding to a throughput of twenty vehicles per minute.

If propulsion and braking are through linear electric motors, traction is independent of the coefficient of friction and, indeed, it is possible to use smooth tires running on smooth surfaces. In this circumstance, if a wheel should lock (less likely since there are no brakes on the wheels) the failed vehicle cannot stop as quickly as is possible by applying braking forces through the linear motors. In this case, Anderson (1978) and Irving (1978) showed that safe headways in the range of one half second or even less are practical, A dividend of the use of smooth tires on smooth surfaces is that the tire noise is thereby minimized.

The required line capacity depends on the average line and station spacing, and the trip density. Anderson (1984) showed that there is a wide range of applications in which a headway limitation of one half second poses no problem for a private-party system. In early applications in which there are only a few miles of line, typical headway requirements are in a range of 4 to 8 seconds. Time is therefore available to prove the headway capability of private-party vehicles before high throughput is needed.

Safety

While one does not wish to think of the possibility of collisions, one must design, first, so that the collision probability is acceptably low and, second, for protection of the passengers if a collision should occur. To make each vehicle as safe as possible in the rare event of a collision, it is necessary to study crash survivability. Anderson (1978) showed that it is necessary to have all adult passengers seated in reasonable proximity of a padded dashboard that contains an airbag. An air-bag is much more effective in a guideway transit system than in an automobile because roll-over and side collisions are not possible —any possible collision involves sudden longitudinal deceleration or acceleration of the vehicle. A seat three-persons wide, necessary for social reasons, meets safety requirements and is about as wide as is practical for engineering reasons.

If the vehicle were designed for four persons, designers have found it necessary, with cost and weight minimization in mind, to have seats for two persons seated forward and two backward. This configuration, however, does not meet the requirements for practical deployment of an airbag and is about tour feet longer than a vehicle designed for three adults side-by-side. The latter, therefore, is to be preferred.

Dependability

Dependability depends on a range of factors, the most important of which are: the use of as few moving parts as possible, low design stresses, modularity, redundancy, failure monitoring and minimum weight. These are the elements of fault-tolerant design. Anderson (1978) showed that application of these principles can produce remarkably high dependability in small-vehicle, private-party systems. Achievement of adequate dependability is the crucial factor—without it discussion of small-vehicle systems would be moot.

One major component-design factor that assures high dependability is the use of a no-moving-parts propulsion system consisting of linear electric motors driven by solid state, variable-frequency drives. Use of optimum variable frequency, easy with microprocessor control, cuts heat dissipation in half, which reduces the possibility of overheating. Coupled with the use of temperature sensors for early detection of overheating and on-board failure management, practical with microprocessors, propulsion-system failures will be extremely care in comparison with conventional transit systems. A second factor, which specifically favors vehicles of the smallest size, is their small weight, which makes it easier to over-design bearings, axles, tires, and other components for long life.

The Interior Width of the Vehicle

The above arguments indicate that the vehicle should be wide enough for three adult passengers. Because human adults vary in size over a wide range, and because there are relatively few people at the extremes of size, it must be assumed that if three persons exceed a certain width they must divide up and take two vehicles.

Increasing the width of the vehicle increases vehicle weight, air drag, side loads on the wheels, required thrust, motor and controller size and weight, and the minimum distance between the main and offline guide-ways; and decreases the torsional natural frequency of the guideway, thus requiring increased guideway size and weight.

For all of these reasons, while the seat width must be adequate, care must be taken to keep it reasonable. It is possible in principle to quantify the increased cost per mile of guideway and per vehicle due to increased vehicle width; and, by human-factors testing, the reduction in acceptance, and therefore in ridership, of too narrow a vehicle. Perhaps, however, an adequate argument can be made on the basis of existing human-factors data.

According to The Human Factors Design Handbook (]981) the 95th percentile male forearm-to-forearm breadth while seated is 19.9 inches and the shoulder breadth is 19.6 inches. The Human Engineering Guide for Equipment Design (1964) recommends that passenger aircraft seats for trips of over an hour's duration be twenty-one inches wide, and for short-haul trips nineteen inches wide. Since a transit trip is likely to last only five to ten minutes, the narrower width can be considered. 1 suggest, therefore. an interior vehicle width of 57 inches, which can also accommodate more than three smaller persons. Because of the need to have the seats fold up to permit entry of a wheelchair, it is desirable to have the seat split up into three 19-inch seats sprung to fold up independently when unloaded.

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9.14 Cabin Size Considerations

The following three drawings illustrate a possible, but crude, PRT cabin design assuming a minimum enclosure over the passenger compartment. The floor is assumed to be 4" thick at the center and the walls 2" thick, giving an interior width and height at the rear seat of 60". We appreciate very much that styling is essential in the design of PRT vehicles, and we trust that improvements can be made on the shape shown here. What we show here are the basic human-factors essentials. For reference, I include two pictures of the Taxi 2000 vehicle, which was designed under my direction.

As an appendix I include a paper I did recently to answer the question: What fraction of vehicles will contain n people, where n = 1, 2, 3, 4, 5? For reference, in a 1990 comprehensive travel survey in the Twin Cities it was found that the daily average auto occupancy was 1.2 and the rush-hour occupancy average was 1.08. I recall a similar survey taken in 1970 when these numbers were 1.5 and 1.2, respectively. One of the MNDOT people we talked to recently said their estimate of the daily occupancy is now closer to 1.3. We have presumed charging a fare per vehicle rather than per person to encourage group riding, but there is no data on how much that would increase occupancy. Many people make the mistake of designing a PRT vehicle for too many people, not taking into account or not thinking about how easy it will be to take two or more vehicles, but as a result increasing system cost with no commensurate benefit.

Cabin design requirements and comments.

1) The cabin design must be attractive and at the same time dignified. As a Chicago sculptor commented, "It must bring out the kid in you!" The big question is this: How do we accomplish this and still meet all of the human-factors requirements? Durability must be a major design consideration to keep maintenance costs down, but this doesn't need to restrict us too much. The cars can be economically built via various molding methods so sculptured surfaces with built-in colors would be a key industrial design feature. Lots of window space would be nice. Convenient, comfortable seats would be great too. Good heating and cooling is essential.

2) The requirement of having a wheelchair enter the cabin through a three-foot-wide door and then turning 90 degrees to face forward fundamentally makes the design asymmetric from front to back.

3) To minimize the vehicle length, it is necessary to have the seats in both the back and front of the cabin folded up when the wheelchair enters. Since in the vast majority of cases there will be no wheelchair, the seats will be normally down. They can be sprung and held down by the weight of a passenger, for example like the standard theater approach of having seats store upright with an easy push down to use them.

4) To include an attendant with the wheelchair passenger, for which we must allow, the back seat must be in three parts, so that after the wheelchair enters and turns forward, the seat nearest the door, whether it is on the right or left side of the cabin, can be lowered to accommodate the attendant as easily as we do with theater seats.

5) These requirements may be specific to the USA because of the Americans with Disabilities Act, and they were strongly required by the disabled community in Chicago. Thus these requirements can and should be the basis for an American standard PRT cabin design.

6) The cabin must have a weight limit. 20 years ago the Chicago RTA specified 750 lb. With some reluctance I suggest 950 lb. Total load is important for the chassis and support structure. Local loads in the car will determine design features. For example, the maximum individual weight will determine the design of the seat bottoms. So both combined and individual weights are important.

7) To accommodate the wheelchair, it is necessary that the interior of the vehicle be 60 inches wide. This is acceptable because we can then make each of the three seats 19 inches wide with 0.75 in spacing between each seat and the left and right inside cabin wall. According to the Human Factors Handbook a 19-in wide seat is comfortable for a two-hour flight.

8) To accommodate the 97.5 percentile male, the distance from the seat top to the inside ceiling of the cabin must be 43 inches. Allowing for the standard 17-in height of the seat, the floor to ceiling height at the position of the seat must be 60 inches.

9) To insure that the vehicle will not tip in an emergency stop at the standard 0.4g deceleration, the large passengers must be encouraged to use the back seats. This can be accomplished by making the front seats narrower and lower to the floor with a lower ceiling so that they would normally be used only by children. This is desirable also because it allows more latitude in the exterior design of the cabin. One disadvantage is that some people, influential people, envision the cabin as having two forward facing seats in the rear and two backward facing seats in the front of the cabin, which would be nice if two couples attend a show together, such as in Branson, MO. How important is this? We must keep the fare down and there is no substantial reason to have 4 adults in one car. Some influential people might want there to be 6 or 8 or 10 adults in a car. This has to be pushed back very strongly or we will be forced to move away from the optimal car design and would increase system cost. Cell phones can be used for essential communication between the groups. In the Taxi 2000 design process, no one involved argued to have the vehicle accommodate 4 adults. Now we get this argument because ULTra and Vectus use four seats, without giving any reason why this makes sense. The Chicago RTA insisted on a 4-seat configuration. In the Taxi 2000 cabin design to accommodate the wheelchair, there was room for a couple of fold-down seats in front that could be used for children when there is no wheelchair present. They would not lengthen the cabin. In PRT it will be easy for a group larger than can be accommodated in one vehicle to take two or more vehicles – they will leave seconds apart and arrive seconds apart, and the occupants will likely talk to each other with their cell phones.

10) We like the inverted U-shaped door concept which opens both on the side and the top so that a person can walk straight in standing up and then sit down. This is particularly important for an elderly person using a walker. Elderly people won’t be able to bend down to get in even if they don’t use a walker. This is essential.

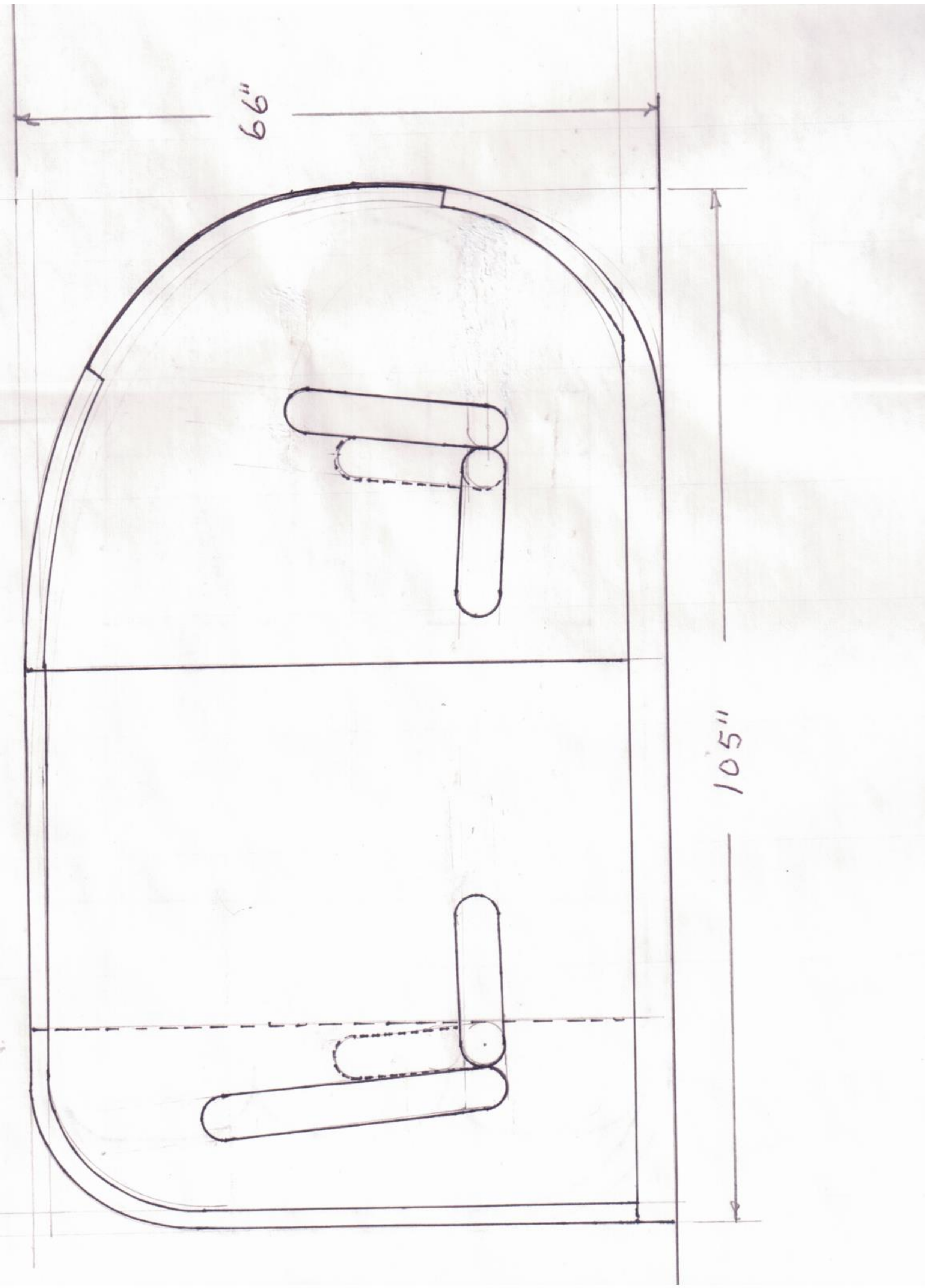
11) The concept of having an inverted U-shaped door slide backwards to provide the door opening is not new. It was used by Transportation Technology, Inc. in their PRT design in the early 1970s.

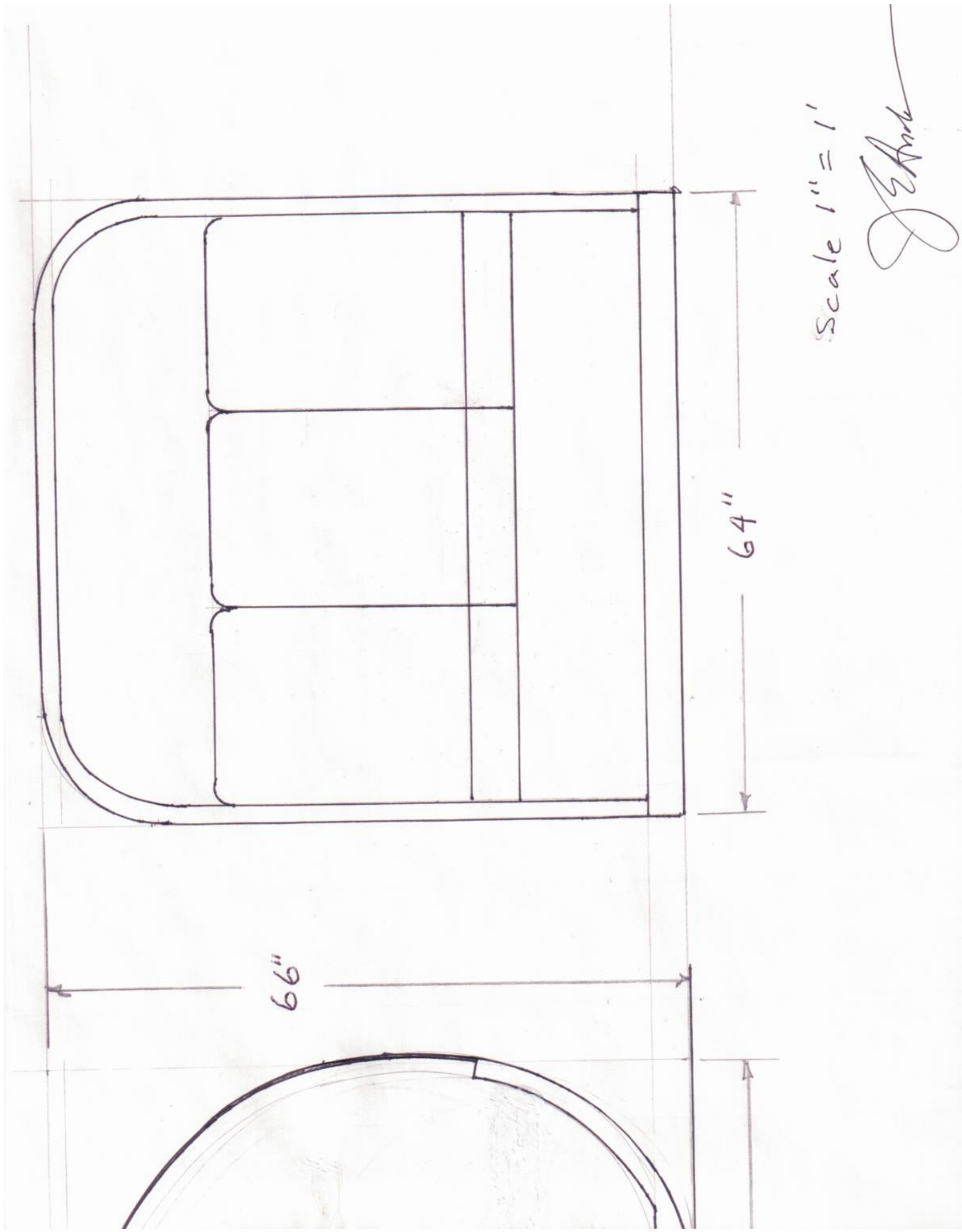
12) There is nothing wrong with using a design similar to the Taxi 2000 design, which has been widely exposed and is therefore not proprietary. There is nothing wrong with us agreeing with Taxi 2000 on a standard cabin design that can be proposed as the American Standard.

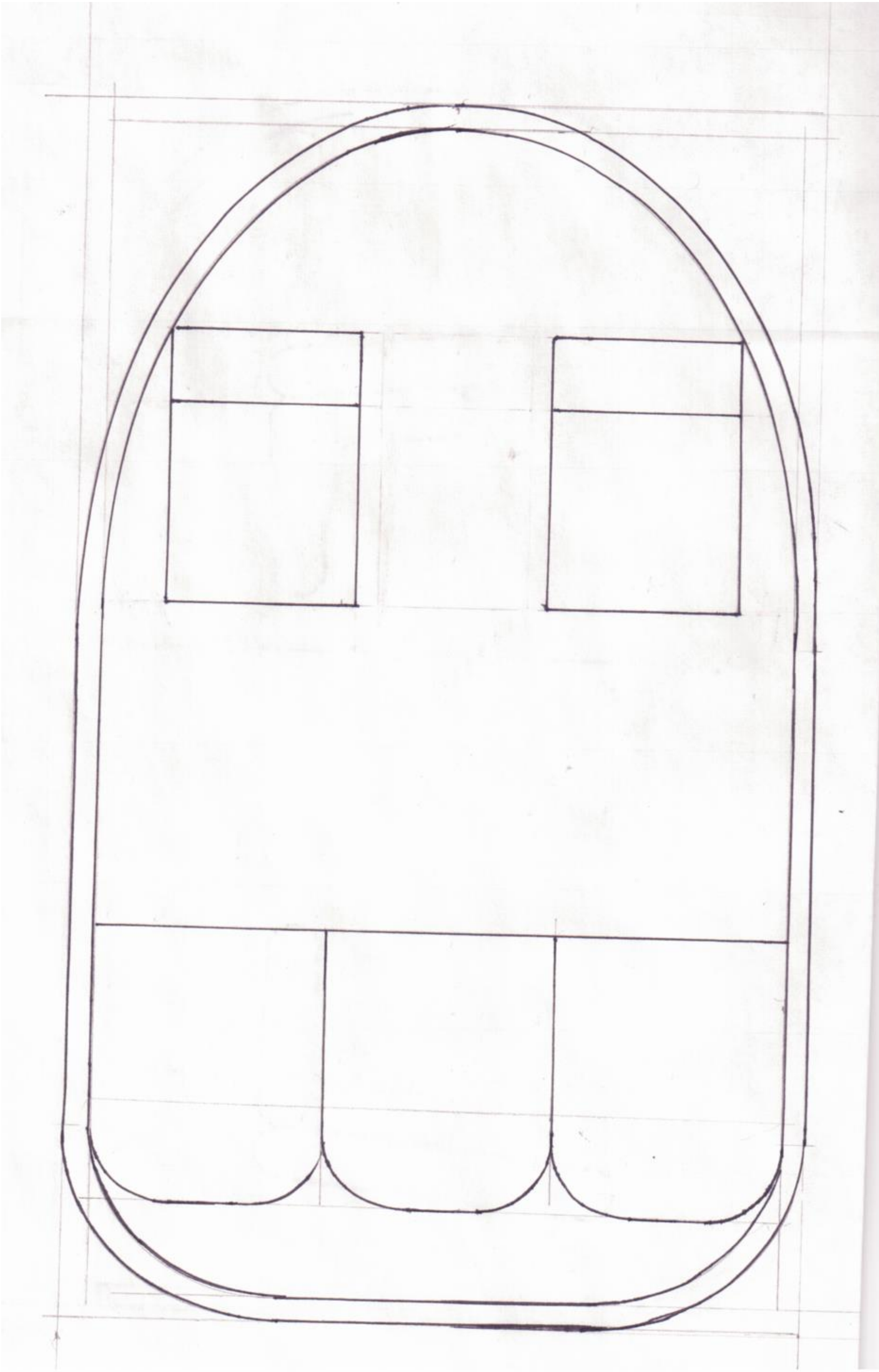
13) I am not comfortable with a design in which the entire back half of the vehicle moves back three feet to provide the necessary entry. Adding three feet to the length of each station berth is not a trivial matter. It would add to the cost of and space required for every station. The alternative is the type of door we designed for Taxi 2000, where a half dozen of us went over the requirements in great detail. That door design is not proprietary. Standard designs must be based on a clear understanding of requirements and criteria.

Taxi 2000 PRT vehicle at Minnesota State Fair

Taxi 2000 PRT Vehicle


66"
105"


64"
66"
Scale 1" = 1'



9.15 The Distribution of People Riding in Vehicles

Let n be the number of people riding in a vehicle, and let $f(n)$ be the fraction of vehicles that contain n people. Assume from the normal distribution in statistical theory that

$$f(n) = ce^{-\lambda n^2} \tag{1}$$

in which c and λ are constants. Then, by definition of $f(n)$, we have

$$1 = c\sum_{n=1}^{\infty} e^{-\lambda n^2} \tag{2}$$

Hence

$$f(n) = \frac{e^{-\lambda n^2}}{\sum_{n=1}^{\infty} e^{-\lambda n^2}} \tag{3}$$

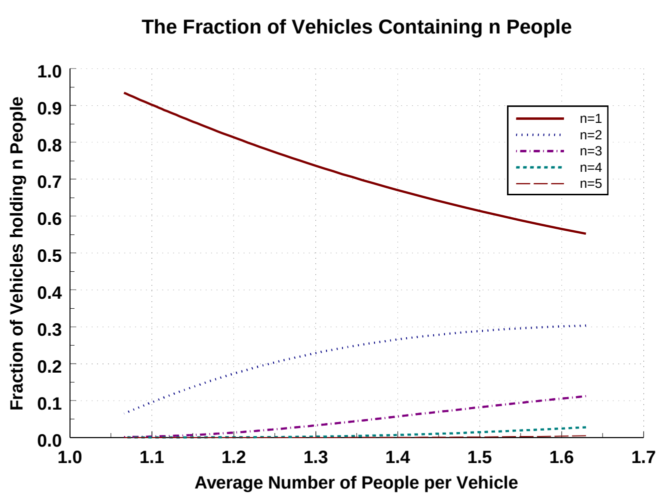
Now, the average number of people per vehicle is

$$\sum_{n=1}^{\infty} nf(n) = N_{ave} = \frac{\sum_{n=1}^{\infty} ne^{-\lambda n^2}}{\sum_{n=1}^{\infty} e^{-\lambda n^2}} \tag{4}$$

Given N_{ave} this is a transcendental equation for λ. Once λ. is found by iteration, we can find $f(n)$ from Equation 3. The calculations are performed in the following program and the results are plotted in Figure 1. Results were calculated also for 100 terms instead of 10. To four decimal places there was no difference.

In 1990 the Metropolitan Council did an expensive area-wide survey of auto traffic in the Twin Cities Metropolitan Area, in which they counted the number of people per vehicle. They found a daily average of 1.2 people per vehicle and a rush-hour average of 1.08 people per vehicle. By charging a fare per vehicle rather than per person, we can expect the occupancy in PRT vehicles to be somewhat higher than found in automobiles. Note from Figure 1 that if N_{ave} = 1.5 the fraction of vehicles that would be occupied by 4 people is about 1%. Taking into account the practice of charging a fare per vehicle rather than per person and thus assuming a daily vehicle-occupancy average of 1.5, we have assumed a design that permits three large adults to sit in one back seat that would fold up in three sections, with two small, backward-facing, fold-down seats in the front for children. With no wheelchair in the vehicle, more children could easily sit on the floor. In calculation of operating costs, we have assumed the vehicles will be cleaned daily. We noted that in PRT if there is a larger group than would be comfortable in one vehicle, it is easy to take two or more vehicles. They can leave seconds apart and arrive seconds apart, can communicate with each other via the cell phones they likely carry, and the ride is not very long. Note that the larger each vehicle is, the heavier the guideway must be and the more expensive the system will be. I hope you are with me in understanding that we face a future in which it will be more and more important to conserve material, energy, and land. Optimizing to a wide range of requirements is essential to the production of a winning PRT system.

```
'This program, PPV.BAS calculates the average number of people per vehicle.
DEFDBL A-Z
CLS
OPEN "PPV.ASC" FOR OUTPUT AS #1
FOR Lambda = .2 TO .9 STEP .01
   Pd = 0
   FOR n = 1 TO 10
      Pd = Pd + EXP(-Lambda * n ^ 2)
   NEXT n
   Pn = 0
   FOR n = 1 TO 10
      Pn = Pn + n * EXP(-Lambda * n ^ 2)
   NEXT n
   Nave = Pn / Pd
   EXPO = EXP(-Lambda)
   f1 = EXPO / Pd
   f2 = EXPO ^ 4 / Pd
   f3 = EXPO ^ 9 / Pd
   f4 = EXPO ^ 16 / Pd
   f5 = EXPO ^ 25 / Pd
   Sum = f1 + f2 + f3 + f4 + f5
   WRITE #1, Nave, f1, f2, f3, f4, f5
   PRINT USING "####.####"; Lambda; Nave; f1; f2; f3; f4; f5; Sum
NEXT Lambda
CLOSE #1
```



9.16 Effect of Passenger Position on Emergency Braking

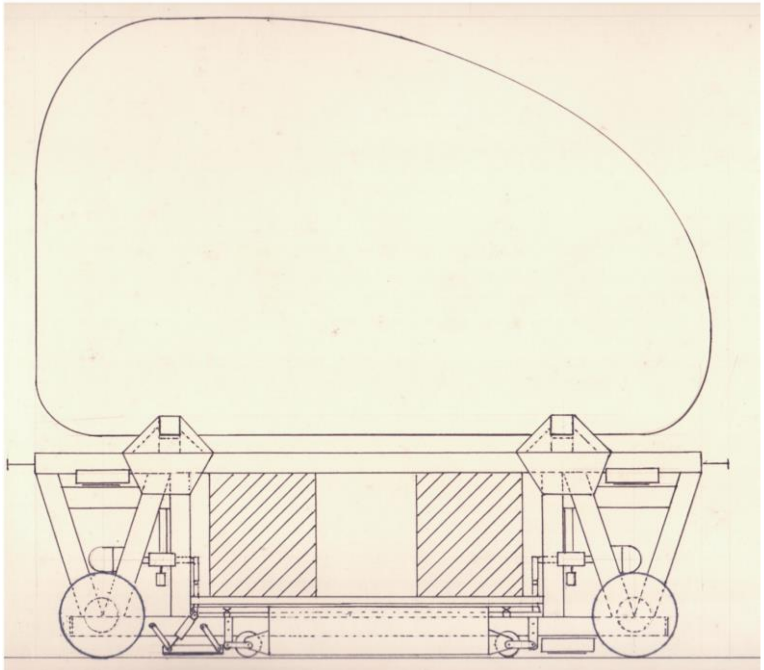


Figure 1. Side View of ITNS Vehicle

Notation

X_{wb} = Wheel base, distance between contact points of front and rear wheels.
W_v = Empty weight of vehicle.
X_{cg} = Horizontal distance from contact point of rear wheel to vehicle center of mass.
Y_{cg} = Vertical distance from running surface to vehicle center of mass.
W_p = Weight of passengers.
X_p = Horizontal distance from contact point of rear wheel to passenger center of mass.
Y_p = Vertical distance from running surface to passenger center of mass.
F_f = Upward force of running surface on forward main-support wheel.
F_b = Upward force of running surface on emergency and parking brake.
During emergency braking, the emergency brake actuator lifts the rear wheel off of the running surface. The design of the parking and emergency brake is discussed on pages 31-32 of the document "Technical Specifications for the Intelligent Transportation Network System."

X_b = Horizontal distance of the emergency brake contact point from the point the rear wheel would contact the running surface.
A_g = Deceleration of vehicle during emergency braking in g's.
μ = Coefficient of friction of emergency brake surface.

Equations

The balance of vertical forces on the vehicle gives the equation:

$$F_b + F_f = W_v + W_p$$

The balance of horizontal forces including the inertial forces on the vehicle gives the equation:

$$\mu F_b = A_g\left(W_v + W_p\right)$$

Moments taken about the contact point of the front wheel gives the equation:

$$F_b(X_{wb} - X_b) + A_g\left(W_v Y_{cg} + W_p Y_p\right) = W_v\left(X_{wb} - X_{cg}\right) + W_p\left(X_{wb} - X_p\right)$$

Thus,

$$F_b = \frac{W_v\left(X_{wb} - X_{cg}\right) + W_p\left(X_{wb} - X_p\right) - A_g\left(W_v Y_{cg} + W_p Y_p\right)}{X_{wb} - X_b}$$

and the coefficient of friction needed to produce a deceleration of A_g is

$$\mu = \frac{A_g\left(W_v + W_p\right)}{F_b}$$

The deceleration that will lift the emergency brake off the running surface is

$$A_g = \frac{W_v\left(X_{wb} - X_{cg}\right) + W_p\left(X_{wb} - X_p\right)}{W_v Y_{cg} + W_p Y_p}$$

Discussion

Results of the above three equations are given in the following Excel Spread Sheet. The concern has been that if the cabin were designed so that there were facing seats of equal size in the front and rear of the cabin it would be possible for one or two large persons to sit in the front seat with no one in the back seat. We must assume that if anything can happen it will happen. The results given below show that if X_p is too large, i.e., if the passengers sit too far forward, in an emergency case in which the parking brake must serve as an emergency brake, the coefficient of friction of the brake, which with an available material can be as high as about 0.8, may be higher than practically achievable if the passengers sit too far forward. Since an emergency deceleration of 0.5 g is sufficient to throw a person into the windshield, we have taken in our control work an emergency deceleration of 0.4 g. Note that with the passengers placed back over the position of the emergency brake, the required coefficient of brake friction decreases as passenger weight increase, but with the passengers farther forward, the reverse is true. Fortunately, in all cases the deceleration needed to reduce the force on the emergency brake to zero is substantially larger than needed.

Effect of Passenger Position on Emergency Braking

Vehicle Weight =	1100	lb
Wheel Base =	90	in
xcg =	40	in
ycg =	31	in
xBrake =	12	in
Emergency decel. =	0.4	g's
yPassenger =	54	in

xPassenger = 10 in

Passenger weight lb	Load on Brake lb	Required Coefficient of Friction	Deceleration for Lift-Off g's
100	605.1	0.793	1.59
150	642.6	0.778	1.59
200	680.0	0.765	1.58
250	717.4	0.753	1.58
300	754.9	0.742	1.57
350	792.3	0.732	1.57
400	829.7	0.723	1.56
450	867.2	0.715	1.56
500	904.6	0.707	1.55
550	942.1	0.701	1.55
600	979.5	0.694	1.55

xPassenger = 40 in

Passenger weight lb	Load on Brake lb	Required Coefficient of Friction	Deceleration for Lift-Off g's
100	566.7	0.847	1.52
150	584.9	0.855	1.48
200	603.1	0.862	1.45
250	621.3	0.869	1.42
300	639.5	0.876	1.39
350	657.7	0.882	1.37
400	675.9	0.888	1.35
450	694.1	0.893	1.33
500	712.3	0.898	1.31
550	730.5	0.903	1.29
600	748.7	0.908	1.28

xPassenger =	60	in	
Passenger weight lb	Load on Brake lb	Required Coefficient of Friction	Deceleration for Lift-Off g's
100	541.0	0.887	1.47
150	546.4	0.915	1.41
200	551.8	0.942	1.36
250	557.2	0.969	1.31
300	562.6	0.995	1.27
350	567.9	1.021	1.24
400	573.3	1.047	1.20
450	578.7	1.071	1.17
500	584.1	1.096	1.15
550	589.5	1.120	1.12
600	594.9	1.143	1.10

9.17 Effect of Non-Steerable Wheels on Road Resistance in Curves

Consider a vehicle of wheel base l moving in a turn of radius R and guided by lateral wheels within a U-trough guideway. To simplify the chassis, reduce cost, and increase reliability, it is suggested that the axles supporting the wheels be fixed and will not steer in turns. In turns, therefore, a side-friction force will be applied to the tires and hence to the chassis from the running surface. The side-friction force on each pair of tires is the coefficient of friction μ multiplied by the normal force on the tires. Let the normal force on the front pair of tires be W_f and the normal force on the rear pair be W_r. The vehicle weight is then $W = W_f + W_r$.

The work required to rotate the vehicle about a vertical axis is $T\theta$, where θ is the angle of rotation of the vehicle about a vertical axis, and T is the torque required to rotate the vehicle, where

$$T = \mu W_f(½l) + \mu W_r(½l) = ½\mu lW. \tag{1}$$

This work must be supplied by a force F in the direction of motion multiplied by the distance $R\theta$ through which the vehicle moves in rotating through the angle θ when the curve radius is R. Equating the two values of work, we have

$$FR\theta = T\theta \tag{2}$$

Substituting the value of T from equation (1), we have

$$F = \tfrac{1}{2}\mu(l/R)W. \tag{3}$$

Equation (3) can be compared with the formula for the road resistance of tires to overcome tire flexing as the wheel rotates:

$$Road\ Resistance = W(a + bV) \tag{4}$$

in which a and b are constants and V is the vehicle speed. Thus in a curve, the dimensionless quantity $\tfrac{1}{2}\mu(l/R)$ must be added to a.

We can estimate this dimensionless quantity. First $R = V^2/A_l$ where A_l is the comfort lateral acceleration, which is 0.25g for seated passengers. The effective increase in road resistance is seen to be inversely proportional to V^2 so consider the increase in road resistance in a 20-mph (8.94 m/s) curve. In this case $R = (8.94)^2/(0.25g) = 32.6$ m. Assume the wheelbase of the vehicle is 80 in or 2.03 m, so $l/R = 0.062$. Every attempt will be made to acquire the smoothest tires possible and they will run on smooth running surfaces. In this case it is not unreasonable to assume $\mu = 0.2$, in which case

$$\tfrac{1}{2}\mu(l/R) \cong 0.0062,$$

which can be compared with a typical value of a of about 0.005. So, in a 20-mph turn, allowing the tires to slide roughly doubles the speed-independent portion of road resistance. At 40 mph, we would get

$$\tfrac{1}{2}\mu(l/R) \cong 0.0016.$$

We can estimate the additional energy use that results from sliding the vehicle in curves. In a 12-mile network with 24 stations, we estimate that 12.5% of the guideway will be curved. We estimate that the energy use of a typical PRT vehicle is about 0.130 kW-hr/veh-mi. The extra energy to overcome the above-calculated friction force in one mile is the resistance force, 0.0062W × 1 mile. Assume an average loaded vehicle weight of 1200 lb × 4.4482 Newtons/lb or 5338 N. Then the extra energy is 0.0062(5338 N)(1609 m) = 53,250 N-m. But one N-m is one Watt-sec. Hence the extra energy expended in one mile is 53.3 kW-sec or 0.015 kW-hr/veh-mile. But this extra energy occurs on the average during only 11.5% of the trip. So on the average, in the whole system, the extra energy as a percent of the total is (0.115)(0.015)/0.130 × 100 = 1.3% at a line speed of 20 mph. If the line speed were 30 mph, the extra energy reduces to $1.3\%(20/30)^2 = 0.59\%$, and at 40 mph 0.33%.

9.18 Tandem vs. diagonal loading in stations

Introduction

A personal rapid transit system permits people to travel when they wish between any pair of offline stations in a network of exclusive guideways, under automatic control. The trip is non-stop and the vehicle accommodates a party of up to three or four people traveling together by choice. No scheduling is required in such a system. Empty vehicles are automatically rerouted every few seconds from stations with too many vehicles to stations with too few vehicles, or from storage during periods of increasing demand and to storage during periods of decreasing demand.

Fundamental to the design and planning of PRT systems is knowledge of the practical throughput of the off-line stations. The throughput has been studied by means of computer simulations and by means of simple analytical formulae. While simulation is essential to quantify the flow in specific cases, a theoretical understanding of the factors that determine maximum station throughput is needed to try to determine the most effective ways to increase it. The problem of required station capacity was studied by Anderson (1972) and the problems of maximum station throughput was analyzed and simulated by Dais (1972), Dais and York (1974), Sirbu (1974) and Liopiros (1974). The purpose of this paper is to report on the author's recent work and to compare it with earlier results.

A number of possible PRT station layouts and operational strategies were reported and used in the development of PRT systems, particularly the German Cabintaxi program, the Japanese CVS program, and the American Aerospace Corporation program. These are first discussed and the author’s conclusions and recommendations are given. Then, the basic "starting-point" formula for maximum station throughput is presented, with a discussion of its deficiencies. One of these is that the mean station dwell time must increase with the number of berths because it is determined in an N-berth station by the longest of N dwell times. Statistical variations in the input flow, which may reduce the maximum throughput and introduce the possibility of wave-offs, are then discussed. Finally, the throughput formula is modified to take into account choking due to the line flow past the station.

Station Layout and Operations

Knowledge of the design of spiral transitions into and out of off-line stations is assumed and is not discussed in this paper. The simplest off-line station has a single spiral transition to a parallel guideway followed by a straight section, followed by a spiral transition back to the main line. The station platform can have any practical number N of loading berths. Increasing N increases throughput if a platoon of N vehicles enters the station simultaneously, unload, then load, then move out, each vehicle individually as it can find an opening in the main line. If the cycle time is T_c, the throughput in vehicles per unit of time is N / T_c.

A problem with such a station is that high unloading or loading time in any one berth delays all of the vehicles behind it. As a result, alternative configurations that use some type of parallel loading have been studied. In systems using air-cushion suspension such as TTI-Otis or Uniflo, the designers proposed that the vehicles enter an off-line track, stop at a berth position, and move sideways into the berth. The vehicles can then leave their berths in any order, but must of course wait for vehicles to pass on the off-line guideway. A new vehicle poised to enter the berth area can move forward to replace a vehicle that has just left. It was found that delays due to moving in and out sideways slowed the system enough that the throughput was actually less than the simple station first described. Also, such a station uses more area. It therefore has no advantage.

Sirbu (1974) studied an alternative parallel-loading station that had a series of diagonal tracks entering loading berths. Vehicles leaving berths continue ahead and leave by a second parallel track. He concluded that the throughput was not thereby increased. Moreover, the complexity and extra cost of such a station was substantial. It was thus dismissed.

We are back to the single off-line guideway illustrated in Figure 1. It was thought that there would be an advantage to have the vehicles first stop in an unloading area, unload, and then proceed into a loading area. Liopiros (1974) studied such a station in comparison with a station that had a common unloading and loading area and found, for the same total platform length, slightly higher throughput with common loading and unloading. Since the peak periods usually involve predominantly either loading or unloading, the problem of passenger interference is small and manageable.

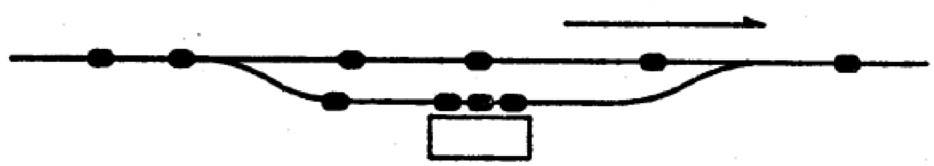


Figure 1. Layout of a Serial-Loading Off-Line Station

Most PRT designers settled later on the single off-line with common loading and unloading. To attain maximum throughput, it is necessary to accumulate vehicles in a holding area in advance of the unloading and loading area so that a batch of *N* vehicles is ready to move forward simultaneously. In an *N*-berth station, such an area must have room for at least *N* vehicles. Even with room for *N* vehicles in the holding area, because of statistical variations in arrival rate there will be times when a vehicle will want to switch into the station, but all of the berths in the holding area are occupied. In this case, to stop in time, the vehicle would either have to start to decelerate early, which delay mainline traffic, or it would have to decelerate at a rate greater than the designated comfort value. Practically, the alternative is to let the vehicle be "waived off," whereupon it circulates around a loop for another try. The number of vehicle positions on the off-line guideway must be determined to keep the fraction of wave-offs to an acceptable level. In the referenced papers, results of simulations are graphed in terms of the fraction of wave-offs. The inconvenience of a wave-off can be made palatable by offering a prize such as a free trip if it should occur.

When a vehicle is ready to leave the station, if there is no interference with line vehicles, it simply accelerates to line speed and merges with the mainline traffic. There is, however, always a certain probability that it will have to wait for an opening. Rather than thus holding up the traffic behind it, station designers proposed that there should be a "staging" area downstream of the unloading and loading area where vehicles would be sent to wait for an opening. While in transit to the staging area they would constantly check the line for openings and accelerate to line speed when an appropriate line slot is clear. Having extra off-line guideway on the upstream side of the station platform is essential to minimize wave-offs. Having extra off-line guideway on the down-stream side increases throughput somewhat at the expense of extra off-line guideway. Because planners always wish to decrease the length of off-line guideway, it may be better to increase N by one or more berths to meet the necessary maximum flow in and out of the station.

Study of various simulations of station operations including the author's shows that the results are significantly dependent on the way the flow of vehicles through the station is managed. It is necessary to insure that the vehicles are moved to the forward-most position whenever possible. If, for example, a vehicle in the last loading berth is ready to go, the vehicles in front of it having left, and the vehicle can't leave because a line slot is not available, the vehicle should be caused to advance to the forward-most empty berth so that vehicles behind it can advance, and then while the vehicle is advancing it must continually as the question: "If I were to accelerate to line speed now, would there be an available line slot?" If the answer is yes, the maneuver must be immediately changed to accelerate to line speed and at the same time, the station-flow-control computer notifies the vehicle behind that the berth the vehicle would have occupied if it had to stop again is available, so that the vehicles behind can change their maneuver profiles to advance as far forward as possible.

9.19 The Optimum PRT Design has the following Characteristics

1. The vehicles are captive to the guideway.
2. The vehicles are supported above the guideway.
3. The vehicles are suspended by wheels.
4. The vehicles are propelled and braked by Linear Induction Motors
5. The LIMs are on board the vehicles.
6. The power source for the LIMs is at wayside.
7. The control system is an asynchronous point follower.
8. The guideway is narrower than the vehicles and required the vehicles to be supported by a vertically oriented chassis.
9. Lateral support for the vehicle is supplied by two pairs of upper wheels and two pairs of lower wheels, giving a total of 8 lateral support wheels.
10. The guideway is a covered steel truss with a 3-inch-wide opening at the top through which the vertically oriented chassis passes.
11. The passenger cabin has one rear seat suitable for three adults, two small fold-down front seats for children, and can accommodate a wheelchair facing forward plus an attendant, a bicycle, or several large suitcases.
12. The emergency and parking brake is located close to the rear wheels.
13. The wheels are fixed and do not steer in turns.
14. The stations are designed for tandem loading and unloading.

Chapter 10. The Future of High-Capacity PRT

PodCar Conference, Molmo, Sweden, 9-10 December 2009.

High-capacity personal rapid transit (HCPRT) is a concept that has been evolving for over 50 years. Notwithstanding attempts to kill it, it has kept emerging because in optimum form it has the potential for contributing significantly to the solution of fundamental problems of modern society including congestion, global warming, dependence on a dwindling supply of cheap oil, and most recently terrorism. The future of HCPRT depends on careful design starting with carefully thought-through criteria for the design of the new system and of its major elements. Many people have contributed importantly to the development of PRT and the author regards the work during the 1970s of The Aerospace Corporation to be by far the most important, without which this author is certain that he could not have maintained interest in the field.

After deriving the HCPRT concept, the author reviews work on the important factors that the design engineer needs to consider in contributing to the advancement of HCPRT, so that after shaking out the good from the not so good features of the basic concept cities, airports, universities, medical centers, retirement communities, etc. can comfortably consider deploying HCPRT systems. We look forward to the day when universities will regularly teach courses on HCPRT design and planning and when a number of competent firms will be manufacturing HCPRT systems. HCPRT is close to moving to mainstream and can bring about a brighter future for mankind.

1. Introduction

This paper was written for the Advanced Automated Transit Systems Conference, Bologna, Italy, November 7-8, 2005. It represents a summary of my work in the field of Personal Rapid Transit over the past three and a half decades and can be considered a sequel to a paper I wrote for the *Journal of Advanced Transportation* Millennium Issue. [1]

It must be remembered in thinking about a new transportation system that transportation is a means to an end, not an end in itself. Many years ago, while at the University of Minnesota, I was invited to give an honors seminar for liberal-arts students on PRT. As the term progressed I asked each student to write a story about what life would be like in a city in which PRT was the major form of transportation. To get PRT into the story various students wrote about calling up the cars and waiting for them, neither of which would be necessary in a PRT system. We concluded that a feature of a city in which PRT was the dominant mode would be that transportation would simply not be a topic of discussion. You can read a story about life with PRT, written by Chip Tappan, Chairman of the Cincinnati Sky Loop Committee.

For reasons that will be apparent from Chip Tappan's story, HCPRT is the "Holy Grail" sought by innovative transit developers since the 1950s. HCPRT addresses a wide range of outstanding problems of our worldwide civilization that have become more and more severe as the decades have passed. These problems include

- Increasing congestion
- Declining downtown activity
- Dependence on oil while demand exceeds production
- Air pollution
- Deaths and injuries from auto accidents

- Costs of transportation
- Excessive sprawl
- Isolation of the poor and of those unable to drive or who prefer not to drive.
- Global warming
- Terrorism

Books can be and have been written on each of these problems, and assuming no new solution, Pucher and Lefèvre [2] concluded: "The future looks bleak both for urban transport and for our cities: more traffic jams, more pollution and reduced accessibility." The thought that a new type of transit system can address all of these problems is remarkable, but this paper and its references show that it can. The attitude needed to think positively in the face of overwhelming problems on a global scale is being developed by a growing number of thinkers, for example Philosophy Professor Glen Martin [3] and Barbara Marx Hubbard [4].

A series of studies sponsored in 1967-1968 by the United States Urban Mass Transit Administration showed that if only conventional forms of transit are deployed, congestion will continue to increase, and with it many of the problems listed above; but, if personal transit systems are deployed, congestion can be mitigated. The most easily obtained summary of this work was published in *Scientific American* [5]. Unfortunately, notwithstanding serious interest at the federal level in the United States for six years after the publication of those results, the new systems were considered too radical for the conventional transit community. They lobbied to kill a budding federal program to develop HCPRT in favor of conventional rail systems that provide a few lines at very high cost while leaving huge portions of urban areas without effective transit service. The turning point was likely the following statement by Frank C. Herringer, Urban Mass Transportation Administrator on March 27, 1974 before the Transportation Subcommittee of the Committee on Appropriations of the U. S. House of Representatives: "This means that a high-capacity PRT could carry as many passengers as a rapid rail system for about one quarter the capital cost." This was too much for the conventional rail community. PRT was too radical for them.

Thanks largely to the work of members of the Advanced Transit Association, work on PRT continued in the United States at a low, poorly funded level until the Northeastern Illinois Regional Transportation Authority became interested in 1989. Their PRT program, announced in 1990, coming as it did from the second largest transit organization in the United States, caused a great deal of renewed interest in PRT. Serious organizations have in the past year issued requests for proposals for PRT systems. In the past month the British Airport Authority announced that they will build a PRT system at Heathrow International Airport using the technology called ULTra, developed at Bristol University in the United Kingdom. Congratulations to them!

Development of a transit system capable of addressing the real problems of urban civilization has required the inventor to start from a clean sheet of paper. The inventor must consider transit in an interdisciplinary way as a field of requirements and characteristics, setting aside known characteristics of existing transit systems that were introduced over a century ago. Developing criteria for a new urban transportation system involves much more than engineering. The system engineer may take the lead, but must work closely with architects, planners, geographers, economists, sociologists, psychologists, political scientists, public officials, and interested citizens. In the following paragraphs I show how, with the support of many colleagues expert in many fields, I developed and recommend to a new generation of transit designers the kind of process I believe can result in success. To have made some progress I "stood on the shoulders of giants" and the new generation can now see much farther based on all of the work done in the past four decades. My first detailed attempt at the theory of PRT was published in 1978 [6]. During the 1970s I became acquainted with eight persons who could clearly show that they independently invented the concept we now call personal rapid transit. I am not one of them but I benefited greatly from meeting and conversing with them all. Their work collectively initiated serious interest in PRT.

2. Design Process

Developing a totally new transit system is a daunting task. Success requires a comprehensive and disciplined design process. During my career I rarely worked on anything that had been done before, which has been an advantage for me. As a design engineer, while a full-time employee at the Honeywell Aeronautical Division and later a consultant to both private and public organizations, I acquired some knowledge of the design process. Over several decades I led senior mechanical engineering students in design projects and studied the work of others who performed research into the design process. This experience led me to develop the following set of 15 rules of engineering design that if followed rigorously will lead to excellent results. I have sadly found, however, that all too few engineers follow such a rigorous set of procedures, and I have observed that designs of those who do not show the lack of discipline.

2.1. <u>Consider the transit system as a field of requirements and characteristics.</u> It is easy for an engineer, and all too common, to jump right into specific designs before thoroughly understanding all of the requirements that relate the subject system to its environment. To make genuine progress, it is absolutely necessary to take the time to study the problem for which an engineering solution is desired in as broad an interdisciplinary context as the problem requires. In the design of a new transit system, this means understanding and documenting all of the desired performance, environmental, social, and economic requirements. By the "field of characteristics" I mean all of the alternative system characteristics possible. For example, a vehicle could be suspended on wheels, air cushions, magnetic fields, or sled runners. Detailed study of the requirements must lead to a set of criteria that will guide the design.

2.2. <u>Identify all trade-off issues.</u> One trade-off issue in transit design is the means to be used for suspension, and four possibilities are given above. We found 45 trade-off issues (see Section 7), certainly not an exhaustive list, but one that must be considered, explicitly or implicitly, in designing a new transit system. By considering such issues explicitly with the criteria firmly in mind, the task of design is clarified and organized.

2.3. <u>Develop all reasonable alternatives within each trade-off issue.</u> Often, by rushing into details too quickly, practical alternatives are overlooked; someone else finds them and develops a superior design. Perhaps more important is that the designer who has not examined alternatives carefully before committing to a design cannot defend the design rationally and then becomes emotionally "locked in" to one approach when others point out superior alternatives. All too often such a designer causes more harm than good in advancing a design.

2.4. <u>Study each alternative until the choice is clear, rational and optimal.</u> This is hard work, but if not done rationally the design may have fatal flaws. Such a process creates designs that are difficult or impossible to better, which is the objective of a good designer.

2.5. <u>Seek and listen *humbly* to comments from anyone who will listen.</u> By explaining your ideas and listening to comments, you clarify them. A difficulty many engineers have is failing to listen humbly, particularly to an outsider. Arrogance is disastrous to good design. A good designer must be humble, a rare attribute.

2.6. <u>Seek advice from the best experts available in every specialty area.</u> It should be obvious that none of us can know the details of every specialty required, yet there is often an innate desire to try to develop a design ourselves. The best design will take advantage of the best information available anywhere, from anyone. A large portion of an engineer's work involves searching for information developed by others. In the age of the Internet, this is much easier.

2.7. Consult with manufacturing engineers at every stage of design. In the United States, particularly, all too many design offices have left manufacturing considerations to the end of the design process, and by grading manufacturing engineers lower than design engineers have informed the able engineer where to concentrate. The Japanese practice of including the manufacturing engineer in every stage of the design process led to superior products that often took most of the market share.

2.8. Recognize that while emotion is a fundamental driving force in human behavior, emotion must not select alternatives. Emotional commitment is vital for any human being to commit fully to a task, but it must be set aside when making design decisions. A good design engineer must be free of emotional "hang-ups" that inhibit making use of all information available, calmly sorting through the pros and cons of each approach before recommending a solution, and being willing to accept someone else's idea when objective analysis shows that it is superior. Too few engineers have a deep understanding of the subconscious factors that motivate and direct thinking. Yet it is necessary for the engineer to put the ego in the background when making design decisions. The following verse from The Bhagavad Gita, written perhaps 4000 years ago, hits the nail on the head.

"Therefore unattached ever
Perform action that must be done;
For performing action without attachment
Man attains the highest."

2.9. Recognize and avoid NIH (Not Invented Here). I worked for eight years in the Honeywell Aeronautical Division's Research Department in Minneapolis. Honeywell management established a design and production group in Clearwater, Florida, partly for the purpose of commercializing systems and components developed in the Research Department. It was found time and again that after designs management wanted commercialized were sent to Clearwater they were changed beyond recognition and for the worse. As a result, a management policy was implemented that required that whenever a project went from Minneapolis to Clearwater, the engineers that developed it went with it to supervise the detail-design process through production. NIH is joked about, but it is a prime phenomenon that destroys profitability of design offices. The motivating drives that produce it must be understood and controlled. The human emotion that says "we can do it better than you can" is okay if it is controlled, but when it prevents an engineering office from making good use of ideas developed elsewhere, as is all too often the case, it is destructive.

2.10. Consider the overall economic implications of each design decision. This requires good market and economic analysis to parallel design analysis. A design is good if it can win in a highly competitive market, and it can do so only by taking economics into account at every step. Unfortunately, cost and economic analysis are not part of most engineering curricula so too many graduate engineers are unprepared and must learn these subjects after graduation, if they ever do.

2.11. Minimize the number of moving parts. Some engineers become fascinated with extremely complex designs, but they too often are subject to more failures and end up with higher life-cycle cost. Examine carefully the function of each part.

2.12. Consider the consequences of failure in every design decision. It is easy to design something if failures are not considered. A good design requires that the best engineers perform careful failure-modes-and-effects analysis as a fundamental part of the design process. It cannot be just something tacked on at the end, as is too often the case.

2.13. Use commercially available components wherever practical. I have mentioned that the temptation to "design it yourself" is strong, but it is expensive and does not take into account that a design engineer cannot be a specialist in very many areas of engineering. There are of course times when a commercially available component just will not do, but such a decision should be made only after commercially available components are considered very carefully.

2.14. Design for function. Sounds obvious, but is too often overlooked. A Japanese engineer reduced the cost of a magnetron for an infrared oven from over $500 as developed by an American engineering firm to under $5 by asking himself what the magnetron is really supposed to do. I reduced the design of an instrument from 90 parts to 19 by asking: What was the real function of the device? The new design passed a much tougher vibration specification than the former.

2.15. Analyze thoroughly. It is much cheaper to correct designs through analysis than after hardware is built. Analysis is hard, exacting work. Most engineers do not have sufficient mathematical background to do such work well and thus blunder along from one inadequate design to another. This "garage-shop" approach has initiated many designs, for example the bicycle and the automobile, but modern airplane and automotive design requires a great deal of analysis corroborated by experiment. Design of a truly cost-effective, high-performance transit system requires the best of modern engineering analysis.

3. General Criteria

Following is a list of general criteria that resulted from much discussion during the 1970s. It is needed to guide the design of a new type of transit, but is not necessarily listed in the order of importance. Specific criteria needed to design the various subsystems come later.

- The energy efficiency must be very high.
- The land requirement must be very small.
- The system must be genuinely attractive to auto users.
- The trip time must be competitive with auto trips.
- Capital and operating costs must be low, desirably low enough to be recovered by fares.
- The system must meet accepted ride-comfort standards.
- The design must meet the requirements of the Americans with Disabilities Act.
- The system must be available at all hours of the day to everyone.
- The system must be able to use renewable energy sources.
- The air and noise pollution must be very low.
- As little material as possible must be used.
- The new system must be at least two orders of magnitude safer than present systems.
- There must be less than about 1 hour of delay in every 10,000 hours of operation.
- The system must not be an attractive target for terrorists.

- The system must not compromise personal security and privacy.
- The system must be expandable without limit.

Meeting these criteria requires a great deal of optimization, a process that is too often ignored because it requires a good deal of engineering mathematics.

4. Derivation of the General Features of the System from the Criteria

The next task is to develop the general characteristics of the new system from the criteria. The first point is that if the system is to be able to attract auto users, it must be competitive in trip time between many points. Also it must be safe and reliable. For these reasons the new system cannot be one more system running on the surface – it must provide an exclusive guideway either elevated or underground. Underground systems are so expensive that it is clear that we had to attempt to devise a low-cost elevated system, the visual impact of which will be acceptable. Consequently, we concentrate on how to design an acceptable elevated system.

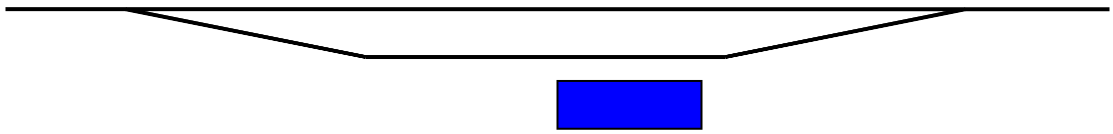
By studying the dynamics of vehicles or trains moving over elevated guideways [7] it became clear that if the people-carrying capacity of the vehicles can be distributed over the guideway in many small units in which adult passengers are all seated instead of a few large conventional vehicles of the same capacity, the weight per unit of length of the guideway can be reduced by a factor of at least 20.

This marked reduction is due to both static and dynamic factors. Statically, if the load is spread in small vehicles, the maximum load on any single span is far less than if large trains pass only every few minutes, and the vehicle weight per unit of length is much smaller if the vehicle is designed for seated passengers only. Dynamically, it was shown [7] that the ratio of dynamic to static deflection is much less with many vehicles moving at close spacing rather than a few vehicles or trains running at large spacing. Indeed, as the headway between small vehicles gets smaller and smaller, the ratio of dynamic to static deflection approaches unity. I found [6] that the governing vertical load on the guideway occurs with fully loaded vehicles standing still nose to tail – the governing load is the easiest to calculate. Moreover, I found that the International Standards Organization (ISO) ride-comfort standard for such a guideway is not exceeded until the vehicles are traveling at above about 45 m/s (100 mph), which covers a very wide range of applications.

The next logical question is this: Would not a system of small vehicles of a given total capacity cost more than a system of large vehicles of the same capacity? Isn't there an economy of scale favoring large vehicles? Many engineers have assumed so. After all, there are many more motors, wheels, etc. in the fleet of small vehicles. Examination of data on the cost and weight per unit of capacity of transit vehicles shows [8], surprisingly perhaps, that there is no economy of scale – the large vehicles cost as much per unit of capacity as the small ones. A major factor in cost is production quantity. Large transit vehicles are assembled pretty much by hand, while higher-production techniques are practical with small vehicles. Moreover, with many small vehicles, the equipment needed to move them around and service them is much smaller, and the required facilities are much smaller. It is clear that if a system of such small vehicles is to work, the vehicles must be controlled automatically.

We have seen that the use of many small vehicles rather than a few large ones reduces the cost of the guideway substantially. The cost of a fleet of vehicles of a given capacity is the cost per unit of people-carrying capacity multiplied by the people-carrying capacity. We then observe that the people-carrying capacity required to move a given number of people is proportional to the trip time – the longer the trip time, the more vehicles there will be on the guideway at any one time. The shortest possible trip time is obtained if all of the trips are nonstop, and this becomes practical if **all of the stations are on bypass**

guideways off the main line as illustrated in the following plan view. This is of course the principle of the expressway and why people prefer to travel on them rather than on arterial streets with all of their stop signs and lights.



An important consideration in developing the criteria for the new system is whether or not the vehicles should be able to run on normal streets as well as on guideways. A system that does this is called dual mode. [6, 10, 27] While its vehicles run on a network of guideways, a dual-mode system operates exactly like a PRT system. Dual mode may have stations similar to PRT stations, or vehicles may leave the guideway without any station platforms, thus saving their cost. Dual mode has the advantages for auto drivers 1) that the same vehicle may be taken from home to any destination, similar to driving an automobile; and 2) that congestion *on the guideway* may be avoided because of the shorter headway and the managed flow possible under automatic control. In many respects, dual mode is much like the system envisioned by advocates of IVHS (Intelligent Vehicle Highway Systems), except that special narrower guideways could be used. Dual mode does not come, however, without disadvantages, most of which are inherent and not subject to technical improvement.

The following are some of the disadvantages of dual mode, which lead me to conclude that it is best to concentrate on systems of small vehicles captive to the guideway. If the distance is too far to walk and oil is too expensive, small electric cars can be used to take people from home to station. Such cars, called “station cars” have already been put into use in the United States at least in California.

1. Dual-mode vehicles will have to be inspected carefully before entering the guideway, and the inspection time will reduce markedly the throughput at each entry point.
2. Maintenance of dual-mode vehicles would be done privately, just as it is with autos today, so the condition of vehicles entering the guideway would be much more difficult to determine than it would be in a PRT system in which the condition of the vehicles can be monitored and maintenance can be controlled.

3. Dual-mode vehicle must be designed for both the street and the guideway, making them heavier and more expensive than captive vehicles. Street vehicles must be designed for side collisions and rollovers, whereas PRT vehicles captive to a guideway do not.
4. The requirement for operation on the street limits flexibility in design of a minimum size, minimum cost guideway.
5. Since dual-mode vehicles would be more expensive than regular automobiles, they would be purchased near the beginning of dual-mode operation by only the wealthy.
6. A question then is how much guideway would have to be built before even a wealthy person would purchase a dual-mode vehicle?
7. At least in early stages taxes would have to pay for installation of the guideway, a guideway that only the wealthy could afford to use. There has been much debate on this question related to requirement for payment for a fast lanes on freeways, and will

be much more contentious when it comes to paying for a whole system of guideways for the rich.

8. One must be able to drive a dual-mode vehicle on city streets, so the idea of dual mode will be of no use to those who can't or don't chose to drive. A characteristic of transit is that it is available to everyone.
9. In downtown areas, dual-mode vehicles cannot always be permitted to enter the street system because congestion could then back up onto the guideway, so the downtown network would have to operate identically with PRT, but with bulkier guideways.
10. Dual-mode vehicles would have to be stored like conventional autos, sitting unused all day, whereas captive PRT vehicles are ready for the next trip as soon as one is completed.
11. The time required to retrieve a dual-mode vehicle at the end of the day downtown will be much longer than the time to wait for a PRT vehicle captive to the guideway.
12. Dual-mode stations would be more complex, expensive, and land-consuming than PRT stations because they must provide PRT-type stations as well as on- and off-ramps for dual-mode vehicles and ramps for rejected vehicles.
13. Dual-mode designers usually speak in terms of only a minimal guideway network being needed, which would render use of the system marginal for those who do not drive.
14. Developing a dual-mode guideway that will meet all of the criteria listed in this paper has not been shown to be possible. Every dual-mode guideway designed thus far has serious problems.
15. Dual-mode ridership has been shown [10] to be no more than PRT ridership.
16. Dual mode suffers from the attempt to combine two different functions, and as a result fails to excel at either.

5. The System Attributes Obtained

By assuming a transit system using minimum sized vehicles operating automatically nonstop between offline stations, we observe that the following attributes are either directly apparent or can be readily achieved:

- Nonstop trips
- High throughput. Similar to automobiles on a freeway, the small transit cars can run seconds or fractions of a second apart rather than minutes apart, as is necessary with the on-line stopping required of buses, streetcars, and trains.
- Small, low-cost, low-visual-impact guideways.
- Around-the-clock availability because the cars can be automatically rerouted into the stations to keep a supply of cars in or coming to each station all the time.
- A short wait in the peak hours when all the cars are in use, and no wait off peak.
- Travel on demand – no schedules. This is very important. The vehicles now need to move only when there are demands for service, which markedly reduces operating costs.
- Close station spacing. With on-line stopping, the farther apart the stations are the higher can be the average speed, but larger spacing between stations reduces access to the system. With off-line stations we have our cake and eat it too – stations can be placed as close together as needed (within a geometric limit) to provide access while a high average speed is maintained. The economics of adding stations to existing lines is very favorable [8, Appendix B].

- Stations sized to demand. With train systems, every station must be as long as the longest train. With off-line stations, the stations can be sized to the expected demand at each station.
- All of these factors contribute to low cost and high ridership.

6. Ridership Potential

Estimation of ridership on a potential PRT system is as important as the engineering factors that need to be understood to design the system, and involves measurement of human judgment and social interaction. We can appreciate intuitively that a system that will be available any time of day or night, with a private ride in seated comfort, will be attractive, but just how attractive? In the period 1974-75 I worked for Colorado's Regional Transportation District on the largest study of transit alternatives ever performed in the United States, and was assigned to follow, understand, and report on the ridership studies.

In so doing I learned that there was an Institute of Behavioral Science at the University of Colorado where the faculty was engaged in studies of social judgment. They were quite interested in using their skills to develop a model to determine ridership on transit systems with new characteristics. Analysis of ridership on conventional transit systems did not need any new techniques because they could do regression analysis on existing transit systems to calibrate their models. With a new system, such conventional models could not be applied accurately because there was no basis on which to calibrate the models. One way used to get around this problem was to develop a video of the new system, show it to people, and ask detailed questions about their preference to ride it. Unfortunately, when facing a real situation people don't always behave as they think they would in the abstract. The way this problem can be solved using the theory of social judgment involves breaking the trip up into detailed steps, devising experiments with a wide variety of people on how they would behave during each step, and then from the results build a model with appropriately weighted factors. There is a wide ranging literature in social judgment with many examples of quite remarkable success. Unfortunately, to my knowledge, such a method is yet to be developed for estimating ridership on true PRT systems. Yet many estimates of ridership on PRT have been and must be made. I mention three:

1. One of the best early PRT ridership studies of which I am aware was performed by Professor Frank Navin of the University of British Columbia [9]. Using a standard logit model he broke time up into walk time, wait time, ride time, and transfer time with different coefficients for each. He then performed regression analysis on transit ridership from several cities to determine the coefficients. He found the following results:

	Low	High
Riding in bus	1.00	1.00
Walking to/from bus	1.65	2.08
Waiting for first bus	4.15	6.34
Transferring	6.62	10.0

This table means, for example, that for every minute spent riding a bus, one minute of waiting seems like from 4.15 to 6.34 minutes. In most ridership studies involving trains and buses, the consultants usually assume the coefficients for walking, waiting, and transferring are each taken as 2, which clearly will bias the results to more bus riders than will actually occur, thus making it more likely that a governing board will expand the bus system. Navin applied his ideas to estimation of ridership on a PRT system and came up with estimates greater than 50% of the daily trips.

2. Work at The Aerospace Corporation [10], using a novel "Monte Carlo" model, led them to conclude that a mode split to PRT in the Los Angeles Area of 30% was reasonable. In the Monte Carlo model they would start the trip at a random point, pick at random an individual in a certain income range appropriate to that point, pick a destination at random, calculate the walk, wait and ride time by both auto and PRT, include a factor for perceived trip cost, and then assign the person to either auto or PRT. They repeated the calculation with new randomly selected passengers until the result converged. The value of 30 % they obtained must be compared with the bus modal split, which for most U. S. cities hovers around 3%.

3. Swedish PRT planning studies performed in the 1990s [11] showed that "PRT can attract 20-25 % of today's automobile trips." They did not describe the method they used in published reports I have seen.

7. Required Tradeoffs

A table (http://faculty.washington.edu/jbs/itrans/jea2.gif) listing 45 possible tradeoffs that must be made in designing a PRT system can be found on Professor Jerry Schneider's web page. We calculated the number of possible combinations to be about 10^{16}. The only way to resolve so many combinations must come through the development of suitable theory and through the disciplined process described above.

8. Control Criteria and Tradeoffs

The new type of transit, HCPRT, will, as concluded above, be fully automatically controlled. The Bibliography given in Section 25 includes more published work on the control of PRT systems than on any other aspect of the subject. Even though I worked as a control engineer in the Aero Research Department at Honeywell, I observed what was going on during the 1970s in PRT control and concluded that a better task for me was to determine what should be controlled, while following the control work of others. Building on the work of others, I saw that a PRT control system should consist of a hierarchy of three levels of control: vehicle control, wayside control by zones, and central control [12, 13, 14] and definitely that it should not be synchronously controlled, i.e., controlled so that a vehicle can be commanded to leave a station only if there is a clear path with no merge conflicts to the destination [15]. The criteria used are the following:

1. Changing conditions. The system must be designed so that the speeds can be reduced when the wind increases above set levels, and that the normal speed can be restored when the wind dies down. Moreover, the system must be responsive to any possible type of failure – system, vandalism, sabotage, or terrorism.
2. Ride comfort. Accepted criteria on maximum jerk and acceleration rates must be met.
3. Fail safety. The system must be designed to fail soft if it is to fail in any way.
4. Modularity & Expandability. The hierarchal system described is modular and line-replaceable units must be used. By breaking up wayside control among zone controllers that serve stations, merge points or diverge points, with the same code in each, any network configuration can be handled.
5. Less than one person-hour of delay for every 10,000 person-hours of operation [16].

6. Maximum throughput. The system must be designed so that there is no safety issue in reducing the line headway to about 0.5 second. This headway will accommodate the needs of a very large network.
7. Interchange flexibility. There are two types of line-to-line interchanges: X and Y. In an X-interchange two lines enter and two lines leave, one set above the other, and the flow diverges before it later merges. Such an interchange requires no central control because all potential conflicts can be solved at the interchange. In a system containing Y-interchanges, the flow must merge before it diverges, creating potential bottlenecks. But the visual impact of the system at Y-interchanges is much less than at X-interchanges and the guideway can be all at one level. Thus in many cases Y-interchanges are preferred and the control system must be able to handle them. I have found that it can do so quite readily.
8. Dead-vehicle detection. The system must be able to know if a vehicle has ceased to function at any location on the guideway.

During the 1970s there was much debate over quasi-synchronous vs. asynchronous control. I started my development of a PRT network control system using quasi-synchronous control, but needing to simulate a system with rather long minimum headway, I found that I could not succeed unless I switched to asynchronous control. Having done so, I found that I needed fewer subroutines and that asynchronous control also worked better at short headway. Asynchronous control does not require clock synchronization, which is artificial. Having developed exact equations for all possible speed changes, as others had done before me, I found that it is preferable to require each vehicle to follow a command trajectory than to control its motion by following the vehicle ahead. Such control is completely stable and is not subject to string-stability problems that plagued car-follower control. Thus, while in the 1970s the debate was between quasi-synchronous control with point-following, i.e., following speed-change commands; and asynchronous control with car-following, I found that the best scheme is an asynchronous point follower.

9. Guideway Criteria

Most of the PRT systems of the 1970-era faded away because of inadequate attention to the criteria for guideway design. That was also true in the Raytheon program of the 1990s. During the 1970s, as a university professor and chairman of the three international PRT conferences I was able to visit all of the PRT developers in all of the industrialized countries where PRT work was underway, study their systems, read their reports, and obtain reactions of others. This experience led me by 1980 to be able to list the following criteria for PRT guideway design.

1. <u>Adequate ride comfort</u>. This seems obvious, but a number of the PRT developers neglected ride comfort until it was too late. Ride comfort requires not only designing to given maximum steady state jerk and acceleration but to meeting ISO criteria on acceptable acceleration vs. frequency.
2. <u>Minimum size, weight and cost</u>. These factors have been argued as being fundamental to PRT design. What I found [6] was that the minimum weight cross section, taking into account maximum vertical loads and maximum lateral wind loads, would be a little narrower than deep. The Aerospace Corporation [10] first reached this conclusion and also observed that this structurally optimum design would give the least visual impact, i.e., the smallest shadow.
3. <u>Span</u>. The guideway should be designed for spans of up to 27 meters (90 ft). Longer spans needed to cross rivers or major highways will use cable-stayed suspension-bridge technology.
4. <u>Three dimensional</u>. The guideway and its manufacturability must be design to accommodate hills and valleys as well as horizontal curves.

5. Weather protection. The system will need to operate in rain, snow, ice, dust, and salt spray, i.e. in a general outdoor environment. Some designers concluded that this required that the vehicles hang from the guideway; however, I found a number of reasons to prefer placing the vehicles on top of the guideway (see Section 10).
6. Guideway heating. The guideway must be designed so that under winter conditions, guideway heating will not be necessary.
7. Resistance to maximum wind load. Codes vary from city to city, so thinking in terms of hurricane winds I designed for 240 km/hr (150 mph) cross winds. I did not design for tornado winds, which can go well over 320 km/hr (200 mph) because it would be cheaper to replace failed sections than to build the entire system to withstand such an improbable load.
8. Resistance to earthquake loads. If an earthquake causes the earth to shear horizontally, as has happened, no design will prevent failure. The most common earthquake load translates to a horizontal acceleration. In the 1994 Los Angeles earthquake, horizontal loads up to 1.6 g were detected. The lighter the guideway, the easier it will be to design the foundations to withstand such a horizontal acceleration.
9. The guideway must be easy to erect, change, expand or remove. The guideway sections must be designed so that the system can be expanded by taking out a straight section and substituting a switch section.
10. Access for maintenance. I visited the H-Bahn design in Düsseldorf in 1974. The cars hung from an inverted U-shaped steel-plate guideway. There were power rails and communication lines on the inside of the guideway but no way to reach them. One had to assume that they would never require maintenance, which is an unacceptable assumption.
11. Relief of thermal stresses. Except at noon, the sun will shine on one side of the guideway, with the other side in the shade, thus causing one side to expand more than the other. In some cases this has caused structural failure.
12. The power rails must be shielded from the winter-night sky. Some PRT systems operate their vehicles with on-board batteries, so for them this is not a problem. However, on-board batteries add weight and must contain enough energy for the worst conditions of wind, grade, and trip length, which increase as the system expands; so it is better to pick up wayside power via sliding contacts. On clear winter nights heat radiates to a very cold space and as a consequence frost often forms on metallic surfaces. In the Airtrans system, which was installed at the Dallas-Ft. Worth Airport in 1972, it was found that on clear winter nights enough frost formed on the power rails that they had to be sprayed with ethylene glycol as a temporary expedient before starting the system each morning. Later they installed heaters in the power rails. A similar problem was discovered in the elevated guideway system installed at the Minnesota Zoo. In systems such as Cabintaxi in which the power rails were covered, frost formation was never a problem.
13. The design must provide adequate torsional stiffness.
14. Design to liberalize the required post-settling tolerance.
15. High natural frequency to obtain maximum speed. This is not as important a consideration as I once thought it was, but all else being equal higher natural frequency is better.
16. Lightning protection. The guideway must be well grounded.
17. Electrocution. It must be very difficult if not impossible for anyone to be electrocuted by the system.
18. Provide space for communication wires. Wireless communication may be practical, but is more likely to be subject to interference. Moreover, the system would likely have to rent the frequencies it needs, which would be prohibitively expensive. Thus there must be space for installation of a leaky cable for communications between the vehicle and the guideway.

19. Minimize electromagnetic interference. The U. S. Federal Communications Commission requires that any new element in a community not interfere with existing electronic devices. The motors or drives on a PRT vehicle may emit electromagnetic noise and the communications system may be subject to electromagnetic noise, so there must be shielding between the inside and outside of the guideway.
20. Minimize potential for vandalism or sabotage.
21. There must be no producers of vibration or noise.
22. Provision must be made for corrosion resistance.
23. There must be no place for water to accumulate.
24. The design must permit the appearance to be varied to suit the community.

Figure 1.

25. It must be difficult if not impossible to walk on the guideway unless walkways are provided.
26. Thought must be given to providing for damping.
27. Curved and branching sections. These are more difficult than straight sections; therefore it is prudent to think through first a design in which the many required curved, merge, and diverge sections will be easy to fabricate.
28. The guideway should be designed for 50-year life.

10. Suspension

Practical means of suspension include rubber tired or steel wheels, air cushions or magnetic levitation. Automated systems have been designed with vehicles suspended below a guideway, on the side of the guideway, and above the guideway. For reasons given in [1] I found that it is best to place the vehicles above the guideway. The need to keep the cross section of the guideway as small as possible and the status of development led me to conclude that wheeled suspension is best. Magnetic levitation requires the use of on-board magnets that will increase vehicle weight, and the surfaces against which they must run need to be wider than with wheeled suspension. Moreover, because of the need for high-speed switching, repulsive magnets must be used, which are more difficult to design than attractive magnets. Superconducting magnets have been used for this purpose in large vehicles but they are impractical in small vehicles. Air-cushion suspension requires a wider guideway than needed with wheeled suspension, resulting in higher costs and greater visual intrusion. In maglev and air-cushion suspension, power must be provided to keep the vehicle levitated. We thus chose wheeled suspension, yet we must keep an open mind and watch additional development to see if our conclusion remains correct.

To reduce noise and to provide some cushioning with wheeled suspension, we selected either pneumatic or the new airless tire recently announced by Michelin. For lateral suspension, solid polyurethane tires are adequate. Some engineers have expressed concern about the narrow guideway for reasons related to lateral suspension; but Mother Nature does not care if lateral suspension is provided on horizontal or vertical surfaces. The effective track width is the distance from the upper left lateral wheels down to the horizontal running surface, across to the right lateral running surface and up to the upper right lateral wheels. We met an important criterion – minimum cross section – by using vertical surfaces for lateral support.

11. Guideway Covers

Careful study of the guideway criteria led me to select a U-shaped steel-truss frame that would be clamped to the support posts with expansion joints at the point of zero bending moment in a uniformly loaded beam, i.e., at the 21% in the span where there will be very little bending as the vehicles cross the span [10]. It is illustrated in Figure 2. A steel truss frame is the lightest weight design possible, and, among other things will reduce the earthquake load on the posts and foundations. The lightest-weight guideway, a truss, will maximize the natural frequency of the guideway, and will minimize the cost of shipping. Computerized analysis has been performed on this guideway by six different engineering firms and a section has been fabricated.

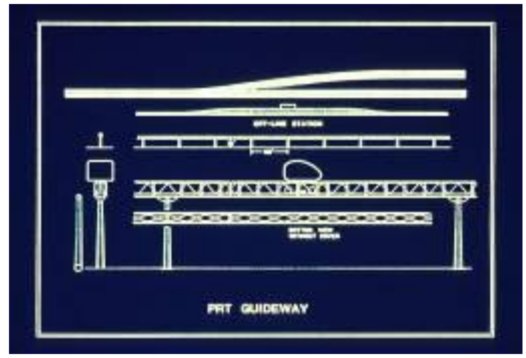


Figure 2.

As shown in Figure 3, covers will be attached to the sides of the guideway. These covers have a narrow slot at the top to permit the chassis to pass through, and are opened at the bottom. They provide the following nine functions:

- They keep out almost all ice and snow, with the remainder easily disposed of.
- By applying a thin aluminum coating inside, they provide electromagnetic shielding.
- By applying a sound-dampening material to the inside surface they reduce noise to nearly inaudible level.
- They shield the tires from the Sun.
- They shield power rails from frost formation.
- They eliminate the problem of differential thermal expansion.
- By curving the covers at the top and bottom with a radius of about 1/6th the depth of the guideway, the lateral air-drag coefficient is reduced from about 2 to about 0.6, with a proportionate reduction in the bending moments on the support-post foundations. Also, curving the covers at the corners will help debris or snow to fall off quickly.
- The covers can be removed or swung down to provide access for maintenance.
- The outside surface treatment of the covers can be varied to suit the community.

12. Capacity Potential

Consider a surface-level tram, streetcar, or light-rail system. A typical minimum schedule frequency or headway in these systems is 6 minutes or 360 seconds. In the United States, the modern light-rail vehicle has a design capacity of about 200 persons, and typically they run in two-car trains, thus moving a maximum of 400 people every 360 seconds. On the other hand, a great deal of evidence shows that HCPRT vehicles can run about 0.5 second apart. Indeed in a program ran by the Automated Highway Consortium and monitored by the National Highway Safety Board four automobiles were demonstrated running about 0.25 seconds apart at 60 mph. So we can assume that a maximum of 720 HCPRT cars can pass a point every 360 seconds. We recommend a 2.7-meter (9 ft) long vehicle with one bench seat that can be occupied by three adults, giving 720(3) = 2160 persons in the same period in which 400 people would pass in light rail cars. In this case the capacity ratio is 2160/400 = 5.4 to 1!

This is a line-haul comparison; however, HCPRT will typically be deployed in networks, which by spreading out the load results in a much smaller requirement for line-haul as well as station capacity than conventional train systems. The problem of PRT capacity needs in lines and stations is addressed in detail in a paper sponsored by the Advanced Transit Association [17].

13. Vehicle Criteria

Up to this point, it has been concluded that the vehicle should be designed to be as small and as light in weight as practical and should ride above the guideway. Now it is necessary to be more specific [18]. Because of the nature of a PRT vehicle captive to a guideway, the considerations that led to a recommended vehicle configuration are different from those that enter into choosing the size of the family automobile. Again it is important to avoid snap judgments that have marginalized certain previous PRT systems. Following are nine factors that should be considered in selecting the vehicle size and configuration.

- Travel behavior. In the U. S. the daily average number of people per automobile is about 1.2 and in the rush period it is less than 1.1, indicating how people travel if they have a choice [19]. Think of the trips you take in one week. In what fraction of them do you ride alone, in what fraction with one other person, what fraction with two, etc.?
- Personal security. The way people travel if they have a choice, at least 90% of them take trips traveling alone. A small percentage of them travel in pairs, and an even smaller percentage in three's or four's, etc. People travel this way in taxis. Group riding by choice can be encouraged in PRT systems by charging a fare per vehicle rather than per person, as is commonly done with taxis. Expecting people to ride with unacquainted persons to fill the vehicles will discourage some people from riding at all. The smaller the vehicle, the higher will be the daily average load factor and the lower will be the overall cost per trip.
- Network operations. It was shown by detailed computer simulations conducted at Colorado's Regional Transportation District [20] that a system of vehicles operating between off-line stations and designed for random-group riding (GRT) runs into a problem that becomes more serious as a network grows, i.e., a vehicle coming into a station with people on board must have been committed to a given route. Thus a person wishing to board can't get into any vehicle, but must wait for a vehicle committed to the route the destination is on. As the system grows it turns out that the number of possible routes increases roughly as the square of the number of loops. Moreover, the system cannot know which of several loading berths the vehicle will stop at until it is switched to enter the station. So, in GRT there is too little time, particularly for slow moving people, to get to the desired vehicle. In short, simulations showed that the operation of such a station is impractical, and that the two practical systems are one that stops at all stations and one in which all people on board are traveling nonstop to their destination, i.e., a true HCPRT system. Moreover, the odds of two unacquainted persons arriving at one station within a few minutes, let alone seconds, of each other intending to go to the same destination increases with the square of the number of stations and becomes much too large to be practical when there are more than six or eight stations[6].

Figure 3. The covered guideway.

- Social considerations. One-person vehicles would minimize system costs, but are not socially acceptable. Two-person vehicles are too small for a wheelchair to enter and face forward. A vehicle with one bench seat, with sections that can fold up, designed for three adults seated side by side will accommodate a wheelchair and it was demonstrated that it will permit the wheelchair to rotate 90 degrees to face forward with room for an attendant. Moreover, to accommodate the wheelchair, there is room to place two fold-down seats in front of the cabin so that, when there is no wheelchair, the vehicle can accommodate three adults and two children. Also, a multi-purpose television screen can be positioned in the middle of the front of the cabin below the windshield. This configuration gives the shortest possible vehicle, which means the shortest possible stations.

- Throughput. The effect of vehicle length is a small factor, but the shorter the vehicle the greater is the practical throughput.
- ADA requirements - wheelchair access. The cabin described above accommodates a wheelchair with attendant, a passenger with a bicycle, a couple with a baby carriage, a couple with large suit-cases, or even a Segway.
- Styling. The vehicle, in particular, must be designed very carefully to attract riders of all ages. The length/width ratio of the cabin should conform to the Fibonacci ratio – 1.618.
- Minimizing system cost corresponds to minimizing vehicle weight, size, and length.
- Finally, with a larger group it is very easy to use more than one vehicle. Portions of the group will leave seconds apart and arrive seconds apart, and on the way can be in touch by cellular telephone or by an intercom system that would be standard equipment for a variety of purposes.

14. Switching Criteria

In many of the PRT designs, switching has been considered an afterthought – something that can be considered later. This is usually a fatal mistake. With the need to switch into and out of off-line stations and from line to line, the ability to switch easily with minimum extra guideway weight is fundamental to the design of any PRT system. Here are the criteria I used. In so doing I found, upon searching through 36 switch patents, that the switch that met the criteria without exception had not been patented.

- No moving track parts. If a moving track part fails, an entire line of traffic is held up, but if a moving part on a vehicle fails, the worst that can happen is that one vehicle will be sent in the wrong direction. An alternative, recommended by The Aerospace Corporation [10], is to switch electromagnetically. If this can be done without excessive vehicle weight and if it can be 100% reliable, it is worth considering. In any case, it has been proposed that there must be a mechanical backup, and if so, the mechanical device may as well be, I concluded, the primary switch.
- Only two stable positions (bi-stability). There can be no chance of a hang-up in the middle.
- The two switch positions should be self-stable without a locking mechanism.
- There should be no possibility of hitting track parts under any circumstances. Thus the switch arm must rotate about a longitudinal axis.
- It must be possible to throw the switch manually from wayside or from the vehicle behind under failure conditions.
- Switch operation must be unaffected by centrifugal forces in turns.
- The switch must operate in all weather conditions.
- The switch must be operable from low-voltage battery power.
- The operation of the switch must be fail-safe.

How these criteria can be met is the subject of two expired patents in my name. These patents are now in the public domain. They can be found on the U. S. Patent Office web page.

15. Dynamics

To meet ride comfort criteria, particularly as the vehicle moves through either merge or diverge sections of the guideway, extensive dynamic-simulation analysis is needed. With today's computer programs, this work is straightforward and will determine certain geometric parameters in the guideway as well as acceptable unevenness or roughness in the running surfaces. With minimum-weight vehicles, the ride is mainly determined by the smoothness of the running surfaces, so how they are designed and how the dimensions are maintained is critical to the operation of the system.

16. Safe Design

Safe design of PRT systems has been the subject of many papers, many of which are included in the Bibliography, Section 25. Safe short-headway flow can be achieved by consideration of four factors [21]:

1. Braking and acceleration accuracy through wheels depends on the coefficient of friction at the running surface, changes in wet or icy weather, wind, and grade. This problem is solved by use of linear electric motors (LEM) for propulsion and primary braking because consistent braking can be achieved under all conditions. There are two types of LEMs, synchronous (LSM) and induction (LIM). LSMs require a winding in the running surface but are more efficient than LIMs. They may be the way to go, but I have yet to see the total tradeoff study, which will involve detailed design that will prove that the overall system cost per passenger-km will be less with LSMs than with LIMs. LIMs require a copper overlay on a steel plate, which is cheaper than a winding and which has been shown to be practical. There are many thousands of LIMs in operation in a wide variety of applications.
2. Reaction time. Human reaction time to emergency situations varies with the person and with the amount of drugs or alcohol consumed. The reaction time of LEMs is only a few milliseconds, hence automatic systems can operate safely at much closer headways than manually driven vehicles, which routinely operate at headways less than two seconds.
3. Braking time. Mechanical brakes can apply the full force, even if actuated automatically, in no less than about 0.5 second, whereas LEMs apply the full force in a few milliseconds.
4. Vehicle length. The vehicle I propose in Section 13 has a length of 2.7 meters (9 ft), whereas a common automobile has a length of at least 4.6 meters (15 ft). Vehicle length enters into the equation for minimum headway, so the shorter the vehicles the better.

The conclusion of many investigators for over thirty years has been that operation of PRT vehicles at half-second headway with the above features is safe, practical, and needed in large applications.

17. Reliable Design

In conventional transit systems, system reliability has been measured in terms of Availability, which is defined as the percentage of all revenue trips that are completed without interruption to a specified degree. This is a crude measure, but is the best that can be done because it is not practical in these systems to use a measure in terms of person-hours of operation and person-hours of delay. In PRT systems, we can record the expected and actual times of each trip, so we can develop a better measure. To distinguish it, I have called the new measure "Dependability" [16] and define it as the percentage of person-hours experienced by people entering and riding the transit cars with delays less than specified. The ratio of person-hours of failure to person-hours of operation can be called "Undependability" and is 1 minus Dependability. The dependability paper [16] shows both how to calculate Undependability and how to measure it continuously as a routine part of system operation. The calculated measure of Undependability depends on normal operations, emergency operations, and the failure characteristics of each component in the system. It is thus an important management tool in maintaining control of the design, and can be used in contract specifications as a specific measure of performance.

During the design process, the question frequently arises as to where to place design emphasis to achieve the Dependability goal at minimum life-cycle cost. This question came up in U. S. military programs when, thirty years ago the Joint Chiefs of Staff issued a memorandum directing that life cycle cost would be of equal importance to performance in future procurements. I was able to solve this problem [22] by considering the system life-cycle cost (LCC) to be a function of the mean times to failure (MTBF) of each subsystem, and within each subsystem each component. This is a constrained minimization problem, with dependability as the constraint, and was first solved by J. L. Lagrange (1736-1813). It has an elegant solution, and gives the MTBF of each component required to meet the specified system Dependability at minimum system LCC. The resulting equation is an important tool for managing the design program.

Study of reliable design requires detailed study of failure modes and effects [23], hazards analysis, and fault-tree analysis. This work was done for PRT during the Phase I PRT Design Study sponsored by the Northeastern Illinois Regional Transportation Authority, and is the subject of Chapter 6 of The Aerospace Corporation book [10]. See also my book [6].

18. The Appropriate Speed

The appropriate line speed of a PRT system has been much debated. The Aerospace Corporation [10], thinking in terms of PRT systems that would serve Los Angeles, assumed line speeds of 20 to 60 mph (8.9 to 26.8 m/s) depending on where the line was located, and they designed a PRT system that could achieve those speeds. DEMAG+MBB, in the design of Cabintaxi [24], chose a line speed of 10 m/s as appropriate for German cities. Indeed such a speed with nonstop travel will give average speeds well above that achievable by automobiles in the inner city because of all of the stops they must make there. Higher line speed can be achieved at higher cost and with higher energy use. In the equation for cost per passenger-km, the factor that improves with average speed to a point is ridership. So theoretically it will be possible, when enough data is available, to find the line speed that will minimize cost per passenger-km. In rough attempts I have made at such a calculation I find optimum line speeds lower than I would have guessed. In a large metropolitan area, one can envision PRT lines along freeways, and in these cases line speeds of perhaps 18 to 20 m/s (40 mph) may be appropriate. There is always pressure to increase line speed because slower speeds seem too tedious. In the 1990 Chicago studies a line speed of 30 mph (13.4 m/s) was specified.

19. Energy Use

The operational energy use of a PRT system can be reduced by the well-known means of minimizing vehicle weight, careful attention to aerodynamic-drag reduction, minimization of road resistance, minimization of speed, and propulsion efficiency. The demand-responsive characteristic of PRT, whereby vehicles move only if necessary, will substantially reduce energy use over that required in conventional transit systems with their on-line stopping. I have compared the energy use per passenger-km in a PRT system with a variety of conventional systems [25]. It should be possible for a PRT system to achieve energy efficiencies, including construction energy, equivalent to an automobile system achieving in the range of 30 to 40 km/liter (70 to 90 mpg) of gasoline. By contrast, using U. S. government data, I found that light rail systems in the U. S. achieve in the range of 4 to 6 km/liter (9 to 14 mpg) of gasoline on a per rider basis. The low value for light rail is due to a combination of factors, mainly inherently low daily average load factor, wasted kinetic energy, and construction energy.

20. Land Use Implications

In the United States, the automobile system requires about 30% of the land in residential areas and roughly 50% to 70% of the land in Central Business Districts. An elevated PRT system requires land only for the posts and stations, which amounts to only one unit of land in 5000 for a system with lines spaced on a square grid 0.8 km (0.5 mi) apart with stations every 0.8 km, which gives a maximum walking distance of 0.4 km. The land under a PRT guideway can be used for walking or bicycle trails, and the system does not impede the flow of surface traffic.

Figure 4. Illustrating tiny land use of PRT.

This enormous reduction in land required for transportation will permit HCPRT to substantially reduce the congestion and air pollution produced by automobile traffic and will reduce the requirement for parking automobiles. As mentioned, because of the service concept inherent in PRT, a PRT system will attract a substantial fraction of the total number of vehicle trips, which means that PRT stations will be attractive sites for development, which means that it is likely that the system can attract enough revenue in reasonable taxes to pay for itself. Not nearly enough work has been done on this means for paying for a PRT system and indeed not enough work has been done on the implications of the very positive impacts a PRT system will have on the urban environment.

In new developments, such as new universities, retirement communities, etc., PRT can bring about the dream of an auto-free facility. For example, about 15 years ago the University of California was looking for a site for a tenth campus and specified that it be auto free. I gave a brief presentation to the site-selection committee of presidents and chancellors of the various UC campuses and found that the effect was electrifying. Unfortunately that site was rejected because it had been inadvertently placed over an Indian burial ground, but the concept, once PRT is proven in daily practice, of an auto-free facility will be extremely attractive to developers.

21. A Bit of History

System	Year first run	Guideway Width, m	Guideway Depth, m	Gross Vehicle Mass, kg
Morgantown GRT	1972	3	1.8	5350
Raytheon PRT 2000	1995	2	2	3000
Taxi 2000 HCPRT	2003	0.89	0.99	815

Consider the progression in design of the above three automated guideway systems. The earliest is the Morgantown system, which is called "PRT" but uses 20-passenger vehicles. The program that developed it was 100% funded by the U. S. federal government. The guideway is a wide trough that, for winter operation, requires snow melting, which is expensive. It is so large and heavy that no other city has chosen to duplicate it. The design contracts were let in December 1970 with the stipulation that the system be operational 20 months later, in time to influence the 1972 presidential election. The team of companies that designed it had never been engaged in a PRT project, had no theoretical background on how to design a PRT system, and had much too little time to perfect a design. Nevertheless, the system is still running every day and is the only system that demonstrates automatically controlled vehicles operating day in and day out between off-line stations.

Figure 5. The Morgantown system.

Next is Raytheon PRT 2000. It used four-passenger vehicles that ran on a test track in Marlborough, Massachusetts. Raytheon and the Northeastern Illinois Regional Transportation Authority (RTA) jointly funded the design and test program. Raytheon abandoned the program after the RTA dropped the system from consideration. This was fundamentally due to two factors: First, the Raytheon division that managed the program was accustomed to taking contracts from government agencies that developed the required specifications. Thus, they had not developed their own independent capability for doing the market surveys and specification development needed to guide their engineers independent of government agencies. Second, the state of the art in PRT was such that the RTA was not able to find a technical-support contractor with any depth of understanding of PRT. This combination sunk the program. Compared with the Phase I PRT Design program, which was based on the Taxi 2000 design, the guideway width and depth doubled, the vehicle weight increased by a factor of four, and the over-all cost tripled. This was too much for the RTA.

Figure 6. The Raytheon system

The third system, shown in Figure 3, is Taxi 2000. I led the design process throughout the program and designed the vehicle, guideway, and control system based on the principles presented in this paper. The vehicle ran automatically on an 18.3-meter-long (60-ft) guideway and over 4000 rides were given with no failures. The system is ready for final design and construction of a test loop that will permit continuous testing of at least three vehicles operating at speeds up to 16 m/s (35 mph). Such a test system is the next logical step before building a real people-moving demonstration.

Estimates of the system costs of the above three systems show that they reduce in proportion to the gross weight of the vehicle – everything scales with vehicle weight.

22. Benefits of High-Capacity PRT

22.1 For the rider

- The system is available for use at all hours. It does not have to be shut down at night.
- The system can be used by everyone without exception.
- The vehicles wait for people, not people for vehicles.
- The trip is short, predictable, nonstop, comfortable and private.
- The trip cost will be reasonable – typically no more than a bus fare.
- The rush period wait time will typically be less than one minute, with no waiting in non-rush periods.
- Everyone will have a seat.
- The vehicles will be heated and air conditioned.
- There will be no crowding.
- There will be no transfers.
- Because the vehicles run on rubber tires and because the motors have no moving parts, very little noise will be generated.
- The probability of accidents will be very low.
- Because the stations will be well lit and monitored, personal security will be excellent.

Figure 7. A comfortable ride.

- The ride will be smooth and comfortable.
- There will be space in each vehicle for luggage, a wheelchair, a bicycle, or a baby carriage.

22.2 For the community in which the system is installed

- The land savings will be huge.
- The system will attract many auto users and if deployed widely will reduce auto congestion.
- The frequency of accidents will be well under one in 10^9 of that experienced with the auto system [23].
- The energy use will be relatively low.
- The system can use renewable energy, thus contributing to a reduction in the need for oil.
- The levels of air and noise pollution will be very low, thus deployed widely the system will contribute to reduction in global warming.
- The system can serve the vast areas of single-family housing found in every city.
- There will be no significant targets for terrorists, so the system should be of interest to Homeland Security.
- The use of the vehicles is much more efficient than in the auto system because as soon as one trip is finished the vehicle is available for another, thus keeping each vehicle in operation about 10 hours a day – 6 to 10 times as much as with an automobile.
- The system will provide faster inside-to-inside transportation.
- There will be easier access to stores, clinics, offices and schools.
- Movement of mail and goods on the system will be swift and easy.

- The land under the system can be used for walking, jogging or bicycle trails.
- More people-attracting parks and gardens will be possible.
- More livable high-density communities will be possible.
- The system will be profitable in many applications.

23. A Summary of Advantages of High-Capacity PRT

- It will create healthy urban environments of unparalleled efficiency.
- Deployed widespread it will reduce the problems of congestion and global warming.
- Deployed widespread it will be a major means of reducing dependence on oil.
- It is not an attractive target for terrorists.
- It is an essential technology for a sustainable world.
- The technology to build it is at hand and is well understood.
- All that remains is final design, construction, test, and deployment.

24. Strategy for High-Capacity PRT Development

The knowledge needed to build public works such as bridges, roads, rail systems, sewers, water systems, dams, buildings, sports arenas, theme parks, vacation resorts, shopping malls, etc. is widespread and is taught widely. There are many private consulting firms ready, able, and willing to design and build these facilities – provided they are financed. Entities whether public or private with the means to finance such facilities develop specifications and then release them in Requests for Proposals. With few exceptions, PRT systems do not yet enjoy this status, as a consequence of which the large majority of entities avoid them even when shown, if they are carefully designed, their superior characteristics.

The engineering science needed to build cost-effective PRT systems has been developed over the past forty or more years. Yet, with only a few exceptions, consultant firms have spent too little time studying the PRT alternative, and when they have the objective has too often been to reject it so that they can get on with what they know how to do. PRT departs fundamentally from conventional transit. It requires a whole new way of thinking about transit and what it can do for a community. This has created controversy. Moreover, each PRT design group has developed and promoted its own configuration in the design of the guideway, vehicle, switch, suspension, propulsion, control, station, power system, operating speed and a host of other factors, unfortunately too often with inadequate planning and system engineering, which resulted in non-viable systems that discouraged the market. In the 1970s, one important result of this plethora of possibilities was to reject them all. It will be the market ultimately, not the designer, that will determine which if any of the proposed systems or combinations of systems will survive. The system engineer interested in developing a new viable version needs first to become immersed in planning studies of real systems in an interdisciplinary setting in order to appreciate fully the criteria needed for success, or otherwise learn in detail from those who have gone before.

The engineering science needed to design PRT systems can be found in the public domain either through books, reports, published papers, expired patents, web pages, and courses given; but this information is scattered, as a result of which many new people entering the field spend unnecessary time reinventing what is already known somewhere. A bibliography of papers is included in Section 25.

PRT network simulation programs and means of calculation performance [26] are needed for detailed study of the layout and performance of any PRT system. Such programs were written in the 1970s at The Aerospace Corporation, IBM, Princeton University, Johns Hopkins Applied Physics Laboratory, the

University of Minnesota, MBB in Germany, and elsewhere. Because the U. S. federal government stopped supporting work on High Capacity PRT in 1974, almost all of the early work stopped before the end of the 1970s. However, today computer speed and memory are enormously greater and cheaper, and software techniques have improved markedly. Superior network simulation programs are being developed and can be developed without need for reference to the past work, although knowledge of the past public-domain work will make the task much easier.

The objective of those of us who have worked to commercialize PRT is to see these systems widely built and used. What is needed could be very much like the National Advisory Committee for Aeronautics (now NASA), which was established by the U. S. Congress in 1916 to advance the science and technology of flight. NACA performed a huge amount of theoretical and experimental work on aeronautics and made the results freely available in a steady stream of reports. American aviation benefited enormously from that work.

For ground transportation there has been no similar initiative, and people everywhere suffer by experiencing increasing congestion, air pollution, accidents, and all of the other well-known problems of conventional transportation. Those of us who understand PRT know that it can, if carefully designed, produce enormous benefits for society everywhere. The requirements for PRT development today are money and expertise. With funds to hire the necessary talent and with the knowledge that exists, PRT can be reduced quite readily to common practice. With demand pull, which has begun through release of several requests for proposals and the decision of BAA to acquire a PRT system, competent firms can be expected to begin to design and manufacture PRT systems, operating systems will begin to appear, and engineering schools will begin offering courses on all aspects of PRT.

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Transitions from Straight to Curved Guideways
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Patronage Analysis
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Life Cycle Cost and the Theory of Reliability Allocation
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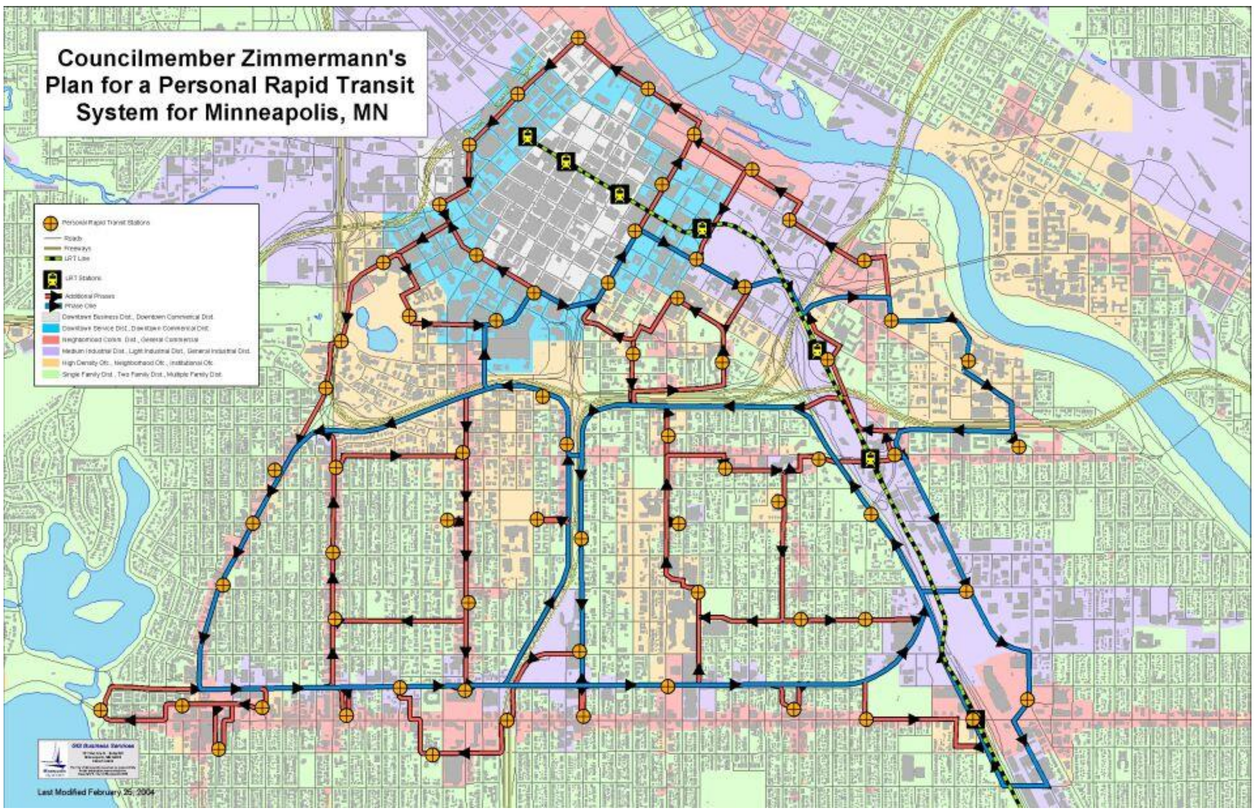


Chapter 11. Questions & Answers about PRT

1. Is PRT "reinventing the automobile?"

No! PRT is a public transit system. It cannot replace the automobile, but its service characteristics are such that it can be expected to attract many more people than conventional transit systems, and it can do so using a tiny fraction of the land required for the automobile. While roughly half the population either cannot or should not be driving automobiles, PRT is accessible to everyone. It will be the environmentalist's dream because of its markedly improved energy efficiency, lack of air pollution, and land savings. Normally the guideways should be spaced not less than a quarter to a half mile apart. They do not replace streets.

2. Can small cars move the large numbers of people who would use general mass transit?

Today, automobiles averaging 1.2 people per vehicle carry more than 97 percent of the urban passenger-miles in the United States. Uninterrupted flow is the key to capacity, not vehicle size. As an example, 60-passenger buses coming two minutes apart, a very high flow rate for an American bus system, provide the same number of capacity units per hour as 3-passenger PRT vehicles coming every six seconds. One PRT line can serve more than six times this capacity, more passengers per hour than come into downtown during the morning rush period via a three-lane expressway.

The line capacity is high because of automatic control, an in-vehicle switch, and electromagnetic propulsion and braking. Automatic control is much safer and more reliable than human drivers, permitting vehicles to be separated by small distances. In-vehicle switches work faster and more reliably than moving-track switches, again permitting vehicles to be closely spaced on the guideway. Linear electromagnetic braking is reliable in wet and icy weather that forces systems using rotary motors and wheel braking to spread vehicles far apart because of skidding concerns in emergency stops.

3. Won't stations get bogged down with all the small vehicles?

Station throughput is determined by the number of station berths, which can be set to meet the demand of any particular station. In general, station throughput is high relative to conventional mass transit because:

- Only vehicles that actually need to stop at a station will enter the station. All other vehicles pass by, thus reducing station traffic relative to conventional systems where all vehicles stop in each station regardless of where passengers are going.

- PRT stations are closely spaced, often within a quarter mile of each other. This is convenient to patrons, who walk only short distances, and results in smaller, less crowded stations.

- The loading time for each vehicle is relatively short, usually completed in a few seconds. As people become accustomed to PRT systems, they will enter and exit vehicles as quickly as cars, increasing station throughput and minimizing trip time.

4. Won't the problems of reliability make the operation of a large fleet of small vehicles undependable?

Actually, because a PRT system will have a large number of small vehicles, rather than a relatively small number of large vehicles, the chance of an individual becoming involved in a failure will reduce in proportion to vehicle size if the reliability of each vehicle is the same. But, because of the use of checked redundancy and advanced failure-management strategies possible within the confines of a PRT system, and the benign environment within the guideway, the reliability of PRT will be substantially higher than a conventional transit system. It has been shown that the requirements for dependability in a PRT system are independent of system size.

5. What happens if a PRT vehicle stops on an elevated guideway between stations?

Questions of reliability, safety, evacuation and rescue are fundamental to the design of any elevated transit system including PRT. Each vehicle has two motors and two controllers, modern failure-monitoring systems, fault-tolerance and fail-safe features. The system has alternative power sources so that a power failure will not leave passengers stranded.

There are over 100 elevated automated transit systems operating in the world today that prove that a vehicle stopping when not intended is a very rare event. If a vehicle does stop between stations, Central Control will talk with the passengers through an intercom system and guide the rescue operation. The vehicle behind will soft engage and push the disables vehicle to the nearest station. In the very unlikely event that the vehicle can't be moved, a rescue team will come with a ladder and help the passengers out of the vehicle. We estimate that in a fleet of 1000 vehicles, one vehicle may have to be rescued once every 75 years.

6. What if there is a power failure?

The vehicles receive their power from DC power rails located inside the guideway. There will always be an alternative power source. One way is to power the system from two different utilities, so that if one fails the other is immediately available to take over. A second way is to power the system from gas turbine-generator sets and to use utility power as emergency backup. A third way, appropriate for maximum energy and peak-power conservation, is to power the vehicles from wayside batteries, which can be charged at night when the power rate is low. During a municipal power failure, vehicles would still receive battery power, so they would simply slow down to conserve energy, finish their trips, and strand no passengers. A fourth way is to use large flywheels as backup power sources. A renewable power source can be used in any of these cases.

7. What if a truck hits a post?

If the guideway runs down the center of an arterial street or on the edge of such a street, highway barriers can be placed to protect the posts or they can be placed on concrete pedestals so that it is not possible for vehicles to hit the posts. The posts are, however, substantial enough so that it would take a high-speed collision of a large truck to shear off a post. If a post were sheared, the guideway will remain intact and the vehicles will remain in the guideway.

8. Will the visual impact of PRT be acceptable?

Visual impact is important in all transit systems. Many rail transit systems are placed underground because a ground-level system requires destruction of too much existing property and an elevated system is too massive and noisy. A PRT guideway has less than five percent of the cross sectional area of a rapid rail system, will generate almost no noise, and has an external appearance that can be varied to suit any specific community. According to one famous sculptor, PRT adds excitement and grandeur to the urban scene, both for what it is and what it does.

People accept elevated structures if they see them as a practical means to a desired end. In the early 1970s, when conventional heavy rail systems were being promoted, officials argued that elevated structures were acceptable. The People Movers proposed in the late 1970s had massive structures (witness the Detroit and Miami People Movers) but local authorities considered them acceptable because they were believed to fulfill a need. ***ITNS*** will have much smaller visual impact and will provide much better service at lower cost.

9. How does a person use PRT?

At each station, there will be several conveniently located ticket machines and a map of the system. The patron, or small group of patrons who want to ride together, determine their destination number from the map and go to the ticket machine to punch in the destination. The machine verifies the destination and displays the fare, which may be paid by cash or by prepaid ticket and is per vehicle rather than per person. The machine then dispenses a magnetically coded ticket.

The patron takes the ticket to a stanchion in front of the first empty vehicle in a line of vehicles and either inserts it into a slot or waves it past the stanchion. This act transfers the memory of the destination to a microprocessor aboard the vehicle, causes the door to open, and assures the patron that he or she is getting on a vehicle headed to his or her station.

The patron or patrons walk into the vehicle, sit down and press a go-button, whereupon the door closes automatically, the control system waits for an opening in the traffic bypassing the station and commands the vehicle to accelerate to line speed. When the vehicle reaches the destination station, it pulls into a berth and opens the door automatically. The patron(s) exit the vehicle and leave the station.

If the patron is regularly going between a certain station pair, he or she can purchase a pass in advance, bypass the ticket machine and go directly to the stanchion in front of the first empty vehicle. PRT doesn't need turnstiles since a valid ticket is necessary to gain access to a vehicle.

10. Is it possible to stop before the end of the ordered trip?

Yes. A stop button will be mounted on the control panel of each vehicle, which if pressed stops the vehicle at the next station.

11. What about access for the handicapped?

PRT will be fully accessible to handicapped patrons and will comply with the Americans with Disabilities Act. Elevators will be provided in elevated stations and the ticket machines and stanchions will include intercoms and Braille plaques to insure ease of use by all patrons. The vehicle accommodates one wheelchair, with a seat for one traveling companion. The platform is level with the vehicle floor to prevent wheelchair bumps and is textured at the edge to assist the blind.

ITNS is designed to be easily accessible to all people, whether handicapped, young, old, carrying heavy bags, traveling with a bicycle, or have any other special need. It has been praised and promoted by groups representing the needs of the handicapped.

12. How much time does a person have to board a PRT vehicle?

As much time as is necessary. The vehicle will not move until the passengers have entered and the door is closed and locked. Loading or unloading time is a statistical variable, which varies from a minimum of about two seconds to a maximum of 15 to 20 seconds.

13. Will you have to ride with strangers?

No! Each vehicle is occupied by passengers riding alone or together by choice. If someone tries to force his way into a vehicle, a button can be pushed inside the vehicle to alert the police.

14. Can a PRT vehicle be entered from either side?

Yes. It is not in general practical to design a PRT network in such a way that all stations are on one side of the guideway. Therefore the cars are designed with doors on both sides.

15. How serious a problem is vandalism?

Vandalism is minimized in the following ways:

By **Surveillance**. The stations will be television monitored with two-way voice communication. They are small areas that can be surveyed easily, and infrared detectors will be used to detect the presence of people so that the operator, in slack times, need not constantly view the screen.

By **Identification**. A means will be provided to permit a boarding passenger to reject a vandalized vehicle. An alarm signal will then be sent to the nearest control room where a human operator is alerted to roll back a video memory unit and make a permanent record of the last passenger to egress from the vandalized vehicle, and to command the vehicle to the nearest maintenance shop. Normal police methods will then be used to apprehend the vandal. Experience at the Morgantown automated people mover system has shown that knowledge of such a procedure, not possible in conventional transit, will by itself deter most vandalism.

By **Psychology**. In public places, vandalism has been greatly reduced by the application of human psychology. Plain walls that look like writing tablets invite being written on. Textured walls and walls with diagonal lines or protrusions markedly reduce graffiti. Appropriate colors, music, architectural design, and plants reduces vandalism. Frequently cleaned public places are not as subject to vandalism as dirty ones.

By use of **Attendants**. In large stations or in stations unusually prone to vandalism it is not unreasonable economically to use attendants, and they may be used if other methods fail.

16. Won't Personal Security be a serious problem?

Personal security is less of a problem than in conventional mass transit, and even sometimes less than in automobiles, for the following reasons:

- The ride is nonstop, direct to the destination, and alone or with one or two other people of choice. One never rides with strangers.

- Computer simulations have shown that in a well-designed system in the rush period about 50 percent of the passengers will wait less than 30 to 40 seconds and 97 percent less than three minutes. During off-peak periods there is no waiting at all. Thus there is little time for commission of acts of aggression.

- Television monitors and two-way voice-communication systems will be placed in the stations to survey the platform, stairways and vehicles. To insure that the screens will be watched, infrared sensors will be placed in the stations to alert the monitoring personal of activity in each station.

- The station platform is typically no longer that 20 to 40 feet and about 12 feet wide, and is easy to watch—much easier than a large, multi-story parking structure. Care in station design will eliminate areas in which a potential assailant can hide.

- A stop button in the vehicle permits the passenger to order the vehicle to stop at the next station for any reason.

- A voice communications system will be installed in each vehicle to be used to call for help in any emergency.

17. Won't the issues of safety make it difficult to insure a PRT system?

The insurance rate for the first operational ***ITNS*** system will be based on the insurer's estimate of the frequency and severity of bodily injury sustained while riding, attending to, or being in proximity of the system. In today's litigious society, it would not do to rush such a system to completion and to permit the public to ride before it was thoroughly tested. Every reasonable practical precaution must be taken in the design of a new PRT system to assure safety, and there will be an adequate period of testing before opening the system for public use.

An extensive series of design features are incorporated into ***ITNS*** both to minimize the probability of failures that may cause injury, and to minimize the consequences of any failure. A remarkable characteristic of PRT is that, because the vehicles are small and light, it is practical to design to assure that no combination of failures can cause injury. The developers of ***ITNS*** are convinced that its system will provide a substantial improvement in both safety and personal security.

Obtaining a reasonable insurance rate for a PRT system depends not only on the design features but also on the program of development and testing undertaken before the public can ride. Before building a demonstration for public use, a half-mile oval test system with one off-line station and three prototype vehicles will be tested. Based on the results of the test program, the first real people-moving demonstration will be constructed, tested, and certified for public use before the public will be permitted to ride. Potential insurers will be invited to monitor the test program in sufficient detail to establish the insurance rate.

18. Isn't there an economy of scale in transit systems, i. e., to carry a given traffic level, won't a system of many small vehicles cost more than a system of a few large vehicles?

The basic features of PRT follow logically as features that minimize the total cost per passenger-mile. These features permit true minimization of guideway cost, vehicle-fleet cost, and operating cost while maximizing service.

- Data shows that transit vehicles cost about the same per unit of capacity no matter how large or small they are. Contrary to intuition, there is no economy of scale. By using nonstop trips, possible with off-line stations, the average trip time of a PRT system is two to three times less than in a conventional transit system, which means that the fleet capacity (number of vehicles × capacity per vehicle) and therefore fleet cost needed to serve a given number of trips is less by the same factor.

- Vehicles of the size required to hold up to three or four seated adults have a much smaller cross section and weigh substantially less per unit of length than large standing-passenger vehicles, and, because of much lower dynamic loading, lead to lower guideway weight (15 times lower) and lower cost.

- To compare operating and maintenance (O&M) costs, we define a quantity called a "place-mile." The number of place-miles of travel in a transit system consisting of vehicles or trains of any size is the number of vehicle-miles of travel multiplied by vehicle capacity. A vehicle-mile is one vehicle traveling one mile. Because PRT vehicles move only when service is demanded, the total number of place-miles per day required to serve a given level of passenger demand is only about a third as much as in a conventional scheduled transit system. Examination of data on O&M costs shows that the O&M cost per place-mile is nearly the same regardless of the type of transit system. Thus the O&M cost of a transit system that carries a given number of people per day is proportional to the number of place-miles per day of travel.

The remarkable result of this kind of systems-economic analysis is a transit system in which the features required to minimize both capital and operating costs are exactly those that provide maximum service, i. e., on-demand, alone or with one or two friends, in seated comfort, anytime of day or night, at a predictable average speed two to three times that possible with conventional transit. The only reason for using large vehicles in urban transportation is to amortize the wages of drivers over as many fare-paying riders as possible. Automation permits relaxation of system characteristics toward a true optimum.

19. How much will a ride cost?

Transit fares are normally set as a matter of public policy, and are as high as the public will bear without significantly reducing ridership. In most conventional systems, the fare covers only about 30% of the operating cost and capital cost is never recovered. Thus, present transit systems require large state and federal subsidies.

Because of its low capital and operating costs, PRT systems will be able to charge fares that are comparable to conventional mass transit, yet will require little or no subsidy. This will permit systems to be installed in communities that need transit but don't have access to large state and federal subsidies.

20. How Was the Vehicle Size Selected?

On a strictly economic basis, one-person vehicles minimize capital cost, but they do not serve obvious social needs. Two-person vehicles are too small for a small family, for taking luggage, or for a wheelchair plus attendant. Also, if a party of three wants to travel together, one of them would have to ride alone if the vehicles hold only two persons, which may be socially awkward. So the vehicle should room for at least three seats side-by side. If the vehicle accommodates a wheelchair that can rotate to face forward, the floor area is such that, in addition to the back seat, there can be two backward-facing fold-up seats in the front sized for children.

Since more than 95 percent of the trips in an urban area are taken by one, two or three persons travelling together, the more people an individual vehicle is required to accommodate the more vehicle dead weight there is per person carried and higher capital and energy cost. By charging a fare per vehicle rather than per person, it is possible that the average vehicle occupancy can be increased over that experienced with automobiles.

We see that the factors that must be considered in picking vehicle capacity are not the same in PRT as in a family automobile. A PRT trip is generally quite short and a group larger than can fit into one vehicle can easily take two or more vehicles, which leave the origin station seconds apart and arrive at the destination seconds apart.

21. Why are the vehicles mounted above the guideway rather than below?

There are several reasons:

1) There must be a certain clearance for trucks to pass below. If the vehicles hang, the guideway must be seven or eight feet higher than if the guideway is below the vehicles. Also, with hanging vehicles, the posts must be along the side of the vehicles and cantilevered at the top. Wind load is one of the major loads on the system. The combination of wind load and cantilevered vehicle load gives a bending moment at the foundation about twice as high with hanging vehicles as with vehicles supported from below, thus the foundation must be twice as large with hanging vehicles.

2) The cantilevered guideway mount cannot provide as rigid a connection to the support post as a bottom-mounted system in which the guideway is rigidly connected to the posts by means of a moment-carrying bracket. Since the two systems must be compared with the same ride comfort, the guideway of a hanging-vehicle system will have to be stiffer and more costly.

3) Switching wheeled hanging vehicles requires that the wheels pass over the slot in the guideway required for the vehicle's support posts. This has always been a difficult problem, and lowers system reliability.

4) Public comments in a system that had both supported and hanging vehicles showed that a majority of people prefer to have the comfort of seeing the guideway beneath them.

A disadvantage of having vehicles ride on top of the guideway is that in a curve the vehicle weight and the centrifugal force exert moments in the same direction, whereas if the vehicles hang from the beam these two moments are in opposite directions. Careful analysis shows, however, that the additional torsional stiffness required if the vehicles ride above is not large enough to throw the tradeoff in this direction, when the other factors are considered.

22. Why are the moving switch parts in the vehicle rather than in the guideway?

There are five reasons an in-vehicle switch is superior to a moving-track switch.

Reliability. The simplicity of the in-vehicle switch makes it inherently more reliable than the in-track switch, and an in-vehicle switch can easily be made bi-stable by means of a spring. The worst that can happen with a well-designed in-vehicle switch is that one small vehicle will be misdirected, whereas if an in-track switch fails, it ties up a whole line of traffic, thus delaying many people. Also, the in-track switch requires an electric or hydraulic actuator mounted in the guideway, which upon failure shuts down the line. The result is that the required reliability cannot realistically be attained if the switch is in the track, but is easily attained if the switch is in the vehicle.

Capacity. Because of the time required 1) to move an in-track switch, 2) to verify that it is locked in position, and 3) to be able to stop before the vehicle reaches the switch if verification is not obtained, the minimum time headway will be too long to be of use in a PRT system. An in-vehicle switch completely removes this barrier to high capacity.

Ride Comfort. In-track switches often consist of a series of articulated straight pieces of guideway that swing back and forth. Passengers will feel such a strong lateral jerk each time the vehicle passes one of the joints that the vehicle will have to slow down for every passage, and there can be four or five straight pieces in each switch. An in-vehicle switch permits guideway branch points to be made with simple smooth curves, maximizing passenger comfort and minimizing jerk loads on the undercarriage of the vehicle.

Visual Impact. Articulated in-track switches with their actuators attached greatly increase the visual impact of a switch section. Beyond simply being much larger than a simple branch section, in-track switches have a track leading into empty space, which is a discomforting view for passengers as well as passersby.

Cost. An in-vehicle switch has very few moving parts and is very simple and inexpensive to build. An in-track switch is much larger, often consisting of several articulated track sections that move back and forth, and contains many large parts which increase both capital and maintenance cost significantly.

23. Are one-way guideways practical?

Because of the very small guideway and in-vehicle switching, one-way guideways are *an option*, but *not a necessity*. If the guideways are one-way, for a given investment, twice as much land area can be placed within walking distance of stations as with two-way systems. If planners want two-way systems they are easily provided. We have analyzed the problem of extra trip circuity with one-way guideways and find that, with a reasonable layout, the extra travel time going nonstop from origin to destination is so small that the cost per passenger-mile is generally less with a one-way system.

24. Will magnetic levitation help PRT?

Not at urban speeds. Comparisons of systems levitated by magnetic fields, air cushions, and wheels shows that, by using high-pressure, low-rolling-resistance tires, there is no advantage of either magnetic or air suspension over wheels at urban speeds, and indeed serious disadvantages.

25. Can PRT be complimentary to other transit systems?

Absolutely! This is a major advantage of PRT.

26. Where are vehicles stored when not in use?

In an *n*-berth station, *n* vehicles can be stored when there are no demands for service. During the night when demand is low or zero, the bulk of the vehicles will be stored at special storage barns strategically located in the network, usually at the same locations as cleaning and routine maintenance facilities. Because it is not necessary to get a specific vehicle out of storage before the others, the volume of storage facilities per mile of guideway is usually not more than would be required to store about four or five automobiles in a multistory parking structure.

27. What will be the cruising speed?

The first demonstrated ***ITNS*** will have a maximum cruising speed of 35 mph because this is sufficient in major activity centers. To span metropolitan distances, higher speeds are necessary, and the cruising speed is determined by ride comfort and motor power. ***ITNS*** has been designed so that growth to speeds in the range of 45 to 60 mph are practical.

28. How is ride comfort assured?

ITNS vehicles run on smooth synthetic rubber tires of stiffness needed to meet ride-comfort criteria. Since the running surfaces are smooth and adjustable, secondary suspension is not needed.

29. How is snow, ice or debris kept from interfering with operations?

The ***ITNS*** guideway is a truss structure with covers over the sides and part of the top and bottom. There is a three-inch-wide slot at the top for the vehicle's vertical chassis to pass through, and a six-inch-wide slot at the bottom to permit ice, snow, rain, or debris to fall through. A pair of 7.5-inch--wide running surfaces (angle sections) inside the guideway near the bottom support the main wheels and are spaced six inches apart to permit anything that may drop in the top to pass through.

Running vehicles continuously during snow or ice storms will usually be sufficient to clear the running surfaces; but we have designed and tested a plow that, if necessary, will be installed on vehicles to deflect anything that lands on one of the running surfaces down into the slot between. A maintenance vehicle will occasionally inspect the interior of the guideway with a television camera and will be equipped to remove any foreign material.

30. What about energy use?

Because of frequent stopping and starting, about two thirds of the operating energy used by today's transit vehicles or automobiles in an urban area is kinetic energy lost in heat as the vehicle is braked to a stop. Therefore, elimination of the intermediate stops by itself almost triples energy efficiency.

Careful attention to vehicle-weight minimization, streamlining, lowering of road resistance by careful selection of tire parameters, and use of electric propulsion that eliminates idling energy add to efficiency put PRT in a class by itself in terms of energy efficiency. The electrical energy use will be less than 200 watt-hours per vehicle-mile. The power will peak at about 20 kW per vehicle and will average about 4 kw per vehicle.

31. What about air pollution?

The vehicles run on 600 volt DC electricity that can be supplied from wayside batteries or flywheels that can be charged by any electrical energy source including renewable energy such as wind, solar, or biomass. The system produces air pollution only in the processes of manufacture and at the power plant, both of which can be closely controlled.

32. How quiet is the operation of a PRT vehicle?

Movement of the vehicles will be much quieter than automobiles. They are propelled and braked through linear electric motors, which are driven by variable-frequency drives. Such drives may produce a humming sound, which is minimized by careful design and by sound insulation. Since there is no braking or traction through the wheels, the tires are smooth and they run on smooth surfaces, so the tire noise will be substantially less than produced by an automobile. There are no other noise-producing elements.

33. Will the use of electric and magnetic components adversely affect the health of riders?

Because the vehicles weigh a small fraction of conventional rail transit vehicles, the electric current required is correspondingly less and any magnetic field in the cabin will be proportional to the current. While there are at present no generally accepted safety standards that limit human exposure to magnetic fields, care has been exercised in the design of the vehicles to minimize the exposure of passengers to magnetic fields.

The motors are designed to constrain the magnetic fields to their immediate vicinity and are located remotely from the passenger compartment, which also desirably lowers the center of gravity of the vehicle. Residents living or working near a PRT guideway will not be exposed to any significant increase in magnetic fields since the power to the vehicles is provided from 600-volt DC power rails inside a shielded guideway. Harmful effects of transmission lines have been reported only when the lines carry several hundred thousand volts.

34. Will PRT guideways withstand earthquakes and high winds?

The elevated guideway is designed to the local code for maximum accelerations during earthquakes and the maximum expected wind load. The guideway is a small, light-weight, flexible, steel structure with thermal expansion joints in every span, a configuration well suited to surviving earthquakes and high winds. The possibility of aero-elastic coupling such as caused the collapse of the Tacoma Narrows Bridge has been studied, and it was found that features that prevent such catastrophes are exactly those selected for the ***ITNS*** guideway for other reasons.

35. How can we be so sure of the characteristics of *ITNS* in advance of testing?

Because the design has been reviewed so thoroughly and because it was found that achievement of the characteristics described is well within the state-of-art.

36. How does a PRT system prevent someone from placing a bomb in a vehicle to be delivered to another destination?

The most likely scenario would be for someone to place a time bomb in a wheeled cart (assuming it is too heavy to be carried), enter the station, purchase a ticket for the desired destination, go through the usual procedure to cause the vehicle door to open, wheel the load in, press the "Go" button, and walk away. The timing device would have to be quite precise but it could not take into account possible random merging delays along the route; however, by timing such trips in advance, the time window for detonation may be found to be satisfactory.

But, the software will be configured to activate the “Go” button only when the door is closed. Thus the person carrying the bomb will have to ride with the bomb.

The normal deterrent is the television surveillance system that insures that a picture is taken of the bomb carrier, but this is likely not enough. Since we have assumed that unaccompanied parcel freight will sometimes be carried on PRT vehicles, it is necessary to require that any parcel be inspected before it can be loaded without an accompanying person. Often this will be a function of a station attendant if there is one.

It will be standard procedure to detect automatically any unattended parcels that could be sent. This could be done by use of weight sensors in the seat or infrared sensors to detect the presence of a person in the vehicle. Without an indication of presence, central control could be automatically alerted to reroute the package to a remote location where a bomb could be deactivated.

Finally, one must ask why a terrorist would find it more convenient to deliver a bomb by PRT rather than in an automobile or van where the possibility of detection is much more difficult, particularly in a future unoccupied car under automatic control. An important advantage of PRT is that every element is spread out in small units, whereas history shows that terrorists who deliver bombs, suicide bombers or otherwise, want to denote them in crowds. Bombers like high-value targets. PRT eliminates them.

37. Why has it taken so long to get true PRT into operation?

The PRT concept germinated in the early 1950s and received enough attention by the mid1960s to be the subject of government-funded analysis. By the early 1970s, there were many competing ideas on how to design automated transit systems, but there was no theory of PRT and there were insufficient funds to explore the dozens of alternative design features. This "Tower of Babel" discouraged decision makers, caused government funding to dry up, and left the continued search for an optimum configuration up to a few people.

A major reason it was possible since the 1980s to carry PRT research and development far enough to regain the attention of major transit decision makers was the emergence of the personal computer and associated software. Finding the optimum transit configuration and proving it required sophisticated and data-intensive engineering and economic calculations, detailed simulations of control and vehicle dynamics, and a great deal of data processing, which during the 1970s was much slower and required large resources, generally funded only by governments. The PC enabled engineers of ordinary means to purchase enough computer power to develop the optimum system and element designs. In parallel, the development of powerful fault-tolerant microprocessors and software elements have placed the control requirements of PRT well within the current state-of-art.

While many new ideas have emerged from institutional research during this century, new ideas in previous centuries generally emerged only when the individuals who discovered and developed them could do so without anyone else's approval. Development of PRT required understanding of engineering sciences and sophisticated technology melded with the individual initiative of earlier centuries, a marriage made possible by the low-cost, high-performance personal computer.

The PC and the microcomputer, coupled with the development of the necessary transit systems theory, test and operational experience with a wide variety of automated transit systems, the realization that conventional rail transit systems cannot solve the problems of congestion in cities, and the steady worsening of congestion and air pollution have made it possible for the idea of PRT to reemerge. Careful research over decades has shown no flaw that will or should stop the development of PRT, but rather that PRT is a badly needed solution to a variety of transit problems. It is a new configuration of now very ordinary parts well within the current state-of-art.

Development of new concepts in public transportation differs from development of many other emerging concepts in that the resources needed to prove a concept are large, many people are involved in deciding to take a positive step, the level of credibility must be unusually high, and the "fear factor" that drove military programs is not present. In such circumstances, it is not surprising that decades have been required to bring the concept of PRT to maturity.

38. Who would build the system?

Our plan is that final design and construction supervision for the test system be managed by a small group of system engineers under my direction. Building the test system requires structural engineering for the guideway, mechanical engineering for the chassis, a specialty design firm for the cabin, electronic and control engineering for the control system, and civil engineering for the station and maintenance facility. We have prepared a series of requests for proposals for the various specialty tasks to be given to a selection of firms known to us. Fabrication and construction will be contracted similarly. From our experience, this procedure is preferable to trying to find one large firm to oversee the whole project because it is more difficult in such a case to ascertain that the individual engineers are truly educated and motivated to the success of the project. Once the test system is built and the testing is completed, the system will be ready for deployment, and by that point the company will have expanded sufficiently to manage large project, likely in co-operation with a large construction company.

39. If you have a city who wants to do this, where would they come up with the money to pay for it?

a. The first necessary step is a planning study
    i. to determine the precise layout of guideways, stations, and maintenance and storage facilities,
    ii. to estimate the peak-hour and yearly ridership,
    iii. to estimate the capital and operating costs, which will require information developed in detail during the test phase, and
    iv. to explore how the system could be financed.

FTA grants are available for this planning process if a city petitions for them. Federal planning money has been provided for PRT studies in Providence, SeaTac, and Cincinnati.

b. The second step is to build the system. Our studies show that the costs will be low enough and the ridership will be high enough that all or almost all of the funds can be recovered from fares. Thus, with data from the test and planning programs available, past experience has shown that financing can likely be provided from one of the large investment houses.

40. Where will you build the test system?

This depends on the source of financing. If financing came from your area, the test system could be built nearby and the financier would have major ownership in the detailed plans and specifications needed to build similar systems anywhere.

41. Would off-line stations present problems with parking?

I have noticed that there are very large parking lots all along the portion of the Branson Highway 76 corridor where the theaters, hotels, and restaurants are located. With our system in place, one can easily envision people arriving in Branson along U.S. Highway 65 wanting to park near the junction of Highways 65 and 76. Thus, major parking would have to be provided near that junction, but not necessarily at one spot since the system can be designed to loop to several parking lots.

42. What would the maintenance cost be?

A number of studies of the maintenance cost have been made that indicate a figure in today's dollars of about 20 cents per vehicle-mile. The major cost is for labor for operators and maintenance personnel. To that is added the cost for energy and for spare parts. One can note that these vehicles are much simpler than automobiles, and thus the maintenance cost will be proportionally less, but we have added the cost of maintaining the stations and guideways. Moreover, since the vehicles run in the shade on smooth rails with no rough roads to traverse, the maintenance of the wheels and tires will be substantially less than with automobiles.

43. Did you say 2 to 14 berths per station or 2 to 14 berths?

I meant 2 to 14 or perhaps more berths per station depending on the estimated maximum flow of people per hour.

44. What is the grade ability of these motors, i.e., linear induction motors (LIM)?

In amusement parks, LIM propulsion has been used to drive cars vertically, i.e., at 90 degree slopes. With these types of motors, the grade ability depends on getting rid of excess heat, and thus it depends on the power expended as the vehicle moves up a hill, which is proportional to the grade times the speed. For a relatively flat city, forced air cooling is used, and should be adequate for grades up to about 10% or 12% provided they are not excessively long. For steeper, longer hills liquid cooling can be used. The bottom line is that the motors will be designed to the grade requirements of the city.

45. What will be the length of a station?

Ten feet multiplied by the number of berths for the station platform. The length of the transition curves in and out of an off-line station are proportional to the line speed. For example, at 25 mph, the transition curve is 125 feet long. So the total off-line guideway length for a three-berth station counting waiting berths would be 340 ft.

46. Is air conditioning, heating and ventilation a problem?

We will use a standard small-auto air conditioning system with the compressor operated by an electric motor. We will use electric heating and ventilation fans. Units are commercially available for all of these functions.

47. Do you have an estimate of cost per mile for the system?

We have made many estimates of cost. They depend very strongly on production quantity and labor costs. With two stations and 50 vehicles per mile, we estimate between $12M and $15M per mile.

48. Would there be federal money available for a smaller city to do a study?

Federal planning money for PRT has been obtained by Providence, RI, Cincinnati, OH, and SeaTac, WA. The FTA policy is to help a city achieve the transit goals it sets for itself. All FTA planning money must be sent through a Metropolitan Planning Organization, of which I understand there is one for Southwest Missouri. Branson officials would have to work with their MPO to obtain planning funds, but with political support that should be possible.

49. Does the federal government provide money to build the system and then rely on the local population to support it?

The federal government has provided about 50% of the cost of construction of rail systems and then expects the local population to pay any operating subsidy. Methods of financing of ITNS would be one of the tasks of a planning study. We expect that the ridership for our system will be sufficiently high that a reasonable fare will cover all of the operating costs and a very significant portion of the capitol cost, possibly all of it. In this case private financing may be possible.

50. What is a typical fare?

On the Minneapolis rail system, the peak-period fare is currently $2, the off-peak fare is $1.50, and the mobility-impaired fare is $050. I believe that is quite typical of many cities.

51. What is the break-even fare?

a. For the above-mentioned Minneapolis rail system the break-even fare is $9.62.
b. For ITNS, we expect the break-even fair to be lower than a reasonable average fare that the city could charge.

52. How would construction time compare to a standard road system?

Construction of *ITNS* is much simpler since much less land is required. The guideway-support posts are about 22 inches in diameter at the base. The first task is to build a foundation for each of the posts, which are spaced nominally 90 feet apart. The type of foundation depends on the type of soil, thus foundations may be a flat concrete slab about four-feet on a side, or they may be a three-foot diameter circular column of concrete to a depth that again depends on the soil conditions. Digging the hole and pouring the foundation, with reinforcing bars and studs inserted, is a task that may take with an experienced crew two to four hours. Once the foundation has cured, a crew will align and bolt a factory-manufactured post to each foundation, possibly using shims for accurate alignment. Allowing an hour per post is quite ample. The next crew will appear with factory-manufactured and preassembled guideway sections, typically 45 feet along and then welded into 90-foot sections. Bolting and aligning a 90-foot section, and connecting power and communication cables, can be done with an experienced crew in no more than about two hours. So the installation time for one 90-foot section would be about a day, so we are looking at about two to three months per mile. This compares the time for installing a surface rail system of two to three years.

53. The slides didn't show a guideway that looked like a truss. It showed a guideway that looked more substantial. Is there a reason for that?

I showed in one picture a sideview drawing of a truss guideway, and then another picture in which the guideway was covered. With a little more time in a presentation, I could have explained this process better and I could have discussed the nine reasons for the covers.

54. One slide showed a PRT system built with a pipe for a guideway. This would have the advantage that water or something else could be run through the pipe.

This is true, but the weight to be supported would then substantially increase, with a substantial increase in cost. Power or telephone lines could be run through a pipe guideway, and we can do that by running lines in the space between our covers and the steel truss guideway.

55. How would extreme topography affect the system?

The beauty of our small truss guideway is that it can be bent in a factory accurately in computerized jigs and fixtures to follow any reasonable hill or curve. By “reasonable” I mean that the curves must be designed to ride comfort limits, which are based on international standards (ISO). If a hill is too steep, the ride will be uncomfortable to a person when going downhill.

56. Could we place guideways at grade?

Certainly, but that means they become a barrier to cross traffic and would have to be fenced off to prevent injury or malicious damage, thus taking up much more land than if they were elevated. Along a freeway, where cross traffic wouldn’t be a problem, they could be placed near the ground. Because of the need for drainage, I don’t recommend placing them on the ground, unless underground. Placement is a planner’s decision.

57. In running along our main highway the overhead wires would have to be incorporated in the guideway and much of the signage would have to be repositioned.

After driving down your main highway, I can easily see that a lot of retrofitting would have to be done to install our system, but considering the retrofitting done to accommodate a conventional rail system, much less.

58. Do you have comparisons of PRT with roads of various types?

The first part of the answer to this is that ITNS is a transit system, a system designed to service people who cannot or should not drive automobiles as well as people who can, but in many cities the argument for a rail system is that it will cut congestion – indeed that is often the major argument given. The concept is that a land-efficient system will provide capacity using much less land. To make this argument stick, a new guideway system of any type must be able to attract enough riders so that it will indeed reduce road congestions. Conventional systems have had very little effect on congestion in most cities, which is a major reason we have continued to work on ITNS. In making a comparison with roads, the cost of congestion must be included, and in many places that is substantial. Another argument is that a secure system like ITNS will reduce accidents substantially. Many, but not enough, studies have been made in the United States to look at the overall community benefit of a rail system of any type. Many of such studies have been made in Sweden.

59. What is our cross section width?

Our guideway, with covers attached, is about 35 in wide.

60. How much right-of-way do you need?

Only about 10 square feet every 90 feet for a post and a space about 12 feet wide by 40 feet long every half mile or so for a station, or a total of about 0.02% of the urban land.

61. Do passengers have any control mid-trip to change destination?

We recommend three buttons in each vehicle – a GO button, a STOP button, and an EMERGENCY button. The first will work just like in an elevator. The STOP button will stop the vehicle in the next station, where the passenger can get out and reorder a trip. If you press the third button, an operator will ask via the intercom what is wrong. If you say you are sick you can be rerouted to the nearest hospital faster and more reliably than possible via an ambulance. We think that the trip should be ordered in the origin station so that the absolute minimum of action is needed once on board. If the destination could ordered on board 1) an extra machine would have to be placed on board, 2) some people would fumble around and delay the trip and hence others behind, and 3) if the fare is a function of distance, people would quickly realize that they could pay for the shortest trip then while on board change to the desired destination hoping to leave without paying, thus complicating system operation. The bottom line though is that we talk here of features that can be specified by the system purchaser. This is one of the policy issues that must be negotiated between the supplier and the purchaser.

62. What about less densely populated areas?

For ITNS to break even, it is necessary for the population density to be above about 2500 people per square mile. But if the same economic criteria were applied to *ITNS* as are currently applied to so-called "light rail," which in the case of Minneapolis has a deficit of $8.63 per trip, then a much lower population density could be served. Here we could enter the debate between those who strongly believe that urban sprawl must be contained, those who argue that sprawl is good and is the life style people want, and those in the middle who see that the vast single-family-house density will remain and needs to be served. I lean with those who believe that in a future energy-and-resource-starved world that those who have opted to live far out from town willing to endure a long commute will suffer the most as the cost of energy increases. If possible they should be given incentives to move to higher density areas, but there are many factors besides transportation that drive decisions as to where to live.

63. I would like more information on Alternatives Analysis – it sounds like the Feds have already determined that PRT isn't an option. Is that right?

The questioner should consult the Federal Transit Administration web site www.fta.dot.gov to get the latest rules. The constraints lie more in the consulting community. You simply can't expect a transportation consultant to recommend a system that is not fully proven in daily operation. The cases, mentioned above, when local people have received funding for planning studies that include PRT, there were local influential people who studied PRT sufficiently to advocate strongly that it be included. If certain people in a community, through study of the various web sites, decide that PRT should be given a fair shake in an alternatives analysis, they should meet frequently to study the issues carefully, ask all of the questions they can, and on that basis make informed recommendations.

64. How does the system add cars when many people are getting on the system a fair distance away and no empties are being freed up?

As soon as a trip is complete, the vehicle used for that trip is freed up for another trip and can be called by a downstream station that needs an empty vehicle. During the night, there will be many unneeded vehicles, which will be stored on special sidings where they can be called quickly to meet demands for service. If the line speed is 30 mph, the time to traverse one mile is 2 minutes. Thus, in a very short time, vehicles can be called from remote parts of the network. The system software is designed to reroute empty vehicles from stations of excess to stations of need any time of day or night. More detail can be found in the paper "A Review of the State of the Art of Personal Rapid Transit." How quickly a demand can be served is measured in terms of wait time, which depends on the number of vehicles in the system. The number of vehicles required is the total demand in groups traveling together per unit of time multiplied by the average trip time in the same units of time, and must be sufficient to meet a given wait-time criterion. The number of vehicles required and the number of berths required in each station is determined from a series of detailed simulations of the system based on given demand between all station pairs.

65. What sensors are there in case of a break in the track or if a car stops in front of you?

Frequent conferences are held around the country on "Smart Structures." These are structures, such as bridges, in which strain gages have been placed at strategic locations to report severe strain or, heaven forbid, a break. As a back up to the normal control functions, each vehicle will be equipped with a sonic sensor that will detect the presence of a vehicle closer ahead than it is supposed to be, either straight ahead or on a merging guideway. When triggered, this independent control system has an independent path to cause the brakes to be applied and signals the malfunction to the cognizant zone controller, which if it were functioning normally would have already have sensed the failure.

66. An affirmation of the idea of placing solar panels on the sides of the guideway to drive the system.

I had commented that based on calculations from data provided by a solar-energy expert, solar panels on the sides of the guideway could collect about 400 kW per mile, whereas the system needs a maximum of only about 200 kW per mile. A means of energy storage would of course have to be part of the system.

67. How can the system be used for goods movement? Wouldn't truckers unions be against that?

Once the system is in place, it will be obvious that passenger vehicles can be used in off-peak hours for movement of many types of goods, and that special freight vehicles could be added for freight not suitable to be carried in passenger vehicles. This would affect some types of local truckers, such as UPS delivery trucks, but would have no effect on long-haul trucking. It raises the classic problem that occurs whenever a new technology is introduced. This is one reason to introduce any new system gradually.

68. It appears that these systems are designed for urban and suburban applications. Are there areas where the system is not practical?

The main factor here is the acceptable line speed. As line speed increases, the power required to overcome air drag increases as the cube of speed and factors such as kinetic energy, curve radius, and stopping distance increase as the square of speed. On the other hand, ridership to a point will increase with line speed. The equation for cost per passenger-mile will thus have both the numerator and the denominator increasing with speed, and there will be a speed that will minimize the cost per trip. I have found that this value is lower than one would guess. Yet, many people wonder if the same system can be used for intercity travel, which, to be competitive, would require higher speed. I have found that the guideway I have designed permits a speed above 100 mph, so the speed limitation for a vehicle designed for normal urban speeds will depend on the power rating of the motor. A tradeoff decision would have to be made as to the maximum speed permissible with a given motor. It is possible that vehicles having motors of two different sizes could run on one guideway, meaning that one would have to transfer to go from an urban trip to an intercity trip. This assumes that it would not be economical to use the largest motor for all trips. Once the off-line station system is in operation, it will be quickly seen that it has a major advantage for interurban travel: Every town along the way could have a station without sacrificing trip speed for any trip. A problem with proposals for intercity rail using on-line-station technology is that the cost is higher because large vehicles are needed to obtain adequate capacity, and the ridership will be lower because the stations must be much farther apart to keep the average speed competitive. Higher cost and lower ridership mean of course higher cost per passenger-mile. In a case I illustrated the cost per passenger-mile would be higher by a factor of at least 12 when compared with ITNS.

69. What is the carrying capacity of the vehicle built and shown?

The vehicle I showed has a seat about the width of the back seat of a luxury automobile, and there is room for two fold-down seats in the front of the cabin, thus giving a five or six passenger capacity, depending on how large the passengers are. I set the maximum load at 850 lb. In a new design, the maximum load and vehicle layout will be two of the issues negotiated.

70. If someone is running late to a meeting, this isn't the way to go is it?

That depends on how close you are to the origin station and destination station. If reasonably close, the system would get you there faster and more reliably than by any other means.

71. Is it just "fear of the new" that has prevented your system from being built?

This is an interesting and complex question. A standard answer given over and over again is that a municipality can't select a system that is not fully proven. Following White House interest in PRT in the early 1970s, conventional transit interests and interests in new automated guideway systems that were clearly inferior to High-Capacity PRT combined to lobby to kill a budding federal HCPRT project. For many years after that cities were told to only consider proven transit systems while no program was in place any more to prove new systems. It was perceived that the development of HCPRT would render obsolete other systems in which there were vested interests sufficiently strong to kill the HCPRT program. A problem is that conventional transit has strong, well-funded lobbying while promoters of new systems have no serious money for lobbying and have to try to convince people with decision-making power that the new idea should be supported because of its superior characteristics. I am aware that there are people who oppose the new systems. You can read the debates on at least the following two web pages: http://faculty.washington.edu/jbs/itrans/ and http://kinetic.seattle.wa.us/prt. When people approach me wanting to work with me, I ask them to first read those debates and then decide if they want to assist our effort. No one who approached me thusly was turned away by the arguments given against PRT, but of course I was talking to a self-selected group of people who were not afraid of new ideas. History is full of cases like this. A problem with ITNS is that the serious entry fee is high and it is necessary to convince not only engineers, but planners, politicians, financiers, and activist citizens that the effort is worthwhile. If the Wright Brothers had to go through all this to get an airplane flying, they may never have succeeded.

72. Why does the one in Sweden have such a big, bulky guideway?

The one in Sweden was built by the Korean steel company Posco and has the web page www.vectusprt.com. I showed a picture of it taken by a friend who attended a conference at its site in Uppsala, Sweden in October 2007. It uses as the basic guideway structure a steel pipe that appears to be about 20 inches in diameter. Any good structural engineer can easily calculate that, because the material in a pipe can't all be used efficiently, use of a pipe as the basis for a crossing a span with a given load rather than a truss requires about four times as much steel. In designing a truss one puts as much material as possible in tension or compression, which is much more efficient. I puzzled as to why they did this. The only rational I can imagine is that Raytheon Company used a pipe as the basis for their guideway because they own a steel company that made that type of pipe for the oil and gas industry and the PRT project manager was told by higher authority to use the pipe, not thinking about cost minimization. Seeing that a large American company chose a pipe, perhaps the Korean company thought there must be a good reason and simply followed. There is still time for Posco to switch to a truss guideway.

73. Have you envisioned feeder systems for the stations, for example "park & ride" or something?

If you examine the surface rail systems called "light rail" that many U. S. cities have installed, you will find that they have the same problem – worse because for a given cost such a system has many fewer stations and hence the people will have to go to fewer, larger stations, but better because the service characteristics of "light rail" are markedly inferior to the service characteristics of PRT so for that reason "light rail" won't need as many parking spaces as PRT. In both cases, some people will walk to the stations and some will ride or be dropped off. For those who ride, there must be parking space, if not in lots then along nearby streets. Part of the planner's job in laying out a PRT system is to provide for parking. This requires a careful estimate of ridership projected into the future.

74. What would you recommend the average citizen do to promote PRT?

I would recommend teaming with similarly minded people and studying the literature starting by punching "Personal Rapid Transit" into your favorite search engine. There are several citizens groups that promote PRT. Get together and talk to your political leaders until you find one or more who will work with you. In this way, at least the cities of Providence, SeaTac and Cincinnati obtained federal funds to do detailed PRT studies. In my case, while teaching at the University of Minnesota and at Boston University in my senior engineering design courses I often assigned the class to do a layout design of a specific PRT system, which is the way to get into all of the practical problems of installing a system. There are a few basic guidelines that I can give you.

75. Where was Chicago going to put their system?

Rosemont, east of O'Hare Airport, was selected for the first system. At the beginning of the Chicago Regional Transportation Authority PRT program they invited suburbs to be considered for the first installation, following which 26 suburbs responded and some of them hired consultants to help them develop detailed proposals. The list was narrowed down to six suburbs, then four, then two, then Rosemont, who spent over $50,000 on their proposal.

76. Do you address how many people these systems may employ?

In a $1.5M PRT Design Study for Chicago a detailed model was developed to estimate operating and maintenance costs. It included estimates of the number of operations, maintenance, and cleaning personnel required, which will decrease as people learn their tasks.

77. How often would the cars need maintenance?

We plan that the interior of each car, which will be designed for easy cleaning, be cleaned once a day and more often if necessary. Since the cars generally run on elevated guideways, the exterior will not have to be cleaned as often. How often depends on the amount and type of dust particles in the air. The linear induction motors themselves have no moving parts – there is no need to change oil or oil filters because there are none. The motors normally will be air cooled with electrically powered fans equipped with sealed bearings. The wheels will have sealed bearings. The cabins will be equipped with heaters, ventilation fans, and an air conditioner which will generally need servicing no more often that is the case with automobiles. The cabin will also have lights, a communications system, and, as mentioned above, three buttons. This equipment, as well as the on-board computer, will need occasional replacement, but no more often per mile of travel than we experience with automobiles.

78. The one at Heathrow – there were other systems, weren't there? What are some of the other systems. What happened to those other systems?

The most complete list of PRT systems of which I am aware is given on Dr. Jerry Schneider's award-winning website http://faculty.washington.edu/jbs/itrans/. Here is a list of most of the systems developed during the 1960s and 1970s and my knowledge of the status of each:[21]

System	Status
Monocab	No longer active
Transportation Technology, Inc.	One system running at Duke U hospital
Alden StaRRcar	Was basis for Morgantown system, but the design was changed drastically.
Uniflo	No longer active
Dashaveyor	No longer active
Ford ACT (Automatically Controlled Transportation)	Operated in shopping center in Dearborn, MI. No longer active
British Cabtrack	No longer active
The Aerospace Corp PRT	Basis for 1972 White House initiative. No longer active.
Cabintaxi (DEMAG+MBB)	Test system operated in Hagen, FRG, from 1973-1979. No longer active.
Japanese CVS	Test system operated near Tokyo. No longer active.
French Aramis	Test system operated near Paris. No longer active.
Swiss ELAN-SIG	No longer active.

A book can be written about each of these programs and some have been. The more interesting question is why these systems are no longer active and why that does not decrease our enthusiasm for PRT? Much of my answer can be found in my papers or in http://kinetic.seattle.wa.us/prt and in my textbook *Transit Systems Theory*, which can be downloaded free from www.advanced-transit.org[22]

79. Would there be resistance from the auto manufacturers to this system?

One day in the early 1970s I got invited to breakfast with the President of the Motor Vehicle Manufacturers' Association (MVMA). He said they were interested in assisting the development of PRT and wanted to help. In 1975 I learned that General Motors was working on PRT and wanted to exhibit a 100-foot system at our September 1976 International Conference on PRT in Denver. Following that conference the conference committee determined to form a society (www.advancedtransit.org) to encourage the development of PRT and other types of automated

[21] See *Personal Rapid Transit II*, University of Minnesota, February 1974, for a description of each.

[22] Almost all PRT programs that died are no longer active because of a flaw in the guideway design. I discuss this in my paper "How to Design a PRT Guideway," Automated People Mover Conference, ASCE, Atlanta, GA, May 31-June 3, 2009.

transit. In our first year we received a check for $25,000 for our operations from the MVMA and in the subsequent two years we received a check each year for $10,000 from General Motors. This interest died when heavy lobbying from the conventional transit community caused the Urban Mass Transportation Administration to withdraw their interest in PRT development. Recently, the World Business Council for Sustainable Development produced a report signed by CEOs of leading auto and energy companies that indicates great concern about future sustainability and even mentions PRT.

80. What about ventilation?

We have designed ventilation into our cabins per specifications of the American Society of Heating & Ventilation Engineers.

81. What would be the minimum height? In terms of safety?

The clearance of the guideway depends mainly on cross traffic such as fire engines or moving vans. In a 2006 Branson Transit Study, the consultant specified 14.5 feet. Along the sides of freeways the guideway could be lower to the ground. How far from the ground is a planner's decision, but I would recommend it be high enough so that people and animals can comfortably walk underneath.

82. With gas prices and focus on sustainability are there federal dollars available?

Federal dollars have been available for systems the local community wants. But to realize that conventional transit won't do the job and to determine what new system would be desirable requires local study. This will take a good deal of effort on the part of a few leaders. In the United States, such interest developed in Chicago, SeaTac and Cincinnati but is yet to lead to deployment of systems. On the other hand, as a direct result of the Chicago PRT project, extensive planning work has been done on PRT in Sweden and England; and a PRT systems has been built at Heathrow Airport in London.

83. What did Chicago do? How was Raytheon involved?

In April 1990 the Northeastern Illinois Regional Transportation Authority (RTA) released a request for proposals for two parallel $1.5M PRT Design Studies. My company, with Stone & Webster Engineering Corporation as prime contractor, won one of those studies. The other went to the Swiss company Intamin. After these studies were completed, the next step was to pick one of these two groups to design, build, and operate a test system, with half the cost picked up by the private company. S&W was not in a position in 1992 to do that. In the last minute Raytheon Company, with whom I had been working for many years, decided to bid for the test program. In June 1993 they won, showing in their proposal that they were going to build the system that came out of the S&W study. When they started in October 1993, a new team of managers and engineers came in, threw out all of the previous plans, and proceeded to design a system with the vehicle weight increased by almost a factor of four, the guideway width and depth doubled, and the overall cost more than tripled. As a result the RTA simply stopped talking about PRT and Raytheon left the field – embarrassed for their lack of systems engineering.

84. Have any of the large metro hospitals talked to you? Would it be possible to have a hospital car?

Early in the start of my program I had a hospital car sketched and included it in our presentations. The University of Minnesota hospital has talked to me many times. I have visited many hospital complexes in the United States and find considerable interest *if* they can be shown a proven system. As mentioned above, TTI-Otis built a hospital system in the Duke University Hospital. Also the German joint venture DEMAG+MBB built and operated since about 1976 a hospital system for the Zigenhein Hospital Complex in Kassel, FRG.

85. Is the sustainability and environmental community working with you?

Some individuals in these communities have been interested in our work, but I can't say that that community is working with me. The main problem is to get enough information into the minds of enough people to make a difference. This is a difficult, expensive task.

86. What is missing from your presentation is the payback compared with conventional technology.

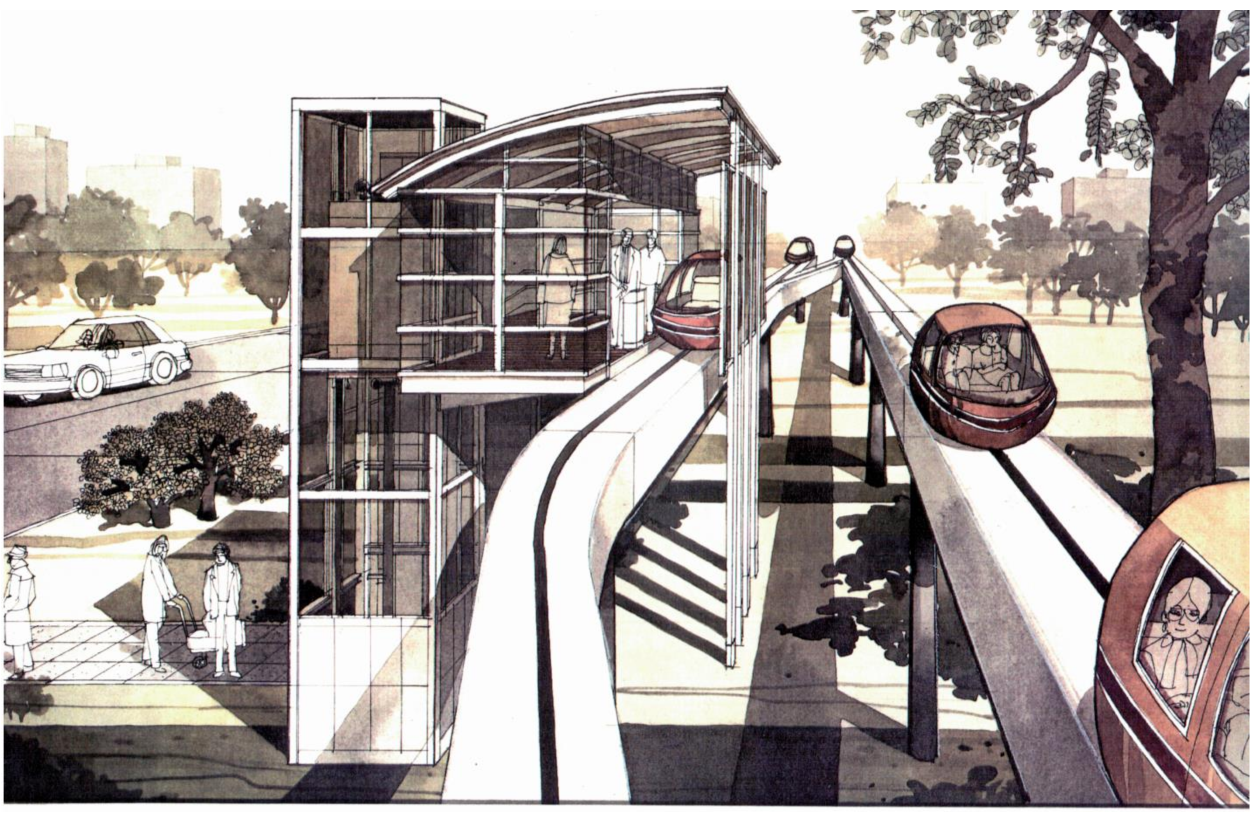
I had time to show only one slide on such a comparison – the cost per daily rider between the Minneapolis rail system and a PRT system we designed several years ago, which showed that the cost per daily rider for PRT would be no more than about $1/12^{th}$ the per daily rider cost of the rail system. An excellent paper has come out recently from Sweden on this subject: "Severe shortfalls in current public transport – and why Podcars (PRT systems) may make the difference," by Göran Tegnér and Elisabet Idar Angelov, WSP Analysis & Strategy, Stockholm, Sweden.

87. Could you run the cars in a tube?

One could. Uniflo, mentioned above, did that. The enclosed guideway ended up to be 14-feet high. One must design to a maximum horizontal wind of at least 120 mph, and with such a large cross section, the foundations for the posts get very large. Moreover, one would have to have windows in the tube. One of my mechanical-engineering colleagues calculated the air conditioning load for summer operation, which was enormous. In short, the capital and operating costs of an elevated system in a tube become too high to be competitive.

88. Could your own car run on the system?

There is a whole body of literature on this idea. It is called "dual mode" and the best source of which I am aware is on Dr. Schneider's webpage, which is mentioned above. The system I have designed, and the systems the Advanced Transit Association has studied in detail and advocated are single-mode systems in which the vehicles are permanently attached to the guideway, where maintenance is easier to monitor and control. To run your own car onto the guideway would require on and off ramps and inspection at each station, which would markedly increase the cost of each stations. Also, the guideway required to accommodate your own car would be much larger and more expensive than the narrow truss guideway I have designed. Compare our PRT system with the so-called "light rail" systems that are being installed in many cities. Our system will be in the range of 3 to 4 times less expensive per one-way mile than light rail system, and because you can place the stations on the average half the spacing of stations on a light-rail system, you would have 6 to 8 times as many stations for a given cost. If a transit system has *n* stations, for each of these stations there are *(n-1)* possible trips, and thus a total of *n(n-1)* possible trips. Ridership can be expected to increase roughly with the number of possible trips, so that for a given cost the PRT system will be able to attract a great many more riders, not only because of the increased number of trip possibilities but because of its 24/7 service with short to zero wait nonstop to the destination. Access to the PRT system will occur in exactly the same way as access a conventional light-rail system, and moreover you don't need a driver's license to use a PRT system. Thus, PRT enters the field of urban transportation from the transit side, i.e., how to design a transit system that will be low enough in cost and high enough in ridership to come close to or exceeding the break-even cost. Dual mode enters the field of urban transportation from the auto side – how to increase the capacity of freeway lanes and how to avoid the tedium and attention required to drive an automobile safely. These are desirable goals. The problem has been to achieve them in an acceptable way.



Chapter 12. The Intelligent Transportation Network System

The Intelligent Transportation Network System (ITNS) is a totally new form of public transportation designed to provide a high level of safe and reliable service over an urban area of any extent in all reasonable weather conditions without the need for a driver's license, and in a way that both maximizes ridership and minimizes cost, energy use, material use, land use, and noise. Being electrically operated it does not emit carbon dioxide or any other air pollutant, and requires no oil.

This remarkable set of attributes is achieved by operating vehicles automatically on a network of minimum weight, minimum size exclusive guideways, by stopping only at off-line stations, and by using light-weight, sub-compact-auto-sized vehicles.

We now call this new system ITNS rather than High-Capacity Personal Rapid Transit — a designation coined decades ago.

Contents

1. Introduction

In their book *The Urban Transport Crisis in Europe and North America,* John Pucher and Christian Lefèvre, discussing only conventional transportation, concluded with this grim assessment: “The future looks bleak both for urban transport and for our cities: more traffic jams, more pollution, and reduced accessibility.”

In the report *Mobility 2030: Meeting the Challenges to Sustainability, 2004* by the World Business Council for Sustainable Development, which was endorsed by the leaders of major auto and oil companies, the authors site grim projections of future conditions but no real hope for solutions.

C. Kenneth Orski, in his *Innovation* Briefs for Nov/Dec 2006 reports on Allan Pisarski’s report *Commuting in America,* Transportation Research Board, 2006, which concludes that “driving alone to work continues to increase,” “carpooling’s share declined by 7.5% since 1980,” transit currently accounts for 4.6% of the trips, and “walking to work has suffered a sharp decline . . . a reality check for those who claim to see a trend toward ‘walkable communities.’” Orksi goes on to report that “not only is population dispersing, it is dispersing farther and farther out, leapfrogging over existing suburbs.” This means more driving and driving longer distances.

In spring 1989 I was informed that during a luncheon attended by the Northeastern Illinois Regional Transportation Authority (RTA) Chairman it was agreed that "*We cannot solve the problems of transportation in the Chicago Area with just more highways and more conventional rail systems. There must be a rocket scientist out there somewhere with a new idea!*" The Illinois Legislative Act that established the RTA had given the new agency an obligation to "encourage experimentation in developing new public transportation technology."

The new idea they needed was called High-Capacity Personal Rapid Transit (PRT). The best of all versions developed in the 1970s is shown in Figure 15.1. It *was* developed by rocket scientists, in this case at The Aerospace Corporation between 1968 and 1972 [1][23]. We now call the new system *ITNS* to distinguish it as a type of automated highway rather than as a type of transit; however, the generic name "PRT" is deeply imbedded in the automated-transit culture and cannot be avoided. A March 2006 European Union Report concluded: "The overall assessment shows vast EU potential of the innovative PRT transport concept" [2].

In April 1990 the RTA issued a request for proposals for a pair of $1.5 million Phase I PRT design studies. Two firms were selected and after the studies were completed the RTA selected my design, which is an upgrade of the Aerospace system, for a $40 million Phase II PRT design and test program. Unfortunately, that program was not directly successful, not due to any flaw in the basic concept, but due to the lack of deep understanding of it by the lead engineers and their managers. That program was, however, indirectly very successful because it inspired many inventors and planners in many parts of the world to begin to investigate PRT. There is more and more evidence today that *ITNS* will solve many urban problems.

The objective of this paper is to seek and describe a solution to the problems of urban transportation that meets the design requirements and criteria.

2. The Approach to Solution

Many years ago, while at the University of Minnesota, I was privileged to hear a lecture by Cal Tech Professor Fritz Zwicky, who had been engaged during the 1940s in the urgent problem of the design of jet engines. Germany had them and we didn't. Zwicky developed a design concept he called "Morphology" and to explain his concept he wrote a book *Morphology of Propulsive Power*. He referred to his approach to design as the "morphological approach," which attempts to view all problems in their totality, without prejudice, and with absolute objectivity. After years of experience in the practice and teaching of design I realized, with Zwicky's help, that the first step in a design process is to comprehend deeply and follow rigorously a comprehensive set of rules of engineering design. I make no claim that my set of such rules [35], which is indebted to Zwicky's formulation, is complete, and I would welcome collaboration with other experienced engineering designers on a more comprehensive set. I have observed that the less successful PRT designs have suffered primarily from violating one or more of these rules. What is now commonly called "risk

[23] [n] is the nth reference in the list at the end of this paper.

management" consists mainly in following rigorously such a set of rules. My contribution was also inspired by my reading, as a young design engineer, the rules of engineering of W. J. King, which have been reproduce in summer 2010 issues of *Mechanical Engineering*. Beginning with these rules, the design processes I used to arrive at my conclusions about the design of a PRT system began by <u>defining the requirements</u> for the solution, which took many years of involvement in transit issues. We then diagrammed all combinations of system attributes <u>without prejudice toward pet solutions</u>. We then <u>analyzed</u> <u>thoroughly</u> all reasonable alternatives in each combination until it became clear which is best, and we perform subsystem and component tests where needed. We let the system requirements dictate the solutions, and avoid letting prejudices govern. This is not an easy process, and it requires an in-depth understanding of the engineering sciences and the necessary mathematics, but is a vital one.

3. <u>The Problems to be Addressed</u>

- Increasing congestion.
- The use of oil in transportation.
- Air pollution.
- Many people killed or injured in auto accidents.
- People who cannot, should not, or prefer not to drive.
- The lack of a serious alternative to the auto.
- Excessive land use for roads and parking.
- Excessive energy use in transportation.
- Road rage.
- Terrorism.
- Excessive sprawl.

4. <u>Requirements of the New System</u>

To address these problems, a new transit system must be

- Low enough in cost to recover all costs from fares and other revenue.
- Highly efficient in operation with renewable energy sources.
- Time competitive with urban auto trips.
- Low in air and noise pollution.
- Adequate in capacity.
- Visually acceptable.
- Low in material use.
- Low in energy use.
- Low in land use.
- Safe.
- Reliable.
- Comfortable.
- Expandable without limit.
- Able to attract many riders.

- Available at all times to everyone.
- An unattractive target for terrorist attacks.
- Compliant with the Americans with Disabilities Act.
- Operational in all kinds of weather, except for extremely high winds.

5. Derivation of the New System

It will not be possible to reduce congestion, decrease travel time, or reduce accidents by placing one more system on the streets – the new system must be either elevated or underground. Underground construction is extremely expensive, so the dominant emphasis must be on elevation. This was understood over 100 years ago in the construction of exclusive-guideway rail systems in the United States in Boston, New York, Philadelphia, Cleveland, and Chicago. A serious concern, though, was the size and cost of the elevated structures. Several inventors, working in the 1950s, realized that if, as illustrated in Figure 5.1, the people-carrying capacity is distributed in many small units, which is practical with automatic control, rather than a few large ones; and by taking advantage of light-weight construction, the guideway weight per unit length could be reduced by a factor of at least 20:1! This enormous difference is the fundamental reason for the low cost of the system that has been called PRT.

Offhand, it is common to assume that there must be an economy of scale, i.e. the cost of large vehicles per unit of capacity must be lower than the corresponding cost for small vehicles. Examination of data in Figure 5.2[24] show, however, that this is not so. Each point in Figure 5.2 represents a transit system, with costs normalized to take into account inflation. While there is a great deal of scatter, we see that a line of best fit is close to horizontal, i.e., *vehicle cost per unit of capacity need not increase as vehicle capacity decreases.* A major reason for this finding is that a higher rate of production reduces unit costs.

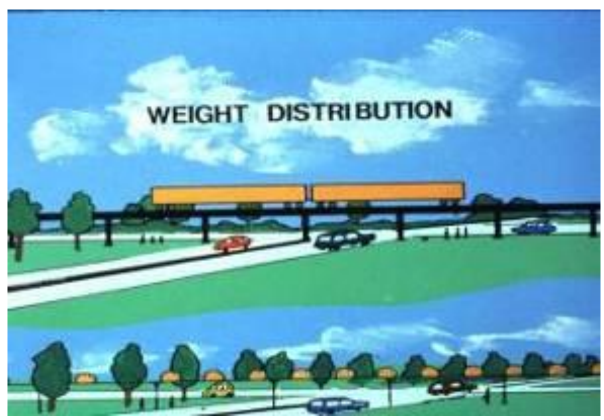


Figure 5.1. Guideway Weight and Size.

[24] This data was mostly taken from the *Transit Compendium,* which was published by N. D. Lea & Associates.

With this finding in mind, consider the cost of a fleet of transit vehicles. The cost of the fleet is the cost per unit of capacity, roughly independent of capacity, multiplied by the people-carrying capacity needed to move a given number of people per unit of time. The major factor that determines the required people-carrying capacity is the average speed. If, for example, the average speed could be doubled, the number of vehicles required to move a given number of people would be cut in half.

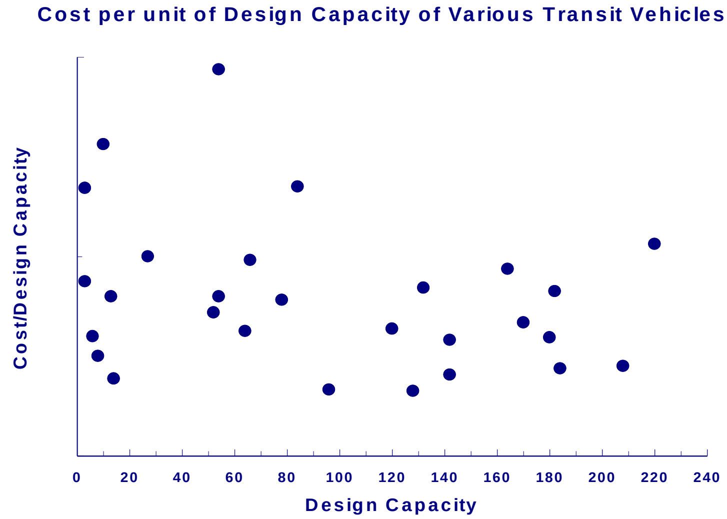


Figure 5.2.

The greatest increase in average speed without increasing other costs is obtained by arranging the system so that *every trip is nonstop*, and the trips can be nonstop if all of the stations are on bypass guideways off the main line as shown in Figure 6-1.

6. Off-Line Stations are the Key Breakthrough!

Figure 6.1 is a picture of a portion of a model PRT system built during the 1991 Chicago PRT Design Study. It shows the simplest type of off-line station, in which there is a single by-pass guideway and the vehicles line up in tandem in a series of two to about 20 berths. A number of authors have estimated the capacity of such stations in vehicles per hour as a function of the number of berths [1], [3].[25]

The advantages of off-line stations are:

- Off-line stations minimize the fleet size and hence the fleet cost because they maximize the average speed. This was discussed in Section 5.
- Off-line stations permit high throughput with small vehicles. To see how this can be so, consider driving down a freeway lane. Imagine stopping in the lane, letting one person out and then another in. How far behind would the next vehicle have to be to make this safe? The answer is minutes behind. Surface-level streetcars operate typically 6 to 10 minutes apart, and exclusive guideway rail systems may operate trains as close as two minutes

[25] To allow for the case in which one party takes an extraordinary amount of time to enter or exit a vehicle, some PRT designers have designed stations in which each parked vehicle can enter or exit the station independent of other vehicles. Three factors cause us to recommend against such stations: 1) Due to interference, the throughput of these stations is disappointing, 2) these stations require much more space and cost much more than the single-by-pass design, and 3) because elderly or disabled people generally avoid the busiest hours, the statistical average peak flow will not be much decreased by the occasional presence of such persons.

apart, whereas on freeways cars travel seconds apart, and often less than a second apart.

- Off-line stations with small, auto-sized vehicles thus give the system a line capacity at least equal to a freeway lane. Such a capacity or maximum throughput permits the use of small guideways, which minimize both guideway cost and visual impact.

- Off-line stations permit nonstop trips, which minimize trip time and increase the attractiveness of the trip.

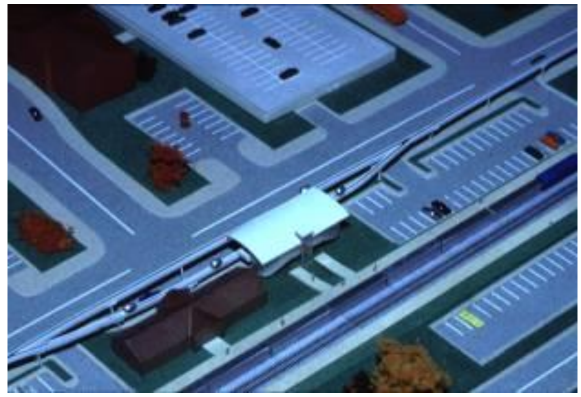


Figure 6.1. An Off-Line Station

- Practical use of the nonstop trip means that the average waiting time for a second and independent party is generally too long to be of interest.[26] Hence the trip is taken either by one individual or by a small party traveling together by choice.

- Off-line stations permit the vehicles to wait at stations when they are not in use instead of having to be in continuous motion. Thus, it is not necessary to stop operation at night – service can be available at any time of day or night. Moreover, compared with scheduled, all-stop service, the amount of travel per seat per day reduces by more than a factor of two, which reduces the operating cost by about the same amount.

- With off-line stations there is no waiting at all in off-peak hours, and during the busiest periods empty vehicles are automatically moved to stations of need. Computer simulations show that the peak-period wait will average only a minute or two.

- Stations can be placed closer together than is practical with conventional rail. With conventional rail, in which the trains stop at every station, the closer the station spacing, the slower is the average speed. So to get more people to ride the system, the stations are placed far enough apart to achieve an average speed judged to be acceptable, but then ridership suffers because access is sacrificed. The tradeoff is between speed and access – getting more of one reduces the other. With off-line stations the system provides both high average speed and good access to the community.

- Off-line stations can be sized to demand, whereas in conventional rail all stations must be as long as the longest train.

All of these benefits of off-line stations lead to substantially lower cost and higher ridership.

[26] Reference 19, page 89, equation 4.5.22.

7. <u>Tradeoffs</u>

Following is a series of tradeoffs that defined *ITNS*, on each of which can be found in Chapter 9. The underlined alternative is the one selected.

Dual Mode vs. <u>Single Mode</u>
<u>Supported</u> vs. Hanging Vehicles
Air cushions vs. maglev vs. <u>wheels</u>
Rotary motors vs. <u>linear motors</u>
<u>Linear induction motors</u> vs. linear synchronous motors
<u>Motors on board</u> vs. motors in guideway
Power source on board vs. <u>power source at wayside</u>
Synchronous vs. quasi-synchronous vs. <u>asynchronous</u> control

The Vehicle's Cabin Configuration

The minimum-sized cabin of ITNS must

- Enable a wheelchair to enter from the station platform and then turn to face forward, and to accommodate an attendant. This requires an interior width of 60" and a space from a folded-up seat to the front of 60", considering that only the portion of the roof at the seat needs to have full height.
- Have an interior height at and above a 17" high seat sufficient to accommodate a 97.5 percentile male.
- Have a door that permits an elderly person using a walker to walk straight in standing up without obstruction.
- Have an exterior shape that minimizes air drag, because air drag is the major consumer of energy even at speeds as low as 25 mph [24].
- Have an exterior shape that is as attractive as possible.

The minimum-sized cabin has the following additional features:

- It easily accommodates three adults sitting side by side.
- Its length is minimized by designing the seat in three equal parts that fold up to accommodate the wheelchair. The seat closest to the door can be folded down for the attendant.
- It permits the installation of two fold-down and backward-facing seats at the front for children.
- It permits the cabin to carry a bicycle, a baby carriage, large luggage, or other such objects.
- It permits a television screen visible to the passengers sitting in the main seat to be installed in the middle of the front of the cabin between the two fold-down seats.

- It permits a panoramic view of the surroundings.

Additional required features of the cabin are

- A heating, ventilation, and air conditioning system.
- A two-way system for communication with central control.
- A “Go” button.
- A “Stop” button that stops the car at the next station.
- An “Emergency” button that permits the passenger to contact central control.
- Reading lights.
- Room behind the main seat for the on-board computer and the air-conditioning unit.

A rough sketch of a minimum-sized cabin is as follows:

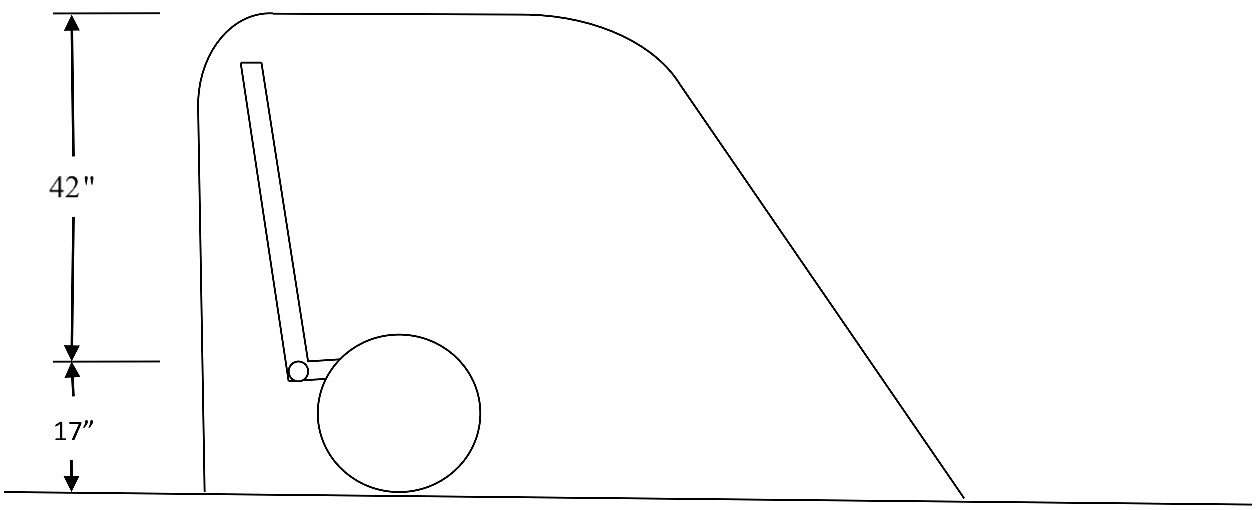


Figure 7.1. Sketch of Minimum-Size Vehicle.

For comparison, following are several illustrations of the Taxi 2000 cabin, the design of which was led by Dr. Anderson to meet the minimum requirements.


Figure 7.2. The Taxi 2000 Vehicle, designed by Dr. Anderson.

The Guideway Configuration

Up to now we have concluded that the system we are designing will use minimum-sized vehicles captive to the guideway and operating between off-line stations. From conclusions reached in Chapter 9, the vehicles will be supported above the guideway, will run on wheels, and will be propelled and braked by linear induction motors obtaining their power from wayside via power rails. Further progress is obtained by noting that the minimum weight guideway will be a steel truss structure clamped to the support posts and narrower than the vehicles,[27] which will lead to the use of a vertical chassis of unique design. For the following reasons, the guideway will be covered except for a narrow slot at the top to permit a narrower vertical chassis to pass through:

1. To minimize the interference of snow and ice with the operation of the vehicles.
2. By placing a thin layer of aluminum inside the covers, electromagnetic interference of the motor drives on the community surrounding the system is minimized and any possible interference from outside on the communication means inside the guideway is minimized.
3. To eliminate any frost formation on the power rails.
4. To eliminate any differential thermal expansion and the resulting stresses due to the sun shining on only one side of the guideway.
5. To eliminate the effect of sun shining on the tires and other chassis components and thus to enable the tires to operate in the most benign outside environment possible – in the shade of the sun with no potholes or curbs to run over and no torque applied to the wheels.
6. By applying a radius on the top and bottom of the covers of at least one sixth the depth of the guideway the side drag force on the guideway due to wind is minimized.
7. By applying a sound deadening material on the inside of the cover, noise that may be produced by the motor drives is minimized.
8. To provide access for maintenance even though an important design requirement is that nothing inside the guideway should require maintenance.

[27] [17], Chapter 10; [5] and [37].

9. To permit the community to select the color and texture of the exterior surface of the guideway covers.

9. The Optimum Configuration

I have accumulated 37 requirements for design of a PRT guideway. They are given in Chapter 8. As chairman of three international conferences on PRT, I was privileged to visit all automated transit work on the planet, talk to the developers, and observed for over a decade both the good and the bad features. The requirements listed in Figure 9.1 are the most important, and, from structural analysis [5] I confirmed The Aerospace Corporation's conclusion that the minimum-weight guideway is a little narrower than it is deep, taking into account 150-mph crosswinds with no vehicles on the guideway and 70-mph crosswinds with a maximum vertical load of fully loaded vehicles nose-to-tail. I compared hanging, side-mounted, and top-mounted vehicles and found ten reasons to prefer top-mounted vehicles.

Figure 9.1

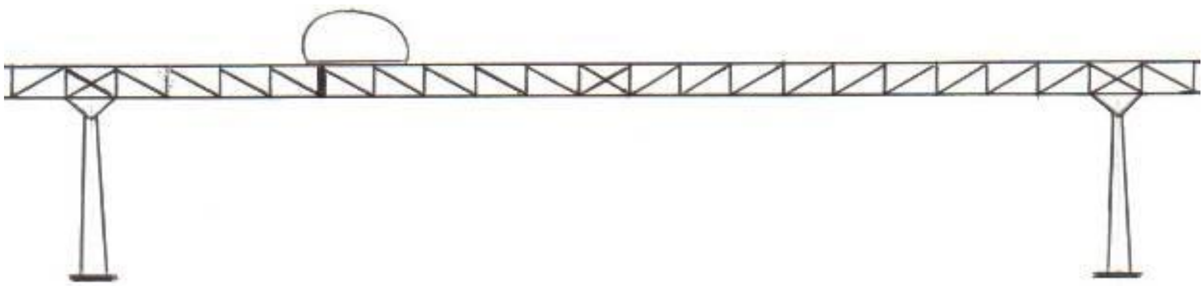


Figure 9.2. A Low Weight, Low-Cost Guideway

Such a guideway has the smallest possible visual impact. It has minimum weight if it is a truss as shown in Figure 9.2, which is scaled to posts 90 ft apart. The heavy vertical line indicates the location of an expansion joint in each span. A stiff, light-weight truss structure will have the highest natural frequency, which results in the highest comfortable cruising speed. It will be most resistant to the horizontal accelerations that result from an earthquake. By using robotic welding it will be the least expensive to manufacture, transport (in 45-ft sections welded together in the field) and erect. The analysis reported in [5] has produced the properties needed to meet all requirements. I observed over decades that whenever a PRT program died, and there have been many, the major reason could be traced to a problem with the guideway design. I thus addressed that problem in a paper [28] that I presented at the 2009 APM Conference. In that paper I pointed out that the design of a PRT guideway requires a much higher level of system engineering than is apparent in the designs that have failed.

A series of U-frames are placed each at a position of one of the vertical lines shown in Figure 9.2. The only close dimension is between the inside left and right surfaces of the U-frame where the upper and lower angle running surfaces are located.

The vertical chassis, only 2 inches wide, is shown in Figure 9.3 with its attachment to the cabin. Comprehensive finite element analysis has been performed on the joint to insure that it is sufficiently strong and conservatively designed. The main support wheels are shown. They run on a pair of 8×6×1/2-inch steel angles. The side support wheels are also shown. These tires are polyurethane of stiffness determined from a dynamic simulation[28] of the vehicle passing through a merge or diverge section of guideway, which determines all of the maximum wheel loads. The switch arm is shown with its bi-stability leaf spring. In the merge and diverge sections of the guideway, switch rails are placed to contain the vehicle in the desired direction of travel through the switch. They are flared to permit comfortable engagement and disengagement. The power rails, which transfer 600-volt D.C. power to the vehicles from wayside power sources, are shown.

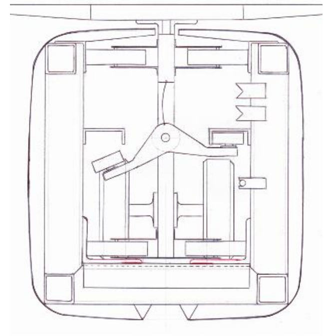


Figure 9.3

After studying all practical means of suspending vehicles, we found that the smallest guideway cross section and hence the lowest guideway cost is obtained by use of wheels. Our wheels will use either high-pressure pneumatic tires or a new airless tire that provides the same suspension characteristics. Because our tires don't have to pass over chuck holes and curbs, they can be much stiffer and hence of much lower road resistance than automobile tires. The art of manufacturing highly reliable axles and bearings is well developed, and since our tires will run on smooth surfaces away from the damaging rays of the sun and don't transmit thrust or braking, they will last much longer than automobile tires.

There are many ways a vehicle can be propelled. We selected linear induction motors (LIMs) because they enable the vehicle to accelerate and decelerate at planned rates regardless of the coefficient of friction of the running surface and thus will enable the vehicles to operate safely at much lower headways than would be possible if we propelled and braked using rotary motors. An added advantage of LIMs is that they have no moving parts. Reference 31 provides more detail.

Figure 9.4, in which north is to the left, shows how PRT could begin to serve a portion of Downtown Chicago. The PRT guideway is shown in red.

Figure 9.4. An Application in Downtown Chicago

[28] J. E. Anderson, "Lateral Dynamics of the ITNS Vehicle"

10. <u>Control</u>

Control of PRT has been investigated at many organizations since the 1960s. I have published [4] a bibliography of papers on control of PRT that have been useful as we have developed the control system for *ITNS*. My detailed papers related to control are listed [10 – 13]. I add to this collection of papers a paper [29] that summarizes our knowledge of how to obtain safe, reliable short headways. The *ITNS* control hardware consists of computers, sensors, and a communications medium.

10.1 Computers

All computers in *ITNS* are dual redundant, sometimes called "dual duplex." This means that each "computer" is two pairs of microprocessors. The output of each pair is compared every one hundred milliseconds. Any error detected in one of them causes control to go to the other pair. The vehicle is permitted to finish its trip and is then directed to a maintenance shop. With this arrangement the mean time between serious events is extremely long, longer than anyone will believe without checking the calculations [10]. The methodology we use was obtained from Boeing papers developed during their work on AGRT [30].

For vehicle control three types of computers are needed: computers on vehicles, computers at strategic wayside locations, and a central computer. Each section of guideway is managed by a wayside computer called a zone controller. There will be station zones, merge zones, diverge zones, and line zones. Each zone controller commands specific maneuvers to specific vehicles as needed and each individual vehicle computer carries out these commands. The mathematics needed to command every one of the maneuvers a vehicle can make has been worked out, programmed, and checked. These maneuvers consist of moving from one speed to another, for example from a station to line speed, slipping a certain distance relative to another vehicle ahead on the other leg of a merge, and stopping in a given distance. With today's high-gain controllers and by using linear induction motors, the position of a vehicle can be controlled almost as closely as we can measure it, which is substantially closer than necessary [29].

Each zone controller provides the line-speed signal in its domain. If anything goes wrong, it removes the speed signal to vehicles behind the failed vehicle, which causes the vehicles behind the failed vehicle to slow to creep speed – slow enough to be safe but fast enough to give the passengers confidence that they will soon enter a station. When a vehicle reaches a maneuver-command point, the zone controller transmits the appropriate command maneuver to that vehicle, and the vehicle controller causes the vehicle to follow the required time sequence of positions and speeds. The zone controller calculates the same maneuver sequentially for each vehicle in its domain and compares it with the vehicle's position and speed as a basis for corrective action if necessary. Adjacent zone controllers communicate with each other.

The central computer balances traffic in certain conditions and accumulates data on the performance of the system. The data rates, computer speeds, and memory needed are well within the capability of today's computers.

10.2 On-Board Position and Speed Sensing

The position and speed of each vehicle is measured on board each vehicle by means of digital encoders placed in the main bearing of each of the four wheels. Averaging the left and right output gives the correct measurement in curves. Having encoders in both the fore and aft wheels provides redundancy. These encoders register at least 4096 pulses per revolution, or with the 336.6 mm (13.25") OD tires we plan to use about 0.26 mm (0.010") per pulse. With this accuracy, experimental evidence has shown that we can differentiate to obtain accurate speed measurements. If, however, the assumed OD was in error by say 1%, the distance measurement would be in error by 1%. Thus, we will calibrate each vehicle as it leaves a station by means of fixed magnetic markers. In this way we will know the position of each vehicle to an accuracy of less than 25 mm (one inch).

10.3 Wayside Position and Speed Sensing

The position and speed of each vehicle is measured for the wayside zone controllers independently of the on-board measurements by suitably placed pairs of wayside magnetic markers. When a vehicle reaches the first marker, a pulse is sent to the cognizant wayside computer, which detects its position at that time. When the vehicle reaches the second of the pair a known and short distance ahead, by measuring the time interval between markers we determine speed. We can measure the time interval to an accuracy of a few nanoseconds, which means that we measure speed to less than one part in a million – well better than needed.

10.4 Independent Backup Emergency Control

While the dual duplex system described is extremely reliable and the software to run it has been checked tens of millions of times with random inputs and no errors, we must assume that some unknown dangerous situation could occur. Thus a completely independent backup control system is provided that measures the inter-vehicle spacing by means of a sonar system and brakes through a separate emergency brake, which operates independently of the main support wheels. It is also the parking brake and is activated and checked every time a vehicle stops. This added feature further extends the mean time between unsafe incidents.

10.5 Communication

Each vehicle will be equipped with a transmitter and a receiver capable of sending information to and receiving information from a commercially available leaky cable placed on the inside of the guideway. We prefer this method to GPS because GPS will be susceptible to hacking and will be affected by solar storms [27]. The zone controllers talk to and from the leaky cable.

By providing no access to the Internet, this type of communication is completely secure and cannot be interfered with by hackers.

10.6 The state of the art of modern safety-critical, real-time control systems.

Today, computers routinely land airplanes on aircraft-carrier decks. Our computers respond to and correct speed and position every 5 millisecond. The instruments we use to measure position and speed are much more accurate than we need. Wayside zone controllers monitor the motion of each vehicle 10 to 20 times each second. Code has been developed to control any number of vehicles in networks of any size or configuration [24]. Our vehicle has very few moving parts. The switch has no moving parts in the guideway. Our motors have no moving parts. Our motors, motor controllers, sensors, and power-supply systems are redundant, meaning that a single failure is not noticed by the riders. Our computers, as mentioned, are dual duplex, which means that each of the on-board and wayside "computers" is really four computers. If one computer aboard a vehicle fails, the vehicle continues to its destination on the good computers, drops off its passengers, and then proceeds empty to the maintenance shop, all within a few minutes. If, even with all of this redundancy, which is remarkably inexpensive today, a vehicle should stop on the guideway away from a station, the vehicle behind will soft engage and push it to the next station.

Today, at any one time, there are as many as 80,000 aircraft operating in the skies over the United States. They operate most of the time under automatic control with air traffic control systems at the various airports keeping track of dozens of aircraft by using computers to track each aircraft. This is a much more sophisticated operation than needed with PRT and goes on every day in a system in which a failure means loss of an aircraft and all of its passengers. The bottom line is that the control of PRT vehicles safely and reliably is well within the current state of the art.

11. <u>System Features Needed for Maximum Throughput Reliably and Safely</u>

The features needed are illustrated in Figure 11.1.

1. All weather operation: Dual linear induction motors (LIMs) provide all-weather acceleration and braking independent of the coefficient of friction of the running surface.

2. Fast reaction time: LIMs react within a few milliseconds. Human drivers react in between 0.3 and 1.7 seconds. The on-board computer updates position and speed every 5 millisecond.

3. Fast braking: Even with automatic operation the best that can be done with mechanical brakes is a braking time of about 0.5 sec, whereas LIMs brake in a few milliseconds.

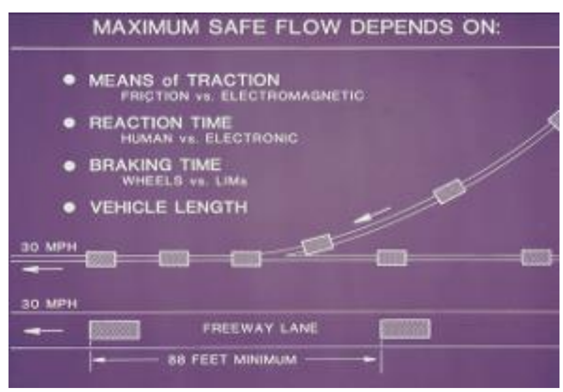


Figure 11.1. How to achieve maximum safe flow.

4. Vehicle length: A typical auto is 15 to 16 feet long. An *ITNS* vehicle is only nine feet long.

These features together result in safe operation at fractional-second headways, and thus maximum throughput of at least three freeway lanes [9], i.e., 6000 vehicles per hour. During the Phase I PRT Design Study for Chicago, extensive failure modes and effects analysis [10], hazards analysis, fault-tree analysis, and evacuation-and-rescue analysis were done to assure the team that operation of the system would be safe and reliable. The resulting design has a minimum of moving parts, a switch with no moving track parts, and uses dual duplex computers [11]. Combined with redundant power sources, fault-tolerant software, and exclusive guideways; our studies performed during our Chicago PRT Design Study showed then that there will be no more than about three person-hours of delay in ten thousand hours of operation [12]. A method [13] for calculating the mean time to failure of each component of the system that will permit the system dependability requirement to be met at minimum life-cycle cost was developed and used during the design process.

12. Is High Capacity Possible with Small Vehicles?

A common question is to ask how ITNS could handle the traffic in and out of a stadium. People wonder how small vehicles can do a job that it is common to believe can be handled more quickly by buses or trains. First one must recognize that most of the people who attend games at a stadium arrive and leave in automobiles, and this is likely to continue to be true in the foreseeable future. For those who prefer to use public transportation, let's compare ITNS with buses or trains. The advantage of ITNS is that the stations are on by-pass guideways so that the stopping and starting of vehicles does not affect main-line movement. Because buses and trains stop on line, they must be spaced far enough apart so that they don't interfere with one another. The typical minimum time spacing for surface-level rail systems is no closer than 6 minutes. Typical light rail cars can handle a maximum of about 180 people, so a three-car train can carry 540 people every six minutes or 90 people per minute. With ITNS, the main line can handle practically up to about 60 cars per minute. ITNS vehicles have a capacity of 5 people, but let's assume only 3 people per vehicle. That would enable us to carry a maximum of about 180 people per minute, or twice the maximum throughput of a light-rail system. I simulated the flow of people given me by Cincinnati people attending a Cincinnati Reds ball game. I found that I could handle the flow into and out of the stadium by placing one 14-berth PRT station on each of the four sides of the ball park. A comprehensive discussion of the throughput potential of *ITNS* lines and stations is given in reference [7]. It is shown there that a 14-berth station can handle a maximum of about 1200 cars per hour or about 20 cars per minute, so four of them can handle 80 cars per minute. With 3 people per car, the system would handle 240 people per minute, which is 2.67 times the capacity of a light rail system. A PRT network able to attract this much traffic must be quite extensive and should be designed to transport people from under-utilized remote parking areas, saving on infrastructure cost development.

In 1973 Urban Mass Transportation Administrator Frank Herringer told Congress that "a high-capacity PRT could carry as many passengers as a rapid rail system for about one quarter the capital cost" (see Figure 12.2). Notwithstanding that this pronouncement was backed up by the work of a competent R&D staff, the result was to ridicule and kill a budding federal HCPRT program. PRT was a threat to conventional systems, but it was an idea that would not die. Work continued at a low level, which is the main reason it has taken so long for PRT to mature, but now with much improved technology. Today, over 40 years later, following Moore's Law, computer memory per unit volume has increased by a factor of $2^{40*2/3}$ or over 100 million to 1. During that time period, computer speed has increased by a factor of more than 6 million. Moreover, programming languages and computer design tools have matured markedly. Certainly, the task today is much simpler than it was in 1973.

During the 1990's the Automated Highway Consortium, under federal grants, operated four 17-ft-long Buick LeSabres at a nose-to-tail separation of seven feet at 60 mph or 88 ft/sec on a freeway near San Diego [9]. Figure 12.1 shows six of the LeSabres running at short headway. Since the minimum nose-to-nose separation was 24 feet, the minimum time headway or nose-to-nose time spacing was 24/88 or 0.27 second, which gives almost twice the throughput needed for a large *ITNS* system. The automated highway program was monitored by the National Highway Safety Board. *Thus the 1973 UMTA conclusion was more than proven in the 1990s.* Because of problems associated with automated highways that are not relevant to *ITNS*, the USDOT did not continue this program. Yet the demonstration of such short headway is of major significance for *ITNS*. I am very much aware that, notwithstanding the 1973 assertion of the UMTA administrator given in Figure 12.2, automated transit has been reported to be restricted to headways no shorter than the so-called "brick-wall" headway, which for urban speeds is about two seconds.

Figure 12.1. Automated Highway Experiment.

I discuss this in some detail in References [11] and [29]. Early PRT systems must be small and they do not require headways less than two seconds, so the brick-wall headway is not an impediment to PRT development. The ultimate safety criteria must be given in terms of injuries or incidents per billion miles of operation. PRT must demonstrate that its rate will be well under that for modern rapid rail systems, and our detailed studies show us that we will be able to do so and thus will be able to confirm the 1973 statement of the UMTA Administrator given in Figure 12.2. Thus, at the present time, the safety of fractional-second headways need not be a subject of debate – we must and will prove it.

CURRENT OPTIMUM HEADWAY ON PRT SYSTEMS

Mr. CONTE. What is the present optimum headway capacity that has been developed for PRT's?

Mr. HERRINGER. The shortest headways demonstrated by a federally funded PRT development were realized at TRANSPO 1972. Both the Ford and Monocab systems were capable of 8 second headways. German and Japanese high capacity PRT developments, in the full scale prototype test phase, are aiming for minimum headways between one-half and 1 second.

TARGET FOR HIGH CAPACITY PRT DEVELOPMENT

Mr. CONTE. What areas are being investigated for purposes of increasing the capacity of PRT systems and how far in the future are the results and benefits?

Mr. HERRINGER. Higher capacity will significantly improve the cost effectiveness of PRT as an urban transportation choice. By increasing capacity, more revenue passengers can be carried on the expensive guideway investment, thus improving capital utilization. A useful measure of capital utilization in a transportation system is the system cost per lane mile divided by the passenger capacity in seats per lane mile per hour. This number is about $800 for a rapid rail system and approximately $200 for an advanced high-capacity PRT system. This means that a high-capacity PRT could carry as many passengers as a rapid rail system for about one quarter the capital cost. I would like to introduce the following table in the record to clarify these points:

[The following follows:]

CAPITAL COST COMPARISON BETWEEN PRT AND RAPID RAIL

System	Capacity (seats per lane hour)	Cost (millions per lane hour)	Cost (dollars per lane mile per seat per hour)
Washington Metro (648 seat trains, 120 s headways)	19,500	15.2	780
Dallas/Fort Worth "Airtrans" PRT (16 seat vehicles, 18 s headways)	3,200	2.6	812
Planned PRT development (12 seat vehicles, 3 s headways)	14,400	4.0	360
High-capacity PRT (4 seat vehicles ½ s headways)	28,800	6.0	208

The table indicates that shorter headways permit high-capacity operation with smaller vehicles, thus permitting essentially nonstop service at all times.

UMTA recognizes the advantages of shorter headways to achieve higher PRT capacities and better service. The planned PRT system development program (for possible application in Denver) will achieve headways in the 3-second range. This system will be available for urban deployment in approximately 3 years. A DOT program leading to the development of a short, one-half to one-second headway, high-capacity PRT system will be initiated in fiscal year 1974.

TSC'S AC PROPULSION SYSTEM

Mr. CONTE. What is the innovative a.c. propulsion system that TSC plans to develop and test?

Figure 12.2. A page from the Congressional Record [9], March 1973.

13. How does a person use *ITNS*?

Figure 13.1. Pick a Destination and Pay the Fare

Figure 13.2. Transfer Destination to Vehicle

As shown in Figure 13.1 a patron arriving at a station finds a map of the system in a convenient location with a console below. The patron has purchased a card similar to a long-distance telephone card, slides it into a slot, and selects a destination either by touching the station on the map or punching its number into the console. If the patron is blind, he or she can request oral commands by a procedure that will be developed in consultation with the blind. The memory of the destination is then transferred to the prepaid card and the fare is subtracted.

Figure 13.3. Riding nonstop to the destination.

To encourage group riding, we recommend that the fare be charged per vehicle rather than per person. As shown in Figure 13.2, the patron (an individual or a small group) then takes the card to a stanchion in front of the forward-most empty vehicle and slides it into a slot, or waves it in front of an electronic reader. This action causes the memory of the destination to be transferred to the chosen vehicle's computer and opens the motor-driven door. Thus no turnstile is needed. The individual or group then enter the vehicle, sit down, and press a "Go" button. As shown in Figure 13.3, the vehicle is then on its way nonstop to the selected destination. In addition to the "Go" button, there will be a "Stop" button that will stop the vehicle at the next station and an "Emergency" button that will alert a human operator to inquire. If, for example, the person feels sick, the operator can reroute the vehicle to the nearest hospital faster than by any other means.

14. Why will *ITNS* attract riders

- There will be only a short walk to the nearest station.
- In peak periods the wait time will typically be no more than a minute or two.
- In off-peak periods there will be no waiting at all.
- The system will be available any time of day or night.
- The ride time will be short and the trip time predictable.
- A person can ride either alone or with chosen companions.
- The riders can make good use of their time while riding.
- Larger groups can easily split up into two or more vehicles, which will arrive at the destination seconds apart.
- Everyone will have a seat.
- The ride above the city will be relaxing, comfortable, scenic, and enjoyable.
- There will be no transfers.
- The fare will be competitive.
- There will be only a short walk to the destination.

A number of investigators [14] have developed models to predict ridership on PRT systems, which show ridership on PRT in the range of 25 to 50%. The U.S. average transit ridership is currently 4.6% [15], which includes New York City. Outside of New York City the average is closer to 3%, indicating that scheduled, all-stop transit is not used by 97% of urban residents. Accurate methods for calculating ridership need to be developed because the system needs to be designed but not over-designed to meet anticipated ridership.

16. Economics of *ITNS*

Based on a system-significant equation for cost of any transit system per passenger-mile, I have shown [19] that the system that minimizes this cost has all the characteristics of the true PRT concept. Figure 16.1 show the Minneapolis "light" rail system called the "Hiawatha Line." I put "light" in quotes because the cars weigh 109,000 lb, almost twice the weight of an average heavy rail car. According to a 2007 version of www.metrotransit.org the capital cost of this system was $715,300,000 and its ridership was 7,270,000 rides per year or 19,910 rides per day. That works out to almost $36,000 per daily trip. Metro Transit said that the annual operating cost was $19,850,000. Amortizing the capital cost at the OMB-specified 7%,[29] the total annual cost is $69,900,000 or $9.63 per trip. The average trip length is reported to be 5.8 miles, so the cost per passenger-mile is about $1.66. Based on the posted Metro Transit schedule, the average speed is 8 mph. In comparison, the total cost per vehicle-mile of an automobile ranges from 32.2 cents for a subcompact to 52.9 cents for a full-size utility vehicle [20]. Auto cost per passenger-mile is 20% less. Based on Metro Transit data, I calculated the average fare on the Hiawatha Line to be only $0.99, which is slightly more than 10% of the total cost.

[29] The web page of the federal Office of Management and Budget directs that capital costs be amortized at 7%.

We planned and estimated the cost of an 8-mile PRT system for downtown Minneapolis. It is compared with the Hiawatha light-rail line in Figure 16.2. Our estimate for the capital cost was about $100 million and a professional ridership study showed about 73,000 trips per day. Because this PRT system has not yet been built, let's double its cost. Then the capital cost per daily trip would be $2740 – 7.6% of the corresponding cost per daily trip for the Hiawatha line. The annual cost for capital and operation is typically about 10% of the capital cost and we can expect the annual ridership on a PRT system to be at least 320 times the daily ridership. On that basis the total cost for each trip would be $0.86. With this PRT system, the study showed an average trip length of about two miles so the break-even fare would be about $0.43 per mile – 26% of conventional light rail.

Figure 16.1. Minneapolis-Airport (Hiawatha) light rail.

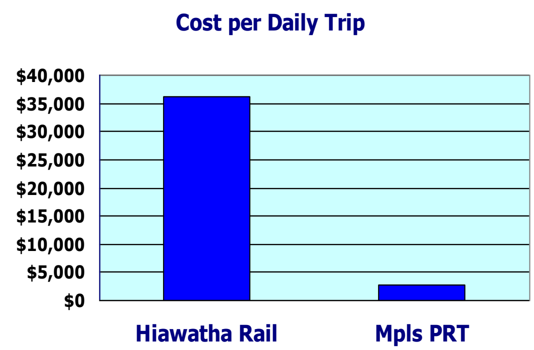


Figure 16.2. Cost Comparison

What would be the cost per passenger-mile on a built-out PRT system? Figure 16.3 shows the cost per passenger-mile on a square-grid PRT system as a function of population density for values of the fraction of all vehicle trips taken by PRT, called the mode split, from 0.1 to 0.7. Several studies [14] suggest that an area-wide PRT system with lines a half mile apart would attract at least 30% of the trips. On this basis, one can see from Figure 16-3 the relationship between population density, mode split, and the fare needed for a PRT system to break even. As mentioned in Figure 16.3, revenue will be obtained not only from passenger trips, but from goods movement and advertising as well – roughly half is a reasonable estimate, meaning that a passenger would have to pay only half the amount determined from Figure 16.3. For example, if the population density is 6000 persons per square mile (Chicago density is about 13,000 people per square mile) and the mode split to PRT is 30%, the break-even cost per passenger-mile for capital and operation is about 40 cents, of which the break-even cost for the passengers would be about 20 cents, which can easily be recovered from fares.

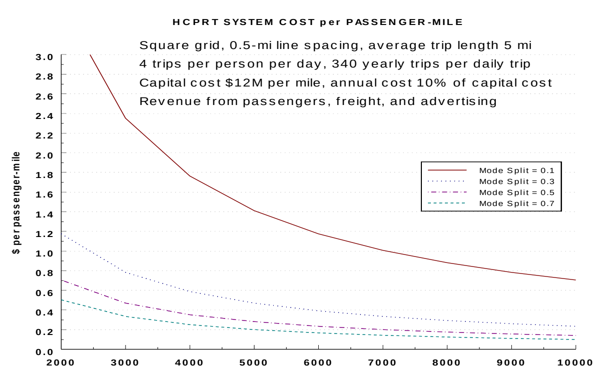


Figure 16.3. Cost per passenger-mile.

17. <u>Land Savings</u>.

Figure 17.1 shows a freeway running on the left side at capacity – about 6000 cars per hour [21]. This is a three-lane freeway with the fourth lane an acceleration lane. Figure 17.2 shows the people riding. In almost 90% of the autos there is only one person, occasionally two, and very occasionally three. (In a 1990 study, the Twin Cities Metropolitan Council found that the average rush-hour auto occupancy was 1.08 and the average daily occupancy was 1.2.)

Figure 17.1. A Freeway Running at Capacity.

Figure 17.2. The People Riding.

Figure 17.3 shows all of the people moved to the center and Figure 17.4 shows the vehicles in which they could be riding. This pair of guideways can also carry 6000 vehicles per hour – the throughput of the entire three-lane freeway. We would normally put these guideways along the fence lines so that the stations would be near people's destinations, but the figure illustrates the land savings. A typical freeway width from fence line to fence line is about 300 feet.

Figure 17.3. The people moved to center.

Figure 17.4. All riding *ITNS*.

The two *ITNS* lines in the middle of Figure 17.4 take up only 15 feet of width, giving a width reduction per unit of capacity of 20:1 or 5% of the land area. But, land for an *ITNS* system is required only for posts and stations, which with guideways a half-mile apart is *only 0.02% of city land*. The land underneath the guideways can be used for walking or bicycle trails and would not interfere with pedestrian, vehicle, or animal crossings. The auto requires about 30% of residential land and roughly 50% to 70% of the land in downtown areas. This enormous land savings permits development of safe, low-pollution, energy-efficient, quiet, environmentally friendly, high-density living.

Figure 17.5 illustrates the tiny fraction of land required by *ITNS*, which can carry substantially more people per hour than the arterial streets shown. An area formerly cleared for surface parking could be restored into a park or garden, thus making the inner city more people-friendly and reducing the summer temperature because concrete and asphalt absorb sunlight and immediately heat the surrounding air, whereas plants soak up solar energy as they grow, and while growing absorb carbon dioxide from the air.

Figure 17.5. A restored park thanks to *ITNS*,

18. Energy Savings

Minimum energy use requires very light-weight vehicles; smooth, stiff tires for low road resistance; streamlining for low air drag; and efficient propulsion, all of which are designed into *ITNS*. Unlike conventional transit, in which the cars must run to provide service whether or not anyone is riding, the cars of *ITNS* run only when people wish to travel. Studies have shown that this on-demand service reduces the number of vehicle-miles per day of operation needed to move a given number of people by more than a factor of two, which lowers the energy use and operating cost in proportion [19]. Moreover, conventional transit must stop and start frequently, which means that the kinetic energy of motion must be applied and removed many times during a typical trip. While some energy can be recovered by regenerative braking, stop-start behavior substantially increases the energy use per trip. An additional point is that when an *ITNS* vehicle finishes one trip it is immediately available for another, unlike the automobile, which lies dormant most of the day. The result is that one *ITNS* vehicle will serve many more trips per day than automobiles, thus saving the energy of construction of many automobiles, each of which weighs roughly twice the weight of an *ITNS* vehicle.

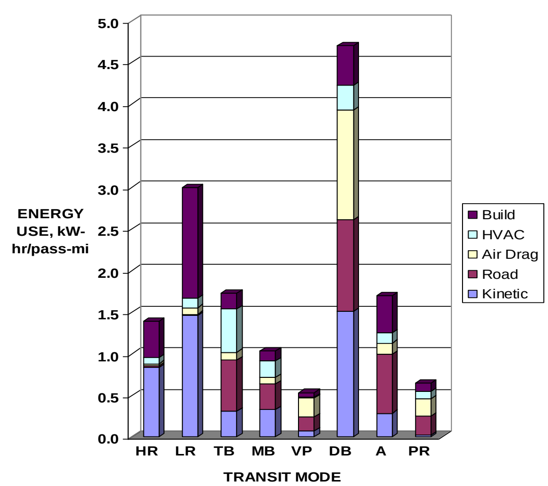


Figure 18.1. Energy use per passenger-mile.

Figure 18.1 gives a comparison of the energy use per passenger-mile of eight modes of urban transportation – heavy rail, light rail, trolley bus, motor bus, van pool, dial-a-bus, auto, and PRT [22]. Data for the first seven of these modes are averages from federal sources. The energy use for kinetic energy, road resistance, air drag, heating, ventilating, and air-conditioning, and construction are shown. In summary PRT will be more than twice as energy efficient as the auto system under the new federal guidelines, which in turn is almost twice as energy efficient as the average light rail system.

Suppose we consider providing energy for *ITNS* by means of solar panels placed on the sides and top of the guideway. The better solar modules will produce about 180 peak watts per square meter. Considering that only one side of the guideway would be exposed to the sun; we will have about 2200 square meters of solar panels per mile, which, when the sun is shining would produce about 400 kW. The maximum power use by an *ITNS* vehicle counting heating or air conditioning is about 4 kW. Thus, under peak conditions, solar energy could power 400/4 = 100 vehicles per mile. Multiplying by a line speed of say 30 mi/hr, the corresponding flow rate would be 3000 vehicles per hour or about 50% more than the peak flow on one freeway lane. But here we are interested in the average daily flow, which is a small fraction of the peak flow; hence the daily average number of vehicles per mile is much less than 100. Thus, with peak solar radiation, solar panels on the sides and top of the guideway will likely produce substantially more energy than needed. The surplus energy can be stored in batteries, flywheels, hydrogen, compressed air, or pumped storage plants to be returned when needed.

19. <u>Reconsider the Problems</u>

.

ITNS addresses all of the problems listed in Section 2, of which congestion, dependence on oil, and global warming are much in the news. According to Andrew Euston, now retired from the U. S. Department of Housing and Urban Development where he was Coordinator of the Sustainability Cities Program, PRT "is *an essential technology for a Sustainable World.*" William Clayton Ford, Chairman of the Ford Motor Company has been quoted [27] as saying: "The day will come when the notion of auto ownership becomes antiquated. If you live in a city, you won't need to own a car." Auto executives understand that continuing to sell an exponentially increasing number of automobiles every year on a finite earth, notwithstanding increased energy efficiency or use of renewable energy, while autos already clog cities, is not a tenable future.

<u>And the solution:</u> An optimum combination of very small vehicles running under full automation between off-line stations of minimum-sized and elevated guideways 1) reduces the land required for transport to a tiny fraction of that required by the auto system, 2) permits each vehicle to be reused once a trip is finished, thus enabling one vehicle to serve the trips requiring many automobiles and markedly reduces the land required for parking, and 3) can attract in the USA at least ten times the ridership experienced on scheduled, all-stop transit. With its high energy efficiency and ability to use non-polluting energy sources *ITNS* is *the clear answer to a serious problem of industrialized civilization.*

20. Significant related Activity

- The British Airport Authority has a PRT system (ULTra) in operation at Heathrow International Airport to move people and their luggage from parking lots to terminals.

- The Masdar project in Abu Dhabi has installed a PRT system using the Dutch system 2getthere for a first-phase system, and a small number of vehicles are now in operation.

- During the summer of 2010 the government of India announced that they plan to install PRT systems in 17 of their cities.

- Shanghai plans to install a 20-km, 20-station, 500-vehicle PRT system.

- The Mexican Government awarded grants to a group in Guadalajara to develop a PRT system called MODUTRAM. The test system began operation in January 2012.

- On February 8, 2010, the Minnesota Department of Transportation released a "Request for Interest – Personal Rapid Transit (PRT): Viability and Benefits." It was available on www.dot.state.mn.us/transit/. On August 18, 2010 they held a workshop on PRT.

- On February 4, 2010, the organization Connect Ithaca, LLC, released a request to potential PRT suppliers for information for a Cost Analysis for a Preliminary Feasibility Study of PRT in Ithaca. The study was contracted by the New York State Energy Research and Development Authority and the New York State Department of Transportation. Their 216-page report of the study is dated September 2010.

- A brochure entitled "Podcars[30] – new travel on track: A sustainable travel option" was distributed by the Swedish Ministry of Enterprise, Energy, and Communications at the 3rd Conference on Pod Cars, held in Malmö on 9-10 December, 2009. It concluded that "there are a number of possible projects and a number of possible suppliers of pioneer (Pod Car) systems." ". . . pioneer lines for podcar traffic could be a reality in 2014."

- On August 31, 2009 the City of San Jose, California, released a Request for Proposals for San Jose Automated Transit Network FFRDC (Federally Funded Research and Development Center) Development Services to assist the City in the development of an Automated Transit Network (ATN). ATN is defined as Personal Rapid Transit. This is the first such effort in the United States since the Chicago PRT project. San Jose contracted with The Aerospace Corporation to help them identify the system they need, the report of which was released in fall 2012.

- The Korean steel company Posco has built and is operating a demonstration of their PRT system, called Vectus, in Uppsala, Sweden. In 2011 they broke ground on the installation of their system in the South Korean city Suncheon.

[30] Swedish name for Personal Rapid Transit.

- In Fall 2008 the City of Santa Cruz, California, invited potential PRT suppliers to submit qualifications to build a PRT system, which now makes four cities in California interested in PRT.

- In December 2008 Frost & Sullivan [28] released a 100-page "Executive Analysis of the Global Emergence of Personal Rapid Transit Systems Market," which concludes with the statement: "Currently, the growing global emphasis on implementing eco-friendly transport systems have been paralleled by technology advances and increased technological expertise. As a result, PRT has progressed from being a high-tech specification vision into a practical, cost-effective and flexible transport system."

- The New Jersey State Legislature funded a study very favorable to PRT. It was released in April 2007, and is available on several web sites.

- In March 2006 official research by the European Union concluded: "PRT contributes significantly to transport policy and all related policy objectives. This innovative transport concept allows affordable mobility for all groups in society and represents opportunities for achieving equity. . . PRT is the personalization of public transport, the first public transport system that can really attract car users and which can cover its operating cost and even capital cost at a wider market penetration. PRT complements existing public transport networks. PRT is characterized through attractive transport services and high safety. " [2]

- In 1998, after a year of study, the Advanced Elevated Rail Committee of a Cincinnati businessmen's organization called Forward Quest recommended my design over 50 other elevated rail systems, some of which existed in hardware and others were paper designs.

- During the 1990s the City of SeaTac, Washington, spent about $1 million on studies of PRT and await a viable PRT system. These studies were initiated in 1992 with a $300,000 grant as a result of two presentations I gave, one to a group of 60 officials in SeaTac, and the other to 40 members of the Washington State Legislature.

21. Development Strategy

With the assistance of colleagues, I developed a new HCPRT design, improved over prior work and now called *ITNS*. Experienced systems engineers and engineering companies need to be recruited to work with the company as soon as the needed funds are available. Our approach is as follows:

Seek first a modest-sized application where the decision process is relatively easy, and find investors who believe we can meet their requirements. At this writing, we have identified several dozen of such applications. The first real people-moving demonstration must convince a skeptical transportation community that *ITNS* will work as projected. We have several candidates, but they must be preceded by the following pilot program:

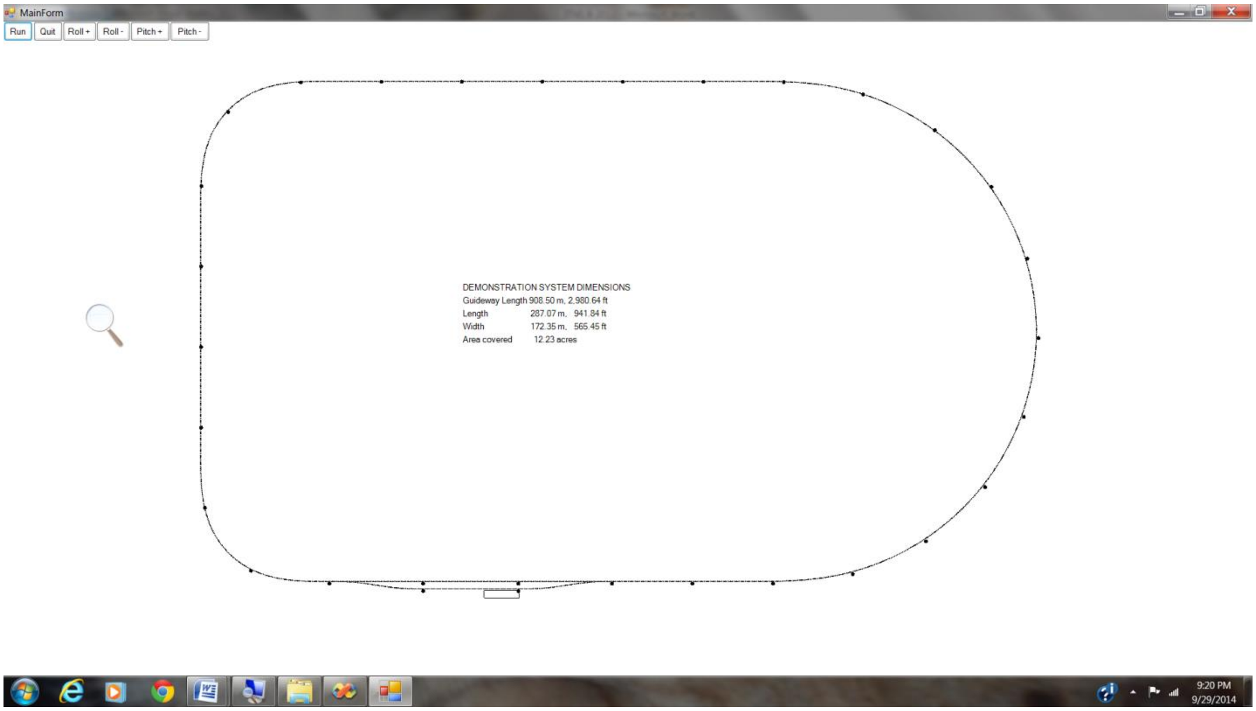


Figure 23-1. Pilot Program Guideway.

The minimum Pilot Program needed to ready ITNS for applications is a half-mile loop designed for a maximum speed of 35 mph and includes changes in elevation. We need no more than one off-line station and three vehicles to ready the system for production. The guideway of such a system occupies a space 942 feet long by 566 feet wide and covers 12.23 acres. Since it will be elevated, it occupies a very small fraction of that land. The engineering program has been defined in great detail and will enable full operation within 15 months of the notice to proceed. This facility will enable us to prove the specifications needed to assure success of the first people-moving application as quickly as possible and will provide a test bed for many years apart from applications for proving new design features. Drawing on many years of experience in theory, development, planning, design, and construction, we estimate that we can complete this program in 20 months for no more than US$30 million with ample allowance for site engineering on the first application and for worldwide marketing. We have completed sufficient planning for such a program to enable us to proceed immediately, and today's design tools will enable us to ready the final designs for manufacture much more quickly than formerly possible. In today's term, we are "shovel ready."

In cooperation with others, we will continue to

- inform consultants, planners, and financiers;
- perform planning studies for specific applications; and
- teach and promote the teaching of the engineering, economic, and planning sciences of *ITNS*.

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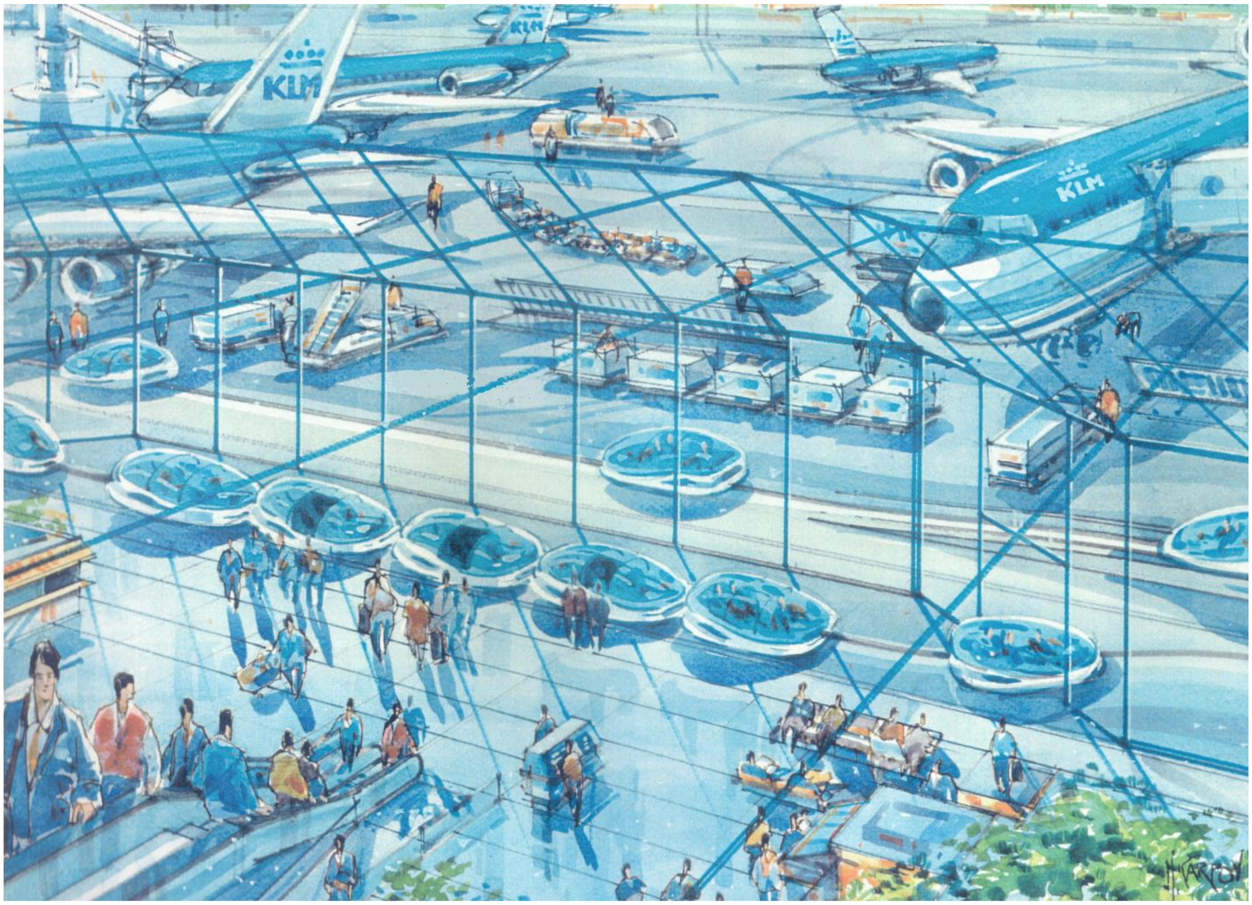
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Task #1. Management & System Engineering

1.1Program Goal

The goal of this task is to show that all requirements and specifications for the Intelligent Transportation Systems PRT system have been met before building the first application. A prototype **Test Track** will be built and operated. Three vehicles, having functioning cabins, will be built and tested.

1. Engineering Management and Systems Engineering

   1.1 Resolve policy issues with the client and thus agree on all design requirements.
   1.2 Become familiar with all codes and standards that may affect the design and inform the other engineers of findings of importance.
   1.3 Review and finalize the required subsystem specifications.
   1.4 Identify and negotiate contracts with subsystem suppliers.
   1.5 Establish all design loads.
   1.6 Maintain a library of relevant papers, reports, and books.
   1.7 Dynamic Analysis
      1.7.1 With correct vehicle mass and radius of gyration, perform dynamic analysis of lateral motion of vehicle passing through a diverge sections of the guideway under side wind and unbalanced passenger load to reconfirm lateral tire loads and stiffnesses, the position of switch arm, and the switch-rail flare needed to meet ride-comfort criteria.
      1.7.2 With correct vehicle mass and radius of gyration including sprung and damped passenger seat, perform dynamic analysis of pitch, fore-aft, and up-down motion of vehicle to verify main-support-tire and seat stiffness requirement to maintain ride comfort in presence of guideway irregularities and operation of the control system.
      1.7.3 With correct switch-arm inertia, perform dynamic analysis on operation of the switch mechanism to determine spring and rotary solenoid properties.

   1.8 Weight & Cost Control
      1.8.1 Develop model for estimation and control of vehicle weight.
      1.8.2 Develop model for estimation and control of system cost.
      1.8.3 Develop model for estimation and control of O&M costs.
      1.8.4 Monitor all design tasks to keep within weight and cost targets.

   1.9 Project Direction
      1.9.1 Educate and supervise all engineering teams.
      1.9.2 Develop and maintain the over-all schedule.
      1.9.3 Provide inter-task coordination.
      1.9.4 Work with clients.
      1.9.5 Manage

1.9.5.1 The office
1.9.5.2 Procurement
1.9.5.3 Engineering aids

1.10 Safety and Reliability
Responsible for system level safety and reliability issues.

1.2 Project Management

1.2.1 Mission Goals & Milestones

Mission
To provide necessary mobility in cities while reducing congestion, air pollution, energy requirements, the need for oil, and the land required for transportation.

Goal

To develop, produce, install, and maintain the world's leading PRT system in a variety of expandable applications in a highly competitive worldwide market.

Major Milestones

- Establish an organized, working team within six months.
- Complete the design of the basic components within 12 months.
- Have all components for the test system installed within 15 months.
- Have the test system operational in 20 months.
- Complete the test program in 26 months.
- Begin construction of the first application in 30 months.
- Complete and certify the first application within 48 months.
- Have four applications in planning, construction, or operation within 60 months.

1.2.2 System Components

Guideway Assembly	Basic truss guideway
	Switch rails
	Guideway-post bracket
	Post
	Foundation
	Cover & attachments
Vehicle Cabin	Rear shell
	Front shell
	U-shaped door
	Windows
	Seats
	Floor assembly

	Door motor assembly	
	Air conditioner	
	Heater	
	Ventilation system	
	Lights	
	Command buttons	
	Communications system	
	Television	
	Wiring system	
Vehicle Chassis	Frame	
	Main support wheels & brackets	
	Lateral support wheels & brackets	
	Switch assembly	Switch arms
		Switch wheels
		Rotary solenoid actuator
		Bi-stability spring
		Slaving mechanism
		Snubbers
		Proximity sensors
	Propulsion assembly	Pair of LIMs
		Pair of VFDs
		LIM carriage
	On-Board battery power supply	
	Parking & emergency brake	
	Shock-absorbing bumpers	
	Supports for power pick-up shoes	

	Supports for transmitter & receiver	
	Wiring system	
Station	Structure	
	Elevator	
	Stairway	
	Fare collection and destination	
	Ticket consoles	
	Lighting system	
	Motion detectors	
	Communications system	
	Sprinkler system	
Wayside power system	Dual power supply	
	Converter to 600 volt d. c.	
	Wiring	
	Power rails	
	Power pick-up shoes	
Control system	Leaky-cable communication line	
	On-board transmitters & receivers	
	Wayside transmitters & receivers	
	On-board digital encoders	
	Wayside magnetic markers	
	On-board computers	Speed control
		Switch operation
		Door operation
		HVAC operation

	Zone-control computers	Data collection & transmission
		Speed & Position monitoring
		Maneuver commanding
	Central computer	Empty-vehicle dispatching
		Traffic monitoring & control
		Data collection & interpretation
	On-board software	
	Zone-control software	
	Central software	
Maintenance shop	Structure	
	Lateral transfer table	
	Cleaning bays	
	Maintenance bays	
	Diagnostic instruments	
	Tools	
Vehicle storage facility	Section of guideway	
	Roof	

1.2.3. Use of Funds needed to prepare to Build ITNS Pilot System

Status:

In competition with 12 other offerings, the system won a $1,500,000 Design Study sponsored by the Northeastern Illinois Regional Transportation Authority. Subsequently it won additional international competitions in SeaTac and Cincinnati even before hardware was built. One full-sized automatically controlled, linear-induction-motor-propelled vehicle was designed, built, and operated on a 60-ft segment of guideway for thousands of rides with no failures — it worked exactly as intended. The design has matured through extensive analytical work, computerized analysis of all important issues, and many discussions with manufacturers.

Project Objectives:

The system has been defined in sufficient quantitative detail so that we can proceed immediately with the next step, which is to build and operate a full-scale pilot system large enough to permit vehicles to operate continuously around a loop at a maximum speed agreed to with the funder. We suggest 35 mph, in which case the loop will have about half a mile of guideway and will cover 12 acres. The facility needed to demonstrate to the world that these systems will be safe, reliable, and ready for applications will have one off-line station; three vehicles; a maintenance shop; and a classroom for training technicians, engineers, and planners and for presenting the system features to visitors interested in purchasing the system for specific applications. To show how applications will function and to provide an essential planning tool, we have developed a simulation program that can simulate a system of any configuration and any size. Using readily available visualization tools, we will show the decision maker exactly how a system would appear and work in any specific application.

Next Step:

We need to assemble a team of engineers capable of developing and documenting all specifications; procuring the components either through purchase or manufacture; supervising the manufacture and assembly of the system; subjecting the system to all necessary tests aimed at proving safety, reliability, and comfort; and training operating personnel. The work of building and operating the pilot system is divided into twelve tasks:

1. Management and System engineering
2. Safety and reliability
3. Cabin
4. Chassis
5. Guideway with posts and foundations
6. Guideway covers
7. Control
8. Propulsion and On-Board Power
9. Wayside power supply,
10. Station, maintenance, presentation facility
11. Test program
12. Planning and marketing

Each task requires engineers with different skills. A systems engineering group will direct the project and assure its safety and reliability.

This program is divided into two phases:

1) Assembly and education of the core team, development of the specification and construction documents, and determination of costs.
2) Procurement, construction, test, training, assistance with planning of applications, and marketing.

Use of Funds for the $5,000,000 first phase:

1. Secure the Test Facility site of approximately 12 acres.

2. Assemble and educate the core project team.

3. Retain qualified engineering and architectural consultants.

4. Prepare construction documents for the chassis, guideway, propulsion system, wayside power, station, maintenance facility, and classroom.

5. Complete the final specification of the control system to needs of the client.

6. Retain a cabin design firm to prepare the final design of the cabin.

7. Secure manufacturing partners for guideways, propulsion, chassis, and cabin,

8. Secure construction partners for site construction, guideways, off-line stations, and cabin

9. Update the detailed Project Schedule and detailed Project Cost Estimates.

10. Secure permits and approvals necessary for construction.

11. Prepare Test Facility Capital Funding Plan.

12. Prepare Test Facility Operations Plan.

13. Prepare Education/Outreach and Public-Information Plans.

14. Secure Test Facility Capital Funding.

15. Prepare marketing materials and initiate an extensive marketing program.

1.2.4. Engineering Program for Testing

Contents

The Test System

To develop proven plans and specifications needed to build and install ITNS we plan to build a test system, the guideway for which is illustrated below. A minimum test facility needed to demonstrate system safety, reliability, ride comfort, and performance requires a loop guideway with one off-line station and at least three vehicles. The flow of vehicles will be counterclockwise. As illustrated in Figure 1, the track has one large curve, a curve banked up to 8º and designed to permit vehicles to travel comfortably up to 15.7 m/s (35 mph), and two small banked curves designed to require the vehicles to slow down to 9 m/s (20.1 mph). There is one off-line station at a lower level about 1 m above the ground designed to handle three vehicles, with the incoming and outgoing transitions designed for 9 m/s. The large curve has an upward grade such that at its end the elevation is 4 m above its beginning. The track continues on the north side at the upper elevation around the northwest small curve, and then has a downward grade dropping it 4 m so that the southwest curve is at the level of the station. The distance around the oval track is 814 m (2670 ft or 0.51 mi). The off-line station adds an additional 95 m making a total guideway length of 909 m (2982 ft, 0.57 mi). In the north-south direction the loop spans 173 m (566 ft) and in the east-west direction 210 m (942 ft). The loop covers 3 hectares or 12.5 acres.

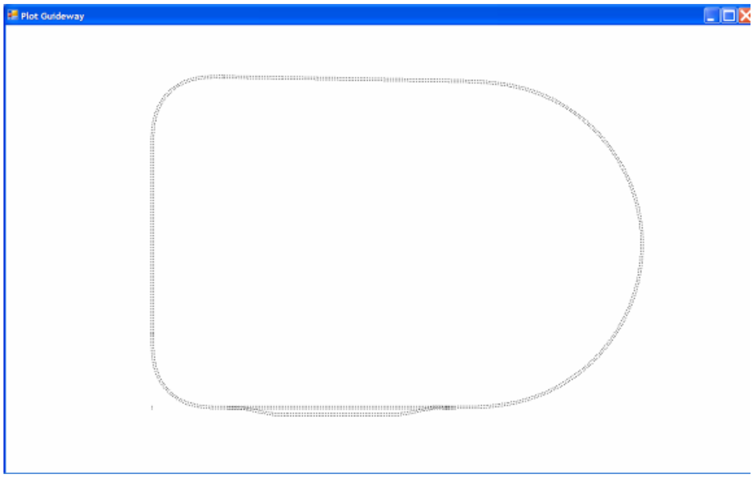

Figure 1. Plan view of test guideway.

Status of the Design

Dr. Anderson initiated the design of a new PRT system in 1981 following 13 years of activity in the field of PRT as a Professor of Mechanical Engineering, where he coordinated a 16-professor interdisciplinary task force on new concepts in Urban Transportation, chaired three international conferences on PRT, studied the work on automated transit systems underway in eight industrialized countries, consulted for governments and industry, and developed a textbook *Transit Systems Theory*, which laid out engineering science needed to guide the development of PRT system. With this background he developed comprehensive lists of criteria for PRT design and analyzed about 45 trade-off issues before initiating his design work.

Figure 2.

His design has been worked on and reviewed successively by five engineering companies including a $1,500,000 design study sponsored by the Chicago Regional Transportation Authority, and, before any hardware was built, won international competitions in Chicago, Seattle, and Cincinnati. Subsequently he designed and supervised the construction of the automatically controlled PRT vehicle shown in Figure 2 and the 60-ft (18.3 m) piece of guideway on which it operated flawlessly for thousands of rides as an exhibit at the 2003 Minnesota State Fair.

Required Tasks

1. <u>Policy Issues</u>

Trade-off analysis, codes, and standards provide most of the information needed to initiate a design, but there remains a range of issues that must be settled between the designer and the investor before detailed designed work is initiated. These issues involve

Safety and Security
Handicapped Access
Passenger Comfort and Convenience
Operational Convenience
Ticketing
Weather
Loading
Performance
Standards

We have prepared recommendations in each of these areas and are ready to discuss and settle them with the client.

2. <u>System Engineering and Safety</u>

An essential part of any program to commercialize an automated transit system is a program aimed at assuring the safety of the system. This requires understanding of all elements of the system as they by affect the safety of the passengers, and hence the safety team is also the systems engineering team. Safety has been the prime consideration in the development of ITNS from its initiation, and will be supported by an experienced engineering staff devoted to all aspects related to safety throughout the design and test program.

3. <u>The Guideway and Posts</u>

The guideway cross section is illustrated in Figure 3 and the side view in Figure 4. The guideway is a truss structure or space frame clamped to posts spaced 90 ft (27 m) apart, with expansion joints at the 20% point. The basic element of the design is a series of vertically oriented U-frames spaced 4.5 ft (1.37 m) apart to which the running surfaces, tube stringers, and diagonals are attached. The guideway has been subject to computer analysis by five different companies, which have led to successive improvements. With the current policy issues settled what remains to be done is to develop production drawings, verify the required sizes of the straight and curved elements when subjected to agreed loads, fabricate, install, and adjust.

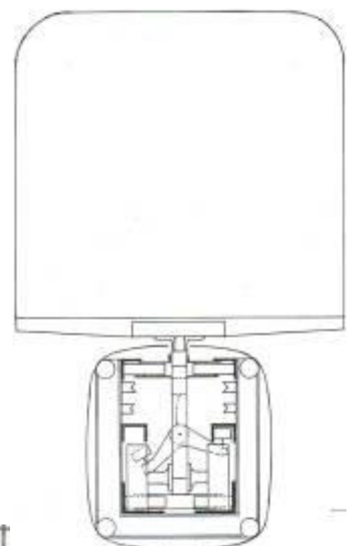

Figure 3.

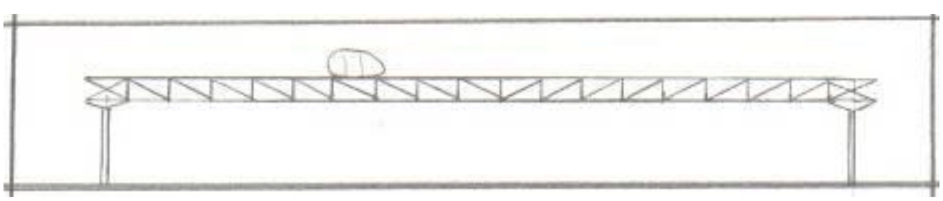

Figure 4.

4. The Guideway Covers.

The truss guideway will be covered as shown in Figures 3 and 5. The purposes of the covers are to

- Keep out ice and snow
- Provide electromagnetic shielding
- Reduce noise to nearly inaudible level
- Shield the tires from the Sun
- Shield the power rails from frost formation
- Eliminate differential thermal expansion
- Reduce air drag
- Provide access for maintenance
- Improve appearance

Figure 5.

What remains to be done is to select the fabricator, develop the final design details, fabricate, and install.

5. The Chassis

A drawing of the chassis, with an outline of the cabin on top is shown in Figure 6. Following five rounds of design, the remaining tasks are to develop a 3-D computer drawing of the chassis, perform the necessary finite-element analysis to insure the soundness of the design with the policy issues settled, build and fatigue test the switch arm, procure the components from known suppliers, fabricate and assemble.

6. The Cabin

The cabin is the signature of the system – the one most viewed component. Taking into account settled Policy Issues, the detailed specifications for the cabin have been developed, one of several known detail designers will be selected, the automatic door will be fatigue tested, and three cabins will be fabricated and attached to the chasses at the test site.

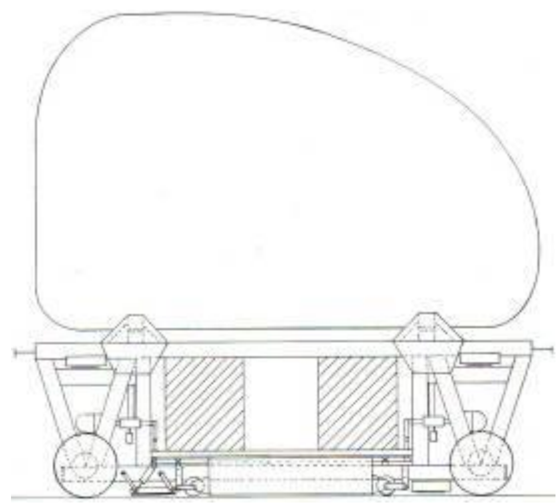

Figure 6.

7. The Control System

Based on 30-years of experience, the Chicago RTA $1.5 million design study, and subsequent work, the control system configuration has been defined. The system software necessary to control a fleet of PRT vehicles of any size operating on any three-dimensional network configuration has been developed, and the hardware components have been identified. What remains is, with knowledge of the current state-of-art, to settle on the various parameters, make the final selection of the components, partition and program the software into that required in the vehicle and wayside computers, assemble, and test.

8. The Propulsion System

Each vehicle will be propelled by a pair of linear induction motors (www.force.co.uk), each of which is driven by a standard variable frequency drive. The specifications have been written, subject to possible modifications based on settlement of the policy issues, and we are ready to procure and install the motors and drives from a known supplier.

9. Wayside Power and Guideway Electrification

The specifications for this equipment is known, mainly based on the Chicago studies, and we are ready to select the contractor who will do the final design, procurement of equipment, installation and test.

10. The Civil Works

The test site will need a station, a maintenance shop, and a test office. With the policy issues settled, we will select an architect to do the detailed design and construction supervision. The civil works also include the design and installation of the foundations for the guideway posts.

11. The Test Program

The test program is designed to verify safety, reliability, ride comfort, and performance. We have detailed lists of the subsystem and system tests required to produce proven plans and specifications.

1.2.5 The ITNS Development Program

1. Take time to understand the problem and the criteria for solution.
2. Understand, debate, and agree on the policy issues.
3. Walk through the tradeoff issues and the considerations that were needed to resolve them.
4. Assign lead individuals in the following areas:
    a. Systems analysis, specifications, application studies, and costing
    b. Safety and reliability
    c. Guideway structures
    d. Vehicle dynamics
    e. Cabin design
    f. Chassis design
    g. Power and propulsion
    h. Control
    i. Station & maintenance-facility design
    j. Test program
    k. Procurement and subcontracting
    l. Marketing and sales
5. Define the analysis, design, and test program needed in each area.
6. Accomplish the detailed design tasks and supervise subcontractors.
7. Supervise the design and construction of the test facility.
8. Plan and conduct the necessary test program to prove performance, safety, and reliability.
9. Train operating and maintenance personnel
10. Develop marketing materials
11. Educate planners and decision makers
12. Procure orders for systems
13. Work with consultants to perform application studies
14. Work through and resolve legal and governmental issues.

1.2.6 Duties of Lead Members of the ITNS Engineering Team

Systems Engineer

- Assist the Director of Engineering in coordination and follow-up on all elements of the Pilot Program.
- Assist the DE in resolving with the client all policy issues.
- Maintain a file of system requirements and design criteria.
- Identify all codes and standards to which the system must comply.
- Review ASCE APM Standards for compliance where relevant.
- Review and finalize all sub-system specifications.
- Negotiate contracts with major sub-system suppliers.
- Maintain and up-date a system life-cycle-cost model.
- Maintain a library of relevant papers, reports, and books.
- Assist in establishing a training program for planners, engineers, and technicians.

Safety Engineer

- Review and up-date prior work on hazards analysis, fault-tree analysis, and FMEA.
- Tabulate data on component reliability from available data sources.
- Estimate system dependability and hence safety using available model.
- Estimate component MTBFs that meet system-dependability criterion at minimum life-cycle cost.
- Examine all potential fire hazards and recommend solutions.
- Examine in detail the safety implications of component and subsystem designs, and recommend changes when necessary.
- Become conversant in safety technology, for example through the System Safety Society.

Lead Mechanical Engineer

- Demonstrate proficiency in computerized design tools for static and dynamic analysis.
- Demonstrate proficiency in supervision of finite-element analysis.
- Supervise the design and fabrication of the vehicle passenger-carrying cabin.
- Supervise the design and fabrication of the vehicle chassis.
- Supervise the design and fabrication of the guideway covers.
- Supervise the design and fabrication of the lateral vehicle-transfer table.
- Supervise the design of the computerized jigs & fixtures needed to fabricate curved sections of guideway and the robotic guideway welding system.
- Document.

Lead Electrical and Control Engineer

- Become familiar with existing work on ITNS control system hardware and software.
- Supervise the design, fabrication, installation, and test of the control system.
- Become familiar with existing work on ITNS LIM propulsion system and supervise its specification and installation.
- Supervise work on specification, procurement, and installation of the on-board and way-side power systems.
- Document.

Lead Structural Engineer

- Beginning with existing work on the guideway design, develop a computer model to analyze all stresses and deflections under given loads in both straight and curved sections of the guideway, posts, and post-guideway bracket.
- Document the design of the guideway, post, and post-guideway bracket design.
- Assist in identifying the guideway manufacturer.
- Supervise fabrication.

Lead Civil Engineer

- Survey the pilot-system site and provide a drawing showing the location of the posts, the wayside power system, and the structures.
- Supervise the design and construction of the station, maintenance facility, visitor center, and training center for the ITNS pilot system.
- Supervise the design and installation of the foundations.
- Supervise the landscaping of the pilot-system site.
- Document.

Lead Test Engineer

- Become familiar with the planned test program.
- Become sufficiently familiar with the system's components to be able to supervise the necessary tests.
- Supervise the test program.
- Document.

Lead Planning Engineer

- Become sufficiently familiar with the existing system-simulation tool to be able independently to perform system simulations of increasing complexity.
- Work with planners in planning the details of applications.
- Review and up-date existing system economic model.

1.2.7 Engineering Tasks and Skills needed to Commercialize *ITNS*

Area of Responsibility	**Tasks**	**Skills Required**
Systems Engineering	Responsibility for coordination of all aspects of the design.	Proven experience in systems engineering.
Standards	Review all applicable standards and report to the project managers specific system and component requirements	Experience in dealing with engineering standards
Safety & Reliability	Responsibility for all aspects of system safety, dependability, hazard analysis, fault-tree analysis, and failure modes and effects analysis. Documentation of all procedures used to insure safety in keeping with accepted standards for operation of automated transit systems. Based on existing information and methodology, develop and maintain a model for calculating system dependability.	Strong experience in the areas defined by the task description.
Weight & Cost Control	Develop computer models for weight control of the vehicle and cost control of the system. Maintain contact with all subsystems designers to keep models up to date. Report to project director and operations officer any deviations from target weight and cost. Develop model for calculating operation and maintenance costs.	Industrial engineer with at least five years of experience. Strong analytical ability required.
Vehicle Dynamics	Perform lateral dynamic analysis of vehicle moving through merge and diverge sections of the guideway with the worst combination of side loading (wind + centrifugal) + maximum unbalanced load to verify stability, required maximum tire loads, tire stiffnesses, switch placement, flared switch rails, and ride comfort requirements.	Mechanical engineer having experience with dynamic-analysis computer tools.

Finite-Element Analysis	Perform FEA, finalize the specifications of the post-guideway bracket, the switch arm, and the chassis-cabin attachments.	Extensive experience with FEA tools.
Test Program	Review available descriptions of all necessary tests, define the test program, supervise all testing and document the results.	Chief test engineer with proven experience in engineering testing.
Control System	The software for the system and vehicle control has been defined and the required types of hardware have been identified. Based on this information, complete the design of the operational software and hardware, supervise procurement and installation of the components in the test system, update the test plan, and supervise testing.	Operational computer software and hardware experience. Understanding of differential equations and engineering mechanics.
Propulsion, & Power System	Specify LIM-VFD system and power-supply and distribution system, both on-board and at wayside. Identify suppliers and work with them to finalize the designs. Supervise installation in test system.	Electrical engineer with experience in power systems.
Guideway, Posts & Foundations	Perform computer analysis of the guideway & post design. Develop foundation design. Coordinate space requirements inside guideway with the chassis designer. Develop the final design and drawings. Specify and supervise design of computerized jigs, fixtures, and robotic-welding equipment for guideway fabrication.	Structural engineer with experience in use of computer structural analysis and structural design tools.
Vehicle Chassis	Design includes wheel-axle-bearing assemblies, LIM & VFD, shock absorbers, switch assembly, parking and emergency brake, mounting of power-pick-up shoes and transevers, equipment compartment for control and a/c components, frame, wiring, interface with cabin. Develop final design drawings, find necessary suppliers, and supervise fabrication of the chasses.	Mechanical engineer with vehicle-system experience including computer tools for dynamic analysis of vehicle systems.
Vehicle Cabin	Review the design requirements. Develop bid documents and find cabin fabricator. Work with fabricator to develop and build the final design. Supervise fabrication. Consider styling, structural design, thermal design, material selection, human factors, HVAC, aerodynamics, seat, automatic door operation and fatigue testing, lighting, push-button controls, interface with chassis.	Mechanical engineer with experience in vehicle design.

System Planning & Design	Responsible for planning and design of specific applications including computer-graphics simulation of portions of system, and operational simulation to determine system performance and size and layout requirements. Determine ridership. Coordinate and negotiate with clients. Working with power engineer, specify power feed to system	Transportation engineering preferably with prior experience with PRT systems. Strong analytical ability.
Director	Overall direction, supervision, and education of systems engineering team.	Extensive experience in quantitative PRT systems analysis, planning and design.
Operations Officer	Responsible for project planning, daily coordination, facilitation and expediting.	Engineering background with experience in project planning and expediting.
Contracts and Purchasing	Responsible for negotiating contracts and for purchasing of components and subsystems.	Experience with engineering contracts and purchasing.
Support	Develop and support means for maintaining financial and accounting records and project controls. The human-resource functions also fall under this responsibility.	Previous experience in support management.

A winter weather testing project

1.3 The Business

1.3.1 Intellectual Property Issues related to ITNS technology

The technology proposed is of the generic class for over 40 years called Personal Rapid Transit. There are a great many ways to design such a system, many examples of which have gone into full-scale testing and in a few cases into operation, but with features that severely restricted the market and have caused almost all of them to be ultimately rejected. During the 1970s, the most promising PRT system and the exception was developed by The Aerospace Corporation[31]. The University of Minnesota Task Force on New Concepts in Transportation, which I coordinated, proposed in 1973 that this system be tested at the Minnesota State Fair Grounds. By charter The Aerospace Corporation cannot manufacture, so they attempted every way they could to find a manufacturing company that could carry their PRT system into operation, but were not successful mainly because manufacturing companies prefer to exploit technology they developed internally.

After engaging in the field of PRT for 13 years, and at a time when lobbying from conventional transit sourced had prevented any significant government action on PRT, I initiated a new design for which the following patents were assigned to the University of Minnesota and licensed exclusively licensed to my company, then called Automated Transportation Systems, Inc.

U. S. Patent Number	Issue Date	Title
4,522,128	June 11, 1985	Switch Mechanism
4,671,185	June 9, 1987	Switch Mechanism
4,665,829	May 19, 1987	Guideway Construction and Method of Installation
4,665,830	May 19, 1987	Guideway Construction and Method of Installation
4,726,299	Feb. 23, 1988	Method & Apparatus for Controlling a Vehicle

The basic physical characteristics that define a personal rapid transit system are:

1. Small vehicles occupied by people grouped by choice or one person alone.
2. An exclusive guideway with the stations on sidings off the main line.
3. Fully automated control.

In addition to these characteristics, our analysis of many alternatives led to the following specific characteristics of my design:

1. The vehicles ride on top of the guideway with the chassis inside the guideway. They are supported vertically and laterally by means of commercially available wheels.

[31] Jack H. Irving, Harry Bernstein, C. L. Olson, and Jon Buyan, 1978. *Fundamentals of Personal Rapid Transit*, Lexington Books, D. C. Heath and Company.

2. To minimize guideway weight and size, the smallest and lightest-weight vehicles are used and are designed to accommodate one wheelchair passenger plus an attendant.
3. To further minimize guideway weight, size, and cost; the guideway is narrower than the vehicle, thus requiring a novel vertical chassis, which was also used by The Aerospace Corporation.
4. A steel-truss guideway clamped to support posts and covered in a way that minimized weather problems; provides electromagnetic, noise, and solar shielding; minimizes side air drag; provides for maintenance; and permits a customized appearance. Features of our design permit accurate alignment of adjacent sections of guideway and ease the problem of assembly and replacement of guideway sections.
5. Propulsion and normal braking are by means of a pair of commercially available Linear Induction Motors activated by commercially available variable-frequency, variable voltage drives and powered by wayside power sources via power rails and sliding contacts.
6. Parking and back-up braking by means of ball-screw-actuated high-friction brake pads that bear down on the running surface.
7. Automated switching using no moving parts in the guideway with switch arms activated by rotary solenoids and made bi-stable by means of leaf springs.
8. Hierarchical, asynchronous, point-following control that permits indefinite system expansion. Leaky cables provide communication between vehicles and wayside, and digital encoders on the vehicles measure position and speed.

To assemble the system quickly, efficiently, and in a way that meets a great many requirements; including all of the loads that may be applied to the vehicles and guideway, industry standards that must be met, and extreme environmental conditions; has required a great deal of engineering analysis and development of analysis tools. I have 1560 pages of engineering work that performs these analyses and documents the necessary computer programs. This forms the intellectual property that defines our design. The fact that our design is unique in the world is a result of having rigorously followed comprehensive and specific rules of engineering design.

1.3.2 Plan for Commercialization

Contents

1. Introduction

The purpose of this document is to explain the need for a new form of urban transportation suitable for a sustainable future and to describe how we plan to meet the need. We discuss the characteristics of the new system, the market for it, some background information that has led to the present situation, the kind of business that can grow out of the new ideas, and our interest in pursuing that business. The ideas that led to the current status of the system proposed grew out of research, teaching and other activities at the University of Minnesota led by Professor J. Edward Anderson, which led to development of an optimized form of Personal Rapid Transit (PRT). Many papers and volumes have been written about PRT and many more about the history of the idea and the various systems called PRT. He has worked in the field of PRT since 1968, first as a mechanical engineering professor interested in contributing to its advance and, after 13 years in the field, as a developer of a specific system. Throughout this period he gave many courses and lectures related to PRT and investigated first hand every reasonable PRT system development program in the world. His motivation for continuing in a difficult field resulted mainly from his work in coordinating and lecturing with many others in a course called “Ecology, Technology, and Society,” which since 1970 was taught for 18 years to over 4000 students, many of whom changed their career directions as a result of exposure to a wide range of energy and environmental problems in an interdisciplinary setting.

2. The Problem of Urban Transportation

The alternatives to the automobile considered today for movement of people in cities are heavy rail, light rail, buses, and ferries. Electrically operated heavy-rail systems, called subways, Metros, etc., were introduced in the United States in New York, Boston, Philadelphia, Cleveland, and Chicago over 100 years ago. In recent times such systems have been built in San Francisco, Los Angeles, Washington D.C., Atlanta, Baltimore and Miami as well as in many cities in other countries. These systems have the advantage that their guideways are exclusive and hence can offer much higher average speeds than surface-rail systems (streetcars or light-rail systems) operating in mixed traffic. But they have the disadvantage of extremely high cost, which means that few lines can be built.

Because of high cost, advocates of conventional rail transit decided in 1975 that the surface-level streetcar was the only reasonable alternative available, and they came up with the brilliant marketing strategy of calling it “light rail,” notwithstanding that the cars are generally much heavier than heavy-rail cars! The rails can be “light” only if the cars travel at slow speeds, as did urban streetcars, which were introduced in the 1880s and expanded rapidly until 1917, when the mileage of active track declined as rapidly as it rose because of competition from the automobile.[32] When “light-rail” cars are caused to travel at 50 to 60 mph between stops, as they now do, the rails must be as heavy as those of the so-called heavy-rail systems. Because of operation on streets rather than on exclusive rights of way, light-rail systems cost roughly one third of heavy rail systems. They are therefore being considered and built in many cities; however, the characteristics of these systems cause problems:

1) They are subject to the cross traffic of the city, which slows auto traffic thus increasing congestion and causes accidents.

2) The trains must stop on line and at every station. In so doing on city streets, the practical minimum schedule frequency is roughly 6 minutes or only 10 trains per hour. To achieve say the capacity of one freeway lane, which is about 2000 passengers per hour, each train must accommodate at least 200 people. This results in large cars now weighing over 100,000 lbs each – so heavy that the roadway underneath must be reinforced. Data show[33] that the busiest light-rail line in the United States attracts only a fraction of the traffic of one freeway lane.

[32] B. S. Pushkarev, J. M. Zupan and R. S. Cumella, *Urban Rail in America*, Indiana University Press, Bloomington, 1982, page 6.
[33] http://www.publicpurpose.com.

3) Because the trains must stop at every station, the stations must be placed at least one mile apart to achieve an average speed of even 20 mph. Such a speed is usually not competitive with auto average speeds. Slower speeds and long walks to a station result in disappointing ridership, so low that the data show that such systems have virtually no effect on congestion, which is customarily the main argument given to the public for building them.

4) The system must be heavily subsidized because of low ridership and high costs. The capital costs are paid entirely out of public funds, and on the average about two thirds of the operating costs are publicly funded.

The conventional alternative to urban rail is the bus, which was first introduced around 1910. In most cities, buses are the primary means of movement for people who can't afford automobiles – a dwindling portion of the population. Ridership is low mainly because it takes typically one to two hours longer each day for the average person to travel by bus rather than by automobile. Buses are much cheaper to acquire than rail systems, but because of frequent stopping, jerky motion, and diesel fumes they don't attract as much ridership as the heavier, smoother-riding, rail vehicles. However, because the service characteristics of both buses and rail systems are so inferior to those of the automobile, transit use in all but a few cities of very high density remains below three percent, albeit increasing as a result of high gasoline prices.

There is a strong need to do something about increasing congestion. Many metropolitan areas are planning to spend over 60 percent of their transportation budgets over the next few decades on conventional transit[34], notwithstanding that their own data show that such an increase in the transit budget will result in at most less than one percent more urban trips taken by transit. With only the present options available, the future looks bleak. We are advised to tolerate increasing congestion and we accept unhealthy levels of air pollution, notwithstanding technical advances in emission reduction. Transportation departments are helpless to provide adequate mobility for an aging population living in the vast lower density areas of our cities and we continue to accept in the United States millions injured and roughly 40,000 people killed each year in auto accidents. There is a clear need for a new alternative, which requires understanding of fundamental ways to decrease costs while markedly increasing ridership.

3. The Solution and its Benefits

The direction public transportation must head has been known since a series of studies funded by the U. S. federal government appeared in the late 1960s that showed that if only conventional transit is deployed congestion will continually worsen, but if new personal rapid transport (PRT) systems could be widely deployed, they would attract enough riders to decrease congestion.[35] Over the past forty years the problem of design of an optimum PRT system has been studied, not only on paper but by building experimental systems. The leading example of PRT today – the one developed by Dr. Anderson[36] – has been under development for over three decades.

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[34] ibid
[35] W. F. Hamilton and D. K. Nance. "Systems Analysis of Urban Transportation." *Scientific American*, July 1969.
[36] It won competitions in Chicago, SeaTac, and Cincinnati.

PRT minimizes capital cost by using many small, lightweight, automated vehicles spread over a guideway, which can be of very light weight because its weight is proportional to the vehicle weight per unit of length.[37] To keep the vehicles separate from common road traffic, the guideways are usually elevated, which markedly increases safety and decreases trip time. The land saving is great because land is needed only for posts and stations. PRT maximizes ridership by using relatively small off-line stations. Such stations have the following outstanding advantages:

A *PRT* Off-Line Station

High Throughput. Since the vehicles do not stop on the mainline, if the same propulsion and braking system used with automobiles were used, the mainline throughput would be equivalent to one freeway lane of traffic. However, by using automatic control and linear electric propulsion and braking, throughputs equivalent to at least three freeway lanes become practical.

On March 27, 1973 Frank Herringer, then Administrator of the Urban Mass Transportation Administration, told the U. S. House Transportation Appropriations Subcommittee: ". . . a high-capacity PRT could carry as many passengers as a rapid rail system for about one quarter the capital cost." A "rapid-rail" system is an exclusive-guideway rail system that can, based on safety considerations, accommodate at least three times as many trains per hour as a surface-level rail system. The Congressional Record in which Herringer's statement is made is duplicated on page 11 of the paper "An Intelligent Transportation Network System (ITNS)," which can be found on the above-named web page. His statement was made 36 years ago and was backed up by detailed analysis by his R&D staff. As everyone knows, the technology of control and computation has advanced markedly since 1973. On page 10 of the ITNS paper an example calculation is given showing why optimized or "high-capacity" PRT will carry substantially more people per hour than a surface-level rail system, which can deliver no more than 10 trains per hour past a given point. The reason high-capacity is practical with small vehicles is the same reason freeways are attractive: no stopping on line and nonstop trips.

Close Station Spacing. Since vehicles do not stop on line, adding stations does not reduce the average trip time. Therefore stations can be placed much closer together than practical with conventional rail systems, thus making the system convenient to many more people. In many cases, adding stations to an existing guideway reduces the break-even fare.[38]

Nonstop Service. By using vehicles of the smallest practical size occupied by either one individual or a small group travelling together by choice to a given destination, each trip is nonstop, thus minimizing both trip time and the number of vehicles required.

Little or No Wait. Computers reroute vehicles from stations with a surplus to stations with a deficit, hence they wait for people any time of day or night rather than requiring people to wait for vehicles.

[37] J. E. Anderson, "The Structural Properties of a PRT Guideway."

[38] J. E. Anderson. "Optimization of Transit-System Characteristics."

Excellent Service at All Hours. The patrons travel in seated climate-controlled comfort and in private, either alone or with chosen companions at any time of day or night.

Vehicles run only when there is demand, which markedly increases energy efficiency and decreases operating costs.

The use of reliable, in-vehicle switching, which has been developed, means that the guideways can be arranged in interconnected networks covering areas rather than just a corridor. Transferring, which is a major deterrent to conventional transit, is eliminated. The availability of highly reliable components used in redundant pairs and fully automatic control means that such a system is fully achievable today and will provide a level of safety and reliability well beyond that possible with conventional systems at line capacities up to the equivalent of three freeway lanes of travel.[39] Personal security is achieved in stations by providing adequate lighting, motion sensors, television monitoring, two-way communication, and because the time spent in the station is very short. Since the trip time will be less in the central city than possible even with automobiles (they must stop at stop lights), the ridership can be expected to be many times higher than attained by conventional transit.

The following system features result in substantial benefits for the community, which make building and deploying the system an attractive business.

- High levels of transportation availability using a tiny fraction of the community's land.
- No direct air pollution.
- High energy efficiency – at least four times better than an average auto.
- Safety for both passengers and nearby pedestrians and motorists.
- Substantial reduction in transport noise.
- Minimum cost per passenger-mile, resulting in many cases in deficit-free operation.
- Accessibility to transit service for a large fraction of the urban population.
- Very little disruption during installation.
- New freedom for older and mobility-impaired individuals.
- Livable higher density, meeting visions of new urbanites.
- A substantially improved urban environment.

As we enter the age of the end of cheap oil and as increasing carbon dioxide in the atmosphere is becoming more and more widely recognized as a serious problem, the demand will continue to increase for a form of transit that can be deployed widely and inexpensively, that is time-competitive with the automobile, that can be run on renewable energy, and that need not emit carbon dioxide or aerosols.[40] This increasingly makes the business of supplying PRT systems more and more attractive. We can, as has been said, "do well while doing good."

The design of Dr. Anderson's PRT system, ITNS, was accomplished over many years starting by listing a comprehensive set of requirements and physical characteristics derived from 1)

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[39] J. E. Anderson, "PRT – Matching Capacity to Demand."

[40] While less well known, the phenomenon of "Global Dimming" due to increasing aerosols is cooling the atmosphere.

comprehensive interdisciplinary analysis of the needs of the traveling public and the community; 2) mathematical analysis of the physical characteristics of a transport system required to minimize life-cycle cost per passenger-mile; 3) involvement in and study of numerous real-world planning studies; 4) careful study of about $2 billion worth of work on experimental systems built during the 1970s in seven industrial countries, and 5) feedback from hundreds of presentations given at home and abroad. Over $32,000,000 of sweat equity and treasure has gone into ITNS with contributions from dozens of people and four major corporations.[41]

A remarkable finding[42] was that the characteristics of a transit system that minimize cost also maximize ridership. Most of the new transit-system designs, while automated to reduce operating cost, still used the service concept of the 19th Century – large vehicles stopping at all stations. The real breakthrough came when several innovators realized that a complete break with the past would be needed if they were to be able to compete economically with auto transport. Today, technology has reached the point where the new system is completely practical and indeed during the 1990s the National Automated Highway System Consortium demonstrated the key concept of safe, reliable operation at fractional-second headways.[43]

A point of fundamental importance is that the software system needed to operate a PRT system of any size and configuration has been developed[44],[45]. Dr. Anderson's design, shown in the figure to the right, is the industry leader in the field of PRT, having won competitions in SeaTac, Chicago and Cincinnati, while no other similar system won any competitions.

Why Small Vehicles can Yield Large Capacity

Imagine driving your car down a freeway lane. Imagine stopping in the lane, letting a person out and another person in. How far behind must the next car be to make such an operation safe? The answer is *minutes* behind. Surface-level light-rail trains operate typically no closer than 6 or 7 minutes apart, heavy-rail systems on their exclusive ways operate as close as two minutes apart, and buses operate as close as one to two minutes apart.

[41] Davy McKee, Raytheon, Stone & Webster, and Hughes.

[42] J. E. Anderson, "Optimization of Transit System Characteristics."

[43] Corinna Wu, "Look, ma, no hands! – automated highway system." *Science News*, September 13, 1997.

[44] "developed" here means that we have worked out all of the mathematics and logic needed to control vehicles automatically; to command them to perform the necessary acceleration, deceleration, slipping, and speed-change maneuvers; and to command the movement of empty vehicles needed to run a PRT network system of any complexity. We have tested these algorithms by subjecting them to exhaustive headway checking. What is left to do is to install the code into separate computers in vehicles, in wayside zone controllers, and in central computers along with the necessary sensors and communication means in a real, full-scale application.

[45] J. E, Anderson, Some History of PRT Simulation Programs.

On the other hand, automobiles on freeway lanes operate on the average as close as two *seconds* apart and often considerably closer notwithstanding a highway safety recommendation of three-second spacing. The maximum throughput of a freeway lane is a little over 2000 people per hour, assuming an average occupancy of 1.2 people per car. To get the same throughput, a light-rail system operating on a 6-minute schedule or ten trains per hour must carry 200 people per train. This is why on-line-stopping leads to large vehicles.

The difference between conventional transit and autos on freeways is *on-line vs. off-line stopping*. PRT uses off-line stations similar in function to the ramps leading off and on a freeway. Off-line stations enable PRT to can carry very significant numbers of people per hour using the smallest sized vehicles. The smallest-size vehicles are most efficient because the daily average auto occupancy in the United States is only about 1.2 people per auto. That is the way people chose to travel if they have a choice – from where they are to where they want to go when they want to go, and that is most often either alone or with only one or two other people. PRT accommodates basic human travel needs rather than requiring people to accommodate to the needs of the transit system.

Braking and accelerating through wheels plus manual control limit automobile systems to a minimum average throughput of about one vehicle every two seconds. By using non-traction propulsion and braking, i.e. linear induction motors and electronic control, PRT vehicles can average two vehicles per second, which is an improvement of a factor of four, giving an average throughput in people per hour equivalent to at least three freeway lanes of auto travel.[46]

4. Background and Status of the Development Program

The development of ITNS has its origins four decades ago when the principal designer, Dr. J. Edward Anderson, became interested in PRT as a professor of Mechanical Engineering at the University of Minnesota. He organized a 15-professor interdisciplinary task force on new concepts in urban transportation; chaired three international conferences on PRT; edited over one hundred papers on PRT that resulted in published proceedings; visited people working on PRT in Canada, England, France, Germany, Japan, Sweden, Switzerland, and the United States; studied their reports; worked for nine months at the Colorado Regional Transportation District in a large study of transit alternatives; worked for 18 months as a consultant at Raytheon Company on a PRT development program; taught courses on transit systems analysis and design; wrote the textbook *Transit Systems Theory*[47]; debated U. S. DOT officials on transit alternatives, and consulted for the State of Indiana on a study of PRT for Indianapolis. This provided 13 years of in-depth experience in all aspects of PRT, which enabled him to accumulate detailed criteria lists before initiating the design of the current system.[48] Moreover, Dr. Anderson followed a rigorous design process.[49]

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46 "Safe design of PRT systems."

47 Available on www.advancedtransit.org

48 "The Future of High-Capacity Personal Rapid Transit."

49 "Rules of Engineering Design."

An important conclusion reached was that, given the political environment as it relates to transit development, the only place where a successful PRT system development program could mature was in a research university. Industry required too soon a return on investment to do the necessary work and government had too many agendas to lead a successful PRT development program. That solid beginning has been the sustaining factor in continuing on the road to ITNS.

With that beginning, while CEO of Taxi 2000 Corporation, ITNS has been under continual development for over 25 years with the aid of four major corporations. In 1990 it was funded by a $1,500,000 design study sponsored by the Northeastern Illinois Regional Transportation Authority (Chicago RTA)[50]. Beginning in January 2002 an additional $800,000 in private investment was received. In the six-month period beginning in September 2002 one prototype vehicle was built and operated regularly for thousands of people since April 10, 2003 under automatic control on a 60-ft section of guideway powered by wayside batteries with no failures. The design has been thought through and criticized again and again. Detailed specifications have been prepared on the components in terms of a set of Requests for Proposals for final design and construction of the cabin, the chassis, the guideway, the control system, the propulsion system, the wayside power, the station, and the maintenance facility. Our program for building a full-scale demonstration system is summarized in Appendix C.

People often ask why it has taken so long. A major reason is that ITNS is so much better than existing transit that it has been a threat to proponents thereof. In 1974 as a result of heavy lobbying from the rail industry, a budding federal program to develop high-capacity PRT was canceled and subsequently cities have been given no encouragement to consider new systems. Subsequently, because of a growing realization that PRT is an essential and eminently doable technology, work has continued encouraged by small private groups and organizations. The Chicago RTA program of 1990 was our great hope that PRT would be realized, but largely because of a mixed bureaucratic agenda that program went sour and we had to start over. Today, largely because of the Internet, a growing and essential constituency of support has been developing that will insure success.

5. Competition

There are three types of competition for ITNS:

1. **The Automobile. ITNS** will compete with the auto in many instances in which the nonstop trip, no-transfer service, and very small wait time will make it advantageous for certain trips. We have estimated in Appendix D that it is reasonable to expect in the denser portion of cities that, because of the cost and inconvenience of parking, as much as one third of auto travel may be diverted to ITNS.
2. **Conventional Rail Transit such as Light Rail Transit.** Competition from this source is not a result of superior performance or cost effectiveness, but a result of heavy lobbying and the attractive power of large federal grants. Once the short-walk, short-wait, private, seated-ride, secure, nonstop travel features of PRT as well as its high capacity and low cost are recognized, it can be expected that interest in conventional rail will diminish substantially.

[50] All the reports of that study are available.

3. **Alternative forms of PRT.** In January 2002 the Advanced Transit Association released a report on all of the PRT system development programs (www.advancedtransit.org) for which they could find information. Moreover, the web page http://faculty.washington.edu/jbs/itrans/ discusses all of the automated guideway transit and monorail systems either in operation or under development anywhere in the world. In 1993, following a three-year process and 12 proposals, the Chicago RTA selected Dr. Anderson's system as the PRT system into which they were willing to invest $20 million, with Raytheon Company as prime contractor also agreeing to invest $20 million. But by choosing to depart from Dr. A's design Raytheon built a demonstration system that was too large and too expensive to find a market. In 1992, inspired by the Chicago work, a $300,000 study of alternative means of moving people was completed at the Seattle-Tacoma International Airport in which buses, light rail, large-vehicle people movers, and PRT using Dr. A's specifications were examined. Even though the consultant arbitrarily quadrupled its costs, a 17-member steering committee voted unanimously for PRT. The most comprehensive comparative study of all of the alternative elevated rail systems for which information was available in 1998 was performed under private financing by the Advanced Elevated Rail Committee (www.skyloop.org) of Forward Quest, a businessmen's organization in the southern portion of the Cincinnati Metropolitan Area. On their web page, they explain the comprehensive process they used to select the system designed by Dr. Anderson out of over 50 elevated rail systems as their preferred circulation and distribution mode. Work on all of the other forms of PRT now active were inspired by and started after the Chicago RTA project.

   The most prominent in 2009 are ULTra (www.atsltd.co.uk), Vectus (www.vectusprt.com), and the Dutch system 2getthere, which was selected for the first phase of a PRT project called "Masdar" in Abu Dhabi, United Arab Emirates. From data on their own web page, ULTra is a low-capacity, small-range system not suitable for cities where snow falls in the winter. The Vectus guideway is a half meter diameter pipe to which the running surfaces are attached with linear induction motors in the track. It will be substantially more expensive than a truss guideway with linear induction motors in the vehicles. 2getthere is a wire guided system designed to operate on surface streets.

6. Barriers to Market Entry

Once PRT is in commercial operation, it can be expected that some large companies now in the automated transit business will try to design competitive systems. Based on expired patents, they will in time be able in time to duplicate our hardware; but the software that drives the vehicles is critical to any successful PRT system and, starting from scratch with no prior experience, that takes more time to produce. Others will eventually enter the PRT field, but only after expenditure of larger sums and time than they will have initially anticipated. It takes a great deal of patience to wade through a necessary and large volume of relevant literature presently not easy to obtain. Moreover, most inventive engineers who accept the challenge of designing a new transit system will find greater pleasure in starting with their own ideas and will convince their managers that their approach is best. When they get deeply into the design they will have too much committed to make fundamental changes. Successful PRT design required a great deal of study and observation before committing to a specific design. We have followed such a path.

7. Funds Required if ITNS were to be Created Today by a new group of Engineers

ITNS unique among PRT systems in that it has won every competition it has entered. There are two basic reasons:

1. As mentioned, its development was preceded by the 13 years of intense activity. This activity permitted the principle designer, Dr. Anderson, to gather a large array of requirements and criteria for design, which could never have been discovered without studying the results of many PRT designs over an extended period.

2. Dr. Anderson accumulated the necessary engineering knowledge through practical work in industry and through his engineering training. This included understanding how to analyze structures of all kinds, how to carry engineering design projects through to release to production, how to analyze and design vehicle control systems, how to do the space mechanics needed to develop programs to analyze space-curved guideways, how to analyze the dynamics of vehicles, how to analyze a complex electrical circuit, how to understand a complex electromagnetic device like a linear induction motor, how to manage a large group of engineers towards a specific objective, how to develop computer programs that can control the vehicles of an ITNS system of any size and any configuration, how to analyze the heat-transfer properties of a vehicle body, how to analyze the economics of an engineering system, how to develop the necessary theory of PRT, and how to synthesize an engineering design.

Experience with other PRT systems has shown that without this kind of background, serious mistakes have been and will be made, such as have been made in the ULTra and Vectus designs, that will render resulting PRT designs non-competitive, as was the case with the Chicago RTA/Raytheon PRT project, where $65,000,000 was spent with no positive result. No engineering group, working in a period of time acceptable to an investor group, will have the patience needed to come up with such a comprehensive analysis of the requirements of a successful PRT design. Thus the question "What would be the cost of creating the current design today by a new group of engineers?" is essentially unanswerable, but would be a very large number.

8. Challenges to Marketing ITNS Technology

Our most difficult marketing challenge is that, notwithstanding that one vehicle designed by Dr. Anderson has operated successfully for thousands of rides on a short segment of guideway; the system does not yet exist in a full-system implementation. Because some people cannot conceptualize it, they doubt it ever will exist. Analogous technologies (e.g., Morgantown and the Raytheon RTA prototype) that do exist are very different from the current technology and are too expensive. We must show people a prototype installation where they can "kick the tires" and see that the technology really works as we are confident that it will. We need to develop a demonstration where vehicles can run around continuously at planned speeds.

Even ITNS networks built entirely with private money will have to use public rights of way. Acquiring the permits to do so will raise political issues. Putting together a coalition of local interests to deal with those issues requires unusual ingenuity, even if there were no vested transportation interests to deal with. But there are vested interests, foremost those that have grown up to promote conventional rail transit technology. As highway congestion has grown, the advocates of rail technology have fought to establish it as *the* alternative to the automobile in cities everywhere. PRT to them is a "spoiler"; one they seem to perceive will eventually obsolete their favorite system. Yet, PRT can complement conventional rail as a collector and distributor and it can make conventional public bus systems more efficient by intercepting them at the edge of the downtown area. Typically bus systems spend as much time in the downtown area as they do in moving from a suburb to the downtown.

So, ITNS technology will have to overcome both the need to educate and political inertia. It will have little outside help in trying to do so. With few exceptions, transportation consulting firms have been able to learn little about PRT generally or about our particular version of it because, with few exceptions, they have not been able to obtain funds to study PRT.[51] As a result most of them have had strong interests in the technological status quo. When potential customers, public or private, look to established firms for technical advice on what we have to offer they typically encounter both misinformation and disinformation.

There is thus a challenging educational job to be done with customers, public officials, professional engineers, and the academic community – not to say the general public – before many of these systems can be built. Fortunately, the technology will sell itself with anyone who once can ride it. (Thus, a demonstration facility and a first commercial installation are both essential to developing a large market.) Beyond that, optimized PRT technology is the only thing that can compete for any significant share of what must otherwise be automobile trips in an increasingly affluent world that wants personal and not "mass" transportation. And, automobile companies have, through the World Business Council on Sustainable Development, supported detailed studies that show the dire need, without saying so directly, for optimized PRT (ITNS) as a way to maximize the efficiency needed to move people. People who see the technology at work will understand that. The editorial from the Chicago Tribune shown on page 1 resulted from an announcement by the Chicago Regional Transportation Authority that they would embark on a PRT development program. It shows the kind of enthusiasm that PRT can generate.

Investors looking for confirmation of all this must be wary about their choices of technical advice. Because there have been since 1974 no U. S. federal government funds available to work on PRT, very few firms have any hands-on experience studying the application of PRT technology. Fortunately, as a result of the Heathrow, Uppsala, and Masdar projects this situation is changing rapidly. There are few academics who can claim any first-hand knowledge of PRT, though many have followed the evolution of PRT technology on their own initiative and a few

[51] The outstanding exception now is CH2M Hill, who was given the contract to oversee the PRT work in Masdar.

have led planning studies of PRT systems. None of these sources can give reliable advice without first educating themselves in detail about what is being proposed here.

9. Getting where we are today

A long struggle has been required to bring the new system to commercial reality. Reflection on past failures of similar systems to achieve commercial success shows that these failures occurred because not until recently have there been enough people on all sides of the problem – engineers, planners, public officials, economists, investors, and interested citizens – to form a critical mass of those who appreciate both the compelling need to find a solution to the problem of congestion and that ITNS constitutes an important solution. The Internet has made possible the study of material on PRT by an ever-increasing number of people – now worldwide.

In 1989 the Chairman of the Chicago RTA said: "We know we can't solve our transportation problems in the Chicago Area with just more roads and more conventional rail systems. There must be a rocket scientist out there somewhere with a new idea." We met them shortly thereafter and they immediately embarked on a program to acquire PRT, first with a request for proposals for a pair of $1,500,000 design studies. Dr. Anderson and his colleagues won one of these studies with Stone & Webster as prime contractor. Unfortunately, S&W could not finance the next phase, which would be a $40,000,000 program leading to a full-scale test track, so Raytheon Company joined Dr. Anderson and his team and matched the RTA's $20,000,000 commitment, with the work to be done in one of its governmental divisions. The RTA staff was not equipped to handle such a project and therefore hired a firm to do so. Since there were no firms known to them skilled in PRT technology they hired a firm skilled in the closest technology – large-vehicle people movers. Unfortunately the differences between such systems and true PRT are profound. The resulting compromises resulted in a system too large and too expensive to find a market.

By January 2000 Dr. Anderson was free of Raytheon and was able to offer his system independently. During the 1990s he was able to respond to planners interested in applications. There have been enough of them – several dozen – to convince us that the market is very large, large enough to require the major new industry described in Appendix A. To be interested in investing in our enterprise, it is of course necessary to be convinced that we have the technology, plans and people needed to succeed in a reasonable period of time. Those who could provide the needed funds have needed to see an application committed, but those who could commit to an application wanted to see the demonstration hardware up and running and a supplier team in place – a classic "chicken-and-egg problem." *The roadblock was the lack of hardware.* People in major national television networks told us they would do stories once we have hardware up and running. *We needed a way to initiate hardware development in much smaller steps.*

10. Solving the Chicken-and-Egg Problem

The solution came through the Securities and Exchange Commission Rule 504 that permits a company to raise up to $1,000,000 from up to 35 non-accredited investors with investments as small as $2000 and any number of accredited investors. A number of people had asked how they could invest and Rule 504 showed the way. Our cost analysis showed that with less than $1,000,000 (2002 costs) we would be able to 1) build one full-scale vehicle operating on a 60-ft segment of guideway, which would permit us to demonstrate the basic features of PRT; and 2) develop and market a plan to raise funds for the next larger step – the demonstration program described in Appendix C. The Rule 504 offering document was first distributed in April 2002 and by mid-August 2002 enough money had been raised to begin letting contracts, which showed the power of the idea among those who knew us. By summer 2002 over $800,000 had been raised and on April 10, 2003 the system was opened to the public. This experience has proven that we can not only design on paper, but the system we designed worked as intended in daily practice for thousands of rides.

11. Getting Hardware Ready

Once we had a practical way to get hardware up and running we began getting the designs ready to bid and sought suppliers who could carry out the various tasks. We had sufficient talent to design, order, and install the necessary components.

In May 2003 the Minnesota High Tech Association invited us to exhibit our system at the 2003 Minnesota State Fair as the centerpiece in their Wonders of Technology Building where about 960,000 people visited during the 12 days of the Fair. As a result, we were able to give over 4000 rides with only one failure – the cable that operates the door on one occasion slipped off its pulley – and markedly increased awareness of PRT, which led to discussions of applications.

12. A Full-Sized Demonstration and Training Facility

The reasons such a program is needed are given in Appendix B. Funds are needed to complete the demonstration system and for market and business development. Demonstration of competence by building and operating the 60-ft system has been important to attract funds for the next phase. The minimum program needed to prepare the system for commercial applications is summarized in Appendix C. The detailed papers that back up the plan are mentioned by title in Appendix E.

A concern is often raised that a demonstration and training facility will delay return on investment by at least two years; however, given our knowledge of today's market, it is likely that the investor will have in mind a first application. Indeed we have four such applications in mind as I write. Starting from scratch, the detailed planning needed for such an application can take place in parallel with the work described in Appendix C and will take about as long. Moreover, the demonstration and training facility can be planned, built, and operated much more quickly than an actual application. Its major cost is in the engineering needed to accomplish it – engineering that is needed in any case to do the final design and specification of all of the components. The cost of the guideway itself is a very small portion of the cost of the demonstration program.

13. The Potential Market for ITNS

How can we estimate the potential market for ITNS in the United States? As a result of marketing activities over the past two decades, we are aware of many specific applications for ITNS in the U. S. and abroad. Again and again, we have compared the characteristics of ITNS with conventional transit in a wide variety of applications and have thus concluded that the need is great and the market is very large. However, it was not possible to secure orders based on a paper design and without a team of suppliers. We now have the team of suppliers listed in Section 19.

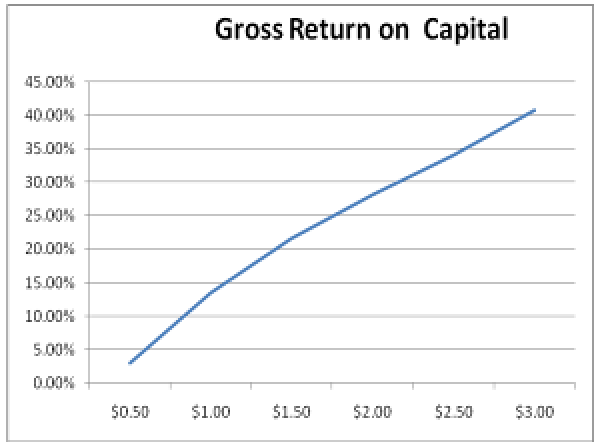
One way to make a quantitative estimate of the market for ITNS is to start with the amount of transit that exists today in the United States. According to the APTA 1997 Transit Fact Book, in 1995 there were in the United States 7.9 billion trips taken on transit with an average trip length of 4.87 miles, giving 38.5 billion passenger-miles of travel by transit. This is slightly less than one percent of the total number of passenger-miles of travel in urban areas in the United States and slightly less than three percent of the trips. Counting empty vehicles, our system will average about one person per vehicle. A reasonable average speed in the denser portions of an urban area is 25 miles per hour. Data[52] show that the daily number of miles traveled by a PRT vehicle, being a private, demand-responsive system like the automobile, will be about 11.5 times the peak-hour travel; and the yearly number of miles traveled will be about 320 times the weekday travel. Thus each vehicle will travel about (25)(11.5)(320) = 92,000 miles per year. Multiplying this number by the number of vehicles gives the yearly number of vehicle-miles taken by PRT. So the total number of ITNS vehicles required to serve all of the passenger-miles taken by transit in the United States would be (38,500,000,000/92,000) = 418,000.

But, whereas transit attracts a little less than one percent of U. S. passenger-miles of ground travel, estimates (see Appendix D) show that it is reasonable to expect PRT to attract many more trips in the denser portions of urban areas. Moreover, ITNS will be applicable to shopping centers, medical centers, airports, universities, national parks, private development projects, etc. where conventional transit is used hardly at all. To get a feeling for the magnitudes, suppose that at full deployment ITNS would attract only as many trips as conventional transit carries now. It is reasonable to assume, on the basis of many studies, that the average application will require about 40 vehicles per mile of guideway. Thus to carry as many passenger-miles as conventional transit carries now (418,000/40) = 10,450 miles of guideway would be required. At an estimated overall system price of $15 million/mi this is a market of $156 billion. As shown in Appendix D, the market for PRT is likely at least ten times as large, or in the United States alone at least $1.5 trillion. The world market can be expected to be several times as large. Considering the need everywhere and the construction time required in other major transportation projects, this market penetration can be accomplished in perhaps 30 years. Tempered with Regis McKenna's remark: "in emerging markets, numbers are rarely reliable," would the truth be higher or lower? What would it be, taking into account the international market? How would PRT International's share of the market shake out in face of competition?

[52] Puskarev and Zupan. "Public Transportation and Land Use Policy," Indiana University Press, 1982.

A critically important factor is the potential ridership that can be attracted to ITNS. Because of the substantially improved speed and quality of service, it can be expected that ITNS ridership will be a great deal more than is possible in conventional transit. How much more is conjecture before these systems are built, but a number of studies have attempted, using the tools of the trade, to estimate ridership on PRT systems. Some of these studies, summarized in Appendix D, show that it is not unreasonable to expect at least ten times as many riders on PRT as in conventional transit in areas in which it is used.

14. The Gross Profit from Building and Operating PRT Systems



The graph shown at the right is based on estimates of the costs of the components of a PRT system having 8 miles of guideway and 27 stations and on ridership estimates for the system.[53] This system, designed for Downtown Minneapolis, is illustrated on page 6. The gross return on investment to the company that would purchase this system and collect the revenue is given as a function of the fare charged per trip. *The required number of vehicles is calculated to meet peak demand, and thus depends on ridership, which will decline as fare increases.* By comparison, a fare of $1.50 per trip is typical of urban bus systems; and, because of their poor service characteristics, typically two-thirds of their operating cost is subsidized. The average cost of a typical automobile per vehicle-mile is more than $0.50[54], so by paying the cost for PRT rides monthly like a car payment the incremental cost of each trip would be of little consequence. By charging a fare per vehicle rather than per person people can share rides to reduce their transportation costs. Moreover, the above estimate of return is based on fare revenue only. Substantial revenue can also be expected from advertising and from movement of goods in off-peak periods.

As the size of a PRT system increases, the number of trip possibilities increases roughly as the square of the number of stations until saturation. As a consequence, the profitability of PRT systems will increase with system size.

15. The Size of the Market

To obtain a feeling for magnitudes, on the previous pages the market possible for PRT in the U. S. was compared to what it would be if all conventional transit systems would be replaced by PRT. This likely will not be possible for a long time, but ridership analysis shows that PRT ridership will be many times conventional transit ridership in the areas where it will be used. The total market for PRT in the U. S. and the world can't be estimated with any confidence in advance of actual experience; but study of its service characteristics, the estimates of ridership already mentioned, and the interest already shown indicates that the market for optimized PRT systems will be large enough to keep the industry busy for many decades. Moreover, we have up to now

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[53] "PRT Forecasts for Downtown Minneapolis." SRF Consulting Group, Inc., July 16, 2001.
[54] See FHWA website.

discussed only urban systems. Once the advantages of the combination of off-line stations and small vehicles are widely appreciated, intercity systems at higher speeds will follow. It is not unreasonable to project the market as a large multiple of the $150 billion calculated above.

16. The Time Required for Market Buildup

It will of course take time for this market to build up. We are now less than six months away from the first operational PRT system, which will be in Masdar in Abu Dhabi, with the Heathrow International Airport system following shortly thereafter. As a result, transportation-consulting firms are already finding it necessary to become educated in the planning of these new transport systems. Courses in universities on the theory, design and planning of them will begin to emerge. After the first few installations have had several years of operating experience, explosive growth in deployments can be expected until the market saturates.

17. Strategy for Market Entry

Experience has shown that transit planners have generally been nervous about the entry of a totally new form of transit that may upset long-set plans and challenge funding sources. Thus it is necessary to seek small initial applications in activity centers where the planners and developers recognize the need for a new solution and are cooperative. Once at least one such applications is in operation in the United States, the major argument against deployment of PRT – that it is not proven in daily practice – will evaporate and with it reluctance to look at new solutions. Thanks to work in England, Sweden, and the UAE, that day is rapidly approaching. We get frequent inquiries from planners who are aware of our work; sufficient to be assured that once a funding source is identified the business will expand quickly.

18. The Business

The business of PRT International, LLC is to commercialize ITNS fully through the steps described below, to seek applications aggressively throughout the world, and to achieve leadership in the field. PRT International plans to engage in marketing, planning or supervision of planning of specific systems, software improvement and maintenance, specification development, product improvement, training, solving institutional problems, coordinating the activities of its suppliers, and franchising the building of ITNS systems in locations around the world. Different suppliers may serve markets in different geographic areas, usually under the supervision of the core team.

19. How the Enterprise will make Money

The enterprise will in the early stages consist of a partnership between PRT International and its strategic partner, presumed to be the investor. This core company will own the detailed plans and specifications developed during the final design and test work summarized in Appendix C. It will make its money from markup on system components, from software-maintenance contracts, from fees for training, and as a small fraction of the revenue from operating systems run by franchisees or concessions. Concessions or franchises will make their money from revenue on ITNS directly from fares and advertising, and indirectly from the increased value of land freed up because of the very small amount of land required by the system. The enterprise will be in competition with other PRT suppliers, and will maintain its position in the market based on its managerial and engineering competence.

20. Principal Risk Factors

1. Management. PRT International is a small start-up company consisting of a team of managers and engineers who thus far have little experience in working together. The investor must be satisfied that such a group, which must enlarge, will work together cooperatively and successfully, and that the new members will be provided opportunities to become thoroughly proficient in the assigned areas of the technology. The burden is on the company to be as certain as reasonably possible that new hires have the knowledge and commitment needed for success. As part of the process of selection of new employees, each will be subjected to a comprehensive interview.

   By working in cooperation with MTS Systems Corporation PRT International will satisfy the need for an established working environment.

2. Technology. ITNS is a new configuration of technologies, albeit all existing technologies. These technologies must function economically day after day with less than one hour of delay for every 10,000 hours of operation for at least several decades and with acceptable ride comfort. Because computations practical only on digital computers are needed in planning, designing, operating, and managing PRT systems, the practicality of these systems has depended on advances in computer hardware, software, and fault tolerance. The investor must be satisfied that the necessary technical advancements exist and that the systems engineering team assembled is sufficiently versed in such technologies.

   The technology proposed has been under development for over 30 years and the specific system proposed by the Company has been subject to extensive design reviews over the past two decades that have shown that the technology is well within the state-of-the art.[55]

3. Competition. Several companies are planning, designing, and building PRT systems. The investor must be satisfied that PRT International's approach to PRT will be strongly competitive and indeed superior to other approaches to PRT, either in the technology or in the people involved.

   None of the other PRT companies offering PRT systems have enjoyed the depth and breadth of experience that Dr. Anderson has had as the world's leading expert on PRT systems. The process that has been the foundation of that expertise is developed in the paper "The Future of High-Capacity Personal Rapid Transit."

[55] J. E. Anderson, "A Review of the State of the Art of Personal Rapid Transit."

4. Code Requirements. Introducing a new system into the present complex fabric of industrial society requires compliance with a wide range of codes and standards. For example, late in the development cycle of the German Cabintaxi PRT system in the late 1970s a German railroad engineer found a standard that required all of the beams on railroad bridges to be at least 12 mm thick, whereas the developers of Cabintaxi had specified 8 mm thickness for the plates of their guideway. The railroad engineers managed to get the elevated Cabintaxi guideway designated as a railroad bridge, and the time required for renegotiation of payment for the extra steel led to cancellation of the program.
   Mainly as a result of the Chicago PRT project (1990-1994), all of the codes and standards required have been identified, the most important of which are the ASCE Automated People Mover Standards, the National Fire Safety Board standards for automated people movers, International Standards Organization ride-comfort standards, and the Americans with Disabilities Act. As the PRT International project begins, all of the necessary standards will be assembled and reviewed.

5. Costs and Schedules. While PRT International's program plan has benefited over many years from a great deal of analysis, design, discussions with manufacturers, and operating experience, meeting the projected costs and schedule depends on securing the services of many skilled personnel and companies. Inability to obtain the services when needed could delay the effort and increase its costs.

   The Company's intention has been to develop the project in the Minneapolis Area where there is a great deal of high tech talent and many small manufacturing firms from which to choose. The Minnesota High Tech Association includes over 700 high-tech firms in the Twin Cities Area.

6. Marketing. An adequate return on investment requires that the company's marketing efforts have secured system orders with the expected frequency. The time required to complete necessary arrangements may be longer than anticipated and the economic situation may continue to deteriorate. Thus the projected program must be conducted in recognition of perpetually imperfect knowledge.

   The Company has already identified more than a dozen good applications, and is cognizant of the need to maintain a strong marketing effort.

7. Risk of Obsolescence. While every effort has been made to insure an optimum, adaptable design – one very difficult to improve or circumvent – other technological breakthroughs may shorten the life expectancy of PRT International's approach to PRT.

   An important strategy in the design of the Company's PRT system has been to use off-the-shelf components wherever possible and to review the state of the art for new ideas that will improve performance and/or lower cost. No one can ever assume that no new technology can render any system obsolete, but the basic ideas that led to the PRT concept and how to optimize it have been thoroughly researched and are amenable to change when new technologies become practical.

8. Possible Need for Additional Funds. While the Company believes that the estimated funding requirements are adequate to cover costs necessary to design, build, and prove its system to the degree needed to obtain orders and hence funding from projects, there can be no assurance that additional funds will not be needed.

   The cost estimates and schedules developed by the Company have benefited from review of similar costs and schedules estimated and achieved on similar projects going back to the early 1970s. This data in addition to mature judgment have let the Company to conclude that its estimates are conservative. Moreover, Dr. Anderson managed the design and construction of a full-scale, automated, linear-induction-motor propelled vehicle that ran flawlessly for thousands of rides on a 60-ft section of guideway. The cost and schedule experience from this project have been incorporated into our current cost estimates and schedules.

21. What Others have Said (The Taxi 2000 system was designed by Dr. Anderson.)

1. "The safety design philosophy of Taxi 2000 deserves praise." Technical Committee on Personal Rapid Transit, Advanced Transit Association, *Journal of Advanced Transportation*, 22:3(1988).

2. "Taxi 2000 and its approach to PRT are first class." Walter H. Stowell, Senior Vice President and General Manager, Raytheon Equipment Division, following intensive two-week study in March 1990.

3. "The Taxi 2000 system is an inherently low-risk development because it is based on mature technology." "We have a very high level of confidence that it will work." "It is a straightforward application." Stone & Webster Engineering Corporation, final report to the Chicago Regional Transportation Authority, April 1992.

4. "I am confident that PRT will prove to be a risk that will pay enormous dividends for this region." Thomas J. McCraken Jr., Chicago RTA Chairman, *PRT Update*, Sept. 1996.

5. "Even when road capacity is sufficient for transport needs, the energy investment in a PRT system can be recovered in four or five years." Eva Gustavsson, Swedish Road and Transport Research Institute, *Journal of Advanced Transportation*, 30:3(1996).

6. "Our recommendation is therefore clear—a PRT system provides such a broad range of desired qualities that it should be given highest priority in research, development, testing, and demonstration for implementation in the urban environment." Göran Tegnér, Business Manager International, TRANSEK Consultants Company, Solna, Sweden. *Infrastructure*, Vol. 2. No. 3, (1997).

7. "PRT has unique advantages in the treatment of travel supply issues in highly condensed areas, where efficient transportation in the face of large trip generation is a critical neces-

sity, such as airports, major tourist attractions, inter-linkage between other transport systems, university campuses, and parks. Further, it offers solutions to maximizing income production via accessibility in the CBD and other dedicated land-use areas, while allowing the concurrent development of auto-free zones, fringe parking, and improved regional transportation linkages to land use clusters." Dr. Lonnie E. Haefner, International Editor-in-Chief of the John Wiley journal *Infrastructure*, Vol. 2. No. 3, p. 65 (1997).

8. "Personal Rapid Transit is the more promising solution for the mobility needs of a sustainable urban future." Andrew Euston, Office of Community Planning and Development, U. S. Department of Housing and Urban Development, February 1997.

9. "Personal rapid transit is one technology that holds great promise for urban transit systems." Emory Bundy, Seattle political scientist. http://faculty.washington.edu/~jbs/itrans/bundden.htm.

10. "Taxi 2000 PRT is our primary selected technology for our project." Sky Loop Committee, Cincinnati, 1998.

11. "Taxi 2000 has undergone extensive engineering and still needs to build a test system. We have no reservations about its ability to perform as advertised." Advanced Transit Association, "Personal Automated Transportation: Status and Potential of Personal Rapid Transit," January 2003, www.advancedtransit.org.

12. "A task force composed of members of the Engineers Club of Minneapolis has conducted a review of the methods by which cost data for Personal Rapid Transit have been determined. It is the collective opinion of the task force that suitable methods have been used to arrive at costs for a system in Minneapolis." The Engineers Club of Minneapolis, May 2004, W. T. McCalla, P. E., Structural Engineer and President.

22. Concluding Remarks

We know from a great deal of experience with the market that there is a huge pent-up demand for cost-effective PRT systems, among which systems the one proposed by PRT International, LLC is the leading example. Current concern with rising oil prices and global climate change accelerate the demand. As a critical step in preparing to serve this market, we demonstrated that in six months from a standing start under Dr. Anderson's leadership one full-sized vehicle operating automatically on a 60-ft section of guideway was built and operated flawlessly for thousands of rides. We seek investors who both understand the benefits and have the necessary confidence that our team, which will grow substantially, can actualize the potential of PRT, now called ITNS.

Appendix A. The Industry

1. **System Owner**. This could be a public or private entity, responsible for seeing that the system is operated satisfactorily, which includes concern for safety, reliability, cleanliness, public relations, advertising, fare collection, etc. Once we find a financial partner with substantial resources, the combined entity may wish to take on this role. The owner will of course enjoy the net profit from the system.

2. **Marketing**. Without marketing there can be no business. Marketing will cause knowledge of and the characteristics of ITNS to become widespread. It will be necessary to prepare videos, CDs, print material, displays, virtual-reality presentations, etc.; attend and participate in conferences and trade shows; meet one-on-one with potential clients; arrange presentations; and do all that is necessary to find clients interested in purchasing an ITNS system so that the site-planning-and-design team can go to work.

3. **Financing**. The function of this group is to locate and secure the financing necessary to build specific systems.

4. **Site Planning and Design.** Each application will require a team of architects, engineers, and planners to work with local officials to locate lines and stations, perform ridership analysis, simulate the operation, and do the detailed design needed to provide plans to the general contractor, who will supervise the installation. There are many transportation-consulting firms that have traditionally done this work under contract.

5. **Specification Development and Supervision.** This is the primary engineering task needed to insure safety, reliability, service and cost containment. It is a task that is never finished because there will be a continual stream of new ideas, products, procedures, and materials that must be considered and incorporated in specifications for new systems in order to stay ahead of competition and maximize profit for the owner. This function can also be called research and development. It encompasses the core engineering, and will include experts in all of the hardware and software subsystems who will gather and analyze information on the performance of existing systems, recommend improvements, design and supervise testing, and follow new developments that may be advantageously incorporated into the system. People in this division will maintain cost, weight, and dependability models of the system.

6. **Manufacturing**.

   a. <u>Chassis</u>. This is a stainless-steel frame to which are attached the wheels, motors, control components, switch, parking brake, bumpers, and air-conditioning compressor. The assembly and testing of the chassis is critical to performance and safety. The chassis frame and all of its components will be subcontracted.

b. Cabin. Subcontract to a firm experienced in vehicle design and assembly, under our specifications.
c. Guideway. Subcontract to a steel fabricator skilled in precision bending of steel and capable of at least using and possibly designing the necessary computerized jigs and fixtures. While the chassis and cabin are standard items, the shape of the guideway to match the curves, hills and speeds of each application vary. Thus there will be a regular flow of data on the coordinates of guideways to the steel fabricator that will require close coordination, cooperation and inspection.
d. Station. There will be a wide variety of station designs depending on the needs of the owner or community in which the system is to be built; however, there needs to be a standardized prefabricated design for those who wish to minimize cost while meeting requirements. We will be responsible for developing and maintaining specifications for the equipment needed in the station, which includes destination selection, fare collection, elevator, lights, television surveillance, motion detectors, voice communication system, and a standardized design of the station building with its details subcontracted to a qualified architect.
e. Ticketing System. Destination selection and fare collection are aspects of the ticketing system. Its specifications differ from those required in a conventional rail system.
f. Power Supply. This equipment is commercially available and will be specified by the consulting firm doing the site design.
g. Propulsion and Braking. Linear induction motors and variable-frequency drives are commercially available.
h. Communication and Control. The hardware is composed of available commodities. The system-control software has been simulated and proven in that environment.
i. Maintenance Facilities. The maintenance operations, layout and use of automated equipment must be carefully designed. While preliminary designs have been developed, this task is best subcontracted to a firm expert in such operations. The facilities will be built under the supervision of a general contractor retained to install the whole system.
j. Vehicle-Storage Facilities. There are many configurations in which vehicles can be stored. The design is likely to be site-specific under the supervision of the general contractor. Storage need not be in heated buildings. Minimum storage can be along a siding with a low-cost roof and siding to keep snow and ice off the vehicles in the winter and the sun off them in the summer. There is ample time from retrieval from storage to the nearest station for the cabin interiors to reach the comfort-temperature range before passengers enter.
k. Administration Facilities. These will be built under supervision of the general contractor.

l.

7. **General Contractor.** Takes the contract to do all of the site preparation and system installation.

8. **System Operator**. It is likely that separate companies will be set up to operate PRT systems for a fee from the owner. These companies would do the actual work of maintaining safety, reliability, cleanliness, etc. The core company responsibility will be to set standards and oversee the operations.

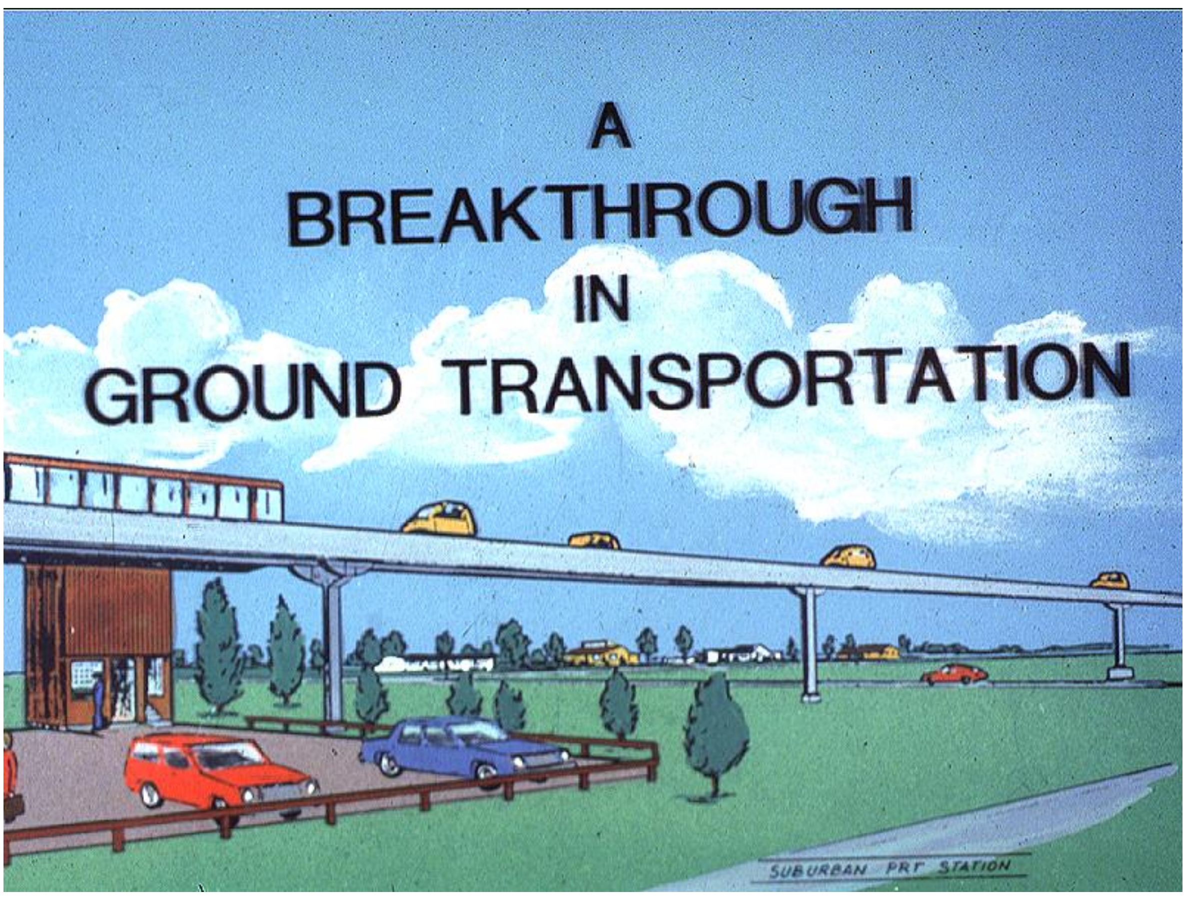
9. **Training.** People will need training for system operations, planning and engineering all the way up to the graduate level. It will therefore be necessary to establish *Training Institutes*. Any person to be engaged in systems operations will have to be a graduate of such an institute. There is much information that a planner needs to know to plan a PRT system successfully, so short courses for planners will have to be developed and taken as a prerequisite to assignment to a specific project. Engineers will need more detailed training, so courses of a year or more in duration will have to be taught.

10. **Government Relations.** There are many regulations and standards that may affect the deployment and operation of PRT systems and, as a result, the core company needs people skilled in government relations to monitor and lobby to protect the company's interests.

11. **Legal.** There will be a great deal of work related to contracts and agreements, and to be certain that the company does not violate any applicable laws.

12. **Accounting.**

13. **Administration.**



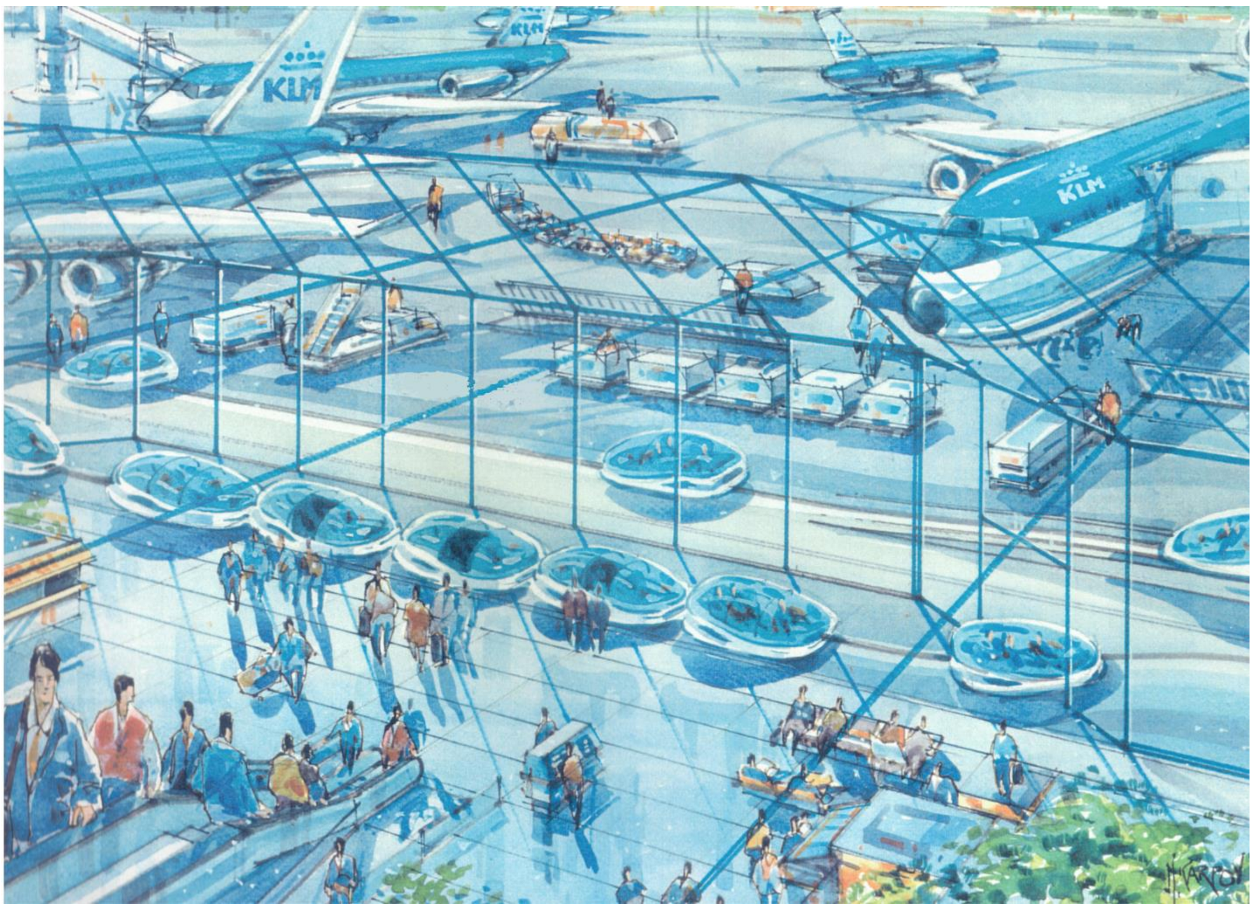
1.3.3. Business Plan

Business Plan

for Commercialization of

An Intelligent Transportation Network System

"ITNS, LLC"



Mission

To provide safe, reliable, and comfortable mobility while reducing congestion, air pollution, energy requirements, the need for oil, the land needed for transportation, and transportation costs.

Goal

To produce, install, and maintain the world's leading transit system in a variety of expandable applications in a highly competitive worldwide market.

Values – Follow the Engineers' Creed

- Give the utmost of performance,
- Participate in none but honest enterprise,
- Live and work according to the laws of man and the highest standards of professional conduct,
- Place service before profit, the honor and standing of the profession before personal advantage and the public welfare above all other considerations.

Contents

APPENDICIES

Executive Summary

ITNS is a totally new form of public transportation designed to provide a high level of service safely and reliably over an urban area of any extent in all reasonable weather conditions without the need for a driver’s license, and in a way that both maximizes ridership and minimizes cost, energy use, material use, land use, and noise. Being electrically operated it does not emit carbon dioxide or any other air pollutant, and requires no oil.

This remarkable set of attributes is achieved by operating light-weight, sub-compact-auto-sized, automatically controlled vehicles on a network of minimum-weight, minimum-size, exclusive guideways and by stopping only at off-line stations. To achieve reliable all-weather operation, the system uses non-contact electromagnetic motors.

Major Requirements for *ITNS*

The new system will

- Be able to attract many more riders.
- Have adequate capacity.
- Reduce congestion.
- Increase access to the community.
- Operate where conventional transit can’t.
- Not add to environmental pollution.
- Be as inexpensive as practical.
- Save energy.
- Be safe, reliable, and comfortable.
- Operate in all reasonable kinds of weather.

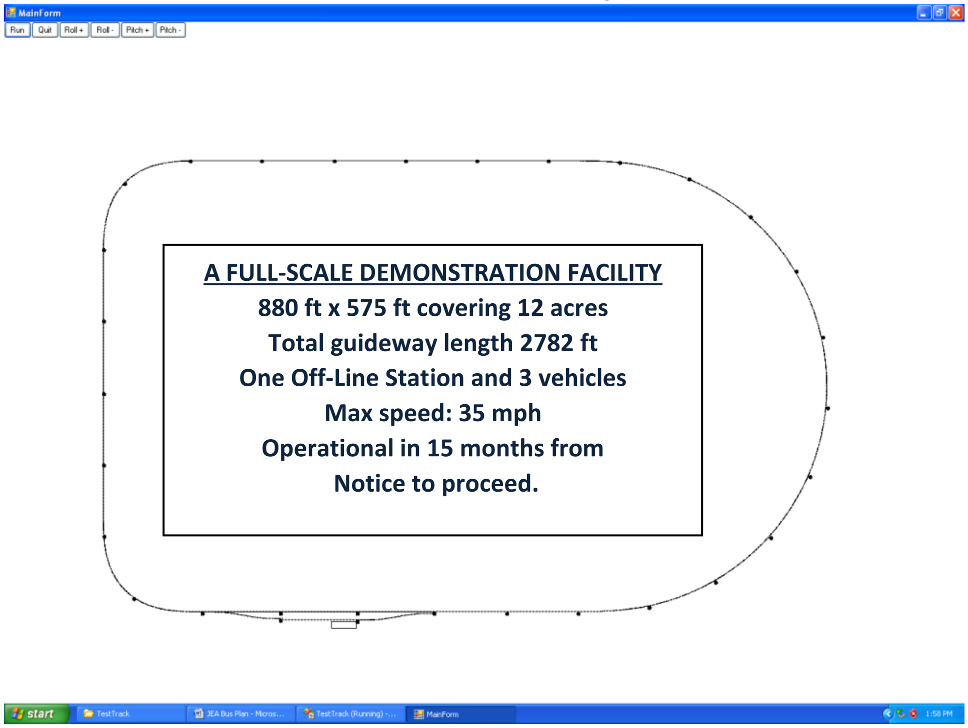
Dr. J. E. Anderson designed and supervised the construction of the fully automatic, linear-induction-motor powered ITNS vehicle shown here. It operated on a 60-ft section of its covered-steel-truss guideway at the 2003 Minnesota State Fair 12 hours per day for 12 days with no failures. It worked exactly as designed.

Here is the builder of the vertical chassis with the linear-induction-motor set not yet installed.

Attributes of *ITNS*

- Off-line stations.
- Fully automatic control.
- Minimum-sized, minimum weight vehicles.
- Small, light-weight, generally elevated steel-truss guideways.
- Vehicles ride above guideway to minimize cost and maximize both rider comfort and speed range.
- Hierarchical, modular, asynchronous control to permit indefinite system expansion.
- Dual duplex computers for high dependability and safety.
- Accurate, dual position and speed sensors.
- Dual linear-induction-motor propulsion and braking for all-weather operation.
- Smooth running surfaces for a comfortable ride.
- High-pressure, rubber-tired wheels to minimize guideway cross section and weight, and to minimize road resistance and noise.
- Switching with no moving track parts to permit reliable, no-transfer travel in networks.
- Guideway support-posts separated by at least 90 ft (27 m) to meet planning requirements.
- Propulsive power from dual wayside sources for high system reliability.
- Adaptable to all renewable energy sources.
- Well lit, television-surveyed stations to insure passenger security.
- Nonstop trips with known companions or alone.
- Adequate speed, variable with application and location in a network.
- Vehicle movement <u>only</u> when trips are requested.
- Automatic empty-vehicle rerouting to fill stations.
- Planned & unplanned maintenance *within the system.*
- Full compliance with the Americans with Disabilities Act.

The Key to a New Multi-Billion-Dollar Industry



The Engineering Program is ready to go for the Demonstration Facility!

$5,000,000 for final design specifications and procurement engineering.
$25,000,000 for manufacturing, assembly, test, marketing, and planning for the first system.

Why the Proof Testing and Demonstration Facility?

- To verify system capital and operating costs with a current team of engineers.
- To prove safety and reliability in advance of the first application.
- To verify ride comfort before the first deployment.
- To allow time to organize for a large business.
- To provide a facility for training engineers, planners and technicians.
- To provide assurance that the first operating system will be successful.
- To correct errors before the first people-moving deployment.
- To provide a controlled environment in which artificially induced test conditions can exceed normal parameters.
- To enable an insurance company to establish a liability rate.
- To test possible improved and more cost-effective components in a controlled environment away from people-moving operations.
- To educate consulting firms asked to evaluate the system.
- To establish the system as “proven technology” for comparison with other transit technologies in major investment studies.

1. Need for a New Solution to Ground Transportation

In their book *The Urban Transport Crisis in Europe and North America*, John Pucher and Christian Lefèvre, discussing only conventional transportation, concluded with this grim assessment: “The future looks bleak both for urban transport and for our cities: more traffic jams, more pollution, and reduced accessibility.”

During a luncheon attended by the Northeastern Illinois Regional Transportation Authority (RTA) Chairman it was agreed that “*We cannot solve the problems of transportation in the Chicago Area with just more highways and more conventional rail systems.* There must be a rocket scientist out there somewhere with a new idea!” The Illinois Legislative Act that established the RTA had given the new agency an obligation to “encourage experimentation in developing new public transportation technology.”

2. Design Approach

Thoroughly understand the *Problem* and *Requirements* for a solution.
Let System Requirements dictate the technologies.
Identify all alternatives in all tradeoff issues without prejudice and with absolute objectivity.
Thoroughly analyze all reasonable alternatives for each issue until it is clear which best meets all technical, social, and environmental requirements.
This is Systems Engineering!
More detail is found in “16 Rules of Engineering Design.” Available on request.
ITNS is superior to alternatives because of rigorous application of these Rules.

3. Major Requirements

In more detail than given in the Executive Summary:

- Costs low enough to be recovered from fares and other revenue.
- Highly efficient operation with renewable energy sources.
- Time competitive with urban auto trips.
- Low air and noise pollution.
- Visually acceptable.
- Adequate capacity.
- Low material use.
- Low energy use.
- Low land use.
- Safe.
- Secure.
- Reliable.
- Comfortable.
- Attractive for riders.
- Available at all times.
- Expandable without limit.

- An unattractive target for terrorist attacks.
- Compliant with Americans with Disabilities Act.
- Operational in all kinds of weather, except for extremely high winds.

4. Major Tradeoffs

1. Exclusive Guideway[56] vs. Mixed Traffic
2. Small Vehicles vs. Large Vehicles
   J. E. Anderson, "Optimization of Transit System Characteristics."
3. Off-line vs. On-line Stations
   J. E. Anderson, "The Intelligent Transportation Network System."
4. Captive Vehicles vs. Dual Mode
   J. E. Anderson, "How does Dual Mode Compare with Personal Rapid Transit?"
5. Supported Vehicles vs. Hanging Vehicle
   J. E. Anderson, "The Tradeoff between Supported vs. Hanging Vehicles."
6. Suspension on Wheels vs. Magnetic Suspension (Maglev)
   J. E. Anderson, "Maglev vs. Wheeled PRT."
7. Propulsion by Linear Motors vs. Rotary Motors
   J. E. Anderson, "Safe Design of Personal Rapid Transit Systems."
8. Linear Induction Motors vs. Linear Synchronous Motors
   J. E. Anderson, "LIMs vs. LSMs for PRT."
9. Motors in Vehicles vs. Motors in the Guideway
   J. E. Anderson, "Motors On Board vs. Motors in Guideway"
10. Power Source at Wayside vs. On Board
   J. E. Anderson, "Power source on board vs. power source at wayside"
11. Guideway Narrow vs. Wide
   J. E. Anderson, *Transit Systems Theory,* Lexington Books, Chapter 10.
12. Control Asynchronous, Synchronous, or Quasi-Synchronous
   J. E. Anderson, "Control of Personal Rapid Transit Systems."
13. Control Point Follower vs. Car Follower
   J. E. Anderson, **"**Overcoming Headway Limitations in Personal Rapid Transit Systems."

Acknowledgement
Dr. Anderson's work on PRT has been inspired by a great deal of work of other engineers, which became known to him via chairing four international conferences on PRT, editing may of its papers, study of the work of every investigator known to him, and by visits to developers of almost every other PRT system under development anywhere in the world. He has often mentioned that the PRT work of The Aerospace Corporation led by its Vice President Dr. Jack Irving is particularly outstanding and that he would likely have stopped working in the PRT field long ago if it had not been for the work of Dr. Irving and his colleagues, which could not continue because of lack of government support. The references given above show that the author of this plan has contributed strongly to understanding of each tradeoff issues.

[56] Conclusions of rigorous analysis are underlined. Papers referenced available on request and give details.

5. *Result: ITNS*

The background of, reasons for, and description of ITNS can be obtained from the following papers:

J. E. Anderson, "Optimization of Transit-System Characteristics," *Journal of Advanced Transportation,* 18:1(1984):77-111.
J. E. Anderson, "A Review of the State of the Art of Personal Rapid Transit." *JAT*, 34:1(2000):3-29.
J. E. Anderson, "The Future of High-Capacity Personal Rapid Transit," European Conference, Bologna, Italy, AATS 2005. http://kinetic.seattle.wa.us/prt
J. E. Anderson, "An Intelligent Transportation Network System." Available on request.
It is also desirable for the potential investor to view the latest version of our Power Point Presentation.

6. Benefits

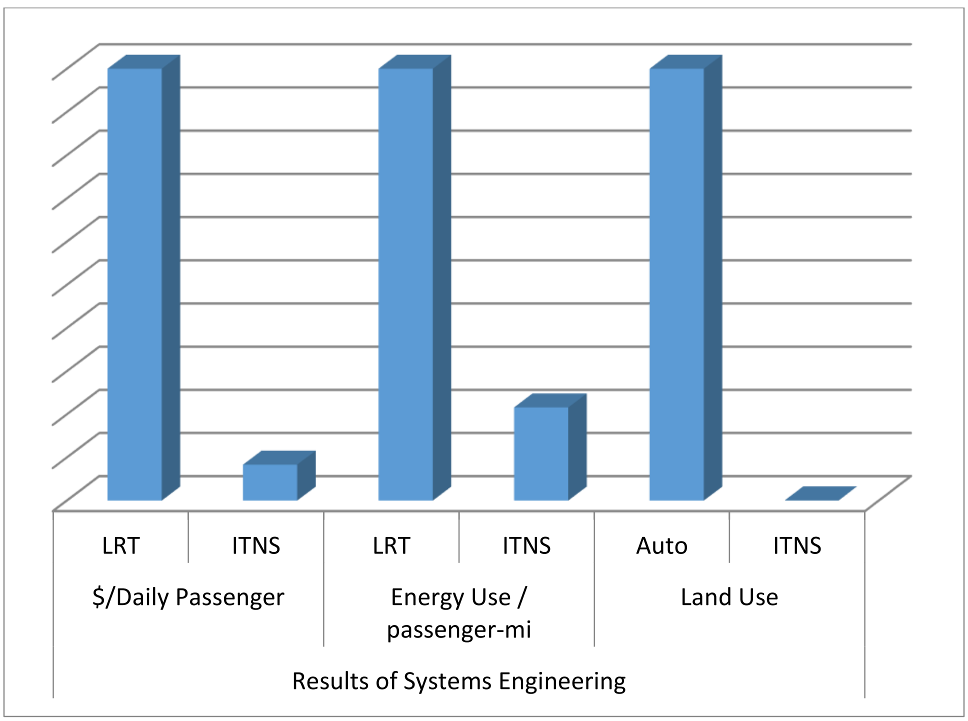
For the Riding Public

- The system is easy for everyone to use. No driver's license needed.
- Vehicles wait for people, rather than people for vehicles.
- Travel is cost competitive.
- The trips are short, predictable, and nonstop.
- Average rush-period waiting less than a minute and off-peak waiting zero.
- Everyone will have a seat.
- The system is available at any hour.
- The vehicles are heated, ventilated, and air conditioned.
- There is no crowding.
- There are no vehicle-to-vehicle transfers within the system.
- The ride is private and quiet.
- One can use a cell phone, text message, read, view scenery, or meditate.
- The chance of injury is extremely remote.
- Personal security is high.
- The ride is comfortable.
- There is space for luggage, a wheelchair, a baby carriage, or a bicycle.

For the Community

- Energy use is very low.
- The system can use any kind of renewable energy.
- There is no direct air pollution. Being more than twice as energy efficient as the auto system and by using renewable energy, total air pollution will be reduced substantially.
- The system is attractive for many auto users, thus reducing congestion.
- Because every trip bypasses intermediate stations, stations can be spaced closer together without slowing the average speed, thus providing both increased access to the community and competitive trip times.
- Stations can be sized to demand, thus decreasing capital costs.

- **Land savings is huge** – 0.02% is required vs. 30-70% for the auto system, and less than 10% of right of way needed for surface-level rail. This is the key factor in the ability of ITNS to reduce congestion.
- As to accidents, no one can say that there will never be an accident, but the rate per hundred-million miles of travel will be less than one billionth of that experienced with autos.
- Seniors, currently marooned, will have much needed mobility and independence.
- *ITNS will augment and increase ridership on existing rail or bus systems.*
- By spreading the service among many lines and stations, there are no significant high-value targets for terrorists.
- Transit subsidies will be reduced.
- More livable high-density communities become possible.
- A pleasant ride is provided for commuting employees, thus permitting them to arrive at work rested and relaxed.
- More people-attracting parks and gardens become possible.
- Safe, swift movement of mail, goods and waste.
- Easier access to stores, clinics, offices and schools.
- Faster all-weather, inside-to-inside transportation.
- More efficient use of urban land.



7. Market-Opening Project

All of the research and development work needed to define ITNS in detail has been completed. The necessary next step to prepare for entry into a very large market is to build and operate an ITNS system of sufficient but not excessive size to demonstrate continuous, safe, reliable, comfortable, and secure operation at expected speeds in all weather conditions except extreme winds. This requires construction of the oval guideway described in the **Executive Summary**, which is sufficient to attain continuous speeds up to 35 mph. One off-line station and three vehicles are sufficient to prove all technical features of the system.

To complete the demonstration it is necessary to recruit and educate a group of engineers who, under Dr. Anderson's direction, will develop procurement specifications for ITNS and its components, direct their procurement or manufacturing, and test the first fully operational system. The project is divided into 12 Tasks, so to be effective, each engineer needs to become familiar in detail with only a small portion of the entire project, thus making it practical to move quickly into a new area.

8. Tasks that must be completed to Commercialize ITNS

Task #1: Management and Systems Engineering.

Task #2: Safety and Reliability assurance.

Task #3: Cabin.

This task will be subcontracted, likely to either the Pasadena School of Design or Hydra Design of Los Angeles.

Task #4: Chassis.

The design and manufacturing will be done internally. Components will be obtained from known sources.

Task #5: Guideway and posts.

These components will be subcontracted. The posts are a specialty item that may be subcontracted to a firm such as Millerbernd, Winstead, MN.

Task #6: Guideway covers.

This is a specialty item that will likely be subcontracted.

Task #7: Control system.

We may subcontract this task to Transit Control Solutions, Inc. or Honeywell.

Task #8: Propulsion and braking.

We intend to purchase LIMs from Force Engineering, Ltd.

Task #9: Wayside power.

Power rails will likely come from Insul-8.

Task #10: Civil works – stations, maintenance, foundations

Task #11: Test program.

Task #12: Planning for the first operational people-moving application.

Over 1400 pages of analysis and specifications back up the program!

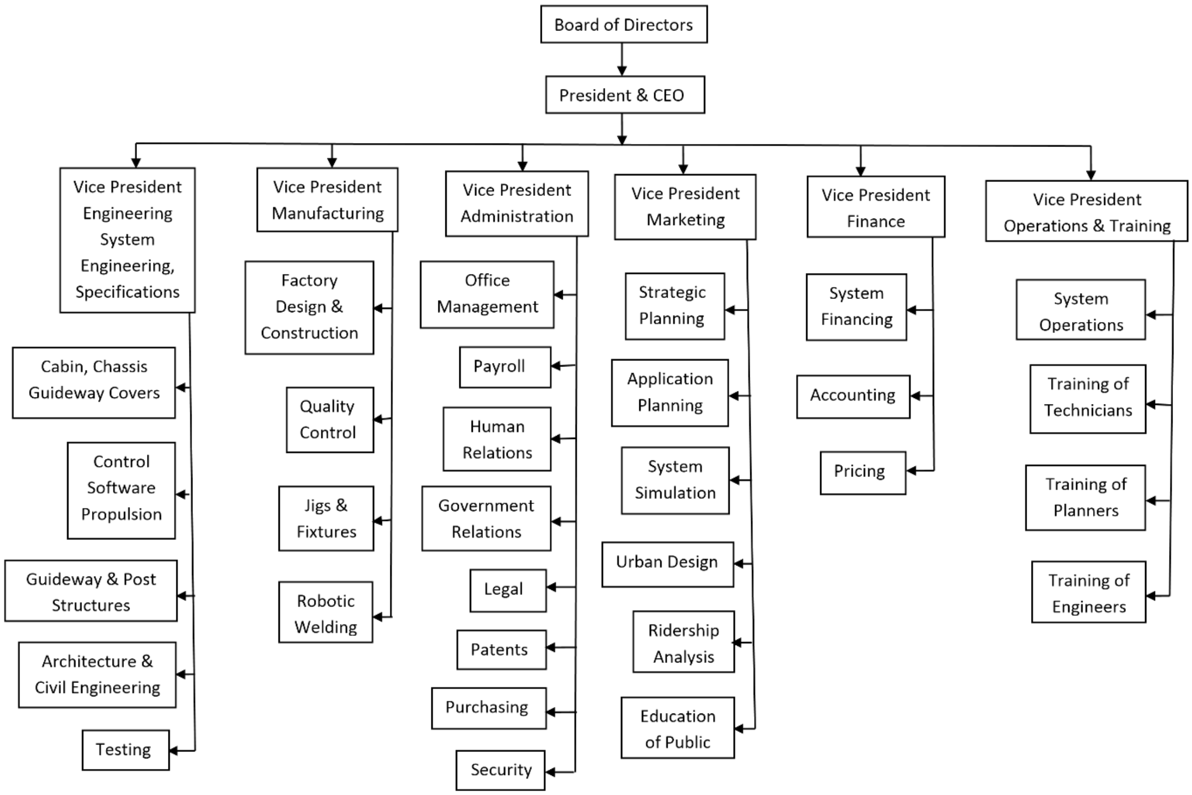
9. Technical Skills needed to Commercialize *ITNS*

Area of Responsibility	Tasks	Skills Required
Systems Engineering	Responsibility for coordination of all aspects of the design.	Proven experience in systems engineering.
Standards	Review all applicable standards and report to the project managers specific system and component requirements	Experience in dealing with engineering standards
Safety & Reliability	Responsibility for all aspects of system safety, dependability, hazard analysis, fault-tree analysis, and failure modes and effects analysis. Documentation of all procedures used to insure safety in keeping with accepted standards for operation of automated transit systems. Based on existing information and methodology, develop and maintain a model for calculating system dependability.	Strong experience in system safety and reliability engineering.
Weight & Cost Control	Develop computer models for weight control of the vehicle and cost control of the system. Maintain contact with all subsystems designers to keep models up to date. Report to project director and operations officer any deviations from target weight and cost. Develop model for calculating operation and maintenance costs.	Industrial engineer with at least five years of experience. Strong analytical ability required.
Vehicle Dynamics	Perform dynamic analysis of vehicle moving through merge and diverge sections of the guideway with the worst combination of side loading (wind + centrifugal) + maximum unbalanced load to verify stability, required maximum tire loads, tire stiffnesses, switch placement, flared switch rails, and ride comfort requirements.	Mechanical engineer having experience with computer tools for dynamic analysis.
Finite-Element Analysis	Perform FEA to finalize the specifications of the post-guideway bracket, the switch arm, and the chassis-cabin attachments.	Extensive experience with FEA tools.
Test Program	Review available descriptions of all necessary tests, define the test program, supervise all testing and document the results.	Engineer with proven experience in engineering testing.
Control System	The software for the system and vehicle control has been defined and the required types of hardware have been identified. Based on this information, complete the design of the operational software and hardware, supervise procurement and installation of the components in the test system, update the test plan, and supervise testing.	Operational computer software and hardware experience. Understanding of differential equations and engineering mechanics.

Propulsion & Power System	Specify LIM-VFD system and power-supply and distribution system, both on-board and at wayside. Identify suppliers and work with them to finalize the designs. Supervise installation in test system.	Electrical engineer with experience in power systems.
Guideway, Posts & Foundations	Perform computer analysis of the guideway & post design. Develop post-foundation design. Coordinate space requirements inside guideway with the chassis designer. Develop the final design and drawings. Specify and supervise design of computerized jigs, fixtures, and robotic-welding equipment for guideway fabrication. Help select fabricator.	Structural engineer with experience in use of computer structural analysis, structural design tools, and supervision of manufacturing.
Vehicle Chassis	The chassis includes wheel-axle-bearing assemblies, LIM & VFD, shock absorbers, switch assembly, parking and emergency brake, mounting of power-pick-up shoes and transevers, equipment compartment for control and a/c components, frame, wiring, and interface with cabin. Develop final design drawings, find necessary suppliers, and supervise fabrication.	Mechanical engineer with vehicle-system experience including computer tools for dynamic analysis of vehicle systems.
Vehicle Cabin	Review the design requirements. Develop bid documents and find cabin fabricator. Work with fabricator to develop and build the final design. Supervise fabrication. Consider styling, structural design, thermal design, material selection, human factors, HVAC, aerodynamics, seat, automatic door operation and its fatigue testing, lighting, push-button controls, interface with chassis.	Mechanical engineer with experience in vehicle design.
System Planning & Design	Responsible for planning and design of specific applications including computer-graphics simulation of portions of system, and operational simulation to determine system performance, size and layout requirements. Estimate ridership. Coordinate and negotiate with clients. Work with power engineer, specify power feed to system.	Transportation engineering preferably with prior experience with PRT systems. Strong analytical ability.
Director	Overall direction, supervision, and education of systems engineering team.	Extensive experience in quantitative PRT systems analysis, planning and design.
Operations Officer	Responsible for project planning, daily coordination, facilitation and expediting.	Engineering background with experience in project planning and expediting.
Contracts and Purchasing	Responsible for negotiating contracts and for purchasing of components and subsystems.	Experience with engineering contracts and purchasing.
Support	Develop and support for maintaining financial and accounting records and project controls. The human-resource functions also fall under this responsibility.	Previous experience in support management.

10. Organization for the Demonstration Program
11.

The proposed organizational structure is as shown in following chart. Over the first six months, we expect the organization to grow to about 20 engineers plus about six to ten members of the support staff. In a year, we expect the staff to grow to a total of about 50 people.



12. The Industry

System Owner. This could be a public or private entity, and is responsible for seeing that the system is operated satisfactorily, which includes concern for safety, reliability, cleanliness, public relations, advertising, fare collection, etc. Once we find a financial partner with substantial resources, the combined entity may wish to take on this role. The owner will of course enjoy much of the profit from all applications.

Marketing. Without marketing there can be no business. Marketing will insure that knowledge and characteristics of *ITNS* become widespread. It will be necessary to prepare videos, CDs, print material, displays, virtual-reality presentations, etc.; attend and participate in conferences and trade shows; meet one-on-one with potential clients; arrange presentations; and do all that is necessary to find clients interested in purchasing an *ITNS* system so the site-planning-and-design team can go to work.

Financing. The function of this group is to locate, secure, and manage the financing necessary to build specific systems.

Site Planning and Design. Each application will require a team of architects, engineers, and planners to work with local officials to locate lines and stations, perform ridership analysis, simulate the operation, and do the detailed design needed to provide plans to the general contractor, who will supervise the installation. There are many transportation-consulting firms that do this work under contract.

Specification Development and Supervision. This is the primary engineering task needed to insure safety, reliability, service and cost containment. It is a task that is never finished because there will be a continual stream of new ideas, products, procedures, and materials that must be considered and incorporated in specifications for new systems in order to stay ahead of competition and maximize profit for the owner. This function can also be called research and development. It encompasses the core engineering, and will include experts in all of the hardware and software subsystems who will gather and analyze information on the performance of existing systems, recommend improvements, design and supervise testing, and follow new developments that may be advantageously incorporated into the system. People in this division will maintain cost, weight, and dependability models of the system.

Manufacturing.

a. <u>Chassis</u>. This is a stainless-steel frame to which are attached the wheels, motors, control components, switch, parking brake, bumpers, and an air-conditioning compressor. The assembly and testing of the chassis is critical to performance and safety. The chassis frame and all of its components will be subcontracted and will be assembled and tested internally.

b. <u>Cabin</u>. Subcontract to a firm experienced in vehicle design and construction, under our specifications.

c. Guideway. Subcontract to a steel fabricator skilled in precision bending of steel and capable of using and possibly designing the necessary computerized jigs, fixtures, and robotic welding facilities. While the chassis and cabin are standard items, the shape of the guideway varies to match the curves, hills and speeds of each application. Thus there will be a regular flow of data on the coordinates of guideways to the steel fabricator that will require close coordination, cooperation and inspection.

d. Station. There will be a wide variety of station designs depending on the needs of the owner or community in which the system is to be built; however, there needs to be a standardized prefabricated design for those who wish to minimize cost while meeting requirements, including those to accommodate persons in wheelchairs, blind, deaf, and other types of disability. We will be responsible for developing and maintaining specifications for the equipment needed in the station, which includes destination selection, fare collection, elevator, lights, television surveillance, motion detectors, voice communication system, and a standardized design of the station building with its details subcontracted to a qualified architect.

e. Ticketing System. Destination selection and fare collection are aspects of the ticketing system. Its specifications differ from those required in a conventional rail system.

f. Power Supply. This equipment is commercially available and will be specified by the consulting firm doing the site design.

g. Propulsion and Braking. Linear induction motors and variable-frequency drives are commercially available.

h. Communication and Control. The hardware is composed of available commodities. The system-control software has been simulated, proven, and must be maintained.

i. Maintenance Facilities. The maintenance operations, layout and use of automated equipment must be carefully designed. While preliminary designs have been developed, this task is best subcontracted to a firm expert in such operations. The facilities will be built under the supervision of a general contractor retained to install the whole system.

j. Vehicle-Storage Facilities. There are many configurations in which vehicles can be stored. The design is likely to be site-specific under the supervision of the general contractor. Storage need not be in heated buildings. Minimum storage can be along a siding with a low-cost roof and siding to keep snow and ice off the vehicles in the winter and the sun off them in the summer. There is ample time from retrieval from storage to the nearest station for the cabin interiors to reach the comfort-temperature range before passengers enter.

k. Administration Facilities. These will be built under supervision of the general contractor.

General Contractor. Takes the contract to do all of the site preparation and system installation at each site.

System Operator. It is likely that separate companies will be set up to operate ITNS for a fee from the owner. These companies would do the actual work of maintaining safety, reliability, cleanliness, etc. The core company responsibility will be to set standards and oversee the operations.

Training. People will need training for system operations, planning and engineering all the way up to the graduate level. It will therefore be necessary to establish *Training Institutes*. Any person to be engaged in systems operations will have to be a graduate of such an institute. There is much information that a planner needs to know to plan ITNS successfully, so courses for planners will have to be developed and taken as a prerequisite to assignment to a specific project. Engineers will need more detailed training, so courses of a year or more in duration will have to be taught.

Government Relations. There are many regulations and standards that may affect the deployment and operation of ITNS and, as a result, the core company needs people skilled in government relations to monitor and lobby to protect the company's interests.

Legal. There will be a great deal of work related to contracts and agreements, and to be certain that the company does not violate any applicable laws.

Patents. As the detailed engineering work proceeds, we will look for items that can be patented.

Accounting.

Administration.

13. Use of Proceeds

Expenses	$K
Organizing & Training	$1,200
Task #1: Management & System Engineering	$2,400
Task #2: Safety Engineering	$410
Task #3: Cabin	$3,250
Task #4: Chassis	$980
Task #5: Guideway & Posts	$8,300
Task #6: Guideway Covers	$450
Task #7: Control	$1,680
Task #8: Propulsion	$325

Task #9: Wayside Power	$640	
Task # 10: Civil Works	$1,980	
Task #11: Test Program	$1,220	
Task #12: Application Planning	$1,460	$24,295
Land for Demonstration System	$65	
Rent & Utilities	$60	
Travel	$50	
Public Relations	$500	
Marketing	$600	
Legal	$200	
Insurance	$30	
Printing/Binding	$40	
Director Fees	$120	
Other Administrative	$55	$1,770
		$26,065
Contingency 15%		$3,910
TOTAL		$29,975

We expect that the demonstration will be fully operational in 15 months from the notice to proceed, and that an additional 6 months will be needed to complete and document the test program. Planning for the first operational system will be initiated as soon as the planning team can be appropriately educated. The first operational segment will begin providing service within 36 months from the notice to proceed with full funding.

14. The Market

The Present State of Urban Mobility

In the report *Mobility 2030: Meeting the Challenges to Sustainability, 2004* by the World Business Council for Sustainable Development (www.wbcsd.org), which was indorsed by the leaders of major auto and oil companies, the authors, assuming only conventional modes of transportation, site grim projections of future conditions but no real hope for solutions.

C. Kenneth Orski, in his *Innovation Briefs* for Nov/Dec 2006 (www.innobriefs.com) reports on Allan Pisarski's report *Commuting in America*, Transportation Research Board, 2006, which concludes that "driving alone to work continues to increase," "carpooling share declined by 7.5% since 1980," transit currently accounts for 4.6% of the trips, and "walking to work has suffered a sharp decline . . . a reality check for those who claim to see a trend toward 'walkable communities.'" Orski goes on to report that "Not only is population dispersing, it is dispersing farther and farther out, leapfrogging over existing suburbs."

Comparisons between Conventional Transit and ITNS

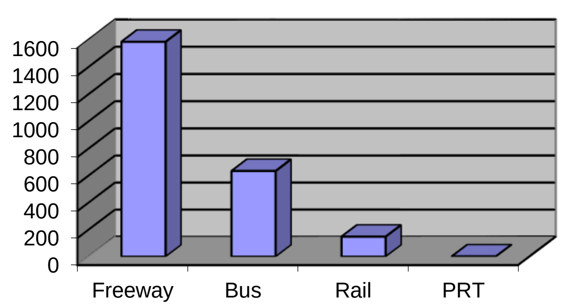
Land Use

Elevated ITNS requires surface land only for the foundations for its posts and for stations. With lines spaced half a mile apart and stations every half mile ITNS requires only 0.02% of the land, whereas the auto system requires about a third of the land in residential areas and typically upwards of 50% of the land in central business districts. Line by line, surface-level, street railways require more than ten times the width required for ITNS.

Figure 1[57] gives a comparison between surface-level right-of-way requirements along a single line for three conventional urban transportation modes and ITNS.

1. A three-lane freeway. With its shoulders, a freeway is about 300 feet wide and can carry 6000 cars in each direction with typical rush-hour occupancies of about 1.1 people per vehicle, or 6600 people per hour per direction. The width requirement per mile is 300(5280) = 1,584,000 sq-ft.
2. A bus system. Assume 30 50-passenger buses per hour (a schedule frequency of 2 min) operating at 80% occupancy on lanes 12 feet wide. With five such lanes per direction the capacity would be 6000 people per hour per direction. A two-way system of that capacity would require 10 lanes, which would require a width per mile of 12(5280)(10) = 633,600 sq-ft.
3. A light-rail system. Assume 10 200-passenger vehicles operating each hour in consists of 4 vehicles each at a load factor of 80%. The capacity per direction would be 6400 people per hour. A two-way light-rail line occupies a width of 28 ft, so the land requirement per mile would be 28(5280) = 147,840 sq-ft.
4. ITNS. A fleet of vehicles with an average occupancy of 1.1 persons operating at 0.6 sec headway gives 6600 people per hour. The surface-land requirement is 9 sq-ft for each post-foundation spaced 90 ft apart plus a 500 sq-ft station every half mile, giving a total land requirement of 1528 sq-ft per mile. Unlike the other systems ITNS does not impede anything that may want to move under the guideway.

Figure 1. Surface Land Required for Right-of-Way for Equal Capacity

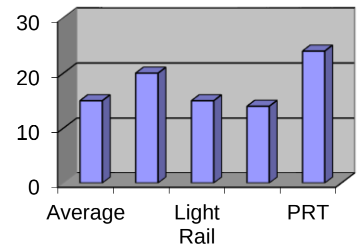


[57] Figures 13.1 – 3, 6 from Paul Hoffman and Jon Carnegie, *Viability of PRT in New Jersey,* FHWA-NJ-200x-00x, 2006.

Average Speed

Figure 2 shows the reported average speeds of three conventional modes of transit compared with the estimated average speed of an urban PRT system. The speeds of the conventional modes is from APTA.

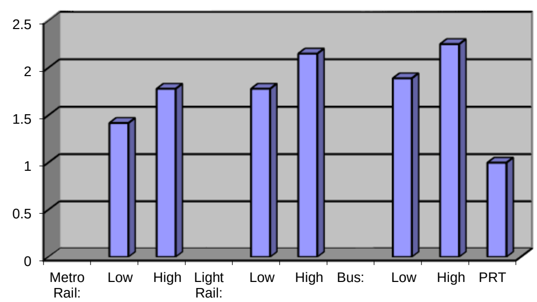
Figure 2. Average Speed, mph



Average Trip Time

The average trip times shown in Figure 3 include for the conventional transit systems typical minimum and maximum wait times including transfer times. Since the average wait time for PRT is very short, here assumed to be one minute, the contrast with conventional systems is even greater than the comparisons of Figure 3.

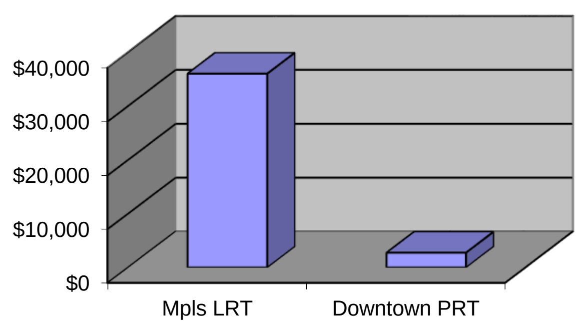
Figure 3. Relative Trip Time



Capital Cost per Daily Trip

The important economic factor in comparing conventional transit with ITNS is the cost per daily rider. The Minneapolis light rail system was reported to have a capital cost of \$720,000,000 and it was announced that the ridership would be about 20,000 rides per day, which gives a cost per daily rider of \$36,000. An 11-mile ITNS for Downtown Minneapolis was subject to a professional ridership analysis, which resulted in an average estimate of 73,000 rides per week day. A cost estimate, based on vendor estimates, was about \$100,000,000 for this system. Since ITNS is new, suppose we estimate \$200,000,000. Then its cost per daily rider would be \$2740, showing that ITNS came in at less than one twelfth (8.3%) of the cost per rider of the light rail system. The comparison is shown in Figure 4.

Figure 4. Capital Cost per Daily Rider



Energy Use

The energy use in kW-hr per passenger-mile of seven conventional modes of transit is compared with ITNS in Figure 5.[58] The names of these modes are abbreviated as follows:

[58] J. E. Anderson, What Determines Transit Energy Use? *Journal of Advanced Transportation,* 22:2(1988):108-132.

HR = Heavy Rail
LR = Light Rail
TB = Trolley Bus
MB = Motor Bus
VP = Van Pool
DB = Dial-a-Bus

A = Automobile
PR = PRT(ITNS)

The energy input required supplies the kinetic energy of the vehicle; overcomes road resistance and air drag; supplies energy for heating, ventilation and air conditioning; and is need to build the system.

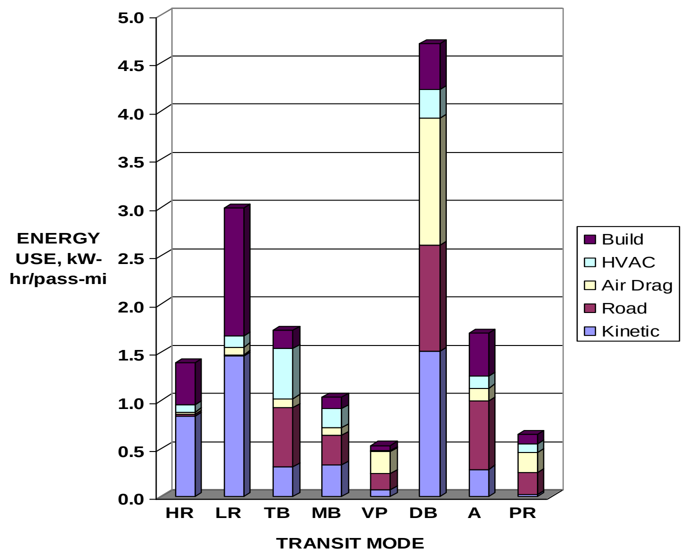


Figure 6. Energy Use.

<u>Summary</u>

ITNS is attractive because of

- Very small land requirement,
- High ridership potential, which together with its low capital and operating cost results in low cost per passenger-mile,
- Energy efficiency that results mainly by eliminating intermediate stops, which means that high average speed can be maintained without going to excessive cruising speed,
- Smaller trip time that results from eliminating intermediate stops,
- Ability to operate from sustainable energy sources, and
- Lack of emissions, which has become more and more important as the need to reduce CO_2 emissions has increased.

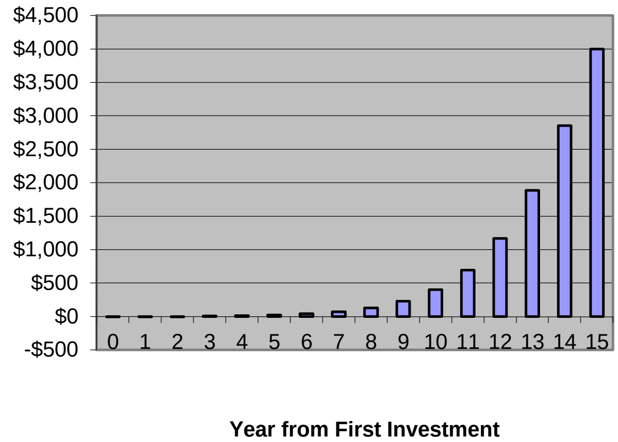
Market Size and Growth Rate

As one measure of market size, consider that in the United States about 8 billion trips are taken on transit every year[59]. Studies show that the ratio of trips per year to trips per weekday is about 300, and for a demand-responsive system the ratio of trips per weekday to the trips in a peak hour is about 10[60]. Thus, there are about $8000(10)^6/3000$ or $2.7(10)^6$ transit trips per peak hour. The number of vehicles required to carry a given number of trips in a peak hour is the peak hour flow multiplied by the average trip time and divided by the average vehicle occupancy. If these trips were to be carried by ITNS vehicles, a reasonable assumption is that the average vehicle occupancy counting empty vehicles is one. The average trip time is the average trip length divided by the

[59] APTA 2005 Transit Fact Book.
[60] Boris S. Puchkarev & Jeffrey M. Zupan, *Public Transportation and Land Use Policy,* Indiana University Press, 1977.

average speed. It is fair to assume an average trip length of 4 miles and with ITNS an average speed of 25 mph, giving an average trip time of 0.16 hr. Thus the number of ITNS vehicles required to carry the number of trips carried daily by conventional transit is approximately $2.7(10)^6$ (0.16) or 430,000. It is reasonable to assume an average of 40 vehicles per mile. Thus the number of guideway miles required would be about 10,700. At a sale price of $15,000,000 per mile, this is a market of approximately $160 billion. Conventional transit in the United States attracts about 4.6% of the daily vehicle trips. A number of studies have shown that ITNS will attract at least five and possibly 10 times as many trips. Once the first operating ITNS system has had a few years of experience, it can be expected that new starts will take place more and more frequently, increasing according to the well-known S-curve. It seems reasonable to suppose that in 30 years 10% of today's transit systems will be replaced or augmented by ITNS, but at five times the ridership. This would correspond to a market of about $80 billion. In any case, from this analysis, the projected growth of the company is shown in Figure 8. A market goal in ten years of $400 million seems attainable. This market will develop slowly but exponentially until saturation is approached. With half the market developed in 15 years, likely no more than 5% will be developed in the first ten years, which is the time during which consultants and educators would be obtaining familiarity with ITNS. Major efforts on PRT are occurring mainly in Europe, where European PRT systems may dominate. It is difficult to say how much of this market or of the Asian market can be captured by an American PRT system. Since, at the present time, there is increased interest in reducing dependence on oil and reducing carbon dioxide emissions, ITNS may catch on more quickly.

Figure 8. Cash Flow in $M



Target Markets

The early markets, mainly for passenger movement, are expected to be found in highly congested business districts, airports, theme parks, office parks, hospital complexes, shopping centers, and retirement communities. There is interest known to us in all of these kinds of applications, characterized by two fundamental factors: 1) the decision-making process is relatively easy, and 2) there is a strong local champion.

The Competition

The most comprehensive web page devoted to Innovative Transportation Technologies is managed by Emeritus University of Washington Regional Planning Professor Jerry Schneider. The address of this web page is http://faculty.washington.edu/jbs/itrans/. There is a growing number of other web pages devoted to new transit technology, the most prominent of which are www.advanced-transit.org, www.gettherefast.org, http://kinetic.seattle.wa.us/prt, www.prtnz.prtinternational.com. Figure 13.9. ULTra.

From these web pages, many web pages devoted to specific systems can be found.

While most of the systems shown on Professor Schenider's web page are not serious competitors, the few that may be are the following:

The figure to the right shows the ULTra PRT system, which has been under development at Bristol University in the United Kingdom and is now moving people and their luggage from parking lots into the terminals of Heathrow International Airport. This system uses a wide guideway, which has a large visual impact and is a snow-catcher in winter months. This system possesses the following characteristics, which will limit its use to fair weather, low-speed, low capacity, small systems:

- Rotary motor propulsion and wheel braking.
- Synchronous control.
- On-board battery power.

The figure to the right shows Korean steel company Posco's Vectus PRT system, a demonstration of which was built in Uppsala, Sweden. As seen in the figure, it uses a wide guideway. Moreover, the vehicles are propelled by linear induction motors mounted in the guideway. These motors must be placed quite close together to be able to emulate continuous thrust. Since at average flows there will typically be no more than about 40 vehicles per mile or one vehicle every 130 feet, the system will require about ten times as many motors as if they were mounted in the vehicles. This will make the guideway heavier and more costly than a system, such as ITNS, in which the motors are mounted in the vehicle – even considering the cost of power rails.

The figure to the right shows the third system we will illustrate. It is called "SkyWeb Express," offered by Taxi 2000 Corporation. This system was designed by Dr. Anderson, who found it necessary to resign from Taxi 2000 Corporation in early 2005. This system is not limited in the ways described above – it is an all-weather system designed to be indefinitely expandable. Since most cities and other entities that may purchase a PRT system require multiple bids, the existence of another system with these characteristics will strengthen the field, and permit deployments otherwise not possible. Our advantages are that we have in our ranks the most experienced PRT expert in the world and thus a stronger and much better educated engineering team.

Market Strategy

The sale of systems costing upwards of $100,000,000 is a complex process. Until the first real application is in operation, the major sales tool will be our demonstration system. It will be the tool needed to provide data on safety, reliability, comfort, and both capital and operating cost. As additional tools we will develop 3-D virtual-reality simulations of specific applications, develop brochures and displays to be used at the many transportation and planning conferences, give presentations at these conferences, and maintain a web site. We can expect that, as has occurred previously, magazines, newspapers, and television stations will be anxious to describe our system at no cost to us. As we keep a growing number of people and institutions informed of our progress, we expect to make the first sales without the need for a worldwide marketing campaign. Indeed, at the end of this section is a table listing 12 applications, in each of which a prominent individual believes that the listed application will be ordered once testing is complete. This list was culled from almost 100 known applications. A great deal of the advertising needed will be provided by other groups and individuals that have already been watching our progress.

On any specific application the process for making a sale is generally as follows:

- We make enough presentations and answer enough questions to convince the entity to look deeper.
- When the entity decides to proceed, the next step is a planning study in which detailed line and station layouts are made in cooperation with local planners, ridership is estimated typically by a specialty firm, a simulation of the application is made with a tool we have developed, three-dimensional visuals are developed to show how the system will appear in place, and costs are estimated. This work will be financed by the entity.
- If from this work the entity wishes to proceed further, having determined that the application can be financed, they may wish to prepare a request for proposals and solicit bids from various PRT companies. In that case, since the system designed by Dr. Anderson has already won competitions in Chicago, SeaTac, and Cincinnati, we are confident that we will be in a strong position to win.
- The selection of a specific PRT system constitutes the beginning of a sale, which generally goes in stages: First is preliminary engineering, in which remaining questions are answered, a more detailed design of the planned system is developed, and its costs are calculated. If the results of this preliminary-engineering process are satisfactory and the needed funds are secured, a contract is drawn for final design, construction, and test.

Pricing Policy

Once we are funded and underway, a critically important task of our management is to determine how to price our systems, taking into account all of the project management costs, marketing and sales costs, education costs, lobbying costs, costs to negotiate and develop appropriate standards, legal costs, patent costs, continuing product-improvement costs, overhead, system-support costs, employee benefits, and profit. The price of our systems must be high enough to cover all costs and profit, but not so high that we discourage sales.

Optimal 10 Year ITNS Funding for 11 Projects

	City	Project Name	Miles Track; Stations/mi	Start Date	Capital Expense	Operating Expense net of Revenue	Contact Information
1	Winnipeg, MN	Urban Area	25 mi, 1.6 sta/mi	2018	$375M	$11M/yr	Gary Holmes (204) 986-8289
2	Fresno, CA	University Campus	10 mi, 2 sta/mi	2019	$150M	$4.5M/yr	Dennis Manning (559) 323-1614 (559) 906-0039 (cell)
3	San Jose, CA	A/P to Rail	34 mi, 2 sta/mi	2019	$510M	$15.3M/yr	Laura Stuchinsky (408) 975-3226
4	Chicago, IL	O'Hare to Loop	35 mi, 1.5 sta/mi	2018	$525M	$17.9M/yr	Tom Riley (312) 953-2233
5	Anaheim, CA	Disney and surroundings	25 mi, 2 sta/mi	2018	$400M	$12.0M/yr	Tom Goff (805) 480-0507
6	Bloomington, MN	MSP to hotels and parking	23 mi, 2 sta/mi	2020	$345M	$10.4M/yr	Dennis Probst (612) 726-8187
7	Branson, MO	Tourist Center	15 mi, 4 sta/mi	2019	$270M	$8.1M/yr	Ken Thornton (816) 935-7103
8	Chicago	Hospital Connector	30 mi, 2 sta/mi	2020	$450M	$13.5M/yr	Tom Riley (312) 953-2233
9	Nashville, TN	Medical Center	5 mi, 3.6 sta/mi	2020	$100M	$3M/yr	Jack Jakobik (615) 343-0473
10	Kauai, HI	City Connector	90 mi, 1 sta/mi	2020	$1170M	$35M/yr	William Rourke (808) 334-1160
11	Auckland, NZ	Airport connector	16 mi, 1.5 sta/mi	2021	$240M	$7.2M/yr	Will Wilson willwnz@gmail.com

15. Valuation

ITNS is a member of the class of transit systems called "Personal Rapid Transit" or PRT and is the leading embodiment of this class. Even before hardware was built, it won competitions in Chicago, SeaTac, and Cincinnati; and a Swedish report concluded that if it were tested full-scale it would be the preferred PRT system for Swedish cities. When hardware designed and supervised by its developer was built, it worked exactly as specified. *ITNS* represents *a paradigm shift* in the means for providing public transit. As a consequence, efforts of the many inventors and engineers who have attempted to introduce this new and markedly superior form of public transportation had to overcome fierce opposition from practitioners of the conventional art. Almost all of them gave up. Compared on a per-passenger-mile basis with the average surface-level urban rail transit system, *ITNS* will cost for capital and operation a small fraction and will use a small fraction of the energy. Moreover, *ITNS*'s efficient use of urban land makes it ideal for applications in which there is no room for streetcars or busses.

How could this have happened? To understand requires that the reader gain some appreciation for the background and motivations of the principal developer of *ITNS*, Dr. J. Edward Anderson, whose biography is given in Appendix B and can be found in *Wikipedia*.

- His first professional job after receiving his Bachelor of Science in Mechanical Engineering had the title Aeronautical Research Scientist, Structures Research Laboratory, National Advisory Committee for Aeronautics, Langley Field, VA, where he received an education equivalent to a Master's Degree in Structural Engineering and contributed to the structural design of the wing of one of the Air Force's most advanced fighter aircraft.
- His second job was as a Senior Design Engineer at the Honeywell Aeronautical Division in Minneapolis, where his first design enabled Honeywell to totally dominate the Aircraft Fuel Gage Business, and his second design won the *Aviation Age* Product-of-the-Month Award.
- He transferred to the Research Department of Honeywell Aero where, after a year of study of the control of aircraft and missiles, he was put in charge of 15 Research Engineers working on autopilots for two of the Air Force's most important new fighter aircraft.
- To satisfy his desire to further his education, while working full time at Honeywell he earned a Master's Degree in Mechanical Engineering at the University of Minnesota, following which in successive years he took year-long graduate sequences in

    - Advanced Mathematics
    - Analytical Dynamics
    - Probability Theory
    - Theoretical Physics

- He was later assigned to Inertial Navigation where he invented and led the development of a new type of Inertial Navigator that is now standard equipment in most military and civilian aircraft.
- A year after Sputnik, he applied for and received a Fellowship to work on a PhD in Aeronautics and Astronautics at the Massachusetts Institute of Technology. His PhD thesis involved electromagnetics and was the only one out of 200 M. I. T. PhD theses that year that was published by M.I.T. Press. It is used by physicists who study the containment of hot gasses by magnetic fields, and now, many years later, still produces royalty checks.
- Upon returning to Honeywell, he was appointed Manager of Space Systems in which role he directed a group of 25 senior engineers on the design of a spacecraft called a Solar Probe, which was to travel inside the orbit of Mercury to gather data on the particles and fields around the sun. After five months of work using only company funds, and after

giving presentations and reports to NASA, NASA sent Honeywell a letter of commendation stating that they considered Honeywell as far advanced as funded contractors who had been working on the Solar Probe for several years. This project led to Honeywell's first spacecraft – an orbital infrared scanner.
- At this point, his yearning to teach led him to accept the position of Professor of Mechanical Engineering at the University of Minnesota.
- Every one of his engineering assignments, including teaching and research at the University, added to and rounded out the knowledge he would need to design a superior PRT system.

In 1968 the Urban Mass Transportation Administration (UMTA) released a report of work of 17 companies and research centers on the application of new technology to public transportation, which became possible only because of knowledge of the work of a few inventors and developers who had initiated and worked on PRT during the previous 15 years. Knowledge of U. S. government interest resulted in a rush of activity not only in the United States, but in all of the major industrialized countries in the world. In almost all cases the rush to riches resulted in poorly designed systems that lacked even the most basic elements of systems engineering and caused a great deal of confusion in transit planning circles.

A successful PRT design required a firm and detailed understanding of the requirements of the design before detailed design could be initiated, which required seasoned understanding of every relevant engineering science, a strong grasp of engineering mathematics, and experience in laying out and promoting PRT systems in specific applications. Good systems engineering required strict objectivity in selecting components, but that required a great deal of research that most of those companies neither had the patience for nor resources to undertake. Such activity could take place in a Research University, and Dr. Anderson plunged in. PRT was the kind of project he had been looking for – one where he could apply his knowledge and skills toward great benefits for mankind.

The difference between Dr. Anderson's approach to PRT and the work of other PRT investigators is in the rigorous process of SYSTEMS ENGINEERING he applied, and that was possible because of the many disciplinary engineering skills he had acquired.

The fact that we are where we are today is, however, a direct result of one outstanding exception: The Aerospace Corporation under the leadership of its Vice President, Dr. Jack Irving. He became interested in PRT in 1968. He and his team did the necessary research, as a result of which the PRT system developed under Dr. Irving's direction attracted the attention of Dr. Anderson and the University of Minnesota Task Force on New Concepts in Urban Transportation that he led. Under the above mentioned UMTA research and training grant and other grants, sufficient funds permitted Dr. Anderson to visit work going on in PRT in many cities in the United States and in Japan, England, France, Germany, Sweden, and Switzerland. These visits, coupled with the research he and his 15 colleagues did, showed unequivocally that the Aerospace PRT System was markedly superior to any other PRT design. Unfortunately, heavy lobbying stopped their work. Improvements made by Dr. Anderson and his team have been due to advances in technology and in continued research and development.

Under the auspices of the University of Minnesota's Department of Conferences, Dr. Anderson chaired International Conferences on PRT in 1971, 1973, and 1975 and edited the proceedings of the first two of these conferences. These conferences brought together 215 researchers, who shared and debated their ideas. It was estimated that by 1980 about $2 billion had been spent on a variety of types of automated guideway transit including PRT. That expenditure provided experimental evidence of features a PRT system should have and features it should not have. Only after 13 years of detailed study of PRT and of the work of other PRT investigators, engagement in PRT planning studies, giving hundreds of presentations and listing to and recording the feedback, work in a major study of transit alternatives in Denver, work on PRT as a consultant to Raytheon Company, serving as the first President of the Advanced Transit Association, work as U. S. Representative of the German PRT system called Cabintaxi, work on PRT as a consultant to the State of Indiana, and assembling findings in the first and only textbook in this field (*Transit Systems Theory,* Lexington Books, D. C. Heath and Company) did Dr. Anderson initiate the design of the system now called *ITNS*.

To design *ITNS,* all of the past work had to be assimilated and understood even though almost all of those efforts had failed. The experimental evidence obtained showed most often how not to build a successful PRT system. Lessons from these activities have been invaluable. It took many years of study of all significant work on new forms of transit as well as detailed planning of them in a variety of specific settings to appreciate all of the requirements of a successful design. There are many ways to design a PRT system, the vast majority of which are dead ends. Dr. Anderson used his knowledge of the engineering sciences, engineering mathematics, and economics to study dozens of tradeoff issues. He aimed to do so with absolute objectivity until the approach to be taken in each issue became clear. Such a *Systems-Engineering Process* was possible only as a result of his in-depth prior involvement in all of the branches of engineering required in the design of *ITNS*.

ITNS represents a culmination of research and development directed at achieving an economical and reliable solution to urban transportation that will minimize use of land, material and energy, will minimize pollution of all kinds, and will provide an unparalleled level of service. Remarkably, this combination of benefits minimizes capital and operating costs. The work that led to *ITNS* was conducted by Dr. Anderson and colleagues at two research universities, in cooperation with three government agencies and five major private companies. A study of other PRT designs shows that without such experiences, mistakes are made and will continue to be made. It is unlikely that any engineering group working in a period of time acceptable today to a group of investors will have the patience needed to arrive at the comprehensive collection of requirements and technology that a successful PRT design requires. The drive to continue had to be self-motivated.

A NUMERICAL VALUATION of the intellectual knowledge and know-how that is represented in the several thousand pages of detailed plans and specifications of *ITNS* is not possible to derive. How much of the work of others, for example The Aerospace Corporation, should be included? Without that work *ITNS* would not exist. *ITNS* is unique. The experiences that led to it are not repeatable. Its value is not only a result of the direct activity that has gone into it, but in the associated work by many companies and governments, without which *ITNS* could never have been developed. The international demand for *ITNS* lies today in every corner of the civilized world, and the return to the investor will far exceed almost any other investment. A lead investigator estimated the worldwide market to be over $1 trillion.

16. Patents

The basic patents granted to the University of Minnesota on the system invented by Dr. Anderson have expired. Once we are underway, we will seek patentable ideas and file for patents as a priority of our development process. We have exhaustively searched for patents upon which we may infringe and have found only one – U. S. Patent 7,617,977 "Ticketing system for personal rapid transit," a method that has been common knowledge for decades and can be circumvented.

17. How the Enterprise will make Money

The company will own the detailed plans and specifications developed during the final design and test work summarized in the Tasks of Appendix A. It will make its money from markup on system sales, from maintenance contracts, from fees for training, and as a fraction of the revenue from systems operated by franchisees or concessions. Concessions or franchises will make their money from revenue on ITNS directly from fares and advertising, and indirectly from the increased value of land freed up because of the very small amount of land required by the system. In many situations all of the costs will be recovered from revenues, making ITNS a profitable private business.

18. Risks

Management. We are a small start-up company that will consist of managers and engineers who thus far have little experience in working together. The investor must be satisfied that such a group, which must enlarge substantially, will work together cooperatively and successfully, and that new members will be provided opportunities to become thoroughly proficient in their assigned areas of the technology. The burden is on the company to be as certain as reasonably possible that new hires have the knowledge and commitment needed for success. As part of the process of selection of new employees, each will be subjected to a comprehensive interview.

By working in cooperation with established engineering companies, we will satisfy the need for an established working environment.

Technology. ITNS is a new configuration of technologies, albeit all existing technologies. These technologies must function economically day after day with less than one hour of delay for every 10,000 hours of operation for decades and with acceptable ride comfort, an outstanding safety record, and at a cost well under that required by competitors. Because computations practical only on digital computers are needed in planning, designing, manufacturing, operating, and managing PRT systems, the practicality of these systems has depended on advances in computer hardware, software, and fault tolerance. The investor must be satisfied that the necessary technical advancements will be used and that the systems engineering team assembled is sufficiently versed in such technologies.
The technology proposed has been under development for over 30 years and the specific system proposed by the Company has been subject to extensive design reviews over the past decades that have shown that the technology is well within the state-of-the art.

Competition. Several companies are planning, designing, and building PRT systems. The investor must be satisfied that our approach to PRT will be strongly competitive and indeed superior to other approaches to PRT, either in the technology or in the people involved.

None of the other PRT companies offering PRT systems have enjoyed the depth and breadth of experience that Dr. Anderson has had as the world's leading expert on PRT systems. The process that has been the foundation of that expertise is described in Section 15.

Code Requirements. Introducing a new system into the present complex fabric of industrial society requires compliance with a wide range of codes and standards. For example, late in the development cycle of the German Cabintaxi PRT system in the late 1970s a German railroad engineer found a standard that required all of the plates in railroad bridges to be at least 12 mm thick, whereas the developers of Cabintaxi had specified 8 mm thickness as wholly ample for the plates of their guideway. The railroad engineers managed to get the elevated Cabintaxi guideway designated as a railroad bridge, and the time required for renegotiation of payment for the extra steel led to cancellation of the program.

Mainly as a result of the Chicago PRT project (1990-1994), all of the codes and standards required have been identified, the most important of which are the ASCE Automated People Mover Standards, the National Fire Safety Board standards for automated people movers, International Standards Organization ride-comfort standards, and the Americans with Disabilities Act. As our project begins, all of the necessary standards will be assembled and reviewed.

Costs and Schedules. While our program plan has benefited over many years from a great deal of analysis, design, discussions with manufacturers, and operating experience, meeting the projected costs and schedule depends on securing the services of many skilled personnel and companies. Inability to obtain the services when needed could delay the effort and increase its costs.

Our intention is to develop the project in an area where there is a great deal of high-tech talent and many small manufacturing firms from which to choose.

Marketing. An adequate return on investment requires that the company's marketing efforts have secured system orders with the expected frequency. The time required to complete necessary arrangements may be longer than anticipated and the economic situation may deteriorate. Thus the projected program must be conducted in recognition of perpetually imperfect knowledge.

We have already identified several dozen good applications, and are cognizant of the need to maintain a strong marketing effort.

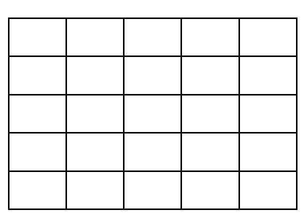
Risk of Obsolescence. While every effort has been made to insure an optimum, adaptable design – one very difficult to improve or circumvent – other technological breakthroughs may shorten the life expectancy of our approach to PRT.
An important strategy in the design of ITNS has been to use off-the-shelf components wherever possible and to review the state of the art for new ideas that will improve performance and/or lower cost. No one can ever assume that no new technology can render any system obsolete, but the basic ideas that led to the PRT concept and how to optimize it have been thoroughly researched and are amenable to change when new technologies become practical.

Possible Need for Additional Funds. While we believe that the estimated funding requirements are adequate to cover costs necessary to design, build, and prove its system to the degree needed to obtain orders and hence funding for projects, there can be no assurance that additional funds will not be needed.

The cost estimates and schedules we have developed have benefited from review of similar costs and schedules estimated and achieved on similar projects going back to the early 1970s. The data in addition to mature judgment have let us to conclude that our estimates are conservative. Moreover, Dr. Anderson managed in six months the design and construction of a full-scale, automated, linear-induction-motor propelled vehicle that ran flawlessly for thousands of rides on a 60-ft section of guideway. The cost and schedule experience from this project have been incorporated into our current cost estimates and schedules.

19. Economics

On the next page, economic factors related to a first system deployed after the demonstration program has been approved, with the promise that the cost of the demonstration will be paid at the rate of $15,000,000 plus interest per year for each of the first two years, and that the funds from the construction bond will be distributed over three years. Revenue is generated every year beginning three years after the notice to proceed to build the system. The operating system for this example is taken as a square network with six north-south guideways and six east-west guideways spaced a half mile apart, as shown below. The corresponding nine square mile transit service area extends a quarter of a mile out from each of the four sides of the network.



As an example, specific values are given for a range of parameters. In a detailed planning study for a first application, these values must be calculated from detailed planning information. In the second from the right-most column on the next page the year-by-year net cash flows (revenue minus payment on the bond and O&M expenses) are given. Beginning in the 31st year, after the bond is paid off, the net profit jumps. In the right-most column the cash flows are discounted at 4.5% per year to allow summing to the total PRESENT VALUE of the profits over 40 years to the city that takes out the bond. The number in the sixth row of the last column, $286,374,730, is that PRESENT VALUE. By comparison, in conventional transit 100% of the capital cost and typically 2/3rds of the operating cost must be covered by taxes; hence the net Present Value of those systems is substantially negative.

City Purchases System & Demo via Bonding. Receives Net Profit every Year!

Application: A Square Network			O&M cost	
Transit Service Area, sq mi	9.0		reduces to	Present
Separation between lines, mi	0.5		95%	Value of
Guideway Length, mi	30.00		of previous year's	40 years of
Stations/mi	2.00		cost each year.	Profits
Total Number of Stations	60		CASH FLOW:	to the City:
Ridership		yr	($135,145,332)	**$286,374,730**
Peak Days/year	340	1	($135,145,332)	$0
People/sq mi	9,000	2	($120,145,332)	$0
Trips/person/day	3	3	$8,885,874	$7,786,661
Mode split to ITNS	20%	4	$9,507,507	$7,972,628
Passenger-Trips / Day/sq mi	5,400	5	$10,098,058	$8,103,197
Off-Peak Light-Freight trips/passenger-trips	0.50	6	$10,659,082	$8,185,064
Total Trips/ yr/ sq mi	2,754,000	7	$11,192,054	$8,224,240
Peak-hrs/Day	10	8	$11,698,378	$8,226,126
Passenger-Trips/ pk hr/sq mi	540	9	$12,179,386	$8,195,563
Performance		10	$12,636,343	$8,136,891
Passenger Trips/pk hr	4,860	11	$13,070,453	$8,053,996
Ave Trip Length, mi	1.60	12	$13,482,857	$7,950,353
Average speed, mph	25	13	$13,874,640	$7,829,066
People/occupied vehicle	1.35	14	$14,246,835	$7,692,904
Fraction of Vehicles empty	0.25	15	$14,600,420	$7,544,335
Percent of operating vehicle fleet in maintenance	0.04	16	$14,936,325	$7,385,555
Maintenance float, vehicles	13	17	$15,255,436	$7,218,512
Number of vehicles	321	18	$15,558,591	$7,044,936
Vehicle-miles/year	39,657,600	19	$15,846,588	$6,866,355
Number of operating vehicles/mi	10.27	20	$16,120,185	$6,684,120
Total number of vehicles /mi	10.70	21	$16,380,102	$6,499,419
Average headway, ft	514	22	$16,627,024	$6,313,296
Average headway, sec	14.0	23	$16,861,599	$6,126,664
System Cost		24	$17,084,446	$5,940,321
Cost of Demonstration	$30,000,000	25	$17,296,150	$5,754,958
Operating Guideway Cost/mi	$5,530,000	26	$17,497,269	$5,571,174
Cost of one station including bypass guideway	$718,511	27	$17,688,332	$5,389,482
Cost of one vehicle including storage guideway	$88,326	28	$17,869,842	$5,210,322
Cost of Control & Communication/mi	$300,000	29	$18,042,277	$5,034,066
Cost of Maintenance Facility/mi	$54,853	30	$18,206,089	$4,861,026
Construction Management Cost/mi	$314,841	31	$42,331,180	$10,815,718
Overhead, Fees and Taxes	40%	32	$42,479,021	$10,386,117
System Cost/mi	$12,014,533	33	$42,619,470	$9,971,729
Cost Of Operating System + Demonstration	$390,435,996	34	$42,752,896	$9,572,198
Interest on Bonded Debt	4.50%	35	$42,879,651	$9,187,156
Time Horizon	30	36	$43,000,069	$8,816,226
Annual Payment on Bonded Debt/mi	$798,982	37	$43,114,465	$8,459,024
O&M Cost/vehicle-mile	$0.33	38	$43,223,142	$8,115,164
First year annual O&M cost (reduced with learning)	$13,087,008	39	$43,326,385	$7,784,256
Annual O&M as fraction of capital cost	3.35%	40	$43,424,466	$7,465,912
First-Year Total Annual Cost/guideway-mile	$1,235,216			

First-Year Total Annual Cost/vehicle-mile	$0.93
Revenue	
Fare per vehicle trip	$2.50
Fare per mile for freight	$1.00
Advertising revenue/vehicle-trip	$0.40
Revenue/year	$45,288,000
Annual O&M Cost as % of Annual Revenue	28.9%
Annual Revenue/System Cost	11.6%
Break-Even Fare	**$1.10**

Appendix A. The Tasks

Task #1. Management and Systems Engineering

The objective of this task is to show that all requirements and specifications for the Intelligent Transportation Network System (ITNS) have been met before building the first application. A prototype **Test Track** will be built and operated. Three vehicles, having functioning cabins, will be built and tested.

1.11 Based on a 72-page document "Technical Specifications," resolve all policy issues with the client and thus agree on all design requirements.

1.12 Become familiar with all codes and standards, almost all of which are known, that may affect the design, and inform the other engineers of findings of importance.

1.13 Review and finalize the subsystem specifications.

1.14 Identify and negotiate contracts with subsystem suppliers.

1.15 Establish all design loads.

1.16 Frequently update the estimated vehicle weight and moments of inertia.

1.17 Frequently update the estimate of system life-cycle cost.

1.18 Maintain a library of relevant papers, reports, and books.

1.19 Using an available program and the correct vehicle mass and radii of gyration, perform dynamic analysis of the motion of a vehicle passing through a diverge sections of the guide-way under maximum side wind load and unbalanced passenger load to reconfirm lateral tire loads and stiffnesses, position of the switch arm, and the flare length of the switch rails to meet ride-comfort criteria.

1.20 Weight & Cost Control

Develop model for estimation and control of vehicle weight.
Develop model for estimation and control of system capital cost.
Develop model for estimation and control of O&M costs.
Monitor all design tasks to keep within weight and cost targets.

1.21 Project Direction

Educate and supervise all team members.
Develop and maintain the over-all schedule.
Provide inter-task coordination.

Work with clients.
Manage
The office
Procurement
Engineering aids

A large series of papers is available to provide details needed for this task.

Task #2: Program of System Safety and Reliability

A major part of any engineering program related to automated guideway transit is to insure that the system will be safe.[61] An agreed definition of safety will be developed.[62] The Automated People Mover Standards require that any APM program have on its staff at least one full-time person devoted to safety issues and who operates separate from the design teams. This person must be familiar with the analysis of safety problems in complex systems that include real-time, safety-critical software. Safety issues include fire safety, robustness and redundancy in the software, design loads and stresses, and all other issues involving safety. Safety was treated in detail in two reports from the Chicago RTA PRT Design Study.[63]

A great deal of systems engineering work[64],[65] has been done to arrive at the current configuration of ITNS. The work under this task is to be sure that the hardware and the system-control protocols are safe and take advantage of the current state of the art. The safety engineering team will

- Review prior work on hazards analysis, fault-tree analysis, and failure-modes-and-effects analysis.[66]
- Tabulate data on component reliability from data sources such as www.e-reliability.com, from the AF Reliability Center at Griffiss Air Force Base, Rome, NY, and from other Internet sites. This work can be updated from the above-mentioned Chicago PRT Design Study.
- Estimate system dependability and hence safety using an available model.[67]
- Estimate the optimum component mean times to failure that meet the system dependability criterion at minimum life-cycle cost.[68]

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61 J. E. Anderson, “Safe Design of PRT Systems,” *JAT*, 28:1(1994):1-15.
62 See the definition suggested in J. E. Anderson, “Overcoming Headway Limitations in PRT.”
63 “Safety, Security & Failure Management Report” and “Fault-Tree Analysis and Reliability, Availability & Maintainability Analysis,” PRT Design Study, Chicago RTA, 1991.
64 J. E. Anderson, “A Review of the State of the Art of Personal Rapid Transit.” *JAT*, 34:1(2000): 3-29.
65 J. E. Anderson, “The Future of High-Capacity Personal Rapid Transit.”
66 J. E. Anderson, “Failures Modes and Effects,” available from author.
67 J. E. Anderson, "Dependability as a Measure of On-Time Performance of Personal Rapid Transit Systems," *JAT*, 26:3(1992):101-212.
68 J. E. Anderson, "Life-Cycle Costs and Reliability Allocation in Automated Transit," *High Speed Ground Transportation*, 11:1(1977):1-18.

- Review the ASCE Automated People Mover Standards to be sure that they are complied with where relevant.
- Examine in detail the safety implications of the component and subsystem design, and recommend changes when necessary.
- Become conversant in safety technology, e.g. through the System Safety Society.

Task #3. Final Design and Assembly of the ITNS Cabin

This task is for the work needed for the final design and fabrication of the vehicle's cabin. The vehicle has a length/height ratio close to the famous Fibonacci ratio $\left(1+\sqrt{5}\right)/2 \cong 1.618$. Three vehicles will be in the preliminary order for testing. The Company needs the assistance of an engineering company with the necessary computer tools and skills to

- Develop the cabin design,
- Produce drawings and specifications from which to fabricate the cabin,
- Select and procure the necessary components, and
- Fabricate or subcontract the fabrication of the cabins as finished units ready to be attached to the chassis.

1. Loading

1.1 Payload: The cabin shall be designed to accommodate a maximum payload weight of 950 lb (430 kg).
1.2 Wind: The cabin shall be designed to a maximum side wind of 70 mph (31 m/s).
1.3 Passenger loads: The cabin shall withstand the load of a 300-lb (136 kg) passenger pushing on the interior components of the cabin. The cabin floor at any point shall withstand a 200-lb (91 kg) concentrated load bearing on an area of one cm^2.

2. Exterior Dimensions

Subject to accepted reasons for change, the expected exterior dimensions of the cabin are: length 104"(2642 mm), height 64" (1633 mm), and width 63" (1600 mm). The walls shall be as thin as practical both from the view of structural strength and heat transfer.

3. Accommodations

The cabin is to be designed to accommodate either a person in a standard-sized wheelchair entering from the side and turning to face forward with an attendant, 3 adults and 2 children, a person with a bicycle, 2 people with large suitcases, or 2 persons with a baby carriage.

4. The Floor

The interior floor of the vehicle shall be at the same level ($\pm$ 0.5" or 12 mm) as the station floor. It shall be covered with a durable commercial grade material that will be easy to clean. The edge of the floor at the door shall be within half an inch of the edge of the station floor. Within the floor there shall be installed electrically conducing material that will shield the passengers from electro-magnetic radiation from the chassis.

3. The Seats

There shall be a forward-facing bench seat at the rear interior of the vehicle in three equal sections that may be folded up individually, filling the interior width of the cabin, with seat backs extending to the interior top of the cabin and tilted backwards by 6^o (six degrees). The back of the seat back at the seat height shall be forward from the rear wall of the cabin 12" (300 mm) to permit space for the equipment described in Paragraph 9. The top of each seat shall be 17" (430 mm) from the interior floor and shall fold up to ease access of a wheelchair or other large object. These seats will have a spring constant of about 200 lb/in (350 N/cm). There shall be two backward-facing fold-up seats at the front of the cabin designed to accommodate small people. These seats shall be spring restrained into the folded-up position when not occupied. The seat material shall be durable, vandal proof, and fire resistant.

4. The Door

One possible door configuration is a single inverted U-shaped automatically powered door 36 in (914 mm) wide that would open by sliding back over the rear shell of the cabin and thus opens on both sides of the cabin as one unit. Other door configurations can be considered. The door shall open or close within 2.5 sec and shall be equipped with sensors that prevent closure on any object. The door-operating mechanism shall be placed under the inside floor of the cabin. To ease entry of a wheelchair, the rear edge of the door shall be in line with the front edge of the bottom of the folded-up seat. The door-operating mechanism shall be designed for a life of 160,000 operations (open and close) and with no more than one failure in 50,000 operations. The seal of the door shall be designed to prevent entry of noticeable amounts of water in a rainstorm of 2 in/hr (50 mm/hr).

5. Windows

The windows, front, back and sides, are to be of a plastic such as LEXAN and should be large enough to permit a panoramic view as the vehicle moves along the guideway, but not so large that they would compromise the structural integrity of the cabin. The material of the windows and the entire exterior shall withstand daily brushless washing and shall be coated to minimize entry of solar infrared energy.

6. Styling

Since the cabin is the one element of ITNS seen most and is the signature of the entire system, styling is critically important. The design should, as one sculptor said, ". . . bring out the kid in you" while portraying dignity to the wealthy purchaser of the system.

7. Aerodynamics

Even at speeds as low as 25 mph (11 m/s) air drag is the largest energy consumer. Also, the power to overcome air drag increases as the cube of speed. There is a substantial amount of information from wind tunnel data on shapes that minimize air drag. Since the system will operate in cross-winds up to 70 mph (31 m/s), side drag is important. As side drag increases, it increases forward drag. The corners connecting the side to the top of the vehicle should be rounded with a radius of at least 10 in (254 mm). For these reasons, air drag is an important consideration in the design.

8. Structural Design

If a U-shaped door is used, the cabin shell is composed of three parts, the front part, the back part, and the door. These parts shall be manufactured from strong, light-weight composite material with metal reinforcements as needed. When the door is open, it is possible for a strong man to push against the top of the front or back part of the cabin in an attempt to see if he can break it. Therefore, as mentioned in Section 1.3, such a loading must be resisted well below the yield point of the material. The cabin contractor or his subcontractor shall have appropriate structural-analysis capability.

9. HVAC

A heating, ventilating, and air conditioning system shall be designed into the cabin, with the large components, such as the compressor and the drive motor, placed in the compartment behind the seat. The designer can assume that the vehicles will be stored in the shade and that the stations have a roof over the vehicles and waiting passengers. Moreover, in ITNS, while the vehicles will be stored power off, the HVAC designer can assume that at least three minutes will pass from the time HVAC is turned on until a passenger enters, which is a more relaxed requirement than necessary in automobile design. The HVAC designer shall work with the structural designer to specify insulation in the walls that, as close as practical, will minimize the sum of the annualize cost of the wall plus the annual cost of heating or cooling energy. The ventilation system shall provide the air exchange recommended by the Society of Heating and Ventilating Engineers. The temperature in the cabin shall be controlled to the median comfort level assuming people are clothed appropriately to the outside weather.

10. Equipment Compartment

The computers that operate all functions will be located in a compartment behind the main seat and there shall be an access door at the rear of the vehicle that can be opened by qualified personnel. The major AC components shall share the same compartment. The seat back facing the equipment compartment as well as all other components of the cabin shall be non-combustible.

11. Passenger and Environmental Controls

There shall be three buttons conveniently located in the vehicle that can be actuated by the passengers: a “Go” button, a “Stop” button, and an “Emergency” button. The “Go” button causes the door to close and signals to the station computer that the vehicle is ready to leave the station. The “Stop” button causes the vehicle to stop at the next station and then the door to open after it is stopped. The “Emergency” button alerts a human operator located in a control station to inquire through a communications system as to the problem. If the rider indicates sickness, the operator can change the vehicle’s destination to that of the nearest hospital. If the rider is in danger, the operator can change the vehicle’s destination to that of the nearest police station. If the rider feels the temperature in the vehicle is too high or too low, the operator can adjust it, etc.

12. Communications

There shall be a two-way communication system in each vehicle to connect an individual vehicle or a group of vehicles to the system’s control room. This system is separate from the communication system that controls the speed and position of the vehicles, which is described separately. There will be a television screen in the front center of the vehicle near the floor. It must be possible for the passengers to turn the set on or off, and if on to switch to site-specific advertising, travel information about the passing surroundings, news, or entertainment.

13. Lighting

The cabin will be equipped with reading lights that can be switch on or off by the passengers. Exterior lighting is optional but low lumen so-called parking lights and red tail lights are recommended.

14. Attachment to the Chassis

The cabin will be built with a pair of 20” long, by 2” wide, by 2” deep inverted wells in its bottom at major structural cross members one near the front of the cabin and the other near the rear to permit bolting to corresponding members of the chassis. As specified in Task 4, these members shall be hollow so that they can accept wires to and from the chassis.

15. Wiring

Only moderate voltages, for example 24 or 48 volts DC, are to be transferred from the variable-frequency drives in the chassis to the cabin. A voltage bus in the equipment compartment shall be used to drive all of the cabin components, I.e., the computer, the door motor, the heater, the air conditioner, the ventilation fan, the lights, the television set, the communications system, and the sensors. The wire insulation shall be non-combustible.

16. Fire Prevention

Fire prevention is of primary importance, which is the reason only a low voltage will be permitted in the cabin. All materials in the cabin shall be certified non-toxic and non-combustible. The cabin shall contain a smoke detector that shall cause the vehicle to stop at the next station and open the door automatically upon detecting smoke. Temperature sensors shall be placed at strategic locations in the wiring and in the electrical components to command the current to be shut off and a warning sent to central control if the temperature exceeds a preset value.

17. Lightning Protection

The cabin designer shall consult with the wayside power team to specify a suitable means for protecting the cabin from a lightning strike.

18. Environmental Specifications

The cabin shall be designed to be operable in the expected range of exterior conditions; temperatures from -45 deg C to + 50 deg C, salt spray, sand storms, and daily brushless cleaning. It is expected that the cabin will be replaced once every ten years. Minimization of the effects of vandalism must be considered in every phase of the design.

19. Cleaning

The cabin designer shall take into account daily external and internal cleaning of the cabin, and shall select materials and designs of the interior and exterior of the cabin for easy cleaning. Since the cleaning means is a part of the system, methods that will minimize damage can be assumed.

20. Cabin Weight

Since the weight and therefore cost of the guideway is proportional to the gross weight of the vehicle, weight minimization of the cabin is important, provided that the cost of weight reduction is not more than about $25 per pound.

21. Standards

The cabin shall be designed to comply with the requirements of USO 9000 and NFSA 130.

22. Changes in the Numerical Specifications

If the design team believes that a change in one or more of the numerical specifications given above is needed, they are to bring their suggested change to the management and systems engineering team with ample justification for the change.

23. Deliverables

Three cabins and all of the drawings and specifications needed to produce them.

Task #4: Final Design and Assembly of the ITNS Chassis

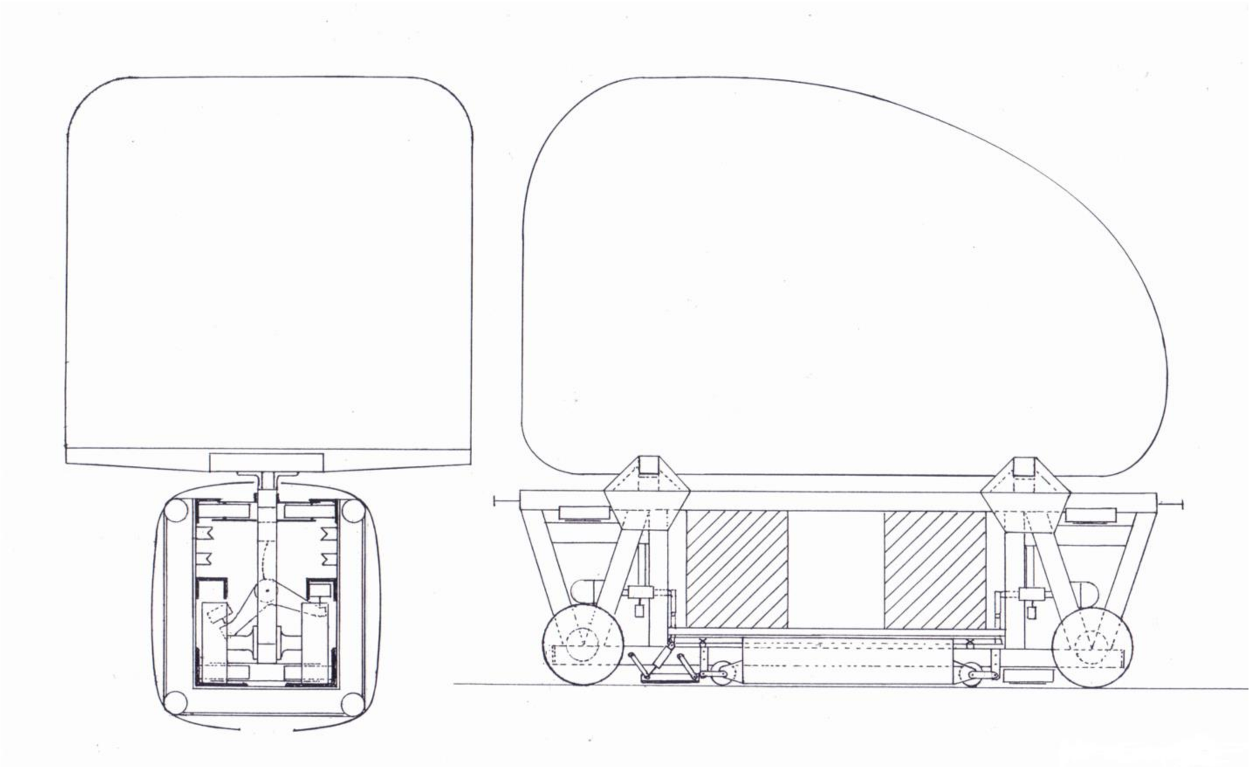

Figure 4.1. Sketch of the vehicle.

This task is for the final design, fabrication, and assembly of the vehicle's chassis. Figure 4.1 is a sketch of the side and end views of the chassis with an outline of the vehicle on top, which has a length/height ratio close to the famous Fibonacci ratio. Three vehicles will be ordered for the demonstration system. The engineers assigned to this task need to be familiar with the necessary computer tools and skills to

1. Perform an accurate quantitative verification of the design[69] with extreme wind and passenger loads to verify the maximum and steady-state wheel loads taking into account final dimensions, weights, and moments of inertia,
2. Produce drawings from which to fabricate the chassis frame and all brackets and linkages,
3. Select and procure the necessary components except for the Linear Induction Motors (LIMs) and their drives,
4. Assemble the chasses as finished units ready to receive the cabin.

The chassis rides inside of a covered guideway and thus is not exposed to the sun; however, rain or snow may enter the 3" wide slot at the top of the guideway, and the chassis must perform in wet or dry conditions in temperatures from -45 deg F to +130 deg F in an atmosphere typically 20 feet above the ground that may contain salt, dust, or sand. Noncombustible material shall be used throughout. The chassis is to be designed for a life time of 20 years, during which time it can be expected to travel 1,600,000 miles. The components must be easily replaceable to minimize vehicle downtime. System cost minimization requires, *inter alia*, minimum guideway weight, which required minimum vehicle weight. Thus, weight minimization of the chassis is important until the cost of weight reduction exceeds about $25 per lb. Safety and meeting required performance at minimum life-cycle cost are the fundamental design requirements.

1. Frame

The frame of the chassis, to which all of the components are attached, is vertical and consists of eight 2x2" high-strength, square steel tubes[70], with rounded internal corners. The top horizontal tube is 104" long. Shock absorbers are secured at each end. The lower horizontal tube is 94" long. Plugs are to be welded into each end to increase torsional stiffness and to prevent debris from entering the tube. The distance between the bottom of the top horizontal tube and the top of the bottom horizontal tube is approximately 21.13." The exact dimension will be determined by analysis of the height needed for the 13" nominal OD main support tires, the height and clearance needed for the switch rail, and the height and clearance needed for the 600 volt DC power rails. The Task #4 engineer will participate in this analysis. The top and bottom horizontal tubes are separated by six tubes, two vertical, and four inclined as shown in Figure 4.1 to provide resistance in a collision between two vehicles at a relative speed of 10 mph. The frame is to be assembled by welding.

2. Attachment of the cabin to the chassis

The cabin is attached to the chassis at two points.[71] The top member of each of the two attachment assemblies is a 20" long 2x2" steel tube with steel squares welded into the ends to increase

[69] See "Lateral Dynamics of the ITNS Vehicle."

[70] Steel has the advantage that it has a fatigue limit, whereas aluminum does not. Steel is easier to weld and has a much higher yield stress. Steel has the possible disadvantage that the sections needed to keep the weight to a minimum may be so thin that their thickness would be limited by buckling, thus potential buckling must be analyzed.

[71] The reason for two-point attachment is to eliminate the need to widen the guideway covers in curves.

torsional stiffness. When the chassis is assembled, these members are inserted into two slots in the floor of the cabin and bolted firmly to the cabin floor. The joint under the top member consists of seven pieces to be bonded together with a high-strength, 4000-psi-shear-strength, epoxy adhesive, such as provided by 3M Company, and also bolted. The center piece is a block of steel 3” longitudinally, 1.5” laterally, and 2” high, hollow in order to enable wires to be passed between the chassis and the cabin. To this block are bonded a pair of high-strength steel angles each 4” wide, 2” high, 5” long, and 1/4” thick. These angles are to be bonded and bolted to the center piece and to each of the two 20” long transverse tubes.

Next a pair of 2” wide channel sections are cut at 45 degree angles and are both bonded and bolted in place as shown in Figure 4.1. Finally a pair of hexagonal 0.020” thick sheets of the same material, of the shape shown in Figure 4.1 are bonded to the sides with cutouts for the transverse 2x2” tubes with the above-mentioned adhesive to provide the necessary shear strength. Detailed finite element analysis is needed to verify the design. If the Task #4 engineer does not have the necessary experience to do FEA, this work can be subcontracted. In this analysis the maximum load shall be taken as a 500-lb wind load on the side of the cabin plus a 600-lb vertical payload offset from the center line of the cabin by 15”. The empty cabin weight will be assumed for this analysis to be 500 lb, and we aim for an assembled chassis weight of no more than 600 lb.

3. Main wheels, axles and bearings

The distance between the axles of the front and rear main-support wheels is 84”. These wheels are nominally 13” OD (actually up to about a quarter inch more) to the outside of the tires, and are 4” wide. The width between the centerlines of the left and right wheels is 13.5”.[72] Each wheel shall be designed to carry a steady load of 550 lb with double this value for about two seconds when passing through the entrance to a superelevated turn. The tires may be high-pressure pneumatic or the designer shall investigate the new Michelin airless tire that has the same properties as a pneumatic tire. The tire stiffness shall be 2200 $\pm$ 200 lb/in. Thus variation in deflection from a fully loaded to an empty vehicle is 900/4/2200 = 0.10”. The needed tire, wheel, bearing and axle assemblies can be purchased to order from a company such as Aerol Co., Inc. The axles will be high-strength aluminum or steel turnings, hollow to reduce weight and to permit wires to be passed from encoders, and bolted to the chassis frame as may be seen in the end view of Figure 4.1. Sealed bearings will be used. They will each contain in the hub a digital encoder with a resolution of at least 2048 pulses per revolution, such as manufactured by Timken. The output of the left and right pairs on each of the fixed axles will be averaged to obtain position and speed, and redundancy is provided by placing encoders in all four main-wheel bearings. Note that the main wheels do not steer, which is acceptable in a light-weight vehicle with a short wheelbase, the more so as the friction of the tires decrease.[73] For reference, the Cabintaxi PRT program during the 1970s found this practice to be satisfactory.

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[72] J. E. Anderson, “Flexing of the Running Surface and Ride Comfort.”

[73] J. E. Anderson, “Effect of Non-Steerable Wheels on Road Resistance in Curves.”

4. Upper and lower lateral wheels, axles and bearings

Four upper lateral wheels provide yaw stability and four lower wheels add roll stability and symmetrical loading. While these additional lower wheels cause the chassis to be subjected to a twisting moment when passing through the entrance to and exit from a super-elevated turn, analysis[74] shows that the offset of the second set of lower lateral wheels from the plane of the other wheels is small enough to be neglected. The centerlines of the upper lateral wheels are directly above the centerlines of the main support wheels. The diameter of the four upper lateral wheels is 6" OD and of the lower lateral wheels if possible 6", both sets with solid polyurethane tires. The maximum load on any one of these tires is 1500 lb for one second,[75] and the maximum steady load requirement for perhaps 5 or 10 minutes is 750 lb each on the pair of lateral tires. The deflection of each of these tires should be approximately 0.150" under the 1500 lb load. Each of these wheels shall be provided with sealed bearings and axles designed to fit brackets, to be designed, that attach to the chassis frame.

To provide a firm anchor for the upper lateral wheels, an additional piece of 2x2" square tube is welded below each of the upper wheels as shown in Figure 4.1. Brackets need to be designed to attach the wheels firmly to the frame.
Firm attachment of the lower lateral wheels requires a pair of arms as shown in Figure 4.1 plus a shear member between the upper and lower arms.

5. The Switch

There will be one switch arm near the front of the chassis and one near the rear as shown in Figure 4.1. The arms are slaved to each other as described below and will be thrown by rotary solenoids, such as manufactured by Johnson Electric, one to throw the switch to the right and the other to the left. A 4" OD polyurethane-tired wheel with its bearing and axle is mounted to each end of each of the two switch arms. The maximum load on one switch wheel is 1200 lb, which is applied for less than one second. The deflection under this load shall be approximately 0.100". The shape of the arm is arranged so that the line of action of the force on the wheel passes through the center of the switch axle, thus making the switch arm self-centering. To make the switch bi-stable, a compression spring is mounted at the top of the center of each switch arm.[76] A finite element analysis of the switch arm with its wheels and axles is needed to determine the exact shape, material properties, and moment of inertia about the axis of rotation. The required stiffness of the spring and the torque pulse required of the rotary solenoid are determined by a dynamic analysis of the switch assembly, taking into account the inertia of the two switch arms and the inertia and friction of the mechanism that slaves one to the other. The center of gravity and strength of the spring must be selected so that a 0.25 g lateral acceleration will not throw the switch. To stop the moving switch arm at the correct position, a snubber, such as manufactured by Enidine, is mounted to a suitably

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[74] J. E. Anderson, "The Offset of the Lower Rear Wheel on the Chassis."
[75] J. E. Anderson, "Lateral Dynamics of the ITNS Vehicle." Running this program with correct weight and inertia will verify the specified values of all wheel loads and deflections.
[76] J. E. Anderson "Analysis of a Bi-Stable Switch."

designed bracket attached to the frame. A proximity sensor is suitably mounted to enable signaling to the control system that the switch has been thrown.

A problem in slaving the two switch arms results because the switch axle must be placed at least an inch above the midpoint between the upper and lower lateral wheels. This determination is made by an analysis of the maximum forces to the left and to the right as the vehicle passes through a merge or diverge section of guideway.[77] But the position of the switch axles at the center of the chassis is occupied by two variable-frequency drives and a battery. The problem is solved as follows: Weld a 2" channel section, flat side up, about 2" above the lower horizontal square tube that forms the lower member of the chassis frame. To increase its strength, add supports as needed. Under the channel section mount a horizontal tube with bearings at two or more positions along the tube to permit the tube to rotate freely. To the top end of each switch axle mount a vertical arm forked at the bottom to receive a similar arm mounted to the lower horizontal tube with a roller at the top. With identical mechanisms at both ends, each solenoid operates both switch arms, one to the left and the other to the right. Alternative mechanisms may be considered. Zero slop is not necessary because the switch arms are made bi-stable by means of the springs.
The switch assembly must be tested separately under load for at least 300,000 cycles before being assembled into the chassis, and must be designed so that the maximum stresses are no more than 75% of the fatigue limit of the steel. Special attention must be placed on designing to reducing stress concentrations.

Inventory of switch parts:

1. Two switch arms
2. Four wheel, bearing, axle assemblies
3. Two switch-arm shafts
4. Two rotary solenoids
5. Two solenoid mounting brackets
6. Two springs
7. Four snubbers
8. Two proximity sensors
9. One long tube mounted on bearings
10. Two upper forked arms to be fixed onto and perpendicular to the switch-arm shafts.
11. Two lower arms each with a bearing on the top end to be fixed onto and perpendicular to the long lower tube.

[77] See the paper "The Optimum Switch Position."

6. The LIM bogie

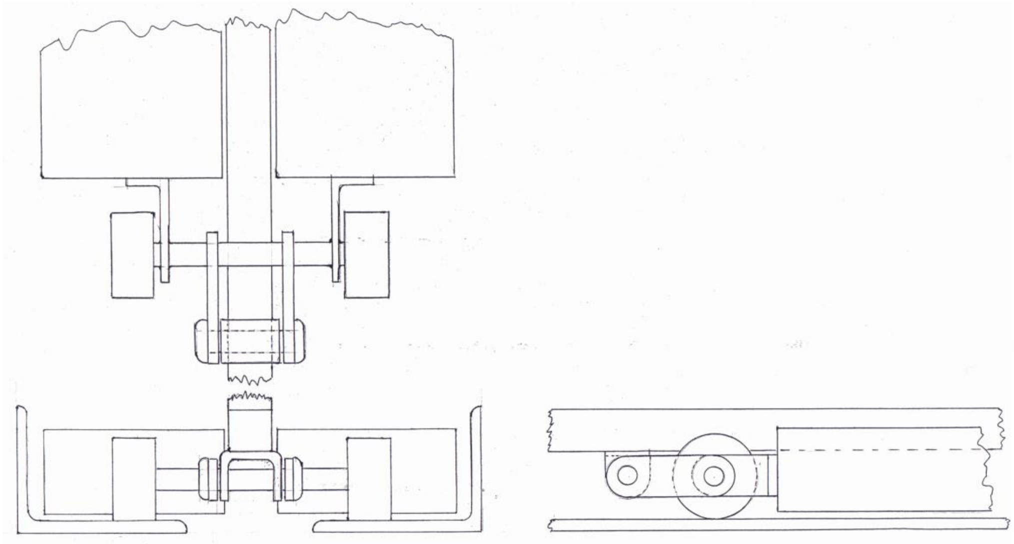

Figure 4.2. LIM-Chassis Connection.

The LIM bogie permits the LIM to maintain a steady 3-mm air gap to its reaction rail while permitting the vehicle to settle at different heights depending on the weight of the passengers. There is a pair of LIMs, one acting against the left running surface shown in the left view in Figure 4.1 and one against the right running surface. To the front and rear of each LIM is welded a bracket with a hole at the free end to receive one of a pair of fixed axles that connect the two LIMs. As shown in Figure 4.2, two 4" OD polyurethane-tired wheels with their bearings are mounted to each of these axles. These wheels must each carry a steady load of 300 lb corresponding to both the weight of the LIMs and the maximum normal force produced when the vehicle is accelerating. To each of these axles is attached a pair of horizontal links approximately 4" long. From the Pythagorean Theorem, if the link length is a and the vehicle can move up or down a total of δ then motion either up or down is $\delta/2$ and the slop the bearing at each end of the link must have is $(\delta/2)^2/2a/2 = \delta^2/16a$. If δ is say $0.015"$ and $a = 4"$ the bearing slop required is only $0.000014"$, which is much less than can easily be achieved. The other end of each of these four links is attached with a journal bearing to a vertical bracket that is fixed to the lower frame member. An alternative to this design is to sense the air gap and adjust it by means of servos at each of the four corners of the LIM assembly. Before investigating such a solution, data needs to be obtained from the LIM supplier on the effect of air gap on thrust and efficiency.

7. Parking & Emergency Brake

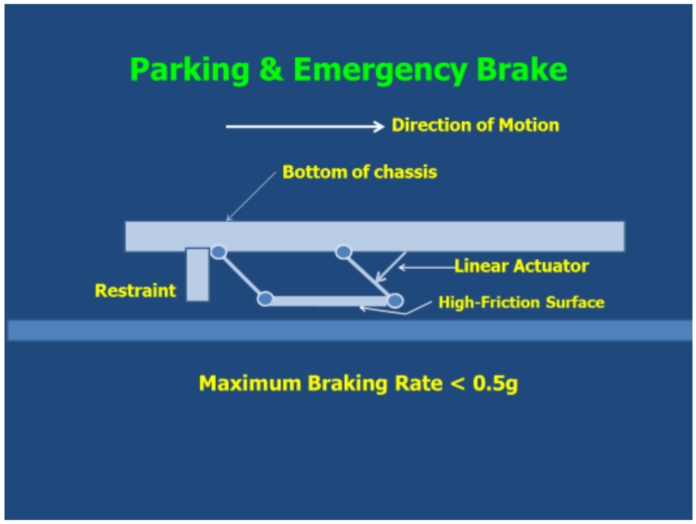

Figure 4.3. Parking & Emergency Brake.

Normal acceleration and braking is applied via the LIMs; however, when the vehicle stops in a station we must turn off the power to the LIMs, in which case it would be easy to move the vehicle either because of a wind or human force. Thus there must be a parking brake that will hold the vehicle in position. The parking brake also serves as an emergency brake while the vehicle is moving and a rare circumstance occurs in which emergency braking is needed and the redundant LIMs, drives, or power supply has failed. Because it is possible though improbable for the wayside power to fail, the parking brake shall be powered by the on-board battery. Power must be applied to the brake only when it is operated. With the brake either fully applied or not applied the power to the brake motor must be switched off. These features are achieved with the arrangement shown in Figure 4.3 near the rear wheel. A pair of brake shoes, one acting on the left running surface and the other on the right, are horizontal members with a high-friction material bonded to the lower side. A pair of links of identical length support each brake shoe at its front and rear. In this way motion of this assembly keeps the shoe parallel to the running surface. The assembly can be actuated by a ball-screw actuator of standard design, which can be chosen so that the actuator will not back up when turned off under load. There must be a stop that prevents the assembly from moving backwards past the vertical position. Each of the two brakes must be designed to resist a maximum vertical force of 500 lb, and a maximum horizontal force of 125 lb.

8. Shock-absorbing bumpers

There shall be a 4-in-stroke shock-absorbing bumper of standard design mounted at the forward and rear ends of the upper horizontal square tube. They shall be constant-force, constant-displacement, spring-return devices such as supplied by EGD Inc. The ends shall be configured to engage in a turn down to a radius of 75 ft. The shock absorber shall have the highest practical in-lb rating.

9. Power pickup

For propulsive power, the vehicle will be supplied with 600 volt DC from power rails mounted inside the guideway as shown in Figure 4.1. In no situation can these power rails rotate and short out. A pair of power-pickup shoes attached to each side of the chassis carry the power to variable-frequency drives. A special problem in a PRT application is that one of the pairs of shoes must disengage and then reengage as the vehicle passes through a merge or diverge section of guideway. Thus there is a potential problem of chattering and hence sparking and excessive wear. Fortunately this problem has been studied experimentally at the Insul-8 facility in Omaha, NE, and found to have a satisfactory solution. The chassis designer shall coordinate with Systems Engineering and the power-supply engineer to design the attachment of the power pickup shoes to the chassis.

10. Transmitter/receivers

Information is carried from the vehicle's computer to the cognizant wayside zone controller and back via a leaky cable mounted inside the guideway. The information transfer device is a pair of transmitter/receivers mounted to the chassis. The chassis designer shall coordinate with System Engineering and the electronics engineer to design the required mounting means.

11. Variable-frequency drive (VFD) mounting

A pair of VFDs are mounted in the chassis. They are the green boxes shown in the picture of the chassis in the Executive Summary. The chassis designer shall coordinate with Systems Engineering and the VFD supplier to design the required mounting means.

12. Battery mounting

A battery, to be specified by the power-supply engineer, is to be mounted between the two VFDs. It is to provide uninterruptible power to the on-board computer, the HVAC system, the switch, the parking brake, and other auxiliary devices. The chassis designer shall coordinate with Systems Engineering and the power-supply engineer to design the required mounting means.

13. Wiring

The chassis designer shall coordinate with Systems Engineering to design the attachments for all of the necessary wiring among chassis components and between the chassis and the cabin. Removing any chance of fire is of fundamental importance in placement and insulation of the wire.

14. Sensors

For test purposes strain gages and possibly other sensors shall be placed at strategic points on the chassis as determined by finite-element analysis.

Task #5: Final Engineering for the ITNS Guideway and Posts

References (all internal papers)

1. "An Intelligent Transportation-Network System."
2. "Guideway Criteria and how they are met."
3. "The Demonstration-System Guideway." (A computer program.)
4. "The Guideway for an Intelligent Transportation Network System."
5. "How to Design a PRT Guideway"
6. "The Guideway Cross Section"
7. "A Dynamic Analysis of the Switch Rail Entry Flare"
8. "The Equivalence between an Earthquake Load and a Wind Load on a PRT Guideway."
9. "Flexing of the Running Surface and Ride Comfort."
10. "Running Surface Stiffness and Tire Ellipticity Requirements for Adequate Ride Comfort."
11. "Vertical Acceleration of a Vehicle due to a Slope Discontinuity"
12. "Vehicle moving on a Flexible Surface."
13. "The Joint between Guideway Sections."
14. "The Deflection of a Curved Guideway."

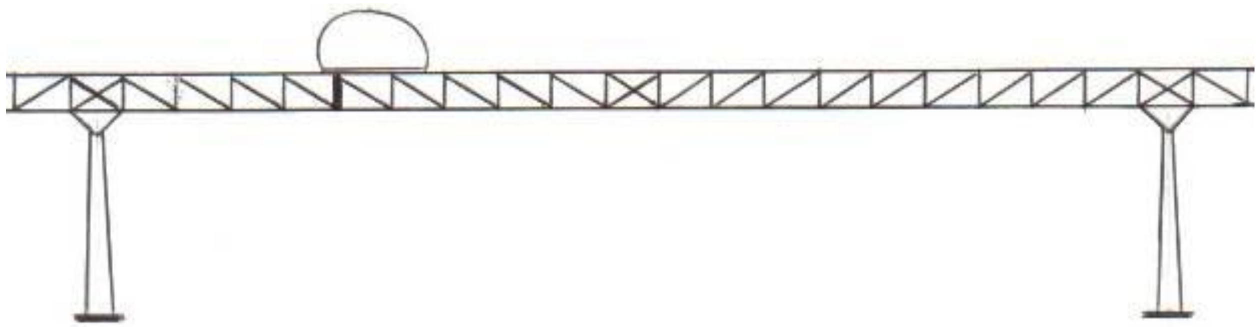

Figure 5.1. A sketch of the Guideway.

The guideway is a covered steel truss, with the elements sketched in Figure 5.1. It is clamped to posts spaced 90 feet apart, and each section has an expansion joint at the 20% point. During our Phase I PRT Design Study for Chicago, Stone & Webster engineers did extensive computer design on both straight and curved sections of an earlier but similar version of the guideway. See Figure 6.1 for the guideway cross section.

This task involves the final design verification of the guideway-post system, preparation for its fabrication, cost estimation for fabrication, and supervision of its fabrication and installation. The three-dimensional test-track layout is described in Reference 3, and the guideway that meets the maximum loading conditions is described in Reference 4. References 5 through 14 provide further information about guideway design.

To operate the Linear Induction Motors a sheet of copper 0.080" thick and 10" wide must be attached to the horizontal, 7.5" wide, surface of each of the main-wheel-support angles and over-lapped underneath. Since the wheels mounted on the chassis do not steer, there will be some wear while traversing the curves in the guideway. Tests performed at Raytheon in 1993 relieved concerns about wear on the copper surface; however, using principles of tribology further analysis and testing of expected wear on the copper surface is warranted. A great deal of information about tribology can be found on the Internet including references to possible consultants. Such a consultant shall be engaged to advise the project.

The Company needs the assistance of a Structural Engineer who has the computer tools and skill required to perform an accurate verification of the design, and the tools needed to produce drawings from which to fabricate the straight and curved sections of guideway. It will be expected also that the Structural Engineer will assist the Company in discussions with the fabricator. An additional firm may be needed to design and build adjustable fixtures that will lay up the guideway sections for fabrication, and also the fixtures needed for robotic welding.
The posts on which the guideway will be mounted are at least 90 ft apart. To ease transportation to the test site, the guideway may be fabricated in 45-ft sections and welded at the test site to form each of the required 90-ft sections.

The guideway shall be clamped to the posts using the assembly illustrated in Figure 5.2. Expansion joints (Reference 13) shall be placed at the 20% point in each span.
The guideway-support posts are planned to be bent up from 5/16” steel plate. They are to be octagonal and tapered from 10” at the top to 20” at the base, where each of them is to be welded to a 2” thick steel base plate, which is to be bolted to a reinforced concrete foundation in which four 1.5” high-strength steel studs, spaced at the four corners a square 24” on a side, are mounted to receive the base plate. The length of each post will be given from planning analysis. Manufacture of such posts is a specialty item. One of the few manufacturers in the United States is Millerbernd Manufacturing Company of Winsted, Minnesota. They would supply the complete post with the bracket on top and the steel base on the bottom. The post-to-guideway bracket has been designed roughly and shall be verified by finite-element analysis.

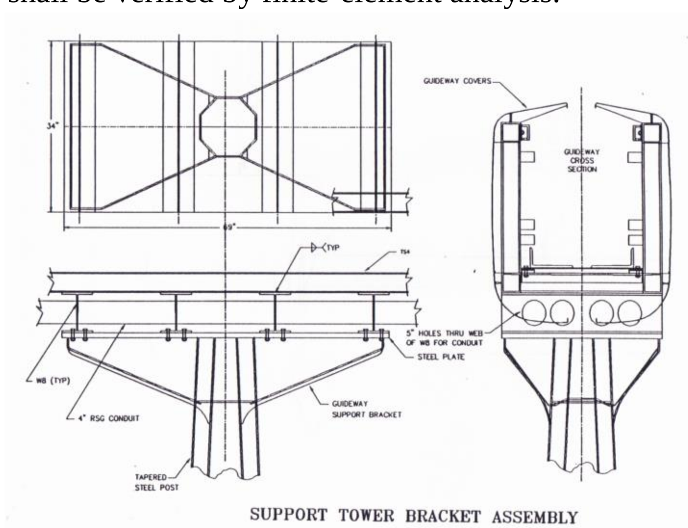

Figure 5.2. The Guideway-Post Bracket.

Brackets are to be designed and built into the guideway to permit a hinge attachment of the covers at the bottom and a latch attachment at the stop, so that the covers can be swung down to permit access to the guideway, however remote the need to do so may be.

Deliverables: A complete set of drawings and specifications that will enable a competent fabricator to fabricate the guideway to the tolerances required for adequate ride comfort. A detailed layout of the guideway required for the first application will be given.

Task #6: Final Design and Fabrication of the Guideway Covers

This specification relates to design and fabrication of covers for the guideway, which must be built in sections of convenient length and curved to conform to the shape of the guideway. The three-dimensional layout of the system will be given. The guideway with its maximum loading conditions is described in Task #5. Figure 6.1 includes a cross sectional view of the cover as it is hinged to the bottom of the guideway and secured at the top.

The radii at the top and bottom corners of each cover are 6 inches and the sides should be slightly bowed for added stiffness. We envision the covers to be molded from fire-resistant reinforced composite material suitable for an outside environment in which temperatures may swing from 130 deg F to -45 deg F. The exterior of the cover shall be able to accept a color and texture specified by a planner, and a thin layer of aluminum is to be sprayed on the inside to act as an electromagnetic shield. Sound insulation may also be applied. The thickness of the covers should be sufficient to ease the process of lowering the cover in the field for possible maintenance inside the guideway in winds up to 15 mph. We envision a cover thickness of about 1/8”. The covers are to be designed to be replaced no more than once every 20 years. The cover is to be fabricated with stainless steel inserts suitable for attachment at the top and bottom of the guideway to brackets fabricated into the guideway structure.

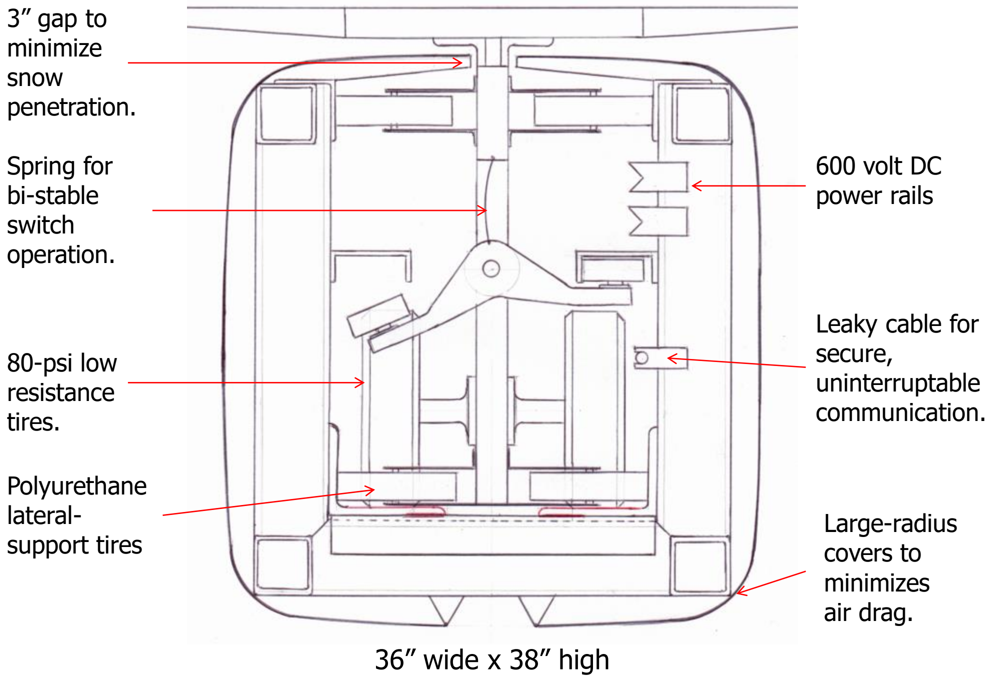

Figure 6.1. Covered Guideway Cross Section.

Deliverable:

A complete set of drawings of the covers in a form needed for fabrication.
Identification and negotiations with the cover manufacturer.
A complete set of covers ready to be installed to the test guideway.

Task #7. The Design and Assembly of the *ITNS* Control System

This task is for the design, assembly, and test of the control system needed to operate *ITNS* vehicles on a full-scale demonstration system.

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2. J. E. Anderson, "PRT Control," *Journal of Advanced Transportation*, 32:1(1998):57-74.
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6. J. E. Anderson, "Simulation of the Operation of a PRT System," *Computers in Railways VI*, WIT Press, Boston, Southampton, 1998, 523-532.
7. J. E. Anderson, "Dependability as a Measure of On-Time Performance of Personal Rapid Transit Systems," *JAT*, 26:3(1992):101-212.
8. J. E. Anderson, "A Review of the State of the Art of Personal Rapid Transit." *JAT*, 34:1(2000):3-29.
9. J. E. Anderson, "Overcoming Headway Limitations in PRT Systems," PodCar Conference, Malmo, 9-10 December 2009.
10. J. E. Anderson, "Failure Modes and Effects."
11. Vehicle Control Software.
12. J. E. Anderson, "Properties of a Linear Induction Motor."

Serious work on the design of control systems required for systems like ITNS extends back to the 1960s.
Reference 1 gives a bibliography of articles on control of HCPRT.
Reference 2 describes the *ITNS* control concept as it had advanced by 1996.
Reference 3 describes the elements of safety and why linear-induction motors are necessary.
Reference 4 shows why synchronous control is not a viable option for any but a very small system.
Reference 5 shows that only speed and position feedback are needed to control an *ITNS* vehicle and derives the gain constants needed in terms of a natural frequency, a damping ratio, a first-order thruster lag, and the mass of the vehicle.
Reference 6 describes the operation of ITNS vehicles in a network of guideways.
Reference 7 defines *Dependability* and shows why it is the most useful measure of on-time performance.
Reference 8 contains important information about control in a systems context.
Reference 9 shows how very high safety and reliability can be obtained.

Reference 10 calculates the MTBFs of many potential failure modes and in the process gives useful information on how the control system works.
Reference 11 is the vehicle-control software program.
Reference 12 derives the equations for the equivalent circuit model of a linear induction motor (LIM) and shows how they are used to optimize performance.

The details of *ITNS* control have been developed and form the basis for the current project, in which we need to take into account advances in technology that may improve performance and/or lower costs. We obtained a significant amount of useful information from Boeing on their control work under the federal Advanced Group Rapid Transit program, which is described in a series of articles in IEEE publications, which are available. During the past five years, we have developed the software programs needed to operate an *ITNS* network of any complexity. When the successful bidder is selected among those we have in mind, we will provide additional information on the details of PRT network control on an as-needed basis.

1. The Control Concept

Control is accomplished by means of three levels of computers: Computers on board each vehicle (VC), wayside zone controllers (ZC), and a central controller (CC). Each VC receives commands from the local ZC and transmits to it position and speed. The CC communicates with each ZC, but not with the VC.

There are five types of zone controllers (ZC):

1) Each station ZC, SZC, controls the movement of vehicles through and around a station.
2) Each merge ZC, MZC, controls operations through a merge section of guideway.
3) Each diverge ZC, DZC, controls a diverge section.
4) A line ZC, LZC, may be needed in a section of guideway too long to be included in one of the other types.
5) The fifth type of ZC, PZC, manages the flow of passengers in a station.

The number of vehicles that can be accommodated in each ZC depends on the data rate. The amount of data that must be transmitted is minimized as described below. The VCs and ZCs are used over and over again without change as the network grows.

2. Dual-Duplex Computers

During a study of automatic control for the federal Advanced Group Rapid Transit program, Boeing found that the best way to meet a federal safety requirement was by using two pairs of motherboards in each computer making the same computations and arranged so that the two outputs of each pair must match at least 10 times each second, and then the common output of each pair must match, otherwise defensive action must be taken. They called this DUAL-DUPLEX. A diagram is shown below. ITNS uses this philosophy in all computers in its system. The Boeing work is described in a series of IEEE papers, which are referenced in Reference 2 and in a series of reports in the public domain. The defensive actions required are discussed in Reference 10.

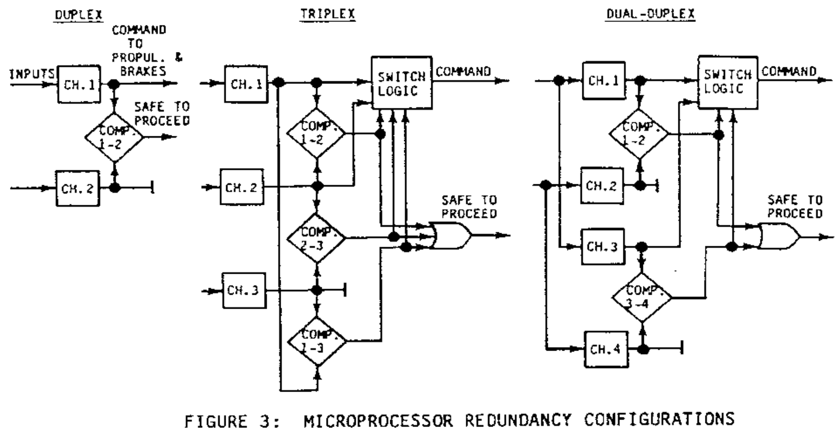


Figure 7.1. Dual Duplex Control.

3. The Vehicle Controller

A block diagram of the vehicle controller is shown in Figure 7.2. The gain constants G_v and G_p are derived in Reference 5. The vehicle is propelled and braked by a pair of LIMs, each of which receives a variable-frequency voltage input from a Variable Frequency Drive (VFD), which receive its command voltages from a software package, which calculates the instantaneous required frequency and voltage. The frequency is a predetermined linearly increasing function of speed. Conversion of thrust commands into voltage commands is accomplished by use of an equation, derived from the equivalent-circuit model of the LIM (Reference 12) that calculates the required voltage as a function of thrust, slip, and frequency.

When operating at constant speed, the vehicle computer receives the command speed from a wayside zone controller (described below) each time-multiplexing interval. If the speed signal is not received in two successive intervals, the vehicle is commanded to a creep speed of about 1 m/s, at which a collision is of no consequence (each vehicle is equipped with shock-absorbing bumpers front and back.)

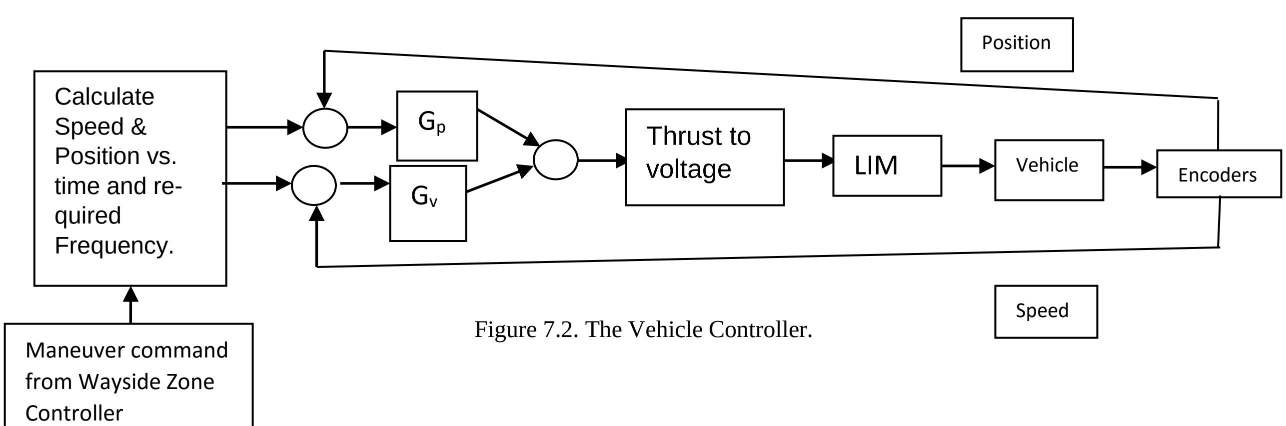


Figure 7.2. The Vehicle Controller.

A wayside ZC transmits to a specific vehicle a maneuver command with a parameter, such as "Stop in x meters." The vehicle controller has in its software the routines needed to calculate the instantaneous speed and position required of any maneuver. It compares these command values with the actual speed and position 200 times per second. The differences are multiplied respectively by a speed gain and a position gain, summed, and then sent as a thrust command to a thrust-to-voltage converter.

Position and speed can be obtained from digital encoders, which can be imbedded in the wheel bearings. The left and right encoder outputs are averaged to give the correct output in turns, and the fore and aft encoders provided redundancy. The accuracy of encoders has been shown to be sufficient to obtain speed by differentiating the encoder output.

In a project for the Chicago RTA in 1991 that involved Raytheon and Hughes engineers, it was determined that the most secure way to transmit data between the vehicles and the wayside zone controllers was via a leaky cable mounted inside the guideway. Leaky cables are now commercially available from multiple sources. Devices that transmit and receive data to and from the communication means need to be designed, built, installed, and tested.

4. Switch Operation

The switch consists of a pair of arms with a polyurethane tired wheel on each end as shown in Figure 4.1, Task # 4. These arms rotate about a longitudinal axis. In merge and diverge sections of the guideway, switch rails are positioned to intercept the switch wheels, thus constraining the vehicle positively as it passes through the merge or diverge section. The switch is rotated by means of a pair of rotary solenoids, one of which throws the switch to the right and the other to the left. The switch arms are held in one of two stable positions by a pair of leaf springs, and their motion is stopped by a pair of commercially available snubbers. If the switch arm is rotated so that the left wheel is horizontal, it is set to steer the vehicle to the left, and if rotated so that the right wheel is horizontal, it is set to steer the vehicle to the right.

The position of the switch is sensed by means of a pair of proximity sensors wired to the VC. When the VC receives a switch command from a cognizant wayside ZC, it determines if the switch is in the desired position or if it must be thrown. If the latter, the VC commands a pulse of current to one of the rotary solenoids, and at the same time commands the vehicle to creep speed about one second later. The action of the switch arm reaching the other position (in about 0.25 sec) is sensed by the cognizant proximity sensor, which informs the VC to cancel the signal to slow the vehicle to creep speed. This is one of the ways in which fail-safe operation is implemented.

5. Auxiliary Functions of the VC.

The VC on each vehicle

- commands opening and closing of the door,

- accepts and stores the destination command,
- changes the destination command if requested by the occupant or by a central operator,
- controls the lights,
- controls the HVAC system,
- senses and responds to overloading,
- senses and responds to smoke in the cabin by causing the vehicle to stop at the next station, alert authorities, and upon stopping causes the cabin door to open,
- keeps track of distance traveled in order to direct itself to maintenance on a predetermined schedule,
- senses incipient failures by means of strain gages, temperature sensors, pressure sensors or vibration sensors and, based on established criteria, dispatches the vehicle to maintenance after causing the passengers to unload, and
- Stores information on all failures for analysis of the mean time to failure.

6. Vehicle Control Program

A computer program has been written to operate the vehicle under the closed-loop control system shown in Figure 7.2 and has been tested with passengers in a vehicle, thus proving that ride comfort is excellent. Position and speed commands are derived to cause the vehicle to perform each maneuver at maximum comfort acceleration and jerk and in minimum time. A computer program has been written and tested over 40,000,000 times with random inputs to calculate each maneuver with specified input parameters.

7. Station Zone Controller (SZC)

A SZC controls the vehicle operations through each station, which requires information on the position and speed of each vehicle under its jurisdiction. It keeps track of the position and speed of each vehicle from the downstream point of merge of the station-bypass guideway with the main guideway upstream to the nearest branch point, whether it is the exit of another station or a line-to-line merge or diverge. The upstream ZC informs its downstream neighbor of the arrival of each vehicle in a “hand-off” operation. The downstream neighbor informs its upstream neighbor when a vehicle in its jurisdiction must slip past the zone boundary to avoid violating the minimum allowable headway to a downstream vehicle. Slip is discussed below in the paragraph describing the merge zone controller.

At a pre-determined position upstream of each station there is a Switch Command Point (SCP). When a vehicle passes this point, its destination is transmitted to the SZC, which determines if is to be switched into the station. Normally, if the destination matches the station number the vehicle is switched in and at the same time the forward-most empty berth is reserved for it. But the station may be so full of vehicles that it can’t accept another, in which case the SZC commands the vehicle to switch away from the station in an action called a “wave-off.”

A short distance down the guideway and ahead of the station, there is a Deceleration Command Point (DCP) at which a vehicle committed to enter the station is caused to begin a deceleration maneuver to stop it at the reserved berth. But before the deceleration command, the SZC notes if there is now a free berth farther downstream, in which case it changes the berth reservation to the new forward-most free berth. At the instant the vehicle reaches the DCP it may be moving at a speed lower than the line speed and it may be accelerating or decelerating while performing a slip maneuver. Thus the maneuver command must take into account the initial speed, initial acceleration, and the distance to stop. Such maneuvers have been programmed and thoroughly checked. While in the station area, a vehicle may be commanded to advance to a newly freed berth, and it may be so commanded while it is engaged in a deceleration maneuver or in a station-advance maneuver. Thus, the SZC must follow the motion of all vehicles in its jurisdiction and be ready to command station-advance maneuvers when required. If the vehicle is in the unloading and loading area, the SZC must determine when it can advance, not only based on availability of a free berth ahead but on the status of loading or unloading and only if the door is closed.

When the forward-most vehicle in the station area has been given a destination to a different station, it may be at rest or it may be in a deceleration maneuver or a station-advance maneuver moving to the forward-most free berth. In either case, the SZC, which keeps track of the positions of all of the vehicles bypassing the station, calculates the position in the mainline and the time of arrival at line speed if it were to accelerate to line speed at each moment of calculation. The SZC calculates the minimum distance to the vehicle ahead on line and the vehicle behind, and only if these distances are within acceptable bounds does it command the vehicle to line speed. The complete set of acceleration-to-line-speed maneuvers has been programmed and thoroughly checked with arbitrary initial speed and acceleration. An additional condition for commanding a vehicle to line speed is that the vehicles bypassing the station are not slipping. Slipping indicates that there may be too much traffic trying to enter a downstream merge, so the system manages excessive congestion by holding vehicles in stations until the congestion has cleared.

When there is an unneeded empty vehicle in the first berth in a station the SZC will give this vehicle the destination of the nearest storage station, whereupon it is released from the station exactly as any other vehicle is released. While the empty vehicle is cruising on line it can be redirected into a station where an empty vehicle is needed. This process is discussed in Reference 8.

8. Passenger-Movement Zone Control (PZC)

In each station there is a computer that controls all functions involved with 1) passengers paying fares, 2) entering their destinations so that they can be transferred to a VC, 3) causing the vehicle door to open, and 4) determining at which berth passengers should prepare to load. The later can be indicated by a green light over the berth. By means of motion detectors, the station computer can estimate the rate of arrival of passengers from the street so that the system can be alerted to send more empty vehicles. The code for these operations has not been written.

9. Merge Zone Control (MZC)

At a predetermined distance upstream of each line-to-line merge point resides a Merge Command Point (MCP). The MZC keeps track of the positions and speeds of all vehicles within its jurisdiction. When a vehicle passes the MCP, the MZC checks the positions of the vehicles on each branch of the merge. If a conflict would occur with a vehicle too close ahead on the other branch of the merge, the MZC commands the vehicle to slip back a distance sufficient to increase the headway to the accepted value. In a slip maneuver the vehicle is commanded to follow a maneuver profile in which it first slows down then speeds up to the original speed. If in slipping, the MZC detects that the headway to the vehicle behind would be too small, the MZC simultaneously causes that vehicle to slip – usually a lesser amount. This slipping of upstream vehicles continues until the next upstream vehicle is far enough behind so that the headway criterion is not violated. Slipping may continue upstream of a line-to-line merge or diverge. If the upstream branch point is a merge, vehicles on two upstream branches may have to slip. This action is programmed into the ITNS network simulation program. A key factor in this action is that the MZC must keep track of the slip remaining for each vehicle so that it commands only the additional slip needed to avoid conflict. The slip maneuver is designed to retard each vehicle from an arbitrary speed and acceleration. All of such slip maneuvers have been programmed and thoroughly checked.

10. Diverge Zone Control (DZC)

Each DZC contains a table of switch commands for every station in the network. These commands may be changed by the CC because of excessive traffic in certain parts of the network. When a vehicle reaches the Diverge Command Point (DCP), which is located at a predetermined distance upstream of the DZC, the DZC requests the vehicle's destination, looks up the corresponding switch command, and transmits it to the VC, whereupon the VC performs all of the actions described above. The distance of the DCP upstream of the clearance point[78] ahead of the diverge point is the line speed multiplied by a conservative estimate of the switch throw time plus the distance required to stop if the VC can't detect that the on-board switch is in one or the other of the two stable positions.

11. Line Zone Control (LZC)

If there is a region of the guideway too remote to be served by one of the above three types of ZC, the function of the LZC is to transmit the line speed to the vehicles in its jurisdiction, to monitor the positions and speeds of the vehicles, and to remove the speed signal if one of the positions or speeds has deviated from the expected values by a predetermined amount. The result is that the VCs, lacking the speed signal, automatically slow the failed vehicle and those behind it that would be impacted to the predetermined creep speed. This monitoring function is also a function of the other three types of ZC.

[78] The point at which vehicles on opposite branches of the diverge would touch each other.

12. Central Control (CC)

The CC is connected by fiber optics to each of the ZCs. Its function is to reduce traffic congestion when necessary and to gather and analyze data. Management of congestion requires that the CC keep track of all of the vehicles in the network by data transfer from the ZC and determine by established criteria when to change the switch tables for certain destinations from certain diverge points. This function has not been programmed into the network simulation program and can be delayed until the planned network becomes large enough so that it is needed.

The CC will gather data on failures in each vehicle and also the difference between each actual trip time and the expected value in order to calculate, via the method derived in Reference 7, the system dependability, which can be used as one of the means of determining if the system meets contracted on-time performance.

13. Network Control Program

Of the above-described controllers, all but PZC and CC have been programmed and checked in a network control program, which will be made available to the Control Supplier. The program permits different speeds in different parts of the network. The simulation program is described in Reference 6.

14. Fault-Tolerance Means

- Wayside zone controller (ZC) emits a speed signal every 100 ms.
  With no speed signal the vehicles in its jurisdiction are programmed to creep speed.
- ZC receives position and speed from each vehicle every 100 ms.
  With no communication from a vehicle, ZC removes speed signal for that vehicle and those behind it.
- All commands returned and verified before action is taken.
- Temperature sensors warn system of possible thruster failure.
- Emergency-brake command ON unless OFF received every 100 ms.
- Throw of switch commands creep speed in 0.5 sec unless canceled by signal from a Proximity Sensor.
- Sonar or radar back-up emergency control.

15. System Control

The demonstration system will use at least two wayside zone controllers, one of which will be used in either the mode of the SZC or both the MZC and the DZC. The other is an LZC, which will command and monitor the section of guideway from the guideway merge point out of the station approximately half way around the track, thus permitting the implementation and testing of the process of handing off information from one zone controller to the next.

16. Data to be transmitted between Vehicles and Wayside.

1. From wayside zone controllers: the speed command every Time Multiplexing Interval (TMI) [79] and maneuver commands when needed. In case of a fault, the zone controller removes the speed command, in which case the vehicles are programmed to decelerate to creep speed.
2. From the vehicles, ID number, speed, and position every TMI. If a vehicle does not receive a speed command in two successive TMIs, it and the vehicles upstream of it are programmed to reduce speed to the creep speed.

17. The Hardware Components

1. Digital encoders mounted on each vehicle to detect position and speed.
2. Transmitter/Receivers to be mounted on the vehicles and at the wayside ZCs.
3. Leaky cables − the means for communicating between vehicles and wayside computers.
4. Wayside magnetic markers to provide independent checks on the speed and position of each vehicle for the wayside zone controllers.
5. The vehicle and wayside computers to be used.

18. Information to be developed by the Control Team

- Data Rate. The practical, verifiable data rate that can be used.
- Time-Multiplexing Interval. From the Boeing work, available in a series of IEEE papers, the basic communication scheme was based on establishing a "time-multiplexing interval" (TMI) that would be divided into segments assigned to each individual vehicle within the domain of one zone controller. If this is still the best practice, the TMI must be selected. It must be short enough to provide adequate position and speed monitoring but long enough so that the data can be transmitted and received without error. Boeing used 40 ms and Raytheon 200 ms assuming more vehicles. The task here is to determine an acceptable TMI, assuming that each wayside zone controller must be able to handle at least 30 vehicles.
- Frequencies. The suitable frequency range for data transmission. Boeing used 100-150 kHz.
- Wayside Sensors. Specifications for the independent means to be used by the wayside zone controllers to verify vehicle speeds and positions, such as magnetic markers.
- Vehicle Sensors. Specifications for the means for the vehicles to obtain speed and position information. We have tested and simulated the operation of digital encoders, and know

[79] These need not be equal intervals. What is essential is that each vehicle in the zone be able to transmit its data to wayside every TMI.

that they would be satisfactory. An alternative method must be clearly superior at lower cost.

- Communication Means. Specifications for the means of communication between vehicles and wayside. If there is an acceptable alternative to a leaky cable it must be less expensive and secure.

- Common-Cause Failures. Boeing recommended using dual-duplex computers, which are defined in detail in their IEEE papers. In such a system there must be no way for the system to introduce common-cause failures. Clarification of means to insure that common-cause faults cannot be introduced is needed.

19. The ITNS Software

The bidder shall be part of the software team to insure a seamlessly integrated, fault-tolerant control system consistent with system dependability, Reference 7, of better than 99.98%.

20. Hardware Procurement and Installation

The bidder shall procure the necessary control hardware, supervise its installation on the test track, and be available during the test program to make adjustments as needed.

21. Deliverables

- Complete specifications for the hardware components of the PRT control system.
- The required software.
- Procurement and installation of all control hardware.
- Supervision of installation of the control hardware and software.
- Consulting as needed during the test program.

22. Decisions Needed During the Demonstration Program

The demonstration program will involve only a few vehicles and likely no more than one off-line station. But much of the complexity of a large system needs to be considered to prepare for commercial operation. In preparation for the demonstration program the following must be selected:

- The operating system.
- The programming language.
- The means of communication between vehicles and wayside – absolute security is a key requirement (most likely a leaky cable inside the guideway).

- The required data rate between vehicles and wayside zone controllers.
- The time-multiplexing interval if a specific time interval is needed.
- The computers to be used.
- The means of position and speed sensing (likely digital encoders).

Task 8. The Propulsion System for *ITNS* Vehicles

This Task is to specify, procure, install, and test a pair of linear induction motors (LIMs) and variable voltage, variable frequency drives (VFDs) that will propel and brake each ITNS vehicle.

1.0 Configuration

The vehicle configuration is shown in Task #4, Figure 4.1, with the LIMs mounted at the bottom of the chassis, which is inside the guideway. A photograph of the first chassis built is shown in the Executive Summary. The vehicle is supported by four main wheels that run on the horizontal surfaces of a pair of 8 in wide by 6 in high by 1/2-in thick steel angles. Lateral support for the vehicle is obtained by means of four side wheels near the top of the guideway and four near the bottom. The reaction surface for the LIMs is the horizontal surfaces of the angles, coated by a 0.080" thick copper sheet. The LIMs are placed between the front and rear sets of main-support wheels, and are supported as a set by four 4-in OD polyurethane-tired wheels, which are attached to the chassis via horizontal linkages, which enable us to maintain a gap of 3 mm between the undersurface of the LIMs and the top surface of 10-in wide copper sheets attached to and wrapped around the main-support angles. In a vertical curve, the gap may reduce to 1 mm or increase to 5 mm for a small fraction of a second. The VFDs are to be mounted in the cross-hatched area shown in the side view in Figure 4.1.

Figure 7.2, Task #7, shows the placement of the LIMs and VFDs in the vehicle's control loop. On the left, the command position and speed are compared with the measured values of position and speed, with the differences multiplied by gain constants and added. The resulting signal is a command to change thrust, which in the VFD is converted into a voltage and frequency command.

2.0 Design Constraints

2.1 <u>LIM Length.</u> With the chassis as shown, the LIMs may be a maximum of 38 in long. If they need to be longer to meet the performance requirements, the chassis will be lengthened accordingly, but only after other alternatives to increase performance are considered.

2.2 <u>LIM Cross section.</u> As mentioned above, the LIMs react against the horizontal surfaces of 8x6x1/2-in steel angles. The inside vertical surfaces of the pair of angles are 21 in apart and with the 1/2-in thickness of the angles there remains a 7.5 in horizontal surface on each. Per supplier recommendation, the horizontal reaction surfaces are to be covered by 2-mm-thick (0.080”) 10”-wide copper sheet with the copper sheet folded around the inner leg of the angle and underneath it. We understand that with this thickness the normal force will be roughly equal to the thrust.

2.3 LIM Air Gap. The air gap between the bottom surface of the LIM and the top surface of the copper sheet is nominally 3 mm. The LIMs will clear the inside vertical surfaces of the angle running surfaces by at least 5 mm, except in merge and diverge sections of guideway where one of the vertical angle surfaces moves away by a large amount.

2.4 LIM Side Gap. This problem is considered in a companion paper “The Required Side Gap in the ITNS Chassis,” in which it is shown that the present design assumes a minimum curve radius of 75 ft, which means that the speed in curves must be 20 mph or greater. In the ITNS design, tighter turns are not needed operationally. In maintenance shops, where in some systems tighter turn radii are used, in *ITNS* lateral transfer tables are used, which are much less expensive.

2.5 Input Power. Propulsive power will be obtained from power rails nominally at 600-volt DC with a variation along the guideway of no more than 10%. The LIMs shall be wound 3-phase normally Y-connected. The maximum phase voltage is 270 volts. During acceleration and deceleration, the power transmitted to the vehicle will vary as shown in the detailed specifications. Since there will be two motors in each vehicle, the power to each will be half the values given.

2.6 Drive Frequency. The motors shall be operated at the frequency at each speed that as close as practical minimizes current.

2.7 Ambient Temperature. The LIMs shall provide full performance as specified in Paragraph 3.0 over the ambient temperature range of -45^o C to +50^{o}C,

2.8 Temperature Protection. Each LIM shall be provided with imbedded temperature sensors to protect against damage due to overheating.

2.9 LIM Cooling. By forced air.

3.0 Thrust Performance Requirements

The performance requirements were calculated assuming that the steady grade may vary from +6% to -6%. Numerical input values are given at the beginning of the computer program included in the detailed task description. Some of these values can be expected to vary as a result of tests. The output performance values at three values of grade are given in Figures 4 a, b, and c of the detailed task description, which will be provided.

Task 9. Wayside Power and the Guideway Electrification

This task is for the design, procurement, and installation of components that will provide power to vehicles on the guideway and to the station, maintenance shop, and test-engineering office. The requirements are the following:

1. To provide power to the vehicles, utility power shall be converted to nominally 600 volt DC and fed to power rails installed inside the guideway with a variation of no more than 10%. The maximum power required by a single vehicle is 40 kW so to provide a margin with three vehicles the wayside power conversion equipment shall be designed to handle 100 kW. Alternative primary power from solar cells or windmills coupled with power storage means shall be considered.

2. The house power needed for the test-facility buildings shall be determined in consultation with the designer of these facilities.

3. Standard power rails suitable for transit applications at speeds up to 40 mph (18 m/s), such as manufacture by Insul-8 or Wampfler, shall be used. They shall be rated at 300 amps. A small opening in the front face of the insulating rail covering shall allow for the insertion of the power-pickup shoes that ride against the stainless steel face of the power rail.

4. The guideway feeder cables and the guideway power rails shall be sized to limit the voltage drop to ten percent from nominal to ensure acceptable performance on a vehicle at the end of a guideway sector under heavy load conditions.

5. Power rails shall be placed only on one side of the main guideway loop and only on the other side through the station bypass guideway with sufficient overlap at the diverge and merge sections leading into and out of the station so that power can be transferred from one side to the other. Power pickup shoes shall be mounted on both sides of each vehicle. Electric current to the power-pick up shoes will be shut off before disengaging.

6. The power-pickup shoes are part of this procurement. They shall be designed to prevent chatter as they engage and disengage at the diverge and merge sections. Tests on disengagement and reengagement were performed at the Insul-8 Omaha facility in 1993-4 during the Raytheon PRT program with satisfactory results.

7. Lightning protection. The vehicles shall be outfitted with lightning protection terminals wired to the on-board ground. This ground shall always be in contact with the ground rail located on the inside wall of the guideway. The ground rails and all metal parts of the guideway structure shall be periodically bonded and grounded to earth. The lightning protection system shall be designed to carry lightning currents safely away from the passenger compartment of each vehicle to insure safety of the occupants.

8. Safety. The power-system design shall insure safety of passengers, operations personnel, emergency personnel, and members of the community. Emergency load-break disconnects shall be available to all personnel requiring access to the guideway. Conductor clearances, insulation, and covering of live parts shall meet National Electrical Safety Code requirements.

9. Codes. The system shall be in conformance with the following codes and standards:

    - American National Standards Institute (ANSI)
    - Electronic Industries Association (EIA)
    - Insulated Cable Engineers Association (ICEA)
    - Institute of Electrical and Electronic Engineers (IEEE)
    - National Electrical Code (NEC/NFPA 70)
    - National Electrical Safety Code (NESC)
    - National Electrical Manufacturers Association (NEMA)
    - National Fire Protection Association (NFPA)
    - Underwriters Laboratory (UL)

Task #10: Design and Construction Supervision of the Civil Works

This task involves the design and construction supervision of the buildings needed for 1) the station platform, 2) a maintenance shop with space and equipment needed to service one vehicle, and 3) office space to accommodate the chief test engineer, three associates, and visitors; for the surveying, design, and construction supervision of the foundations for the posts that support the test-track guideway and the guideway itself; and for the required landscaping.

The requirements are as follows:

> A station platform at least 5 ft above the ground, 12 ft deep, and 30 ft wide to accommodate three 9-ft-long vehicles. The platform shall be open to the elements on the vehicle-loading side, but provided with walls on the other three sides, a roof that covers both the station platform and the parked vehicles, and an entryway for people on the side opposite the positions of the vehicles. There shall be a wall built on the side of the vehicles away from

the station platform to prevent people from exiting on the wrong side. The floor will be of durable, exterior-certified material.

A lateral-transfer table (LTT) shall be placed just upstream of the station platform to permit insertion and removal of one vehicle at a time to and from the station guideway. This device will consist of a guideway section 10-ft long secured to a platform (LTTP) that is supported by four flanged rail-type steel wheels perpendicular to the guideway that ride on a pair of steel rails, with stops at the ends of the rails. In the LTTP's normal position, the guideway attached to LTTP will be in line with the station bypass guideway. In its extended position this guideway will be inside the maintenance shop, the floor of which will be at the level of the guideway running surface, which is about 40" below the station platform. When the vehicle is positioned in the LTT guideway section, the LTTP with the vehicle in place can be pushed laterally until the vehicle is in position inside the maintenance shop. Once the vehicle is serviced it can be pushed to be in alignment with the station guideway, whereupon it can move out of the station. The 10-ft section of guideway mounted to the lateral-transfer table will be equipped with power rails so that a vehicle can be driven through it under normal wayside power.

A maintenance shop shall be placed upstream of the station platform and equipped to service one vehicle at a time. The shop will be equipped with a work bench and appropriate tools and diagnostic equipment. The shop is arranged so that a vehicle can be brought in from outside, wheeled across the shop floor and into the waiting guideway section. While on the shop floor, the vehicle shall be supported by slings from an overhead rail that shall permit the vehicle to be raised to a height suitable for easy work on either side of the chassis. The outside top of the cabin is 100 in above the running surface.

A test-engineering office shall be designed and built with room for four desks, a blackboard, the wayside computer, and an electronic board that will show the positions of the vehicles. The best position of this office is next to the maintenance shop on the side away from the guideway. In this way, the maintenance shop and the office can all be under one roof. The test-engineering office shall be sufficiently large to accommodate a group of ten visitors and equipped with projection equipment.

Provision for state-of-the-art fire safety of the buildings shall be provided.

An accurate survey to locate the positions of the foundations for the posts, which will be nominally 90 ft apart.

Design and construction supervision of the foundations for a loading condition of a 190,000 ft-lb bending moment at the base of each post.

Installation of the posts and guideway.

Landscaping shall be provided per further instructions.

A Security System shall be provided to warn against potential vandalism while operating personnel are not present.

Requirements for PRT station and ticketing in applications

1. An ITNS station must accommodate all kind of people: regular users, occasional users, visitors who have never used it before; people who use cell phones; people who don't; blind people; deaf people; people in wheelchairs, people using walkers; and perhaps other classifications.

2. People's privacy must be protected in the sense that nothing about using PRT should reduce the limited privacy that people now retain.

3. People must be able to select the destination in the simplest possible way -- by viewing a map of all possible destinations.

4. Having selected the destination, there must be a means for paying the fare. To accommodate all types of people it must be possible to pay the fare on the spot. An alternative would be to purchase a fare card at a convenience store, but for a visitor that is an annoying additional step, and he or she may want to pay for just one trip.

5. Having paid the fare, the potential rider must be able to obtain a receipt that will be used to access a specific vehicle, send the destination to the vehicle computer while standing in front of the selected berth, and cause the door to open.

6. If, upon seeing the vehicle door open, the rider notices that the vehicle has been vandalized, there must be a means of rejecting the vehicle and notifying system personnel.

7. For reasons of security, each station must be equipped with video cameras connected to screens at a control room, there must be a means of alerting control room personnel that they must pay particular attention to a specific station, and there must be a two-way voice communications system between the control room and either all stations or one specific station.

8. It must not be possible for a patron to walk out onto the guideway.

9. The station must be well lit and have fire-extinguishing equipment.

Task 11. Testing

To certify that ITNS is ready for people-moving applications the following series of tests shall be performed:

1. Component Tests

1.1 Switch Tests

1.1.1 One complete switch assembly will be operated for an equivalent of 10 years of operation. Since the average vehicle will travel about 80,000 miles per year, and there will be an average of about two switch operations per mile, in 10 years, there will be about 1,600,000 switch operations. Assuming one switch operation every 6 seconds (0.5 sec for the operation and 5.5 sec to cool between operations) there can be 600 operations per hour, 14,400 operations per day, or 432,000 operations per month. Hence ten years of switch operation can be accomplished in 3.7 months.

1.1.2 The switch assembly will be subjected to vibrations in the forcing-frequency range of 4 to 18 Hz to determine that there are no natural frequencies in this range.

1.1.3 One switch arm with wheels attached will undergo fatigue testing. A force cycling between zero and 1000 lb will be applied to one of the arms until either 1,600,000 cycles or failure occurs. The results of this test will be compared with the results of finite-element analysis to corroborate the properties of the switch arm, wheel assembly, and axle, and the bearing.

1.2 Door Assembly Tests

The purpose of this test is to prove the endurance of the door-operating mechanism by operating a complete door assembly in a mock-up cabin at least 400,000 times, which is the estimated number of door cycles in 10 years. This number of cycles can be accomplished in about 33 days.

1.3 Guideway tests

1.3.1 U-Frame Strength Test. The purpose of this test is to determine the load applied at the position of the upper-lateral wheels needed to exceed the maximum yield stress at the lower corner of the U-frame and also the load required to break the U-frame. This test will determine the adequacy of the finite-element analysis used to design the U-frame.

1.3.2 Guideway Bending and Twisting. Mount the first 90-ft segment of guideway manufactured on a pair of mock-up post brackets. Subject the guideway segment to a center load to determine if the ratio of deflection to load agrees with the calculated value, and subject it to a center twisting moment to determine if the ratio of twist angle to torque agrees with the calculated value.

1.4 Vehicle-to-Wayside, Wayside-to-Vehicle Communications

The objective of this test is to optimize the vehicle antenna configuration including its spacing with respect to the leaky cable, to establish link parameters, and to measure performance in a realistic electromagnetic noise environment. The test will determine how strong an electromagnetic field is needed to interfere with the zone local area network (ZLAN) and to measure its radiated field strength versus distance for comparison with FCC limits. This test will be performed in the presence of 600-volt DC traction power in the first segment of guideway fabricated. The test will be completed with and without guideway covers.

2. System Tests

2.1 The Test Facility

The general layout of the test facility is described in the document "Description of Test Track," and the planned test-facility buildings are described in Task #10. The guideway will be divided into two control zones, one extending from the merge point out of the station to the point the small curve begins in the northwest corner of the test track, and the other from that point to the merge point out of the station. With this configuration, the function of hand-off from one zone controller to the next can be tested.

The test facility will permit tests of all vehicles operating in the system to determine all-weather performance, reliability, dependability, maintainability, comfort, public reaction, environmental noise, electromagnetic noise, station capacity, wear, and operating costs. The control room will be equipped with data-collection instrumentation to support the following functions:

2.1.1 Logging of data on each vehicle for:

- Mileage
- Hours of operation, number of stops, number of door and switch operations
- Tests performed
- Speed profiles, accuracy of speed control
- Acceleration profiles related to ride comfort
- Power input
- Failures, consequences, corrective actions, time of occurrence

2.1.2 Performing tests on vehicles

2.1.3 Recording, storing and analyzing data received by the control room.

2.1.4 Overriding each vehicle-control system by the control-room operator. The operator will be able to cause a vehicle to move at a desired speed and to override automatic switching.

2.2 Single-Vehicle Tests and Demonstrations

2.2.1 Control and Communications

2.2.1.1 Speed-profile control. Determine that the vehicle acceleration, deceleration, and jerk rates in moving from rest to constant speed, from constant speed to rest, and from one speed to another are as specified. Measure stopping accuracy at a predetermined point.

2.2.1.2 Control accuracy. Measure the ability of the controller to maintain constant speed in the presence of simulated wind gusts produced by means of a drag brake, and with minimum, average, and maximum vehicle gross weight.

2.2.1.3 Vehicle handoff. Test zone-controller to zone-controller vehicle handoff.

2.2.1.4 Vehicle position and speed measurement. By means of wayside measurements, determine the accuracy of transmitted data on vehicle speed and position as determined by on-board encoders. Because of varying vehicle gross weights, accurate encoder position data requires calibration based on wayside markers as a vehicle moves out of the station. Measure the accuracy of such calibration.

2.2.1.5 Vehicle-wayside communications performance. Measure communications performance of the ZLAN.

2.2.2 Chassis Operation w/o Cabin

2.2.2.1 Chassis weight. Record chassis weight before other tests are performed.

2.2.2.2 Drive performance. By accelerating and braking the vehicle on a preprogrammed schedule, determine that the LIM thrust vs. speed, thrust vs. current, transport delay, and power factor are as expected.

2.2.2.3 Coasting tests. Perform coasting tests to determine the air drag and road resistance coefficients on the vehicle straight and curved sections. Formulae for determining the coefficients are derived in the paper “Coasting Tests.”

2.2.2.4 Acceleration efficiency. Determine the energy efficiency in accelerating from rest to cruising speed in terms of the ratio of the energy to overcome inertia, air drag, and road resistance to the electrical energy input. Perform these tests with minimum, average, and maximum vehicle gross weight.

2.2.2.5 Cruise efficiency. Determine the motor and drive efficiencies at various constant speeds up to 16 m/s. The power output is the force required to overcome air drag and road resistance multiplied by vehicle speed. The power input is the electrical power input to the vehicle from the wayside source.

2.2.2.6 Overall efficiency. Determine the electrical power input to one vehicle required to start a vehicle from rest, circle the oval guideway once, and stop again in calm air. Compare with the value calculated using data from the previous tests.

2.2.2.7 Auxiliary brake. Observe operation of the auxiliary brake under automatic control after the vehicle comes to a stop. Determine the force required to push the vehicle with the brake applied. Observe operation of the auxiliary brake with the vehicle at line speed to simulate an emergency stop.

2.2.2.8 Tire performance. The precision of speed measurement depends on the diameter of the tire to which the encoder is mounted. The tire diameter depends on load and wear. Measure tire diameter by recording encoder output under various load conditions. Measure the temperature of the load-bearing and lateral tires after runs to check for overheating. If overheating is excessive, modify the tire specifications and repeat the test. Measure tire wear.

2.2.2.9 LIM gap. Measure the LIM gap as each vehicle moves around the test track. Determine the closest practical gap.

2.2.2.10 Electromagnetic interference. Measure the radiated electromagnetic noise spectrum with and without guideway covers. Measure vulnerability to externally generated EM radiation.

2.2.3 <u>Cabin</u>

2.2.3.1 Cabin weight. Record empty-cabin weight before other tests are performed.

2.2.3.2 Interior environment. Monitor cabin temperature and humidity vs. external temperature and humidity continuously throughout the test program.

2.2.3.3 Acoustical noise. Measure the acoustical noise level in the cabin and at various distances from the guideway. Perform isolation tests to determine sources of noise.

2.2.3.4 Rain test. Subject the cabin to the maximum specified rain and determine the amount of leakage through the door seal.

2.2.3.5 Fire test. Conduct fire tests of the cabin floor in accordance with NFPA-130 specifications and requirements.

2.2.4 Single-Vehicle Tests

2.2.4.1 Acceleration efficiency. Determine the energy efficiency in accelerating from rest to cruising speed in terms of the ratio of the energy to overcome inertia, air drag, and road resistance to the electrical energy input. Perform these tests with minimum, average, and maximum vehicle gross weight.

2.2.4.2 Cruise efficiency. Determine the motor and drive efficiencies at various constant speeds up to 16 m/s. The power output is the force required to overcome air drag and road resistance multiplied by vehicle speed. The power input is the electrical power input to the vehicle from the wayside source.

2.2.4.3 Overall efficiency. Determine the electrical power input to one vehicle required to start a vehicle from rest, circle the oval guideway once, and stop again in calm air. Compare with the value calculated using data from the previous tests.

2.2.4.4 Auxiliary brake. Observe operation of the auxiliary brake under automatic control after the vehicle comes to a stop. Determine the force required to push the vehicle with the brake applied. Observe operation of the auxiliary brake with the vehicle at line speed to simulate an emergency stop.

2.2.4.5 Tire performance. The precision of speed measurement depends on the diameter of the tire to which the encoder is mounted. The tire diameter depends on load and wear. Measure tire diameter by recording encoder output under various load conditions. Measure the temperature of the load-bearing and lateral tires after runs to check for overheating. If overheating is excessive, modify the tire specifications and repeat the test. Measure tire wear.

2.2.4.6 LIM gap. Measure the LIM gap as each vehicle moves around the test track. Determine the closest practical gap.

2.2.4.7 Electromagnetic interference. Measure the radiated electromagnetic noise spectrum with and without guideway covers. Measure vulnerability to externally generated EM radiation.

2.3 Multiple Vehicle Tests and Demonstrations

2.3.1 System Tests

2.3.1.1 Normal operation. As more than one vehicle becomes certified through the Single-Vehicle Test Program, and between single-vehicle certification tests, operate multiple vehicles as in normal service, first with sand bags representing passenger weight and then with passengers aboard.

2.3.1.2 Station flow. Demonstrate vehicle flow through station and compare with simulation results. Through a station each vehicle follows the commands: Move forward if possible if in the input queue or if in the station with no destination if no passengers are approaching the vehicle. Otherwise wait in the station until a station destination is received and the door is closed. Move to line speed on command from the station zone controller (SZC). Test these operations. Determine that one vehicle stops behind another at the predetermined tolerance.

2.3.1.3 Ride comfort. Determine the acceptance of the ride comfort by obtaining the opinions of passengers of various ages and conditions who have ridden in a vehicle on the test track at various speeds up to the design maximum. Determine in this way if the values of comfort acceleration, jerk, roll rate, and bank angle to which the test track was designed need to be modified.

2.3.1.4 Inclement weather operation. Conduct tests with and without passengers during wind, snow, rain and ice storms. Determine if performance is as required and recommend changes if necessary. Particularly, determine if snow removal methods envisioned are adequate or if changes are needed. Command changes in line speed as required under high-wind conditions and observe the behavior of the vehicles as they slow down and later resume normal speed.

2.3.1.5 Vehicle merging. Demonstrate vehicle merging and compare with merge simulations. Test the operation of vehicles leaving the station and merging with vehicles on the main line at minimum headway.

2.3.1.6 Headway reliability testing. First with sandbags representing passengers, operate the vehicles at closer and closer headways and determine the accuracy and reliability of the inter-vehicle spacing.

2.3.1.7 Endurance tests. Run one or more vehicles continuously to determine failure rates of various components.

2.3.2 Vehicle Tests

2.3.2.1 Vehicle pushing. Demonstrate a vehicle soft engaging and pushing a vehicle ahead into a station, operating the auxiliary brake and switch remotely via a connection to an operator.

2.3.2.2 Rear-end collision. Cause one vehicle to run into the rear of another at speeds up to the rated speed for the shock-absorbing bumper. Measure vehicle accelerations and critical-point stresses and compare with calculated performance.

2.3.2.3 Power interruption, voltage transients and spikes. Test operation with simulated electrical disturbances including power cutoff. Observe operation of the system as it slows down and then restarts.

2.4 Station Functional Tests

2.4.1 Operational Demonstration. Demonstrate station entry and exit by passengers, passenger flow, passenger adaptability, ticket reading and destination programming, vehicle-door control, and vehicle entry and exit by passengers. Obtain data on passenger opinions of the operation.

2.4.2 Check stanchions for ease of use, environmental resistance and function.

2.4.3 Check general station arrangement for ease of use and accessibility.

2.4.4 Check station design and materials for ease of maintenance.

2.5 Central-Control Testing

Demonstrate basic connectivity between wayside zone controllers and central control. Through simulations of multi-station networks, demonstrate central-control operations of data collection, system speed, empty-vehicle movement, and traffic control.

2.6 Fail-Safe, Fault-Tolerant, Failure-Management Tests and Demonstrations

Automatic fail-safe and fault-tolerant mechanisms and failure-management procedures have been designed into the system to detect and respond to anomalies and failure conditions to minimize the risk of personal injury, personal delay, and property damage. Induce failures into the system to determine the system's response to failures in the following areas:

ONBOARD

- ZLAN communications
- Position encoding
- Auxiliary braking
- Vehicle computer
- Collision
- Marker detection and decoding
- Thruster
- Vehicle switching
- Traction power
- Battery and low-voltage power supply

WAYSIDE

- ZLAN communications
- Wayside computers
- Wayside-to-wayside communications
- Vehicle log in
- Central computer
- Wayside-to-central communications

2.7 Operations & Supportability Demonstrations

2.7.1 Reliability & Safety

Establish and maintain a daily failure log and computerized data files, and perform the following analyses:

- Compare actual reliability with system-engineering allocations and predictions.
- Determine component modifications for production models.
- Determine causes and effects of failures and prescribe corrective actions.

2.7.2 Environmental

Establish and maintain a daily weather log and computerized data files. Analyze the effects of water on the operation of the system during the single- and multiple-vehicle tests and demonstrations.

2.7.3 Maintenance, Maintainability, & Supportability

Establish and maintain an equipment maintenance log and computerized data files and perform the following analyses:

- Compare actual maintainability with system-engineering allocations and predictions.
- Establish design criteria for all maintenance-support equipment.
- Refine estimates of operating and maintenance costs.

Task 12. Site Planning and Network Design

The purpose of this task is to initiate a study of an application of ITNS in a specific setting. Also, some of the differences in comparison with conventional transit planning are discussed.

Before initiating detailed study of a specific application, a preliminary analysis must be conducted containing the basic elements of a detailed study. It is intended to obtain an initial feeling for the financial feasibility of the application before going into serious detail. The steps are the following:

- Expected Trip Origins and Destinations
- System Layout Design
- Ridership Estimate
- Cost Estimate
- Financial Feasibility
- Architectural Renderings

Expected Trip Origins and Destinations

The first step in a study aimed at determining whether ITNS will be feasible is to determine where people will be coming from and where they will wish to go. The characteristics of ITNS are such that the existence of the system is likely to have a strong influence on the travel patterns, so the process is iterative. The needed information is both the geographical pattern of origins and destinations and the numbers of people wishing to travel, both in the peak period and on a daily, weekly, and yearly basis.

System Layout Design

The first trial design is the first tentative plan of line and station locations based on the expected trip origins and destinations. The design of a development project is influenced by the type of transit that can be counted on as an alternative. ITNS provides great flexibility in design compared with conventional rail systems for three basic reasons:

1) The required right of way is much narrower—going from a 38-foot strip for a necessarily two-way LRT alignment to land needed only for posts two feet in diameter at the base typically 90 ft apart; and stations, the smallest of which need have a foot print of only about 28 feet along the alignment by 7 feet wide.

2) While LRT systems are virtually always deployed as a single two-way line, the in-vehicle switching system and low cost of PRT permits much greater flexibility. PRT could be in the same alignment or it can, more profitably, be deployed in networks of one-way lines, thus at least doubling accessibility for the same cost.

3) Since PRT stations are all on bypass tracks off the main line, adding a station does not reduce the average speed between stations as it necessarily does in a conventional system, where, if one car must stop, all others behind it must stop.

The analogy to ITNS is, except for width, the freeway, where one doesn't have to slow down on-line to get off. With respect to width, one ITNS line three feet wide has the same capacity as three freeway lanes 36 feet wide, a reduction of 12:1 in the land that must be set aside for transportation, yet ITNS requires land only for the posts and stations.

With on-line stations, as required in LRT, planners tend to place the stations at least a mile apart to increase the average speed to a range competitive with the automobile. With off-line stations, it is possible to have, if it makes economic sense, as many as six or eight stations per mile.[80] In LRT, one can have speed at the sacrifice of accessibility or accessibility at the sacrifice of speed. In PRT one has both speed and accessibility.

The following Section "Principles of Network Design" is required to develop a design. A preliminary design can be suggested if given the necessary information: a plan of the development indicating the expected amount of travel between points.

Ridership

Detailed ridership analysis requires the services of a specialist, and may be quite expensive because much data must be gathered. Preliminary estimates are, however, always necessary. The "modal split" or fraction of vehicle trips taken by transit is influenced by planning decisions such as the design of roads, the ease of parking, and the cost of parking. If the planning decisions are given, the population density, and the locations of residential areas, shopping centers, office parks, etc. a preliminary estimate of the probable amount of travel and can be developed and thus a "ballpark" feeling for economic viability.

[80]See the paper J. E. Anderson, "Optimization of Transit System Characteristics," Appendix B.

Cost Estimate

The above information is enough to use available data to arrive at a preliminary cost estimate. Costs will come down as production quantity increases, so a cost estimate must be made in view of a probable total production quantity at the time the system would be ordered.

Financial Feasibility

A 20-story building would not be financially feasible without elevators. For some people, a stairway is an alternative to an elevator, but for most people there is no alternative to an elevator. A newly planned community may be designed completely around the automobile, as most have been. It is an alternative, but it comes at a price because of the very large fraction of land that the automobile system requires and because of unavoidable congestion resulting from slow movement because automobiles must stop at cross streets and wait for others to pass. The bus is considered an alternative, but its inherent service concept causes a typical bus trip to take about three times as much time as a typical auto trip. Moreover, to provide reasonably frequent service throughout the day, the daily average load factor of a bus system can be extremely low. In the late 1970s, the daily average number of people per Twin City bus was only 2.5. Conventional rail systems and the large-vehicle automated people movers require daytime population densities much higher than most modern developers would like, and if placed in developments of moderate density often produce shockingly high costs per passenger mile.

ITNS, on the other hand, drastically cuts land use, increases average speed and reduces energy consumption by large factors, provides much increased accessibility over on-line-station rail systems, can recover most, if not all its costs, and provides an unparalleled level of service for both people movement and goods movement. ITNS does this while virtually eliminating noise and air pollution. By powering from wayside batteries charged at night, ITNS need not add to the peak utility load.

Determination of its full financial benefit, therefore, requires a comprehensive comparison of the whole planned community with ITNS included and without. Fortunately, we find that financial feasibility quite often does not require any such elaborate study, however valuable it will be. In many developments, financial feasibility can be determined simply by offsetting its cost against the cost of parking structures that wouldn't have to be built, or in savings of the multiple of parking spaces the auto system requires. In any case, a financial feasibility study should start with a several-hour conversation between the ITNS planners and the developer to determine in some detail what is driving the cost of the development.
The internal paper "Economics of *ITNS* Networks" and its Excel companion provide a methodology for estimating the return on investment to an investor for ITNS as it would expand over a metropolitan area.

Visual Impact

Visual impact is always an important consideration. Therefore, to get a preliminary feeling for the appearance of ITNS, several architectural renderings of the system in critical locations are needed.

Principles of Network Design

All of the important parameters involved with network design depend on line speed. Kinetic energy, air drag, curve radius, and stopping distance all depend on the square of speed. The power to overcome air drag increases as the cube of speed; and, with given guideway roughness, however small it may be, the suspension required is more demanding as speed increases. The system will therefore become more expensive as line speed increases, and this must be balanced against the expected increase in ridership as the average trip speed increases. The bottom line is that the planner needs to know how line speed affects cost per passenger-mile. An iterative process, initially based on experience and judgment, is required to determine the optimum line speed.

The minimum curve radius at the desired operating speed depends on ride comfort, which is measured by the lateral acceleration felt by the passengers. The minimum right-of-way width of a pair of cross streets that can accommodate ITNS is 30% of the minimum curve radius. With all passengers seated, as is the case in ITNS, the maximum acceptable lateral acceleration is $A_{max} = 0.20g$, and the minimum radius of a flat curve is $R_{min} = V^2/A_{max}$, where V is the speed in the curve. If the curve is superelevated, i.e., banked, R_{min} is 65% as much.

The minimum distance between branch points is the sum of two distances: the distance the vehicle moves at line speed V during the 0.4-sec switch throw time, plus the stopping distance with a 0.5g emergency-braking rate. This distance is $V \times (0.4 + V/2g)$.

The length of off-line station guideways depend on line speed and the required number of berths. Equations are available to determine these lengths.

Within these restrictions, guideways of any configuration can be deployed; however, certain configurations are better than others. Optimum design of an ITNS network is an art in itself. The following considerations need to be taken into account.

- *Y interchanges vs. multilevel interchanges.* Multilevel interchanges may be necessary for very high capacity, but produce greater visual impact at any one point. It is best to try to lay out a network using Y interchanges and to use multilevel interchanges only if or where necessary and acceptable. Y interchanges have the disadvantage that vehicles must merge before they diverge, thus creating bottlenecks, which can be relieved by using the higher impact multilevel interchange. Fortunately, in a great variety of applications, the network can be laid out so that the capacity is adequate with Y interchanges. Y interchanges are more of a challenge for the control system, but the problems have been solved.

- *One-way vs. two-way lines.* With one-way lines, twice as much land area can be put within walking distance of stations for the same total track length. Moreover, the interchanges are simple and visual impact at any one location is minimum. One-way lines have the disadvantage of more circuity, where circuity is defined as the ratio of the trip length on the network between a pair of stations divided by the direct-line distance. Building the network out of a series of modest-sized loops will minimize circuity. Since the trip time on ITNS is very short compared to the total trip time counting walking, the effect of increased circuity on ridership can, by careful design, be made so small that the cost per passenger-mile is lower with the one-way configuration. There is, however, no reason to constrain ITNS to one-way networks in the way that conventional transit systems, by their nature, must be deployed in two-way configurations. To eliminate vehicle-to-vehicle transfers, two-way systems require complex interchanges.

- To maximize system capacity, networks should be laid out wherever possible with merges and diverges alternating, thus relieving potential bottlenecks. The example shown on the next page has merges and diverges alternating. In developing such a network, it is useful to think of the guideways as rubber bands of the right topology and ready to fit any street pattern.

- Because curved track costs more than straight track, curves should be kept to a minimum. ITNS is not restricted to being elevated. Positioning above ground, at ground level or underground is a planner's decision. The off-line guideways to the stations of an elevated system may be brought close to the ground so that a stairway and elevator would not be needed, but at the cost of a longer off-line guideway and the need to fence off an area on both sides of the station.

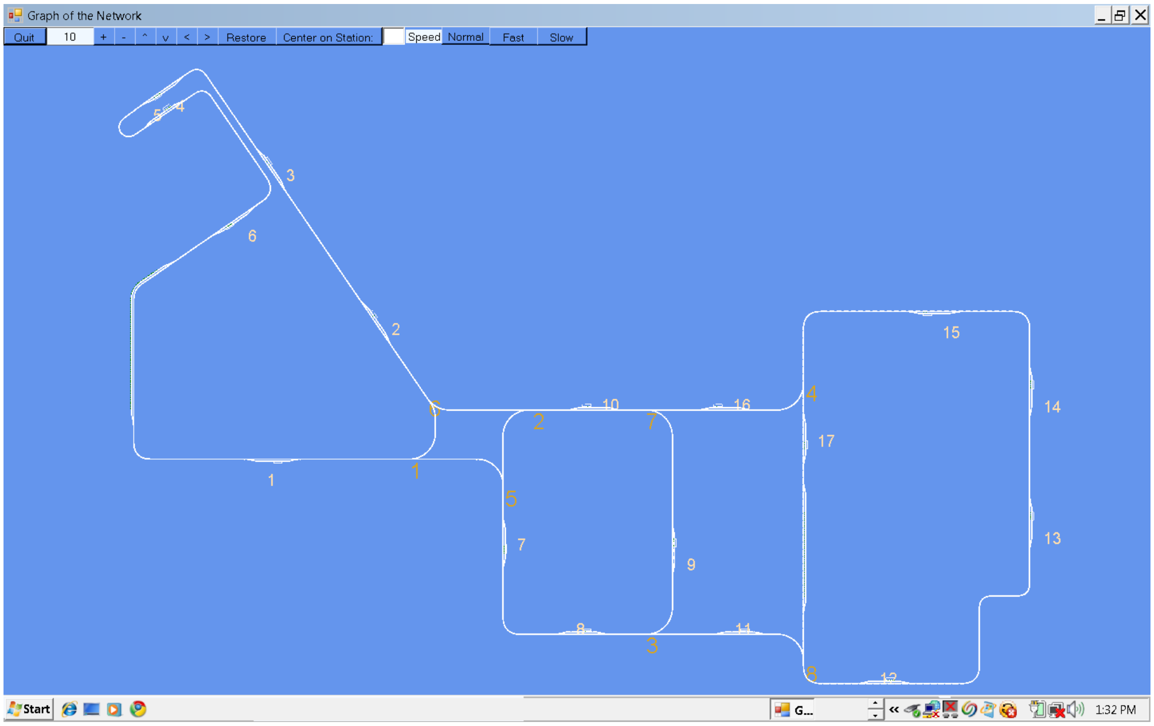


Figure 12.1. An example network.

Appendix B

Biography of the Principle Developer and Managing Director

J. Edward Anderson, BSME, Iowa State University; MSME, University of Minnesota; Ph.D. in Aeronautics and Astronautics, Massachusetts Institute of Technology.

Following his undergraduate work he joined the Structures Research Division of NACA (now NASA), where he received the equivalent of a master's degree in the analysis of structures, developed methods of structural analysis of supersonic-aircraft wings (NACA Report No. 1131), and contributed to the design of the F-103 wing. He then moved to the Honeywell Aeronautical Division where his first assignment was to design aircraft instruments, the first of which was retrofitted into the entire Air Force fleet of over 700 B-47 bombers. The next assignment included the first transistorized amplifier used in a military aircraft and won the *Aviation Age* Product-of-the-Month Award. These projects enabled Honeywell to completely dominate the associated field. He was then assigned to the Aircraft Dynamics Group in the Research Department where he performed computer analysis of autopilots for military and space applications, and later managed a group of 15 Research Engineers in the design of the autopilots for the Air Force's two most advanced fighter aircraft. He was then assigned to the Inertial Navigation Group where he invented and led 20 Research Engineers in the development of a new type of inertial navigator now used widely on military and commercial aircraft. In this role, he was promoted to Principal Engineer, an honor shared by about one percent of the engineers at Honeywell.

He received a Convair Fellowship under which, with a half-salary grant from Honeywell, he enrolled at the Massachusetts Institute of Technology to study for a Ph. D. degree. He became fascinated with magnetohydrodynamics and wrote a thesis entitled *Magnetohydrodynamic Shock Waves*, which was the only M. I. T. Ph.D. thesis that year out of 200 that was published by M. I. T. Press. It was later reprinted by the University of Tokyo Press, and translated into Russian and published by Atomizdat in Moscow. It is still being purchased and currently can be found in the bookcases of physicists who study magnetic containment of high-temperature plasma.

After returning to Honeywell he was sent to Cape Canaveral where he was able to show NASA engineers that erratic behavior in the gyro signals on Col. Glenn's space flight were not due to a malfunction of the Honeywell attitude control system. He later directed a team of 24 engineers in the advanced development of a solar-probe spacecraft and, following a briefing he gave with his staff to officials at NASA Ames Research Center, NASA informed Honeywell that they were equal in capability with its two funded contractors on the solar-probe effort. He had written a report justifying the solar-problem mission, which was used by NASA personnel in testimony to Congress.

In September 1963 Dr. Anderson joined the Mechanical Engineering Department at the University of Minnesota as an Associate Professor and later as a full Professor directed its Industrial Engineering & Operations Research Division. In 1967-8 he spent 10 months in the Soviet Union, sponsored jointly by the National Academy of Sciences and the Soviet Academy of Sciences, after which his research was published in a book *Dynamic Phenomena in Thermal Plasma*, Energia, Moscow.

Upon returning home he became interested in Personal Rapid Transit (PRT) as a necessary technology for a sustainable world. Shortly thereafter he was invited to join a group of physics professors dedicated to stopping the Safeguard Anti-Ballistic Missile system; which led to chairmanship of a Symposium on the Role of Science and Technology in Society; which led to leading an Honors Seminar called "Technology, Man, and the Future;" which led to initiating, managing and lecturing in a large interdisciplinary course "Ecology, Technology, and Society," which was taught every quarter from 1970 through 1988 to over 4000 students from 100 departments in the University with support of the Deans of the Institute of Technology, Liberal Arts, and Agriculture. Simultaneously, he coordinated a 15-professor Task Force on New Concepts in Urban Transportation and chaired International Conferences on Personal Rapid Transit (PRT) in 1971, 1973, and 1975 and was the chief editor of the first two of these conferences. 156 papers were published. In 1972 he briefed NASA Headquarters on PRT in relation to a "NASA Advanced PRT Program" and in December 1972 was asked by a NASA official to chair a National Advisory Committee on the NASA PRT Program. In 1976 he was elected first president of the Advanced Transit Association.

During the 1970s, Dr. Anderson consulted on PRT planning, ridership analysis, and design for the Colorado Regional Transportation District, Raytheon Company, the German joint venture DEMAG+MBB, and the State of Indiana. For several years he was a Regional Director of the American Institute of Aeronautics and Astronautics, and one of its Distinguished Lecturers. He lectured widely on new transit concepts and was sponsored on several lecture tours abroad by the United States Information Agency and the United States State Department. In 1978 he published the textbook *Transit Systems Theory* (D. C. Heath, Lexington Books), which he has used in his course "Transit Systems Analysis and Design." In addition to engineering students, enrollment in this course has included professional transportation engineers from across United States as well as from Canada, England, Sweden, Denmark, Korea, and Mexico.

In 1981 he initiated and led the development of a new High-Capacity PRT system through five stages of planning, design and costing. He developed computer programs for vehicle control, station operation, operation of many vehicles in networks, calculation of guideways curved in three dimensions to ride-comfort standards, study of the dynamics of transit vehicles, economic analysis of transit systems, and calculation of transit ridership. In 1982 he was presented with the George Williams Fellowship Award for public service sponsored by the YMCA and the MPIRG Public Citizen Award.

In 1986 he was attracted to the Department of Aerospace and Mechanical Engineering at Boston University where he taught mechanics, engineering design, and transit systems analysis and design; and where he organized, coordinated and lectured in an interdisciplinary course "Technology and Society." On his own time, he organized a team of a half-dozen engineers and managers from major Boston-Area firms to further develop High-Capacity PRT. In May 1989, the Northeastern

Illinois Regional Transportation Authority (RTA) learned of his work together with Raytheon Company and, as a result, initiated a program to fully develop PRT. This led to a $1.5M PRT design study led by Stone & Webster Engineering Corporation, followed by a $40M joint development program funded by Raytheon Company and the RTA. Unfortunately, Raytheon failed to follow the Systems Engineering principles given in Section 2 of this business plan, the result of which was that their design became too expensive for the RTA. While at Boston University, he developed the Maglev Performance Simulator used by the National Maglev Initiative Office, U. S. Department of Transportation, to study the performance of high-speed maglev vehicles traveling within ride-comfort standards over the curves and hills of an interstate expressway, and licensed it to Grumman and Hughes for $10,000 each.

Following the RTA program, Dr. Anderson gave courses on transit systems analysis and design to transportation professionals, and engaged in PRT planning studies for a half-dozen applications. In 1992 his PRT system (ITNS) was selected unanimously by a 17-person steering committee over bus and rail systems for deployment at the Seattle-Tacoma International Airport. In 1996 he chaired an international conference on PRT and related technologies in Minneapolis. In 1998 his work led to acceptance of his PRT system out of over 50 elevated systems as the preferred technology promoted for the Greater Cincinnati Area by a committee of Forward Quest, a Northern Kentucky business organization.

In 2001-2002 he led the design and construction supervision of a full-scale vehicle that operated automatically on a 60-ft guideway for thousands of error-free rides, many as an exhibit at the 2003 Minnesota State Fair. This system worked exactly as intended. It is shown on page 5. In 2008 he began to develop from basic principles a new and improved version of PRT now called ITNS. He continues the challenging task of determining how to fully commercialize a superior PRT system that will reduce dependence on oil, reduce carbon dioxide emissions, and reduce congestion.

For his patents on PRT, the Intellectual Property Owners Foundation named him an Outstanding American Inventor of 1989. In 1994 he was Distinguished Alumni Lecturer at North Park University in Chicago. In 2001 he was elected Fellow of the American Association for the Advancement of Science for his work on PRT. In 2008 he was named Honorary Lifetime Member of the Advanced Transit Association. In 2010 the Minnesota Federation of Engineering, Scientific, and Technical Societies granted him the Charles W. Britzius Distinguished Engineer award. In 2013 The Aerospace Corporation awarded him its "Technical Achievement Recognition for lifelong dedication to the advancement of transportation technology."

He is a registered Professional Engineer in the State of Minnesota, has authored over 100 technical papers and three books, is listed in 36 biographical reference works including *Who's Who in America* and *Who's Who in the World,* and is the son of Missionary parents with whom he spent years one through nine in China.

1.3.4 How do we know ITNS will Work

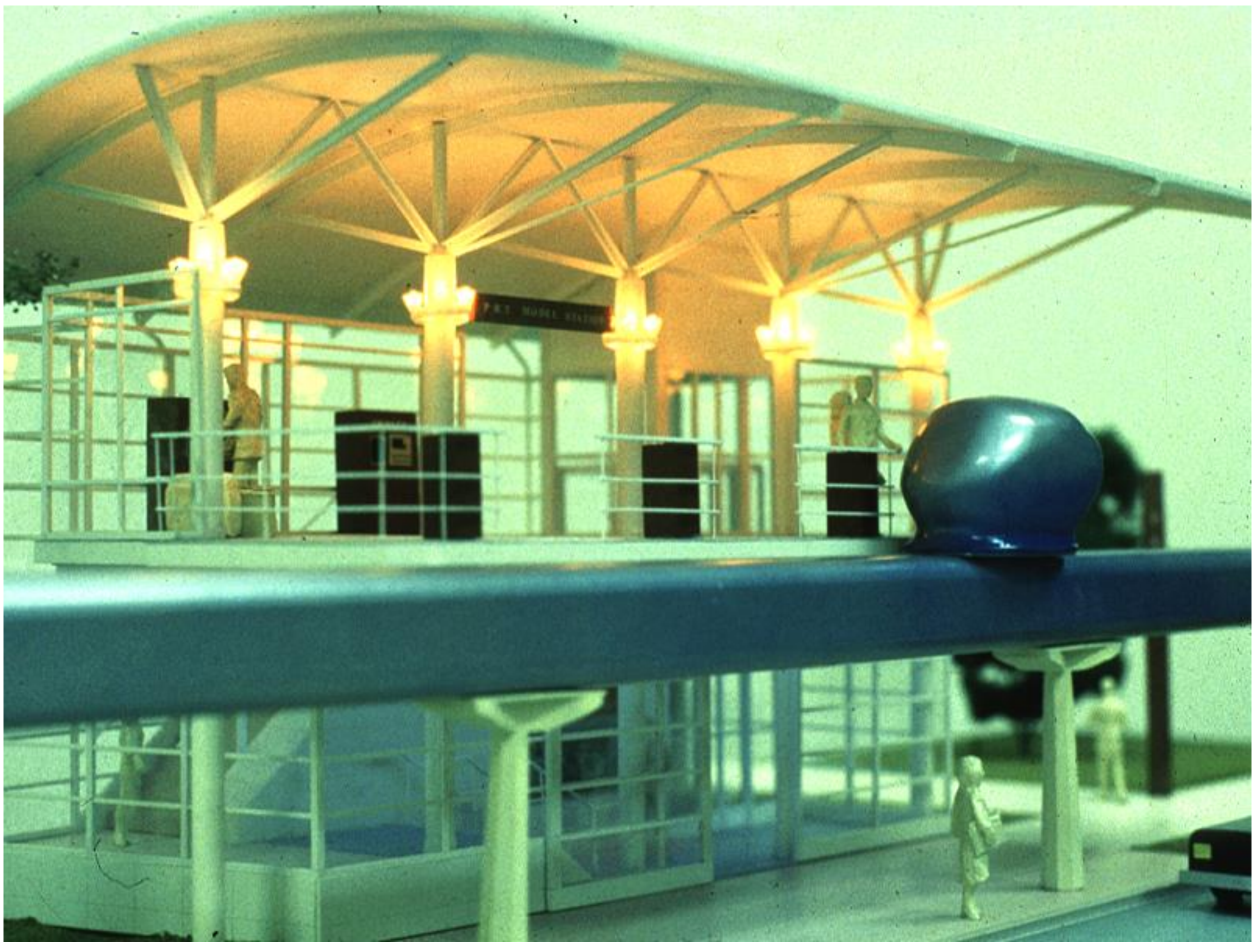
ITNS, an Intelligent Transportation Network System, is a member of the class of transit systems called "Personal Rapid Transit" or PRT and is the leading embodiment of this class. Even before hardware was built, after detailed analyses by other engineers, it won competitions in Chicago, SeaTac, and Cincinnati; and a Swedish report concluded that if it were tested full-scale it would be the preferred PRT system for Swedish cities. A linear-induction-motor driven, fully automatic vehicle that I designed and built ran flawlessly for thousands of rides at the 2003 Minnesota State Fair on a short segment of guideway. The difference between ITNS and similar systems is not in use of exotic, unproven components, but in the application of Systems Engineering to the design of the system, using in every case proven components. I chaired four international conferences on PRT, discussed details with over 200 authors of the papers, and edited the proceedings, thus giving me a broad and deep view of the thinking of every PRT investigator.

I used the following process in the design of ITNS:

1. Thoroughly understand the *Problem* and the *Requirements* for solution.
2. Let System Requirements dictate the technologies.
3. Identify all alternatives in all issues without prejudice and with absolute objectivity.
4. Thoroughly analyze all reasonable alternatives in each issue until it became clear which best met all technical, social, and environmental requirements. This process required in-depth knowledge of all of the relevant engineering sciences, as briefly described in his biography, and practical knowledge of engineering mathematics well beyond that obtained by most engineers.

There is no question that ITNS will work. Every part of ITNS was analyzed independently by Stone & Webster Engineering Corporation in a study for the Chicago RTA and found to work as we had determined and for reasonable costs. The question now is this: With the extensive background of engineering that has gone into ITNS, will a large network of ITNS vehicles work with acceptable safety and reliability and for the costs for acquisition and support that will be the basis for a profitable business. As to safety and reliability, we use the tools and methods that have been developed for military and space applications by major companies including Honeywell, Boeing, Hughes and Raytheon, which today give almost unpredictably high reliability and hence safety. As to costs, we have applied our knowledge of the engineering sciences to minimize the costs of the vehicles, guideway, and control system, always working with manufacturing engineers to insure that our designs can be manufactured economically. ITNS has been designed. What remains is to develop the procurement documents needed to order components and to work with manufacturers to build and assemble them into the system.

1.4 Systems Engineering



1.4.1 The State of Urban Transportation (written in 1970)

The Greeks had a philosophy they identified as "*The Golden Mean*." In one sense or another, too little or too much of anything was harmful. In whatever he did, the wise man strove for the right balance – *The Golden Mean*. Today, this ancient philosophy finds its expression in the term "optimum solution."

A prime example of a solution to a problem gone far beyond the optimum, away from *The Golden Mean*, is the automobile as a means of urban transportation. Unfortunately, indications are that this solution will be carried much further yet from optimum at great expense to urban dwellers before it is forced into a sensible balance with other solutions – other transportation modes. This is happening because we have no effective built-in mechanisms to seek and maintain optimum solutions to urban problems. Forces for continuing present trends for the economic benefit of a few at the expense of the public as a whole are powerful. In key decision-making processes at all levels of government, these forces have held sway over the forces of constructive change. In urban transportation, as well as in other problems, we are being driven further and further from *The Golden Mean*. Without a very considerable increase in the forces of change, the consequence of our dependence upon the automobile in urban life many be the stagnation and death of our central cities.

The current literature is replete with examples of the ill effects of the automobile. Economically, billions of dollars each year are squandered because high-priced businessmen have to crawl through traffic to jobs, appointments, airports, etc.; because trucks get bogged down in downtown traffic; because potential shoppers just don't make the trip downtown. Millions of thankless hours are consumed by mothers locked into the task of children's chauffer. While attending school, young people are forced to work long hours just to maintain their automobiles. Streets are designed with no thought to anything but auto traffic so that kids have few places to ride their bicycles and cause their parents endless worry as they walk to school, if there even is a place to walk. Old people drive long after they should. Even though drunks cause over half the 50,000 yearly auto deaths, judges fail to revoke their licenses because that would remove their means of access to the job. The poor, who we think of once in a while, are simply left out of many opportunities. More or less unwittingly, "the system" has forced almost everyone who can drive into an automobile.

Valuable land is taken off urban tax rolls to build urban freeways, communities are divided, neighborhoods are uprooted, and residents are subject to tiresome freeway noise. Parking lots require so much expensive land in the major activity centers that it has become economical to construct huge parking garages at a cost per space comparable to the cost of the auto itself.

Urban man drives to his job, usually by himself, in a 7 x 17 foot sheet-metal monster that rarely travels over ten miles per gallon of gasoline and is so fragile it is extensively damaged in a collision over two miles an hour, thus skyrocketing insurance costs. He struggles to maneuver his oversized machine into a parking space where it occupies valuable land and where it rests idle all day long. The vast squandering of nonrenewable resources in metals and oil implied by such an inefficient means of transportation is now only perceptibly being recognized. We operate as if there were no tomorrow.

The fact that the automobile is by far the major urban air polluter has been recognized for some time. People who were caught in the thermal inversion on the East Coast early this summer know what it means to be without fresh air. But at the same time the American is bound economically, socially, and in many cases psychologically to his automobile and he is powerless by himself to bring about effective change.

The huge corporations that make up the auto industry will not make significant changes until they have no alternative. For example, it may be that oil could be sold in large quantities for something besides motor fuel (say, for making plastics); but the huge investment in gasoline cracking plants, distribution systems, and service stations is highly specialized and would represent an immense economic loss if the demand for gasoline subsided. Automobile companies depend for their profits on production of large and increasing quantities. If these profits decrease, stockholders no longer get the high return they expected, and as a consequence they sell their stocks. This depresses the value of the stock, which is usually held in large amounts by corporate executives. Thus, these men have a strong personal interest in maintaining the system. The auto industry produces 22,000 cars a day now and expects to be up to 41,000 cars a day by 1980. They are supported by manufactures of tires, carburetors, generators, spark plugs, and hundreds of other specialized items. All of these companies, all of the retail dealers and the service garages would fear a significant economic pinch if anything occurred to substantially reduce the demand for automobiles.

Vast establishments led by the Federal Highway Administration are involved in furthering the construction of roads; and, of course, the road construction industry feels dependent for its survival on the planning of more and more of these roads. The system perpetuates itself by means of trust funds supported by gasoline taxes; which, short of changing State Constitutions, can be used only for roads. We are locked on a course that is steadily eroding the quality of life in our cities.

Up to a point, the automobile and its support system was close to an optimum solution to the problem of mobility, at least for those who could drive. Now, however, in the larger cities of the United States, the auto is assuming the characteristics of a Frankenstein monster. We feel uncomfortable, many of us, about building more roads, more cars, and selling more gasoline. On the other hand, the system for providing all of these things has been institutionalized to perpetuate itself. Substantial changes are now very difficult politically since they will require real or perceived adjustments on the part of millions of people.

What can be done? How can environmental disaster be avoided? Can it be avoided without producing economic disaster? Let's look at some of the things that are being tried. We can show that most of these are feeble attempts – ineffective nibblings at the core of the problem.

First, because of the problem of pollution from auto exhausts, the need to replace the internal combustion engine is urgent. "Fixes" for these engines work well, unfortunately, only when the engines are new. The potential gains will be wiped out by increasing numbers. Nothing at all is done this way to relieve the problem of congestion or the requirement for more and more parking garages.

Alternate modes of transportation need to be introduced. Most cities turn to the bus. The bus is a stopgap to provide badly needed transportation for those who cannot or do not wish to drive. It could reduce congestion if people were coerced in large numbers to ride it. While we may come to this by default at the expense of a considerable reduction in the quality of life, under present circumstances most people, as long as they can choose freely, will choose the private auto. The bus stops and starts many times giving a slow, tedious, often nauseating ride. It is second-class transportation no matter how many embellishments are added. In addition, it pollutes the air, it mixes with street traffic, and it adds to congestion. The bus is no threat to the auto industry.

Because of the inherently poor image of bus service, transportation consultants propose conventional rail systems on exclusive rights-of-way, i.e., metros or subways. By placing the stations one to two miles apart, average speeds up to about 40 mph can be obtained, but at the price of limited access. A cross-town trip is still a tedious stop-start journey. The capacity of these systems is very high – up to 60,000 people per hour, but unfortunately, so is the cost – on the average about $20,000,000 per mile. As a comparison urban freeways can carry a maximum of about 2000 cars per hour per lane and cost from about $5,000,000 to $30,000,000 per mile.

New York City is the only urban area in the United States in which the population density is high enough to justify conventional rail transit. To make it economically sound elsewhere would require forced incentives to live in high-rise apartments near the stations. Short of this, conventional rail reminds one of shooting rabbits with an elephant gun. These systems are simply too expensive for the level of patronage they can attract. If enough lines were built in the average United States metropolitan area to get people where they wanted to go, the cost would be way beyond reason, the disruption would be equal to that of installing freeways, and the patronage would be way below capacity. As a result, the number of miles of lines usually proposed is so small that an insignificant percentage of the population can make use of the systems. For reasons like this, bond issues for rail transit have failed recently in Los Angeles, Atlanta, and Seattle. Rail transit is no threat to the auto industry.

Notwithstanding or perhaps because of the ineffectiveness of conventional hardware to serve the real transportation needs of the urban dweller, the vast majority of the funds in the Mass Transit Bill currently under discussion in the Congress are earmarked for conventional hardware. Even in the case of research and training grants awarded by the Department of Transportation to major universities, the emphasis is to be place on training, not on research. Without research, of course, most of the training will have to relate to conventional transportation modes.

Just as the saddle shops of yesteryear were threatened by the horseless carriage, effective solutions to public transportation in urban areas will be perceived as a threat to the existence of the auto and associated industries in their present forms. Effective solutions are in advanced stages of development in many places in the United States, and their developers have many, many stories to tell about the very strong, often irrational resistance from people associated with the conventional transportation industry. Before discussing these new solutions, it is important to stress that as a matter of policy their deployment should be required to proceed sufficiently gradually so that necessary economic and social adjustments can be made. A transition to more efficient forms of transportation will, however, free a significant portion of individual income for other uses. By thus freeing a part of man's burdens, the introduction of new-concept transportation systems would seem to inaugurate a new era in the history of transportation development. In a free market, what is more economical will be inevitable. In today's climate, "more economical" must, of course, include externalities, i.e., indirect social costs.

A solution to the problem of urban transportation will have to bring about a substantial reduction in the level of air pollution, decrease congestion, minimize direct land use for transportation facilities, avoid disrupting and dividing communities, be fast, convenient, and comfortable enough to attract riders away from their automobiles in significant numbers, and it must be reasonable in cost. Technology exists today to build systems that will meet these requirements. It is available as a result of advances in control theory and practice, digital computers, reliability of components, failure analysis, and systems analysis. Primarily, it is available because a small number of capable inventors envisioned the need some years ago and developed their ideas to the point where their systems can now be ordered and installed within a period of two years.

The idea is as follows: To compete with the auto in trip speed, the public system would consist of cars running on a separate guideway. To avoid the need to stop at intermediate stations the stations would be place on sidings or bypasses so that each trip on a line could be nonstop from origin to destination. To produce minimum physical impact on the environment and to minimize cost, the fixed guideway should be as small as possible. Typically, the car would hold from four to six people. This has the happy consequence that the vehicle becomes more personalized, more like an automobile. For this reason, this form of transit is called Personalized Rapid Transit (PRT). To obtain needed capacities at high levels of safety and reliability, the cars would run at close headways under redundant automatic control. To minimize pollution, the motors would be electric and in fact need ratings of only about 25 hp. Electric power would be required, which, of course, pollutes; but the pollution can be much more carefully controlled in a large plant that can be located away from major population centers.

The public transportation system would consist primarily of a network of PRT lines connecting major activity centers and spaced from about one to three miles apart in accordance with the population density. Since frequent station spacing does not affect the trip speed, stations could be placed about a quarter of a mile apart with closer spacing in the major activity centers. Many locations near stations would exist for people to live who would desire direct access to the system. For those who live too far from a station to walk, the existence of the PRT network makes the electric automobile entirely practical. In this case the range required of such a car is well within the capability of a modest number of conventional batteries. For work trips, subscription bus service could carry people to the PRT stations; for miscellaneous travel, dial-a-bus systems and public electric automobile system could be established. The whole system would consist of PRT lines plus these auxiliary electrically driven vehicles. Stations would be designed to maximize the convenience of the mode transfer. The capacity of the PRT lines would be equivalent to that of about four freeway lanes in each direction but would consume about one tenth the space of a freeway and with some systems much less. The per-mile cost of these lines would be well below the minimum cost of urban freeways. Existence of such system in urban areas could bring about an optimum balance between public and private transportation. People would be free to use their own cars but would have a viable alternative available to them.

PRT is neither a pipe dream nor a paper concept. At least five such systems are in such an advanced stage of development that demonstration lines could be built and operating within two years. These systems are called Dashaveyor, Hovair, Monocab, Starrcar, and Uniflo. A number of firms have system in earlier stages of development. At the present time, Starrcar has been selected for a demonstration at the University of West Virginia, Monocab and Dashaveyor are competing for a demonstration at the Dallas-Fort Worth Airport and it was recently announced that Monocab will be installed by private developers in Las Vegas. Hovair is currently being considered for a demonstration in Denver. Uniflo is being considered for a demonstration at the University of Minnesota.

With all this activity, one is entitled to ask, "What's the problem?" The problem is that these developments are still limping along primarily on private funds. While the Department of Transportation has awarded some modest contracts, the infusion of funds into effective new system is far short of the need. The transportation situation is extremely urgent, but there is nothing close to a national commitment to develop systems like PRT. PRT could be the backbone of an effective solution to the problem of urban transportation. It is the hope for revitalized urban living spaces. As such, it does threaten the vast established auto industry. Opposition to development of PRT manifests itself in many subtle forms. Without strong political backing, it could fade away from a lack of investment capital.

Proper development of PRT requires a much stronger commitment within the Department of Transportation than exists today. To develop such a commitment may require influential political leaders from the nation's metropolitan areas to pound on desks in Washington and demand action. But to develop the knowledge and to bring this knowledge to the attention of our leaders requires continued programs to develop PRT. We can only hope that the modest efforts now underway can be the catalyst to an effective national commitment.

While developments on the physical hardware of PRT and auxiliary systems continue, broader implications of the introduction of this technology need to be considered. Although PRT is designed to counter the harmful side effects of present transportation systems, one should not push for rapid development without considering the broad economic and social implications. As mentioned previously, if an effective PRT system is built, it will reduce the number of jobs available in the auto manufacturing and servicing industry. Since PRT is a much more efficient form of transportation than the auto, it is improbable that it would directly produce as many jobs as it would displace. For this and other reasons, PRT and auxiliary systems should be introduced gradually within a framework of comprehensive urban planning so that practical experience with their impacts can be absorbed before going too far. At the same time it may take strong pressure to introduce PRT fast enough to reverse the trend of decay of our central cities.

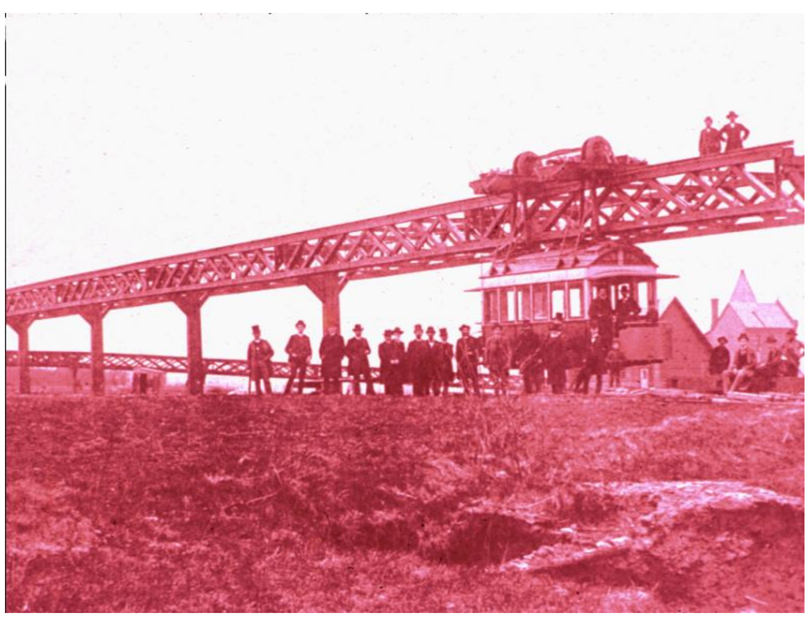
On the national level, the development of PRT and its auxiliaries should be given the status of a national goal. The major developmental systems should be demonstrated as soon as possible in realistic urban settings. Through symposia, reports, etc., data from these demonstrations should be analyzed and made available to urban areas. To do these things will require that the Congress form a NASA-type organization for ground transportation – a need that is long overdue. The precedent for this action has been established through the Urban Mass Transportation Act of 1964. In this act Congress requested a project "to study and prepare a program of research, development, and demonstration of new systems of urban transportation that will carry people and goods within metropolitan areas speedily, safely, without polluting the air, and in a manner that will contribute to sound city planning. The program shall (1) concern itself with all aspects of new systems of urban transportation for metropolitan areas of various sizes, including technological, financial, economic, governmental and social aspects; (2) take into account the most advanced available technologies and materials; and (3) provide national leadership to efforts of states, localities, private industry, universities, and foundations."

On the state and metropolitan-area level, the problem is too urgent to wait for development of a national commitment. Since it is the metropolitan areas that will suffer from inaction, governments within these areas needed to get to work to generate a national commitment, to prepare to use information generated from demonstration programs, and to learn how to achieve an optimum balance between transportation modes. A NASA-type ground transportation administration at the Federal level is needed, but it is not enough. Because the results are intended to be infused intimately into the urban areas, many people within those areas will have to be trained to plan for, install and operate the new systems. Because of strong career commitments, lack of knowledge, preoccupation with immediate problems, etc., it is not at all clear that established metropolitan organizations will be effective in planning for and studying the impacts of radically new systems, even if they are to be introduced gradually.

Before trying to set up new organizations, the metropolitan governments should consider the possibility that the universities located within them may be the natural spawning ground for new transportation systems. Only within the universities is it possible to find an abundance of first-class talent accustomed to working on new things and the variety of talents needed to consider all of the technical, economic, social, political, and environmental impacts of something as comprehensive as urban transportation. The university is, of course, primarily a training ground, a fact that renders it the more suited to participation in this task.

The Aerospace industry should also be of great help. Aerospace engineers are accustomed to working on broad new system problems, as a result of which they have not become ossified from fascination over particular solutions to problems. In choosing groups of systems engineers to do new things, the most important factor to consider is the psychological attitude of the group toward the problem. If they really want to make it work, they will find a way; if they don't, they will be very clever only in inventing reasons to the contrary. At one time makers of wooden sailing ships were the greatest experts in transportation technology. Would you have gone to them with an idea for iron steam-driven ships? I think not.

In summary, the state of urban transportation is critical. Conventional alternatives cannot rescue cities from strangulation due to smog and congestion. Only by shifting to new forms of urban transit can our cities maintain their viability. The backbone of these new forms is Personalized Rapid Transit, a system under extensive private development in the United States. Because of strong legitimate interests in the present transportation systems, strong and visionary political leadership will be needed to effect the necessary change.



An 1880-era elevated transit system deployed in St. Paul, Minnesota.

1.4.2 A Review of the State of the Art of Personal Rapid Transit

This paper begins with a review of the rational for development of personal rapid transit, the reasons it has taken so long to develop, and the process needed to develop it. Next I show how the PRT concept can be derived from a system-significant equation for life-cycle cost per passenger-mile as the system that minimizes this quantity. In the bulk of the paper I discuss the state-of-the-art of a series of technical issues that had to be resolved during the development of an optimum PRT design. These include capacity, switching, the issue of hanging vs. supported vehicles, guideways, vehicles, control, station operations, system operations, reliability, availability, dependability, safety, the calculation of curved guideways, operational simulation, power and energy. The paper concludes with a list of the implications for a city that deploys an optimized PRT system.

Introduction

The concept of personal rapid transit (PRT) has been under development since Donn Fichter and Ed Haltom, working with no knowledge of each other, in 1953 invented the key ideas—a system of small, fully automated vehicles that carry people nonstop between off-line stations on a network of exclusive guideways. Since few people knew about this work, it is not surprising that there are others—this author is aware of a half dozen—who during the 1960s can by documentation lay claim to independently inventing, or perhaps discovering is a better word, the ideas of PRT. The author became interested in PRT in late 1968 and, notwithstanding many obstacles, remains confident that PRT will be seen as one of the major developments of the last half of the 20^{th} Century. Thanks largely to a 1990 initiative of the Northeastern Illinois Regional Transportation Authority, even though it failed directly to produce a marketable PRT system, a growing number of efforts are underway to develop or plan PRT in at least a dozen countries. The Internet now enables us to keep in touch in a way not previously possible. The arrival of the New Millennium will not see a true PRT system in operation, but there is much reason to believe that the first application is not far off.

The reasons PRT is needed relate to cost, size, land use, service, and environmental protection. In 1970 I decided to tackle the problem of implementation of PRT and, incidentally, to not try to design my own system. I did so after organizing and coordinating a large, interdisciplinary course called “Ecology, Technology and Society,” which ran for over 15 years. In listening again and again to lectures on environmental topics by over 20 experts in as many disciplines I was increasingly impressed that PRT could well be a solution to urban problems such as congestion, air pollution, accidents, lead poisoning, noise, the division of communities by introduction of urban freeways, the ever increasing land required to accommodate automobiles, and the inequality in access to jobs and services between those who drive and those who either cannot or should not drive. I had been involved in a year-long Citizens League committee formed to study transit alternatives and found thereby that conventional rail systems were cost effective only in cities of much greater densities than occur in the neighborhoods of single-family homes that had been developing for many decades and cover vast portions of the urban landscape.

Key factors were that a) by use of the smallest practical size of vehicles the guideways could be inexpensive, visually unobtrusive, and would require very little land, b) by developing a reliable, in-vehicle switch, no transfers would be required and that would permit a practical, no-transfer network serving areas where people live and function, c) by using off-line stations, practical with in-vehicle switching, sufficient capacity would be available and the trip could be nonstop, which would make it time-competitive with the automobile, whereas in the typical city using the transit systems available required an increased time commitment of at least an hour a day. Moreover, very lightweight, streamlined vehicles would consume a small amount of energy, and by running them on electricity air pollution could be reduced. Additionally, by careful design, traffic noise could be markedly reduced, and by running on exclusive guideways the level of safety could be markedly increased. My engineering experience coupled with investigation of PRT work then underway convinced me that all of these features were feasible and practical, and led me to devote much of my time to helping PRT mature.

Many people are baffled, when hearing about PRT for the first time, to learn that it has taken so long for it to mature. The detractors argue that the reason is that it is technically flawed. My colleagues and I searched for such a flaw for many years while we continued to develop the technology, and we studied very carefully all of the arguments opposed to PRT that we could find. Today we see no aspect of PRT technology that hasn't been completely worked out, and that is the main subject of this paper. I have been for a number of years a developer of a PRT system so cannot be considered a neutral observer, but, such a role has permitted me to attain the experience needed to be confident that with a modest but necessary investment a cost-effective PRT system that meets all requirements of performance and safety can be in operation in no more than three years.

Some of the detractors argue that even if PRT is technically sound it should not be developed because it will increase urban sprawl. Yet, we find that in the applications we are considering, because real PRT is so land saving it can make a genuine contribution to the development of environmentally sound higher population density in presently built areas of many cities, and it can also provide much needed transportation for those who cannot or should not be driving in presently built areas. Moreover, we are familiar with proposals to build conventional commuter rail systems to the far reaches of metropolitan areas and beyond by the very people urging that urban sprawl be contained. It seems unusually hard for some people to recognize that a system, conventional rail, that appeared in the 19th Century, does not have the service characteristics needed to compete with the modern automobile operating on modern streets and highways, notwithstanding many studies that show that the fraction of auto drivers diverted is almost in the noise of the data. Some of those who argue against PRT and try to urge people that it is a dead issue work for companies who specialize in conventional rail design and construction and fear that their business will decline if PRT attains a foothold anywhere. My response to them is that they should and can get familiar with PRT, and if they do in the long run they will do much better than they do now by fighting it. The state of urban transportation as it can be envisioned without innovation is well summarized in the statement: "The future looks bleak both for urban transport and for our cities; more traffic jams, more pollution and reduced accessibility." [Pucher and Lefèvre, 1996]

The real reason PRT has taken such a long time to develop is that it is a complex technology, although not as complex as many systems now in daily operation; there are many ways to do it wrong and only a few ways to do it right; the unit of sale is large; and the number and specialties of people that need to decide to proceed is large. An interested investor needs to see a market not in general but in terms of a specific entity that has the need and the resources to purchase a PRT system. Yet the entity generally wants to see a PRT system running somewhere else before a purchase will be seriously considered. Recent studies supported by the Swedish Transportation and Communications Research Board form an outstanding exception [Tegnér, 1999]. Moreover, if only one source of supply for PRT components is available, the potential buyers become nervous. They would rather have options, and want to be certain that some manufacturer will be around to supply service and spare parts.

It is common then to feel that it is up to governments to provide the risk investment. But governments by and large a) are influenced most strongly by the conventional transit community that does not understand PRT and wishes that the idea would go away, and b) when they have gotten involved they have been found to be incapable of leading the development of a really cost-effective PRT system, likely due to the mix of enthusiasts, uninformed, and active detractors among the teams they assemble. There is a lot to the theory and practice of successful PRT design and the people assigned to government projects generally have not had the necessary background and have not had the necessary motivation or free time to learn. Additionally, local governments manage existing systems and in general do not have people skilled in the process of development of complex systems. PRT requires a combination of aerospace skills and skills in urban planning and management – fields that have been at opposite poles.

When PRT matures, it will likely be the result of the leadership of a municipality or a private development seeing through their own investigations that they a) can't solve their problems satisfactory with any conventional system, b) become convinced through a site-specific application study that a PRT system can solve their problems at an acceptable cost, c) are aware of a PRT system that can be deployed within an acceptable time frame, and d) have come to understand the management concepts needed to make it happen successfully. At some point, the entity must have enough conviction to be willing to sign a statement to an investor group saying that if the system meets certain specifications they will purchase it. The investment group must likewise, through their own investigations, be certain enough of the technology and the team assembled to design and build it that they are willing to invest. Ideally, the two are the same. The reason it has taken so long for PRT to develop is that the likelihood of assembling all of kinds of people with the necessary degree of understanding and maturity needed is small. Too much arrogance and too much greed have destroyed projects, but the kinds of people involved often have had a measure of both.

The purpose of this paper is to review the state of art of the technology and planning of PRT systems and to envision the characteristics of a community served by such a system. Most of the following discussion is technical, not for fascination with technology, but with a constant eye on the end goal of the technology. Investigation of how to improve and optimize urban transit technology is not an end in itself; it is a means to improvement of the quality of life of people of all kinds. One must investigate the technology with calm detachment, without fascination with technology as such, without prejudice towards one's own ideas, and with the humility to change if ideas superior to one's own are discovered. During 1987-1989 the Advanced Transit Association made a critically important contribution to the advancement of PRT through the report of a two-year study by its Technical Committee on PRT [ATRA, 1989]. An update of that report can be found on www.advancedtransit.net.

Derivation of PRT

The early developers of PRT generally stressed the service characteristic of nonstop, no-transfer travel at any time of day or night, which is possible if the vehicles are small enough so that one small party traveling together by choice can use them. The detractors argued that such characteristics would result in a very expensive system that would not likely be practical. After working in the field for some years, it became clear to me that it was necessary first to be able to argue that, by selecting characteristics properly, PRT can be cost effective. There is a chapter on cost-effectiveness in my textbook *Transit Systems Theory* [Anderson, 1978], but I had to wrestle with the problem off and on for six more years before the analysis was fully satisfactory [Anderson, 1984].

Now, that analysis can be summarized quite easily. First, safe and time-competitive travel requires that the vehicles operate on an exclusive guideway. Such a guideway could be at grade, underground, or elevated. At grade guideways would have to be fenced off and bridged over for cross traffic, which is rarely practical. Underground systems are the most expensive, but can be used when elevated guideways are not acceptable. Planners therefore almost always prefer elevated guideways, which requires the designer to make them as small and as attractive as possible.

Second, guideways that must support conventional-sized rail cars weigh between about 2000 to 3000 lb/ft. If the capacity of those cars is divided into many units of the smallest practical size with attention to vehicle-weight minimization, we found that we could reduce the weight of the guideway to 140 lb/ft, which makes a dramatic difference in cost and size. This finding is not only due to the difference in static loading, but also dynamic loading, which is discussed below.

Third, because the small vehicles that would replace big ones have many more motors, controllers, wheels, etc. unaided intuition usually suggests that the cost of a group of small vehicles must be more than the cost of one large rail car of the same total capacity. However, actual data for a large number of commercially designed transit systems with vehicle capacity ranging from over 200 down to 2 or 3 shows that a least-squares fit to the data is close to a horizontal line, meaning that the cost per unit of capacity is independent of capacity. There is of course a large scatter in the data points, but if a design team concentrates on cost reduction, the data says that they will be able to supply small vehicles for about the same cost per unit capacity as large ones. There are a number of reasons for this finding. Foremost is that the quantity of production is roughly 60 times as large with the small vehicles. Next, smaller components cost less than larger ones. Third, the jigs and fixtures needed for manufacture, rigs needed to move vehicles, and the buildings needed to house them are correspondingly smaller.

Fourth, it follows that the cost of a fleet of transit vehicles, regardless of their size, is directly proportional to the capacity in places for people required to move a given number of people per unit of time. The required capacity, in turn, is inversely proportional to the average speed of the vehicles. For example, if it were possible to double the average speed, half as many vehicles would move the same number of people—the productivity of each vehicle is doubled. Increasing the maximum speed will increase the average speed, but that practice increases costs. The way to make the average speed as high as practical without increasing the maximum speed too much is to make all trips nonstop, which becomes practical if all the stations are on bypass tracks off the main line, and if line-to-line vehicle transfers are practical, i.e. if switching is sufficiently reliable. Non-stop trips become practical if each vehicle is small enough to carry only one party traveling together by choice to a single destination and by use of off-line stations vehicles can wait at stations for people rather than requiring people to for vehicles, thus increasing ridership. Moreover, elimination of mainline stopping makes it possible for the smallest vehicles to maintain flows in people per hour that match a wide variety of demands [Anderson, 1998a].

Fifth, the required size of a fleet of transit vehicles depends on the number of passenger-miles demanded per peak-hour, but all of the economic parameters depend on the number of passenger-miles per year. The higher the ratio of yearly to peak-hour flow the lower will be the transit system's cost per passenger-mile. So we are interested in this ratio, which can conveniently be separated into the ratio of yearly flow to weekday flow multiplied by the ratio of weekday flow to peak-hour flow. These ratios depend on the kind of service offered. Pushkarev and Zupan [1977] showed that for commuter rail into Manhattan the ratio of weekday flow to peak-hour flow was about 4.2, for the New York subway about 6, for bus systems in four Eastern cities between 6.5 and 10, and for auto and taxi 11.4 to 12.2. Thus, the more nearly demand-responsive a system is the higher is this ratio, i.e. the more the traffic is spread throughout the day. On this basis, because of its demand-responsive service character, it is reasonable to assign to PRT a ratio of daily to peak-period flow about 12. In typical transit studies the ratio of yearly flow to weekday flow is usually taken to be about 300, which assumes that the weekend and holiday travel is 42% of the weekday travel. It is clear that the ratio of yearly to peak-hour travel will be higher the more nearly demand-responsive a transit system becomes, which is one of the factors that will reduce the cost per passenger-mile of a PRT system.

Sixth, consider operating and maintenance (O&M) costs. It would be prohibitively costly to let small vehicles be manually controlled, so automatic control is mandatory, and that idea has been widely accepted. Consider the quantity O&M cost per place-mile. Here a "place" is a unit of the design capacity. It is used instead of "seat" because some of the transit systems compared permit standees. By examining federal data on O&M cost per place-mile, we found that the variation in this quantity is remarkably small for conventional rail, buses, automobiles (which of course have no paid driver), and large- and small-vehicle automated people movers. There were a few exceptions, but they were not for systems in extensive use. One can conclude that minimizing the O&M cost per place-mile is related more to good engineering than to the size of the vehicle. We are, however, interested in O&M cost per passenger-mile, which is O&M cost per place-mile divided by the daily average number of passengers per place, which is called the "load factor." So the system with the highest daily average load factor will generally have the lowest O&M cost per passenger-mile. We argue below that the best number of places in a PRT vehicle is three adults plus two children, and the analysis of a number of investigators shows that, counting empty vehicles re-circulating to stations of need, the daily average occupancy of moving PRT vehicles is about one person, giving a load factor of 0.33. This is a result of moving vehicles only when there are demands for service. Examination of data, such as can be found on the FTA web page, shows that the daily average load factor on conventional transit systems ranges from about 0.1 to 0.2. In the late 1970s, the Director of Transit Development for the Twin Cities Metropolitan Transit Commission commented to a small group that the 24-hour average bus occupancy was only 2.5 people per 60 passenger vehicle, giving a load factor of 0.04. This low load factor is inherent with on-line stations because the vehicles or trains must maintain a reasonable frequency in the off-peak hours regardless of the number of people riding. Thus the O&M cost per passenger-mile for a PRT system should be lower than that for conventional scheduled transit by a factor of 1.7 to 8.

The conclusion from this analysis of the equation for total cost per passenger-mile is that it will be minimum if the smallest practical-sized vehicles are used on guideways carefully designed for minimum cost and if the service is on-demand at the highest reasonable average speed. Moreover, the last factor is realized if the stations are off-line and the trips are nonstop. These features maximize the attractiveness of the transit system for riders, i.e., *the exact factors that minimize cost maximize ridership*. All of these factors together define the PRT concept, and we have now shown that it is as ideal a transit system as can be designed in terms of minimum cost per passenger-mile. Within the definition of an ideal transit system there are many possible variations in the design, and it is necessary to study how to optimize the design of every component for minimum cost while meeting all requirements of capacity, safety, reliability, environmental protection, and long life.

Technical Issues

Capacity

A common misperception is that small vehicles can't possibly carry enough people to be worthwhile, forgetting that well over 90% of the traffic in the peak period in most American cities is carried by automobiles with average occupancies of less than 1.1 persons per vehicle. Conventional transit vehicles must be large because they stop on line. To stop on line safely, the vehicles or trains on exclusive rails must be spaced usually no less than two minutes apart, giving no more than 30 trains or buses per hour, and on city streets no less than six minutes apart, giving no more than 10 trains per hour. Consider the size vehicles needed for the flow to match that of a single freeway lane, which can carry up to a maximum of about 2000 cars per hour with, say 1.1 persons per car, or 2200 people per hour. 2200 people per hour divided by 30 trains or buses per hour gives 73.3 people per train or bus, and divided by 10 trains per hour 220 people per train. This requires large vehicles, which, if they run elevated to avoid interference with road traffic, require a large, heavy, expensive guideway. Large guideways require large rights of way, which are scarce, so the tendency is to think in terms of travel corridors rather than areas that conform to the way cities are actually laid out, and to actual traffic patterns. So the use of large vehicles in conventional transit is not the result of the need to achieve significant flows, but because of the limitations of the technology used. With today's technology such limitations do not exist, so transit systems can be designed that come much closer to meeting the real needs of people.

If transit guideways are very small, there are many more locations in a city in which they can be placed, and with today's switching technology, as shown below, these guideways can be interconnected to provide nonstop trips, competitive in speed to the automobile. If, in a city of say 12,000 people per square mile in which a quarter of the trips are taken on PRT and guideways are placed half a mile apart, the average line flow requirement is less than 1000 vehicles per hour and the average station flow requirement is less than 200 persons per hour [Anderson, 1998a]. This line flow corresponds to a minimum time headway of 3.6 sec and this station flow can be accommodated by a two-berth station [Anderson, 1990]. Yet, PRT lines can average more than six times this line flow and PRT stations can average up to about seven times this station flow. Moreover, 12,000 people per square mile is a much higher density than present in most cities, and a transit system that captured a quarter of the trips would be seen as wildly successful. We see, therefore, that PRT can provide adequate service in a wide variety of applications. Early applications will, of necessity, be small and will not require minimum headways below that which is controversial [Anderson, 1998a]. Thus there will be ample opportunity to gain operating experience while gradually reducing the headway to values required for large networks [Anderson, 2009b].

Switching

Since a PRT system will have many small vehicles operating at close spacing switching in and out of stations and from one line to another, practical and reliable switching is the most fundamental design issue. A number of interrelated issues enter in the consideration of the means of switching and in consideration of the design of the guideway in such a way that switching is practical:

- Should the switch be mechanical or electromagnetic?
- Can there be any mechanical moving parts in the guideway?
- How does the issue of supported vs. hanging vehicles affect switching?
- How does the issue of guideway-cost minimization affect switching?
- How does the means of suspension affect switching?
- How is it possible to insure that the vehicle can never impale on the center guideway element at a diverge point? [Anderson, 2009b]

The criteria for selecting the optimum combination of these features, if there is a single optimum, include maximizing reliability and safety, and after that minimizing system cost and visual impact. One of the simplest decisions was to reject the common monorail system in which the vehicle-support element wraps around a beam. With such a structure, the entire beam must switch and this markedly limits the minimum headway at which vehicles can run safely. The designer then has two choices: either remain with an optimum-cross-section box beam with special switch sections or go to a U-shaped beam designed for adequate torsion. The Cabintaxi PRT design [Hobbs, 1977] opted for the former, which, to keep from moving a guideway element to switch, requires a complex and expensive guideway switch section larger than would be desirable for minimum visual impact. The Aerospace Corporation PRT system [Irving, 1978] used supported vehicles on a narrow, U-shaped guideway, keeping in mind the importance of minimizing visual impact as well as the simplicity and reliability of switching. They used electromagnetic switching with an on-board mechanical backup. We calculated the weight of the on-board components of an electromagnetic switch, which discouraged us, so we felt that if there must be a mechanical backup, it may as well be the primary switch, and we found that a switch arm that rotates about a longitudinal axis could be configured to meet all of our criteria without compromise. More recently others have opted for electromagnetic switching, which may be preferable if the weight of the on-board elements is substantially reduced, and if the switch can be made so reliable that no mechanical backup is needed.

Hanging vs. Supported Vehicles [Anderson, 2011]

When we began the design of an HCPRT system, one of the first issues we had to settle was whether to support or hang the vehicles, keeping in mind how this decision would affect switching. We noted the following considerations:

- If the vehicles hang from the guideway, the bending moment at the foundation of the posts due to the combination of maximum vehicle loads and lateral wind loads was about twice the value if the vehicles were supported on top of the guideway, so the foundations would have to be twice as large.
- Considering that the clearance underneath the system must be the same in both cases, the visual impact of the guideway above the vehicles with larger posts cantilevered around the vehicles would be greater than if the vehicles were supported.
- We found that by clamping the guideway to the posts, as suggested by Dr. Jack Irving, for a given guideway stiffness the fundamental natural frequency of the guideway-post system would be substantially higher than for a hanging-vehicle system with its inverted L-shaped support posts. Thus, for the same natural frequency in the two cases, the guideway could be substantially smaller if vehicles are supported.
- If the vehicle is supported on wheels, which we chose over air or magnetic suspension after careful consideration of the effect of the choice on guideway size and system cost, and the vehicle hangs from the guideway, such as was the case with Monocab, the vehicle load supported by the wheels must be transferred to other wheels on other surfaces as the vehicle passes over a slot in the guideway switch section, which is needed to permit the vehicle support arms to pass through in each direction. This extra mechanism reduces reliability and adds to cost.
- With hanging vehicles, the stresses to support the loaded vehicle must be transmitted through its sidewalls, whereas the supported vehicle merely sits on a carriage. Thus supported-vehicle weight can be somewhat less.
- If a portion of the system must be underground, then if the guideway is below the vehicle it can be laid on the ground, which lowers cost.
- The Cabintaxi design group opted for both top- and bottom-mounted vehicles and they built a test track on which they operated both types. Many people rode the system and they found a small preference for seeing the guideway underneath rather than overhead.
- Finally, the main reason some designers opt for hanging vehicles is that in curves the torsional moment due to centrifugal force on the vehicle is in the opposite direction to the torsional moment due to gravity. The effect of superelevation to reduce curve radii is produced naturally if the hanging vehicle is on a hinged suspension system that permits it to swing out in curves. I calculated the size cross section needed to resist the torsional moment and found that to get the same torsional stress in both cases the guideway with supported vehicles needed only 13% more material than with hanging vehicles [Anderson, 2011]. However, permitting the vehicles to swing out in curves must be restricted because

many people get motion sickness, as witnessed in Swedish Railways when the engineers decided to design tiltable bogies to permit banking in curves. This problem resulted in limiting the speed to a much lower value than planned. The same problem most assuredly will occur in hanging-vehicle PRT systems, which means that the designers will find it necessary to limit banking in curves, which reduces the advantage of the hanging configuration.

Considering all of the factors, we chose to mount our vehicles on top of the guideway. With supported vehicles, we need to build superelevation into the guideway in curves, but consultation with steel fabricators convinced us that this was practical and we found that the angle of twist produced by a vehicle traversing a curve in our design was only 1.8 deg [Anderson, 2008].

Guideways

From the experience of observing results of designs of many automated guideway transit systems during the 1970s, we accumulated over 30 requirements for guideway design [Anderson, 2009a]. It is not my purpose here to list them, but to caution the potential designer to think hard about requirements and criteria and study carefully the mistakes of the past before committing to a specific design. It is common to assume that the guideway can be turned over to an average structures group. Unfortunately, the experience of such groups will generally be different and they will usually be in too much of a hurry to research carefully all of the factors involved. The guideway is the largest cost element in a PRT system and its visual impact as well as cost is critical to the acceptance of the system. Many guideway designers did not consider problems of winter weather until they were too far along. Some of these problems are quite subtle, such as the problem of frost formation on power rails during clear winter nights or the problem of differential solar heating. I have listed more than a dozen PRT systems that are now on the trash heap because of overlooking weather problems. Consideration of switching is fundamental to guideway design, as briefly mentioned above.

The most extreme loading condition is a uniform load due to fully loaded vehicles nose to tail [Anderson, 1978, Chapter 10]. Since the deflection of a simply supported beam under uniform load is five times the deflection if the ends of the beam are clamped and the natural frequency of a clamped beam is 2.27 times the natural frequency of a simply supported beam, it makes sense to clamp the guideway to the posts. Dr. Jack Irving [Irving, 1978] suggested this idea. Because the bending moment at the posts is now high, it is desirable to take into account that the point of zero bending moment in a beam under uniform load is at the 21% point, which is the right place to put the necessary thermal-expansion joint. Considering the weight of the guideway itself, my analyses have shown that moving vehicles do not move the point of zero bending moment very much.

Once a configuration is selected that meets all of the requirements, the guideway is designed based on stress and ride comfort. Because it is easier, some designers use natural frequency rather than ride comfort as the second criterion; however, deflection, forcing functions, *and* natural frequency all enter into the consideration of ride comfort. Computer tools are available today that permit detailed analysis of stress and ride comfort in straight and curved sections and in our 1990 Chicago PRT Design Project such analyses was completed. Many designers have avoided dynamic analysis of guideways because it is a hard problem and has not been within the training of many structural engineers. An extremely useful piece of work on dynamic analysis of guideway was done in the M. I. T. Mechanical Engineering Department [Snyder, 1975]. The results are parameterized in a way that makes them useful in the analysis of the guideway for any elevated-guideway transit system. A major result is that the statically designed guideway for a PRT system can operate up to much higher speeds than would be the case for larger vehicles spaced farther apart. I recently updated my work on this problem [Anderson, 1997a] to show the speed range over which a PRT system can operate. An important factor is that by use of asynchronous control, described below, the vehicles are not uniformly spaced, which damps the dynamic guideway deflections. A key finding was that the required guideway weight and therefore cost is directly proportional to vehicle weight.

Vehicles

Because the weight and hence cost of the guideway is proportional to the weight of the vehicles, special attention must be paid to minimizing the weight of the vehicles. Since PRT vehicles are not subject to rollover and side collisions, nor do they have to be designed to run over chuckholes and curbs without damage, their design can be substantially lighter and less expensive than street vehicles. Also, since the length of the station platforms is directly proportional to the length of a vehicle, the shortest practical vehicle will minimize station costs and will shorten the walk to a vehicle. The shortest vehicle will have one seat with a padded dashboard in front of it to prevent injury in case of a sudden stop, however rare that may be. To accommodate a wheelchair, which is necessary because of the Americans with Disabilities Act, the width of the interior and hence the seat must be about 1470 mm. To minimize vehicle length, the seat can be caused to fold up when a wheelchair enters and then is constrained by the padded dash ahead and the seat behind [Anderson, 2012]. In this configuration, no wheelchair tie-down is needed because it can't move very much. A seat 1470 mm wide can easily accommodate three more than average adults; or, for example, it could accommodate a mother, father and two children. Since the daily average auto occupancy in the United States is only about 1.2, almost 90 % of the trips in a PRT vehicle will be taken by only one person. To encourage group riding, the fare should be charged per vehicle rather than per person, which has the additional benefit of simplifying the process of fare collection.

To determine the characteristics required for stability and suspension, dynamic simulations are needed for both lateral and pitch motion. We have developed computer programs to study the motion of the vehicle with various unbalanced-passenger and lateral-wind loads to see that the parameters are selected so that the motion of the passengers through merge and diverge points in the guideway is always within accepted ride comfort standards.

Control

The control of PRT vehicles must satisfy a number of criteria. These include adequate line and station throughput, safety, dependability, ride comfort, changing conditions, dead-vehicle detection, interchange flexibility, the potential of vandalism and sabotage, modularity, and expandability [Anderson, 1998b].

The strategy for control of PRT systems can take several forms. The earliest strategy was called "synchronous" because vehicles were programmed to follow virtual points along the guideway that move at a predetermined speed and fixed spacing. A vehicle ready to leave a station had to wait until it had a clear path to the destination free of any merge conflicts. If, however, there were more than about four merges during the trip, counting station-to-line merges; the wait time becomes too long to be practical [Anderson, 1996a]. The Aerospace Corporation recognized this problem and therefore devised a "quasi-synchronous" strategy in which vehicles could slip slots at merge points. By making all merge points two-in and two-out—a multi-level interchange—advanced knowledge of merge conflicts was unnecessary because the worst that could happen was that an occasional vehicle would be routed along a different path; however, the visual impact of over-under interchanges is often a problem. A third strategy, used by the developers of Cabintaxi, was asynchronous. In this strategy, the vehicles do not follow any particular time slots but move out from stations and through merges as soon as they are ready. A fourth strategy called "point-synchronous" was developed in Sweden. In this strategy, when a vehicle enters a link between line-to-line branch points it is caused to slowly accelerate or decelerate at a rate that causes it to pass the next branch point at a predetermined time. The first simulation we developed followed the quasi-synchronous strategy, which worked very well at half-second headway, but later, for comparison with a competitive system, we needed to simulate much longer minimum headways, in which case we found that the asynchronous strategy was needed. After modifying our simulation to work asynchronously, we found that it also worked very well at the shortest headways and permitted us to delete several subroutines.

In the 1970s those who used the asynchronous strategy also used a vehicle-following strategy in which the movement of each vehicle was based on the motion of the vehicle ahead of it, exactly as we drive on a freeway. Those who used the quasi-synchronous strategy caused each vehicle to follow a moving point computed in a wayside computer, a "point follower." We found it best to cause each vehicle to follow a commanded maneuver, a point, with the exact profile calculated on board to conform to ride-comfort limits. We worked out the mathematics of the entire family of maneuvers required so that the wayside zone-control computer need only command the vehicle to perform a certain maneuver with a given parameter, such as "stop in 20 meters." The wayside computer follows the exact maneuver to look for and respond to any anomaly. We call the preferred strategy an "asynchronous point follower."

To affect a smooth merge, a merge-zone-control computer keeps track of all vehicles within each merge zone. When a vehicle arrives at a merge-command point a predetermined distance ahead of a merge point, the zone-control computer notes if it will conflict with a vehicle farther back on the other branch. If so and if possible, the vehicle may be caused to slip ahead, i.e., to accelerate then decelerate to increase the spacing to the safe value. If not, the other vehicle is caused to slip back, and if in so doing the spacing to the vehicle behind it would fall below the safe minimum, it is commanded to slip simultaneously, and so on. The key to making this procedure work is to keep track of the amount of slip each vehicle has remaining, so that the vehicles can be commanded to slip only as much as necessary. By thus slipping already slipping vehicles, we have found that all merge conflicts are resolved safely without exception. An added dividend is that it is practical to use Y interchanges, which minimize visual impact.

Each vehicle communicates with its zone controller through a leaky cable in the guideway, and gives the zone controller its position and speed every time-multiplexing interval. These intervals are typically 40 to 100 msec long. The zone controller in turn commands the vehicle's speed signal every time-multiplexing interval and when necessary, as mentioned, a maneuver command with a parameter, for example "slip back 1.9 meters." The vehicle controller is programmed so that if the speed signal is absent, the vehicle and those behind it are commanded to slow to creep speed. It calculates the time varying speed and position during the maneuver and feeds that information as commands into a speed-position controller. We were able to show [Anderson, 1997b] that only speed and position feedback are needed (acceleration feedback is not needed) and also found formulae for the gains of the controller in terms of the desired system undamped natural frequency and damping ratio. Boeing engineers [Lang and Warren, 1983] showed how both speed and position could be derived from a digital encoder.

Station Operations

The simplest off-line station is one in which there is one off-line guideway with spiral transitions into and out of the station designed to keep the motion at or below comfort limits on jerk and acceleration. Because the vehicle is slowing down as it enters the station and is speeding up as it leaves, it is possible to save about 40% of the length of the transition if it is calculated from the differential equation for the curve rather than by assuming the speed is constant [Anderson, 2010]. To shorten the length of the entire off-line guideway, it is possible to initiate deceleration before the vehicle is completely clear of the vehicle behind that is bypassing the station at line speed. Doing so requires that we give up an increment of line headway. We found from simple kinematics that by giving up only 0.1 sec of on-line headway at a line speed of 25 mph we could shorten the off-line guideway by 107 ft, and at 30 mph by 127 ft. This is such a large gain that it makes no sense not to take advantage of it, even with systems operating at quite short minimum headways.

In the above-described simplest station, people enter and leave vehicles at the same berth, thus permitting the shortest possible station. The maximum flow through the stations depends on the number of berths, which in our work has varied from two up to 14 berths in stations serving the Cincinnati Reds Ballpark, with typical stations having 3 to 5 berths. The maximum throughput varies from about 300 vehicles per hour with two berths up to about 1400 vehicles per hour with 14 berths [Anderson, 1990]. To maximize flow, or throughput, in an N-berth station there must be $N + N_{ex}$ waiting positions upstream of the station platform for vehicles to accumulate and then move simultaneously into the station area, so that those waiting in the station can load simultaneously after people in the entering vehicles unload. The number N_{ex} is needed to minimize the chance that a vehicle desiring to enter the station cannot do so because there is a vehicle in the last position. The vehicle must then be waved off and must circulate around the shortest route to try again. To keep the number of wave offs below about one in 10,000 trips, I have found that N_{ex}

should be 3. The tolerable number of wave offs is a policy question, and the event can be sweetened by offering a prize such as a free trip.

The operating strategy through a station is "move forward when you can." The system could be designed so that a vehicle in the first station berth ready to advance to line speed could move to a forward staging area and wait for an opening. But this lengthens the off-line guideway while the planner is always trying for good reason to shorten it. If the first few berths are free and a vehicle farther back is ready to go, it accelerates to advance to the forward-most empty berth. While the vehicle is moving forward, to maximize throughput the station-zone computer must be able to monitor the position of each vehicle bypassing the station every 5 to 10 milliseconds in order to command the vehicle in the station to line speed during the maneuver, and this monitoring is going on continuously in every zone. While the algebra to find an opening in the line flow from an arbitrary initial speed and acceleration is a bit complex, we have worked it out and have programmed it in complete detail. The vehicle at rest in the first berth must wait for an opening, but from our simulations, we have not found that reducing this delay would be worth adding waiting positions downstream of the station. It is cheaper to increase throughput by adding one or more station berths. With these considerations, the total length of the off-line guideway is typically less than 20% of the mainline guideway.

Some analysts have proposed that there be a separate unloading platform followed by a length of guideway in which vehicles advance to a loading platform. But this more than doubles the length and hence the cost of the station structure, so it is necessary to examine carefully any disadvantage of unloading and loading at the same berth. Generally, only in unusual situations will there be roughly the same number of people entering and leaving a station. Even if they do, because the occupancy of any vehicle is only one to three people, and usually one, a little human-factors work shows that it not unreasonable at all for the people wishing to load to stand aside while passengers unload.

A disadvantage of the single-line station is that once in a while someone will take an unusually long time to load or unload. The cycle time for clearing N vehicles in an N-berth station is dependent on the longest loading or unloading time, so in any case this means that the expected dwell time for N vehicles will increase with N. In our simulations we assume a normal distribution of loading and unloading times up to a maximum of 20 seconds. If long dwell times occur frequently they will reduce the station throughput, but generally, at least in the busiest periods, people move quite briskly. The flow through a station can be observed in a simulation that I developed. Because of the problem just described, some system developers have designed stations with a series of parallel-loading berths. Simulations have shown, however, that the potential increase in throughput is not impressive, particularly in view of the markedly increased size and cost of such stations as well as the need for access to separate platforms [Liopiros, 1973], [Sirbu, 1973].

A freestanding elevated station will require at least a stairway and an elevator, the cost of which could be avoided if the guideway could be brought close to the ground. The latter could be done but requires vehicles to decelerate downhill and accelerate uphill, and it requires that a section of guideway be fenced off. If this is done, the vehicles should be decelerated to a slow speed such as 2 or 3 m/s on the level and then descend and ascend at this slow speed. This will lengthen the off-line guideway and will reduce station throughput, so it is not obvious without detailed analysis that lowering the guideway into the stations is cost effective.

System Operations

To be routed all a vehicle needs on board is its destination. When it approaches a line-to-line diverge, the zone controller controlling the diverge requests the destination, looks it up in a table of switch commands, and transmits a left or right switch command back to the vehicle. The zone-control computers are connected to the central computer through fiber-optic lines and through them the central computer is aware of the flow of vehicles in all parts of the network. If the flow in some portion of the network is too high and a vehicle approaching a specific diverge could reach its destination along a different path, it can be dynamically redirected to maximize the demand the entire system can carry.

The movement of empty vehicles must be managed in such a way that wait time is minimized. During periods of inactivity typically about 30% of the vehicles can be stored in passenger stations and the rest in conveniently located storage facilities, which are surprisingly small because no specific vehicle need exit first. If all terms of the demand matrix were the same, no empties would be needed; however, if the demand were all in one direction, half of the vehicles would have to return empty. It is not surprising therefore to observe from many simulations that typically about one third of the moving vehicles will be empty. We were able to reduce the average wait time to less than 50 seconds during the peak period in a simulation for Cincinnati in which 80% of the demand was due to people traveling to a Cincinnati Reds ball game. There are two steps to achieving this result. First, when a station calls for an empty vehicle, it is not to serve the passenger just arriving, but the N-th passenger later, where N can be adjusted as a function of the difference between the passenger flow from the street into the station and from the station into the street. The later flow is better known to the system than the former, but the former can be sensed by means of infrared detectors counting entering passengers. When a station calls for an empty vehicle, the station computers in tandem look successively upstream and redirects the first unassigned empty encountered, whether on line, in a station, or in a storage facility.

Reliability, Availability and Dependability

Safety and reliability are of utmost importance in the design of a PRT system. During the design process it is necessary to do hazard analysis, fault-tree analysis, and failure modes, effects and criticality analysis. One of the major mistakes in a number of PRT development programs has been to leave these topics to second-tier engineers. While such analysis techniques are fundamental to the design of PRT systems, they can only be highlighted here. I have treated these problems exhaustively in my HCPRT development program and some of the analysis has been published [Anderson, 1978, 2000, 2001].

Availability is defined as the mean time between system failures divided by the sum of the same quantity plus the mean time to restore service. This definition is commonly used as a measure of on-time performance in conventional transit, but has the weakness that it does not relate directly to the delays of passengers; the reason being that it is impractical in conventional transit to measure the delays of individual passengers. In PRT, on the other hand, since each trip is nonstop and known to the system, we can do better. We therefore define a new quantity "undependability" as the ratio of the number of person-hours of delay due to failures in a given period to the number of person-hours of operation [Anderson, 1992]. Dependability is one minus undependability. Dependability can quite easily be both measured continuously and calculated in a PRT system, and can be used as a precisely defined measure of on-time performance in contractual terms.

Reliability is usually given in terms of Mean Time between Failures (MTBF). In a large system in which there are many components that can fail, it is important to obtain an understanding of the importance of the required MTBF of each component. Striving for the ultimate in each component by over-design may make the system very expensive without a commensurate return. Use of redundancy may be a more cost-effective way to achieve the same result. The lifecycle cost of a component is the sum of the acquisition cost and the support cost. The former increases with MTBF and the later decreases. The sum is a "bathtub" curve with a single minimum point. The system lifecycle cost can, at least in principal, be expressed as a function of the MTBFs of all of the components. We needed to determine how to select the required MTBFs in a way that minimizes system lifecycle cost subject to the constraint of a specified dependability. This is a standard Lagrangian minimization problem and has a beautiful solution in which the required MTBFs are expressed in terms of the properties of normal operation, failure operation, and the slopes of the lifecycle cost curves for each component [Anderson, 1977, 1978j 1996b]. Together with data on component lifecycle cost vs. MTBF available from the Reliability Center at Rome Air Force Base, this equation has been useful in all stages of the design of our PRT system and will continue to be useful as we go into production.

Safety and Security

In the Boeing Advanced Group Rapid Transit Program, which was active from the mid-1970s to the mid-1980s, the engineers were told that they had to design the system to be as safe as a modern rapid rail system. When asked what that meant, they were told to assume that it meant that the system was as safe as if the vital relay, upon which railroad safety depends, had an MTBF of one million years [Milnor and Washington, 1984]. The results of their investigations showed that that this goal could be exceeded substantially by use of checked, dual duplex computers. They also showed that the use of such a system of computers is superior to triple redundancy. It is well known that computers are much cheaper and faster today than they were 15 years ago, so the cost of dual checked, dual duplex computers is not great. Also the size, performance, and cost of sensors needed to detect incipient failures are much improved since the Boeing investigations. We therefore plan to use dual checked, dual duplex computers on board our PRT vehicles, in the wayside zone controllers, and in the central control facility. A "checked, dual duplex computer" is one in which there are two motherboards with self-checking software that can determine if either of the two has a failure and which one. For the vehicle to proceed normally the results of these parallel calculations must compare, and must agree with the corresponding output of the other similar computer. If a failure in one of the units is detected, the on-board computers are programmed to permit that vehicle to finish its trip while informing central and then direct it to the nearest maintenance station for replacement of the faulty component. We have calculated the improvement in failure frequency with redundancy [Anderson, 1999] and have shown how to design the system so that there is virtually no chance of impaling the vehicle on the center guideway in a diverge section.

If any of the failure sensors detects a failure, the on-board computers are programmed to take appropriate action depending on the severity of the failure. The means of obtaining software reliability is not specific to PRT and therefore is not discussed here. Detailed discussions of the safe and secure design of PRT systems have been published [Anderson, 1994a, 1995]. Propulsion has not been discussed here because it is amply covered in the referenced publications. The future of safe, high-capacity PRT, lies, however, in the use of linear induction motors [Anderson, 2009b, 2011b].

Calculation of Guideways

PRT guideways have many curves and may also have hills. The horizontal and vertical curves must be calculated to maintain passenger ride comfort within accepted standards for lateral and normal acceleration and jerk, which for seated passengers are generally 0.25 g and 0.25 g/s, respectively. However, normal upward maximum tolerable acceleration is usually a smaller value. The papers "The Differential Equations of a Plane Transition Curve" and "Plane Curved Guideways" in *Transit Systems Theory* [updated in Anderson, 2010a] give all of the equations needed to calculate plane curves, which is sufficient for operational simulation of most systems in which the desired results are station sizes and locations, wait times, system capacity, and resolution of possible bottlenecks. Based on these equations, we developed a program for calculating the guideways for any application based on knowledge of the coordinates of the apexes of all curves, the distance of each station from the nearest upstream apex and the desired speeds, which may vary.

To specify all curved sections of guideway for a steel fabricator and for simulating the operation of a PRT system in a hilly city, it is necessary to solve the equations for space-curved guideways. These are equations for jerk in the horizontal and vertical planes in terms of orientation and speed and result from setting each jerk to a fixed comfort value. These equations have been derived [Anderson and Anagnostopoulos, 1994b] and have been applied both to the problem of specifying coordinates of guideways for guideway fabricator and to the problem of determining the performance of high-speed ground transportation vehicles traveling along the curves and hills of a freeway at a speed substantially higher than that for which the freeway was designed.

Operational Simulation

The specification of PRT systems is not complete without an operational simulation. A number of such simulations were developed in the early 1970s [Gary, Garrard and Kornhauser, 1976]. The history has been updated. [Anderson, 2007.] These simulations consistently reported average wait times of a minute or less, but the details are likely no longer available. Recently, descriptions and results of simulation have been published [Andréasson, 1992; Anderson, 1998c]. Our simulation is complete in every detail and can be used to run an operational system. While in the 1970s it was sometimes declared that the operation of PRT systems would require huge computers, today our complete simulation occupies less than one 200 thousandths of the memory of a laptop computer. It can be stated that the most complex problem in the development of a PRT system — the operation of a large system, has been completely solved. This was likely true in the 1970s at least in The Aerospace Corporation and Cabintaxi PRT programs, but now the problem is much easier because of the marked increase in memory, capacity, and speed of computers; because of currently available software tools that did not exist in the 1970s; and because the hardware components are now readily available commodities.

Power and Energy

The operational energy requirement per passenger-mile of any transportation system depend on propulsion efficiency, speed, average load factor, vehicle weight, cross-sectional area, streamlining, road resistance, the number of intermediate stops, and the energy requirements for heating and air conditioning. The major inherent advantages of PRT in energy use lie in elimination of the intermediate stops and in increased daily average load factor. The maximum power requirement, which determines the size of the drive, can be cut almost in half with little penalty by gradually reducing acceleration above about half line speed, and by operating at an electrical frequency that minimizes current. This practice is very important because the drive size needed to dissipate heat is proportional to the cube of the maximum current.

Total energy use per passenger-mile includes construction energy. Because of the small size of optimized PRT components, construction energy is substantially less than for conventional rail systems. I worked out an easily programmable formula by which all transit systems can be compared [Anderson, 1988] and showed results for a variety of systems. One main conclusion of the study is that the comparison of energy efficiencies among various transit systems is complex and is often not intuitively obvious. For example, some environmentalists have been convinced that conventional light rail is energy efficient because it runs on steel wheels on steel rails. Analysis shows, however, that the kinetic energy turned into heat at every stop is a much larger user of energy. Some of this energy can be gained back by use of regenerative braking, but the amount is disappointing because the energy input needed to supply the kinetic energy is larger than the actual kinetic energy attained because of propulsion efficiency during acceleration much less than one, and regenerative braking can bring back only a fraction of the actual kinetic energy. After adding the construction energy of an average light rail system, its total energy use per passenger-mile is equivalent to an automobile system achieving about 10 to 12 miles per gallon of gasoline.[81] Considering a future in which energy supply is increasingly limited, this is an unfortunate conclusion considering the number of light rail systems being built. The energy use per passenger-mile of a carefully designed PRT system is less than 10% of that required for the average light-rail system.

[81] On www.templetons.com/brad/transit-myth.html Brad Templetons found, to his surprise, that the average light rail system uses more energy than any other mode of transportation. This result is mainly due to a disappointing daily average load factor.

Conclusions

PRT can be cost-effective in very small applications or in applications of considerable size. In many cases an optimized PRT system can be built and operated at a profit. One of the most interesting near-term applications we have simulated would start with only three stations, and our studies show that a large-vehicle people mover for such an application will be substantially more expensive, would provide inferior service, and will likely have an unacceptable visual impact. So, PRT can start very small and can expand as the need and as the economics [Anderson, 2013] dictate. Once an optimized PRT system is deployed according to the principals given in this paper, a city in which it is deployed would have:

- Fast, all-weather, safe, private, and secure transport.
- Easy movement for everyone, not just those who can drive.
- Efficient use of parking facilities.
- Low air and noise pollution.
- Easy access to land now difficult to develop.
- More accessible stores, clinics, and schools.
- Employees arriving in a good mood and ready for work.
- 24-hour transit service.
- Safe, swift movement of mail, goods, and waste.
- Low street-repair costs.
- Relief from transit subsidies.
- Substantial energy savings.
- More room for people-attracting gardens and parks.
- More livable higher-density communities.
- Less need for urban expansion.
- Resources freed for other purposes.
- Better integration of the whole community.

These are indeed characteristics of a "Humanized Technology" [Fromm, 1968].

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1.4.3 Policy Issues that must be Negotiated

1. Introduction

Certain aspects of the design and implementation of a PRT system are not governed by code or by tradeoff analysis, but are rather a matter of policy. Recommendations on a series of policy issues are given here as a basis for concurrence with the client.

2. Safety and Security

2.1 NFPA-130

The National Fire Protection Association standard applicable to automated guideway transit (AGT) systems, NFPA-130, recommends several constraints on the design of AGT systems including walkways along the guideway and firewalls in stations. These significantly detract from the aesthetics of a PRT system, add to cost and are the subject of debate. NFPA has been accepting proposals for amendments to NFPA-130. Implementation of NFPA-130 standards is at the discretion of local fire officials.

2.1.1 Emergency Walkways

Issue: Walkways along guideways are intended to permit emergency egress in the event of a disabled vehicle or fire aboard a vehicle. They detract significantly from the appearance of a light guideway such as used in an optimized PRT design and add significantly to cost. The wording of NFPA-130 states that the transit system guideway shall incorporate a walkway or " . . . other suitable means for passengers to evacuate."

Recommendation: Local fire officials should be requested to approve the PRT system without walkways for the following reasons:

- Walkways invite illegal use by unauthorized persons.
- Walkways are difficult if not impossible for the elderly and handicapped to use.
- In severe weather, passengers could be exposed to extreme conditions including icing, wind and wind chill.
- Through the use of dual thrusters, fault-tolerant dual redundant control systems, back-up traction power, and conservatively designed sealed bearings, a vehicle will rarely become fully disabled.[82] In the unlikely event that a vehicle becomes disabled, the system will be designed to allow the following vehicle to push the disabled vehicle to the next station under the direction of Central Control.
- In the event that a disabled vehicle cannot be pushed, a cherry-picker can provide an acceptable alternative. A cherry picker with a garaging facility may be purchased for the local fire department as part of system implementation. Fault-tree and FMEA analysis has been used to determine the probability of occurrence of events that require passenger rescue.
- In the extremely rare event of a collision between vehicles, it may be impossible or inadvisable to move

[82] J. E. Anderson, "Failure Modes and Effects Analysis and Minimum Headway in PRT Systems"

the vehicles under automatic control or remote manual control from Central Control. Voice communication between Central Control and the vehicle will help establish this. Should serious personal injury be involved, the injured person may be immobile and the use of a cherry picker offers advantages over carrying a stretcher along a walkway.

- The vehicle cabin will be constructed of fire-retardant materials and will be separated from the primary electrical and propulsion systems. The cabin floor will contain a fire-resistant barrier to any fire started in the 600-volt propulsion equipment in the chassis. A minimum of electrical equipment will be located in the cabin, and it will be limited to low-voltage components.
- Smoke and temperature detectors in the cabin and the electrical compartments will notify Central Control automatically and direct the vehicle to the next station. In general, the next station will be reached in less than a minute and offers the safest egress for passengers, often before they are aware of a fire. People on the station platform will be warned of the approaching vehicle and the vehicle will move out of the station as soon as the passengers egress. Cabin ventilation will be provided.

2.1.2 Stations Attached to or within Buildings

Issue: NFPA-130 has required that stations be separated from buildings by a fire-hardened barrier with a three-hour fire rating.
Recommendation: The three-hour NFPA-130 standard should not be applied. This requirement is too conservative, precludes creative integration of stations with other building facilities and increases costs unnecessarily.

2.2 Passenger Restraints

The perceived similarity between the passenger compartments of PRT vehicles and automobiles suggests that laws governing seat belts and infant/toddler seats may apply. Padded interior surfaces and shock absorbing bumpers should be provided and should offer reasonable protection for adults and older children. Seat belts may also be used if desired but it is best to have the safety devices out of sight. Initial decisions may be changed once safety is demonstrated through long-term operation.
It is important to note that the similarity between PRT and automobiles does not extend beyond the passenger compartment. Unlike the automobile, head-on collisions and roll-overs are not possible in PRT systems. Also, the maximum normal operating speed for the initial deployment of the PRT system is well below that of automobiles on interstate highways. Finally, and most importantly, the greatest cause of accidents in both automobiles and conventional public transportation systems – human error – is eliminated in PRT through automation.

2.2.1 Seat Belts

Issue: Should seat belts be provided?
Recommendation: The PRT vehicles can be equipped with retractable seat belts, but if constraints are still desirable once the extremely low probability of a sudden stop is verified, a better alternative is an airbag that would cover the windshield. While the probability of a collision will be extremely small, seat belts provide an extra margin of safety, both actual and perceived, especially for

those passengers who are uncomfortable traveling without them; however, too few people will actually use them. Seat belts may be added at any time with minimal effort and at low cost.

2.2.2 Infant Seat

Issue: Should an infant seat be provided?

Recommendation: Infant seats may be installed in the form of a fold-down seat in the dashboard. This design is convenient for passengers and should not increase boarding time significantly. Fold-down seats can be added to the vehicle if desired.

2.2.3 Toddler Seat

Issue: Should a toddler seat be provided?

Recommendation: Toddler seats may be incorporated in a similar manner to the infant seats and can be added to the vehicle if desired.

2.3 "Brick-Wall" Stopping

Issue: The "Brick-wall" stopping criteria is a standard required by the 1911 Railway Safety Act to set the minimum allowable distance or time headway between trains. If vehicles are moving along a guideway at line speed under the “brick-wall stop” rule, the distance between each pair of adjacent vehicles must be such that if the leading vehicle comes to a stop instantaneously, the following vehicle has sufficient distance to stop before hitting the stopped vehicle without exceeding the emergency jerk and acceleration comfort limits. The "brick-wall" or instantaneous stopping criteria is conservative because, in a carefully designed PRT system, the probability of an instantaneous stop is negligible.

The minimum allowable headway is important because it determines line capacity. For example, a system that operates at one-second minimum headway has five times the line capacity of a system that operates at five-second minimum headway. Close headway operation (less than two seconds) need not be required in the first public PRT systems; however, it will be required as the PRT systems are expanded into larger networks.

A minimum-headway policy decision will be required if headways are to be reduced below approximately two seconds. With today’s technology, a PRT system can be designed to operate with headways below one-half of a second, effectively providing ten times the capacity of a five-second system. (Such short-headway operation was demonstrated in the 1990s by the National Automated Highway Consortium.) The safety record of the PRT system during safety testing will provide an appropriate basis upon which headway policy can be established.

Recommendation: The first PRT system should be designed to be capable of operating at half-second headway, but operation with passengers below two-second headway must be delayed until certified to be safe. The criteria for safety should be based on the number of incidents that could compromise safety per billion vehicle-miles of operation. This number must be less than one.

2.4 Station-Floor to Vehicle-Floor Interface

Recommendation: The station floor shall be level with the vehicle floor within 6 mm. The edge of the station floor shall be no more than 12 mm from the edge of the vehicle floor.

2.5 Walking on Guideway

Issue: People walking along the top of the guideway present a danger to themselves, vehicle passengers, and people beneath the guideway.

Recommendations: There are several options available to deter people from walking on the guideway; however, none of them positively prevent people from doing so. A list of options follows:

- Build a slope on the top of the guideway covers to make walking and snow accumulation difficult.
- Provide a barrier between the station platform and vehicles with doors the width of the vehicle door that only opens when a vehicle is in place (as with an elevator).
- Post notices indicating the dangers associated with walking on the guideway, and institute a large fine for doing so.
- Provide infrared sensors at the points where the vehicles enter and leave the station that trigger an alarm if a person passes but not if a vehicle passes.

Recommendation: Waist-high walls should be placed at the edge of the station platform, with doors the width of the vehicle door only at the positions adjacent to the stopped vehicle doors, with a control that permits the station door to open only when a vehicle is present. Proximity detectors should be provided at the ends of the station platform to detect someone trying to walk on the guideway.

2.6 Surveillance of Unattended Stations

Issue: Unattended stations could be used by criminals as sites for assaulting or robbing passengers.

Recommendation: A closed-circuit television (CCTV) surveillance system should be installed in each station. Cameras mounted in the stations can be connected to monitors at Central Control. Station platforms should be unobstructed to provide a clear view to the cameras, and the station design should eliminate potential hiding places. Other components and characteristics recommended of the CCTV system follow:

- CCTV coverage of all parts of the station should be provided, including stairwells, elevator doors, ticketing areas and other passenger facilities such as change machines and public telephones.
- Motion sensors will alert Central Control to the presence of more than one person in the station during off-peak or late-night hours. If a motion sensor is triggered, the appropriate camera view will be brought up on one of the Central Control monitors and a bell will ring. (Since there will be many fewer monitor screens than cameras, normal operation would consist of a rotation of

camera views on Central Control monitors.)

- Emergency call buttons should be located in the stations for use by passengers.
- Given an alarm or the detection of a suspicious person, Central Control may dispatch police or security personal to the station and make announcements through the station intercom system.
- Notices in the stations should inform passengers of the security system and associated procedures. The obvious presence of the CCTV cameras and the likelihood of being apprehended will discourage individuals from robbing or assaulting passengers.

Recommendation: All station areas should be monitored by CCTV. There should be emergency call buttons.

2.7 Unwanted Person Entering a Vehicle with a Passenger

Issue: After a passenger enters the vehicle but just before the door closes, a person intent on robbery or assault might enter the vehicle. The passenger would then be trapped in the vehicle with the person for the duration of the trip. Such a problem can also occur with ordinary automobiles.

Recommendation: If a passenger calls for help from the vehicle through either a silent alarm located in the vehicle cabin or the intercom system, police can be directed to the destination station or other station (including the maintenance and control facility) to which the vehicle could be redirected. The unauthorized passenger is then readily apprehended. Notices posted in the stations would inform passengers of these security procedures, and the near certainty of being apprehended would discourage individuals from accosting passengers in vehicles.

Recommendation: In addition to an emergency intercom call button in each vehicle, there should be a silent alarm that annunciates in Central Control. The silent alarm might be activated by a colored, touch-sensitive strip along the windows, but the problem of a child activating it must be taken into account.

2.8 Emergency Door Activation

Issue: In certain situations, such as the cabin filling with smoke or the vehicle loosing electrical power, there is a need to open the door manually.

Recommendation: The door should have a manual over-ride which is readily accessible to fire/life-safety personnel outside the vehicle. Passengers should also have access to a manual over-ride subject to the following limitations:

- The door should remain latched if the vehicle is not in a station.
- The latch should not be readily accessible. For example, it could be behind a breakable access panel or require a complex set of motions to activate.
- In the event that the cabin fills with smoke when the vehicle is not in the station, means of venting must be provided; however, the doors may not be opened. The smoke detector should cause the vehicle to stop in the nearest station and then cause the door to open. This action will generally occur in less than 30 seconds – too little time for smoke to cause serious injury.

2.9 Guideway Support-Pole Protection

Issue: Guideway support poles located adjacent to highways may be struck by automobiles or trucks moving at high speeds. Measures must be taken to minimize the negative consequences of this event. The post could be designed to break away from the guideway upon impact or the base of the post could be designed to resist the impact.

Recommendation: If a guideway support post is located where it may be impacted by a high-speed vehicle, either a highway barrier should be placed around the post to deflect vehicles away or an enlarged bumper-height concrete base pad should be placed at the base of the pole. It is not practical to use a breakaway post in this application. The pole required to support the guideway is far too robust to break away on impact.

2.10 Maximum Station Speed

Recommendation: The maximum speed of a vehicle in the station area should be 8 meters per sec.

3 Access to the Disabled

The PRT system must be designed to conform to the Americans with Disabilities Act of 1990. The issue is the level of disability that must be accommodated.

3.1 Wheelchairs

Issue 1: Quadriplegics use voice-activated wheel chairs. Should the systems (elevator, ticketing, door closure, etc.) also be voice-activated in order accommodate unaccompanied quadriplegics?

Recommendation: Voice-activated systems are not well suited for public transportation systems because of the relatively large amount of random voice inputs in the station area. The design of reliable voice-activated systems would be difficult and costly, and it may not be possible to completely preclude accidental activation of the various systems. Accidental activations could interfere with system operations. Any decision should be made with awareness for these potential problems. It should not be necessary to accommodate unaccompanied quadriplegics. The cabin should be designed so that with seats folded up a wheelchair can enter and face forward following which a seat can fold down for an attendant.

Issue 2: Means of restraining a wheelchair are used in some types of vehicles (e.g. vans). Should PRT vehicles also provide wheelchair restraints?

Recommendation: The wheelchair's own brakes are sufficient in view of the relatively small forces acting on the wheelchair during normal system operation. In a collision, the confined space in the cabin will limit wheelchair motion. Therefore, it should not be necessary to provide wheelchair restraints.

3.2 Visually Impaired

Issue: Blind and visually-impaired people must be able to use the PRT system as easily as any other public transportation system.

Recommendation: Braille plaques and pre-recorded or voice-synthesized messages should be used to provide guidance for the visually impaired. Stations should use similar layouts to maximize consistency, and the platform surface should be textured in the vehicle boarding area. As there are no intermediate stops, it is clear when to exit the vehicle. Also, some degree of audio communication is anticipated.

3.3 Hearing Impaired

Issue: Hearing-impaired and deaf people must be able to use the PRT system as easily as any other public transportation system.

Recommendation: Signs and visual displays should be used as required to provide guidance for the hearing impaired. The ticketing device and the vehicle should include visual display equipment (LCD or video) that may be used for both routine and emergency messages.

3.4 Illiterate & Foreign Passengers

Issue: Illiterate and foreign-speaking passengers should be able to use the PRT system as easily as any other public transportation system.

Recommendation: Visual ticketing and boarding-process information should use graphics and international symbols to the greatest extent possible. In addition, visual display devices for ticketing and in the vehicle could permit the user to select one of several available languages. Prerecorded or voice-synthesized messages could also be available in several user-selected languages.

3.5 The Elderly Person using a Walker

The vehicle entry must be designed to make it easy for an elderly person to walk straight into the vehicle and sit down without having to worry about bumping his or her head.

3. Passenger Comfort and Convenience

4.1 Unacceptable Vehicles

Issue: The activities of a passenger may leave a vehicle in a condition that is unacceptable to subsequent passengers.

Recommendation: The stanchion located at the vehicle berth (for establishing the vehicle destination) should have a "vehicle reject" button. If this button is pressed, one of the following actions may be initiated by Central Control:

- The first time a vehicle is rejected, it should be sent empty to the next open station. If the vehicle is again rejected, it should be sent to the maintenance facility.
- If a passenger rejects two vehicles, Central Control would communicate via an intercom with the passenger to determine the cause(s) for the rejections. Verbal communication is desirable to preclude pranksters from rejecting numerous vehicles for amusement. The station's CCTV cameras may also be used to provide Central Control with additional information.

4.2 Windshield Wipers

Issue: Rain and snow on the vehicle windshield and interior fogging may obstruct the passenger's view.

Recommendation. Hot-air defrosters should be provided to clear condensation and melt snow and ice. A hydrophobic coating could be applied to the windshield's exterior surface to aid water run-off. The use of windshield wipers is not recommended because they require a hard windshield material such as glass. A glass windshield is heavy and would also be expensive given its large size and highly-contoured shape. Glass windshields are also less safe in a collision than the more flexible and fracture-resistant plastic windshields. The windshield wiper arm, blade, motor, and linkage would be high-maintenance items and would add to vehicle cost.

4.3 Station Access

Recommendation: Each station not connected to the second floor of a building should be equipped with a stairway and an elevator.

4.4 Access to Useful Information

Recommendation: Each vehicle should be equipped with a television screen that can be tuned to system information, marketing information, travel information, or entertainment.

4.5 Wave-Offs

Issue: Since people arrive at stations and board at random intervals, the arrival time of vehicles at any station is also random. Each station must be designed to accommodate a certain maximum flow, but account must be taken that that flow may for a short time be exceeded. If there is no room in a station when a vehicle arrives, it must be commanded to bypass the station, i..e., "waved off", whereupon it circles around on the shortest path and tries again to enter the station. Experience with simulations has shown that, because of statistical variations in the arrival rate, an n-berth station must have at least n + 3 waiting positions to keep wave-offs to an acceptable level.

Recommendation: Determine by simulation the number of waiting positions needed to keep the number of wave-offs to any station to be no more than one occurrence in 1000 arrivals and give a prize to the passengers waved off.

4. Operational Convenience

5.1 Disabled Vehicle

Issue: If a vehicle becomes disabled, the vehicle can almost always be pushed to the next station by the vehicle behind, where the passengers can be discharged. The passengers of a pushing vehicle would also be discharged. These passengers must be re-booked to their original destination.

Recommendation: Two options are as follows:

- Once passengers have been discharged from disabled and pushing vehicles, they would be instructed via the stanchion intercoms to wait at their berths for the next vehicle. The next two vehicles entering the station could be automatically programmed to the passengers' original destination.
- The passengers could go to the ticketing machine and be reissued tickets (with voice communication to Central Control).

5.2 Communication

Issue: Communication with the passengers is required.

Recommendation: The preferred approach is threefold:

- Central Control can issue announcements to the following optional locations:
  - Whole system
  - All stations
  - All vehicles
  - A single zone
  - A single vehicle

- Two-way audio communication between Central Control and a single vehicle, a ticketing machine and a station berth stanchion should be provided. Passengers should be able to initiate communication by pressing an intercom button.

- Visual displays in the vehicles and ticketing machines can present information as required to assist passengers with ticketing and boarding procedures.

6. Ticketing

6.1 Fare Policy

Many aspects of fare policy are a function of the ticketing software and can be changed with minimal inconvenience. These are denoted by an asterisk in the following list.

6.1.1 Number of Passengers

Recommendation: The cost of a trip should be per vehicle, not per passenger.

6.1.2 Distance*

Recommendation: The price of a trip should be based on the distance between origin and destination.

6.1.3 Time of Day*

Recommendation: The ticketing system should be designed to provide a different price structure as a function of the time of day or day of the week.

6.2 Ticketing Process

Ticketing may be done in a number of ways. Various approaches can be evaluated on a system-wide basis, including the use of magnetically encoded cards and chip-based smart cards.

7. Weather

The design of the system will accommodate a wide range of weather conditions. The structural design, power requirements, and design aspects to address issues related to ice and snow depend on the range of weather conditions associated with normal, degraded and shut-down conditions.

7.1 Wind

7.1.1 System Operation

Issue: Performance requirements such as the operating speed, maximum continuous grade and wind loads dictate the size of the vehicle propulsion units, power supply equipment and numerous other system components.

Recommendation: Design for no degradation in performance in sustained winds up to 30 mph, degraded service for sustained wind speeds between 30 and 60 mph and no service in winds above 60 mph. Between 30 and 60 mph, the sum of the wind speed and the vehicle speed should be no more than 60 mph.

7.1.2 Maximum Wind

Issue: Certain aspects of the structural design of the vehicle, guideway and support posts are governed by the maximum wind.

Recommendation: With no vehicles out on the guideway away from stations or storage, design for 150 mph (67 m/s) winds with no damage to the vehicle, guideway or appurtenant equipment.

7.1.3 Sharp-Edged Gust

Issue: In downtown settings there may be strong winds blowing down one set of streets with no wind in the cross streets.

Recommendation: Design the car suspension and control so that a vehicle suddenly encountering a gust up to 50 mph (22 m/s) will not be uncomfortable for the passengers.

7.2 Ice and Snow

7.2.1 Freezing Precipitation

Recommendation: The PRT system should be designed to operate throughout the range of local weather conditions, except for winds in excess of 60 mph (27 m/s). The guideway is enclosed except for a 100-mm-wide slot on the top (wider at merge and diverge points), and a 200-mm-wide slot at the bottom to permit precipitation or debris to exit. The power rails within the guideway have additional protection to preclude frost formation resulting from radiation to the night sky. Vehicles will have hot-air defrosters to keep the windshield clear. Propulsion and braking is through linear induction motors so water or light ice on the running rails will not affect acceleration or braking rates.

7.2.2 Snow

Issue: Snow will accumulate on and in the guideway and on the vehicles.

Recommendation: The preferred approach to snow removal is a plow on some of the vehicles which directs snow off the main support rails down through the gap at the bottom of the guideway. A complement of vehicles would be run continuously during storms to prevent significant accumulation. The maintenance facility will be designed to accommodate snow-covered vehicles and the hot-air defroster will keep the windshield clear.

8. Loading

Recommendations:

- The vehicle should be designed to carry a maximum load of 900 lb (410 km).
- The guideway should be designed for fully loaded vehicles nose to tail with a 60-mph (27 m/s) crosswind.
- The unloaded guideway should be designed for a 150-mph (67 m/s) crosswind.

9. Performance

Recommendation: The standard system shall be designed for a maximum speed of 35 mph (16 m/s) and for a maximum steady grade of 10%, and with dependability[83] in excess of 99.99%. Use design features that permit the system to be expanded indefinitely.

10. Physical Characteristics

- The normal span should be 90 ft (27 m/s).
- The normal elevation to the bottom of the guideway should be 16 ft (4.9 m).
- The interior width, height, and leg room in the cabin will be given in a detailed cabin specification.

11. Standards

In the Northeastern Illinois RTA PRT Design Study, the team assembled a list of over 80 specifications of various kinds that will need to be reviewed. The most important of these relate to safety, human comfort, and electromagnetic interference. We have the list of these specifications and they will be incorporated into the detailed component specifications.

Recommendation: Wherever practical all dimensions shall be measured in metric units.

[83] J. E. Anderson, "Dependability as a Measure of On-Time Performance of Personal Rapid Transit Systems."

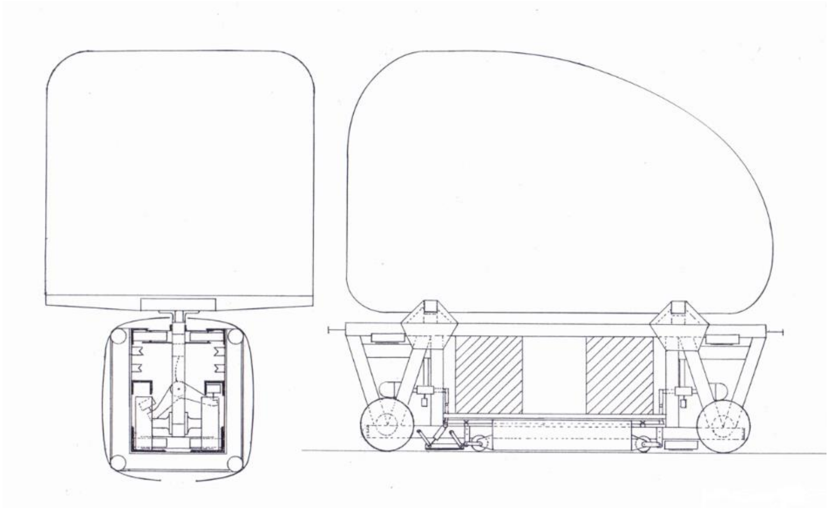

Figure 3-1. A Sketch of the ITNS Vehicle.

12. Cabin Loading

12.1 Payload: The cabin is designed to accommodate a maximum payload weight of 800 lb.

12.2 Wind: The cabin shall be designed to a maximum side wind of 60 mph.

12.3 Passenger loads: The cabin shall withstand the load of a 300-lb passenger pushing on the interior components of the cabin. The cabin floor at any point shall withstand a 250-lb concentrated load bearing on a half-inch by half-inch area.

12.2 Exterior Dimensions

Subject to accepted reasons for change, the expected exterior dimensions of the cabin are: length 104 in, height 65 in, and width 60 in. The walls shall be as thin as practical both from the view of structural strength and heat transfer.

12.3. Accommodations

The cabin is to be designed to accommodate either a person in a standard-sized wheelchair entering from the side and turning to face forward with an attendant, three adults and two children, a person with a bicycle, two people with large suitcases, or two persons with a baby carriage.

12.4 The Floor

The interior floor of the vehicle shall be at the same level ($\pm$ 0.5 in) as the station floor. It shall be covered with a durable commercial grade material that will be easy to clean. The edge of the floor at the door shall be within 0.5 in of the edge of the station floor.

12.5 Seats

There shall be a forward-facing bench seat at the rear interior of the vehicle divided into three equal sections that may be folded up individually, filling the interior width of the cabin with the backs extending to the interior top of the cabin and tilted backwards by 6º (six degrees). The back of the seat back at the seat height shall be forward from the rear wall of the cabin 10 in to permit space for the equipment described in Paragraph 3.12. The top of each seat shall be 17 in from the interior floor and shall fold up to ease access of a wheelchair or other large object. These seats will have a spring constant of about 200 lb/in. There shall be two backward-facing fold-up seats at the front of the cabin designed to accommodate small people. These seats shall be spring restrained into the folded-up position when not occupied. The seat material will be durable, vandal proof, and fire resistant.

12.6 Door

One possible door configuration is a single inverted U-shaped automatically powered door 36 inches wide that would open by sliding back over the rear shell of the cabin and thus opens on both sides of the cabin as one unit. Other door configurations can be considered. The door shall open or close within 2.5 sec and shall be equipped with sensors that prevent closure on any object. The door operating mechanism shall be placed under the inside floor of the cabin. To ease entry of a wheelchair, the rear edge of the door shall be in line with the front edge of the bottom of the folded-up seat. The door-operating mechanism shall be designed for a life of 160,000 operations (open and close) and with no more than one failure in 50,000 operations. The seal of the door shall be designed to prevent entry of noticeable amounts of water in a rainstorm of 2 in/hr.

12.7 Windows

The windows, front, back and sides, are to be of a plastic such as LEXAN and should be large enough to permit a panoramic view as the vehicle moves along the guideway, but not so large that they would compromise the structural integrity of the cabin. The material of the windows and the entire exterior shall withstand daily brushless washing and shall be coated to minimize entry of solar infrared energy.

12.8 Styling

Since the cabin is the one element of a PRT system seen most and is the signature of the entire system, styling is critically important. The design should, as one sculptor said, ". . . bring out the kid in you" while portraying dignity to the wealthy purchaser of the system.

12.9 Aerodynamics

Even at speeds as low as 25 mph air drag is the largest energy consumer. Also, the power to overcome air drag increases as the cube of speed. There is a substantial amount of information from wind tunnel data on shapes that minimize air drag. Since the system will operate in crosswinds up to about 60 mph, side drag is important. As side drag increases, it increases forward drag. The corners connecting the side to the top of the vehicle should be rounded with a radius of at least 10 in. For these reasons, air drag is an important consideration in the design.

12.10 Structural Design

If a U-shaped door is used, the cabin shell is composed of three parts, the front part, the back part, and the door. These parts shall be manufactured from strong, light-weight composite material with metal reinforcements as needed. When the door is open, it is possible for a strong man to push against the top of the front or back part of the cabin in an attempt to see if he can break it. Therefore, such a loading must be resisted well below the yield point of the material.

12.11 HVAC

A heating, ventilating, and air conditioning system shall be designed into the cabin, with the large components, such as the compressor and the drive motor, placed in the compartment behind the seat. The designer can assume that the vehicles will be stored in the shade and that the stations have a roof over the vehicles and waiting passengers. Moreover, in a PRT system, while the vehicles will be stored power off, the HVAC designer can assume that at least three minutes will pass from the time HVAC is turned on until a passenger enters, which is a more relaxed requirement than necessary in automobile design. The HVAC designer shall work with the structural designer to specify insulation in the walls that, as close as practical, will minimize the sum of the annualize cost of the wall plus the annual cost of heating or cooling energy. The ventilation system shall provide the air exchange recommended by the Society of Heating and Ventilating Engineers. The temperature in the cabin shall be controlled to the median comfort level assuming people are clothed appropriately to the outside weather.

12.12 Equipment Compartment

The computers that operate all functions will be located in a compartment behind the main seat and there shall be an access door at the rear of the vehicle that can be opened by qualified personnel. The major AC components shall share the same compartment. The seat back facing the equipment compartment as well as all other components of the cabin shall be non-combustible.

12.13 Passenger and Environmental Controls

There shall be three buttons conveniently located in the vehicle that can be actuated by the passengers: a “Go” button, a “Stop” button, and an “Emergency” button. The “Go” button causes the door to close and signals to the computer that the vehicle is ready to leave the station. The “Stop” button causes the vehicle to stop at the next station and then the door to open after it is stopped. The “Emergency” button alerts a human operator located in a control station to inquire through a communications system as to the problem. If the rider indicates sickness, the operator can change the vehicle’s destination to that of the nearest hospital. If the rider is in danger, the operator can change the vehicle’s destination to that of the nearest police station. If the rider feels the temperature in the vehicle is too high or too low, the operator can adjust it, etc.

12.14 Communications

There will be a two-way communication system in each vehicle to connect an individual vehicle or a group of vehicles to the system’s control room. This system will be separate from the communication system that controls the speed and position of the vehicles, which is described separately. There will be a television screen in the front center of the vehicle near the floor. It must be possible for the passengers to turn the set on or off, and if on to switch to site-specific advertising, travel information about the passing surroundings, news, or entertainment.

12.15 Lighting

The cabin will be equipped with reading lights that can be switch on or off by the passengers. Exterior lighting is optional but low lumen so-called parking lights and red tail lights are recommended.

12.16 Fire Prevention

Fire prevention is of primary importance, which is the reason only a low voltage will be permitted in the cabin. All materials in the cabin shall be certified non-toxic and non-combustible. The cabin shall contain a smoke detector that shall cause the vehicle to stop at the next station and open the door automatically upon detecting smoke. Temperature sensors shall be placed at strategic locations in the wiring and in the electrical components to command the current to be shut off and a warning sent to central control if the temperature exceeds a preset value.

12.17 Lightning Protection

The cabin designer shall consult with the wayside power team to devise a suitable means for protecting the cabin from a lightning stroke.

12.18 Environmental Specifications

The cabin is to be designed to be operable in the expected range of exterior conditions; temperatures from -45^{o} C to +50^{o} C, salt spray, sand storms, and daily brushless cleaning.

It is expected that the cabin will be replaced once every ten years.

Minimization of the effects of vandalism must be considered in every phase of the design.

12.19 Cleaning

The cabin designer shall take into account daily external and internal cleaning of the cabin, and shall select materials and designs of the interior and exterior of the cabin for easy cleaning. Since the cleaning means is a part of the system, methods that will minimize damage can be assumed.

12.20 Cabin Weight

Since the weight and therefore cost of the guideway is proportional to the gross weight of the vehicle, weight minimization of the cabin is important, provided that the cost of weight reduction is not more than about $30 per lb.

12.21 Standards

The cabin shall be designed to comply with the requirements of USO 9000 and NFSA 130.


KLM
112
TAXI
2000

1.4.4. Calculation of Performance and Fleet Size in Transit Systems

Journal of Advanced Transportation, 16:3(1982)231-252.

Abstract

The paper provides a consistent, analytic approach to the calculation, from the demand matrix, of parameters needed to analyze the performance and cost of transit systems. It covers all types of transit systems, including the new automated systems. The basic analysis applies to loop systems, which include those collapsed into line haul systems. We then extend it to apply to all types of network systems in which vehicles may transfer from one line or loop to another. The novel features of the paper lie in 1) the layout of the computations in a straightforward, ordered way, 2) the computation of vehicle dwell times in stations from loading rates, 3) the use of the Poisson distribution to estimate and show how to shorten the passenger wait time in off-line stations, and 4) the simplicity of the means of extending the results to network systems.

Contents

1. Introduction

Economic analysis of transit systems requires calculation of patronage and direct costs, which, in turn requires calculation of travel times, station wait times, fleet size, and vehicle-miles per day. Representing system performance requires that one calculate additional parameters. The purpose of this paper is to derive and present for easy reference equations needed for the above calculations. The methodology presented builds on the work of Anderson (1978), but as a result of additional stages of application to practical problems, extends and simplifies it. The development of the methodology was the result of interest in understanding the characteristics of alternative types of automated guideway transit systems, but it is also applicable to all types of transport systems. Although all detailed analyses of transit systems have required similar calculations (Manheim (1979)), they have usually been programmed on computers in ways that mask their general applicability. Reducing required performance calculations to simple analytical expressions makes application much more rapid, clearer and easier to teach, while simplifying system comparisons—all of which advances the art of analysis of transit systems.

The inputs to the calculations are the demand matrix and the path lengths. Computation of demand requires knowledge of travel times and wait times; thus, the process is iterative: we must first estimate travel and wait times based on past experience, then calculate and use patronage analysis to refine the travel and wait times, etc. The operating headways computed from line flows must, of course, be greater than the minimum safe headway. The paper summarizes major results of the theory of minimum safe headway, which is treated fully in the literature (Anderson (1978), Irving (1978), McGean (1976)).

Calculation of trip times and minimum safe station headway requires the station dwell time (the time the vehicle dwells in a station). Usually the station dwell time is assumed as a fixed value; however, it depends on station demand and headway. Therefore, I have derived formulas for station dwell based on a more fundamental factor: loading rate per vehicle.

In most systems, the station wait time (the average time a person waits for a vehicle) is simply half the station headway; however, in a true personal rapid transit system, it is possible to reduce the station wait time substantially by arranging for one or more empty vehicles than needed to meet average rush-period demand. Indeed, the way such a system would be operated, each station would store as many empty vehicles as possible throughout the day. Only at the busiest stations, where the station headway is very short, would there be no extra vehicles stored during the rush period. I have estimated the station wait time on the assumption that passengers arrive randomly at a fixed frequency, that is, they are Poisson distributed.

The parameters derived and presented are the following:

Station flows
Total system demand
Line flows and weighted average line flow
Passenger-miles per hour
Average trip length
Operating headway
Station dwell time
Minimum safe headways
Round trip time
Fleet Size
Average trip speed
Average trip time
Average number of stops per trip
Vehicle miles per hour, per day
Average peak-hour and daily load factors
Station wait times
Travel-time matrix

The basic transit-system unit is a two-way line or collapsed loop. Therefore, I have derived the parameters for a general loop system (which may be collapsed or not collapsed) in which the stations may be on line or off line, the service may be scheduled or on demand, and the vehicles may be designed to accommodate a group or a single party traveling together. When the formulas differ, I make distinctions. Extension of the formulas to use in network systems is the final step in the analysis. The networks considered are of two types: 1) those requiring manual transfers from line to line, and 2) those in which the vehicles transfer from line to line to permit direct travel from origin to destination.

2. The Demand and Path-Length Matrices

Let the stations or stops of a transit system be numbered in an ordered way, and let n be the number of stations. We can represent demand for service between all station pairs as a matrix:

$$D_{ij} = \begin{matrix} D_{11} & D_{12} & D_{13} & \dots & D_{1n} \\ D_{21} & D_{22} & D_{23} & \dots & D_{2n} \\ D_{31} & D_{32} & D_{33} & \dots & D_{3n} \\ . & . & . & \dots & . \\ D_{n1} & D_{n2} & D_{n3} & \dots & D_{nn} \end{matrix} \tag{1}$$

The symbol D_{ij} represents the number of people per unit of time traveling from station i to station j, that is, let us adopt the convention that the first index represents an origin station, and the second index a destination station. Usually, the units of D_{ij} are people per hour, and the main quantity of interest is D_{ij} averaged over the busiest period of the day, for those values determine the capacity requirements of the system.

Similarly, let l_{ij} represent the distance from station i to station j. If we number the stations consecutively,

$$l_{ij} = \sum_{k=}^{j-1} l_{k.k+1} \tag{2}$$

in which $n+1 \to 1$. If the system is a single loop, we can express the length of the loop as

$$l_O = \sum_{k=1}^{n} l_{k,k+1} \tag{3}$$

For simplicity of notation, we will, without ambiguity, let the length of the link from station k to station $k+1$ be represented by

$$l_k \equiv l_{k,k+1} \tag{4}$$

3. Passenger Flows

We can represent the total number of people per hour originating travel at station i as

$$D_{i\sigma} = \sum_{j=1}^{n} D_{ij} \tag{5}$$

where j is summed over all destination stations, and D_{ii} represents the demand for round trips. Similarly, the total number of people per hour terminating travel at station j is

$$D_{\sigma j} = \sum_{i=1}^{n} D_{ij} \tag{6}$$

The quantity

$$D = \sum_{i=1}^{n} D_{i\sigma} = \sum_{j=1}^{n} D_{\sigma j} \tag{7}$$

represents the total system demand in the hour for which we have found the D_{ij}. The values of D_{ij} of interest are for the peak-flow period, such as the peak hour or the peak 15 minutes. The peak period used in system design determines rush-period waiting times—the shorter the period, the shorter the wait times but the larger the fleet size.

We denote the flow on link $i, i+1$ in people per hour by F_i. F_i is the sum of all the D_{ij} for which the trip passes along the link $i, i+1$. Once we find it in one link, we may find it in the next link from the equation

$$F_{i+1} = F_i + D_{i+1,\sigma} - D_{\sigma,i+1} \tag{8}$$

In a line-haul system, the computation of the F_i is begun by noting, if the end station is numbered 1, that $F_1 = D_{1\sigma}$. We can make the following calculations from knowledge of only the $D_{i\sigma}$, $D_{\sigma j}$ and F_i in one link—the D_{ij} individually are no longer needed. Thus, in making these calculations on the basis of travel counts, it is necessary to count only the total flows into and out of each station, and, in a non-collapsed loop, the flow in one link.

The number of passenger-miles of travel per hour is

$$PMPH = \sum_{i=1}^{n}\sum_{j=1}^{n} D_{ij} l_{ij} = \sum_{i=1}^{n} F_i l_i \tag{9}$$

where, once we have found the F_i, it is clearly preferable to use the single sum to find *PMPH*. The weighted average passenger flow is

$$F_{av} = \frac{1}{l_O}\sum_{i=1}^{n} F_i l_i = \frac{PMPH}{l_O} \tag{10}$$

where l_O is the round-trip length of the loop.

4. Average Trip Length

From equation (9), the demand-weighted average trip length is

$$\langle L_t \rangle = \frac{1}{D}\sum_{i=1}^{n}\sum_{j=1}^{n} D_{ij} l_{ij} = \frac{PMPH}{D} \tag{11}$$

Using equation (10),

$$\langle L_t \rangle = \frac{F_{av}}{D} l_O \tag{12}$$

Equation (12) has this simple physical interpretation: consider a loop system. If, in a fictitious case, there were only one station and the flow of people enters the station, travels around the loop, and egresses at the same station, $\langle L_t \rangle = l_O$, so $F_{av} = D$, i.e., the total system flow would be the same as the total line flow. If F_{av} were $(1/2)D$, the situation would correspond to the case of a two-station loop system, in which $\langle L_t \rangle = (1/2) l_O$.

5. Operating Headway

The headway between vehicles, T, is the time measured at a fixed point between passages of a given point (e.g. the nose) on the vehicles. On a given link i, $F_i T_i$ is the number of people per vehicle averaged over the time period for which F_i is averaged. In a loop system, continuity requires that T_i averaged over the loop time be the same in each link of the loop.

Let C_v be the design capacity in seated and standing passengers of each connected unit, whether it be a single vehicle or a train. Let lf_m be the average load factor (the ratio of people per connected unit to C_v) in the link for which F_i is maximum. Denoting the maximum link flow by F_m, the operating headway is

$$T = \frac{C_v lf_m}{F_m} \tag{13}$$

Choose the design value of lf_m based on behavior of people unloading and loading at stations and the excess capacity for surge loads to be designed into the system. The fleet size will be inversely proportional to the system-design value of lf_m. Then compare the value of T computed from equation (13) with the minimum value of T permissible from considerations of safety. If $T < T_{\min}$ then we must increase C_v until $T \geq T_{\min}$. C_v increases either by using larger vehicles or by training vehicles of a given size. If we train vehicles, we must understand C_v in equation (13) to be the train capacity. Later, we adjust T to accommodate an integral number of operating vehicles and then recompute lf_m from equation (13).

In on-line-station systems, station headway and line headway are the same; however, in off-line-station systems, the station headway at station i, T_{s_i}, depends on the maximum of $D_{i\sigma}$ and $D_{\sigma i}$, denoted $\max\left(D_{i\sigma}, D_{\sigma i}\right)$. If the average load factor of *occupied* vehicles passing through station i is lf_i, in analogy with equation (13),

$$T_{s_i} = \frac{C_v lf_i}{\max\left(D_{i\sigma}, D_{\sigma i}\right)} \tag{14}$$

If the system is a personal rapid transit system as opposed to a group rapid transit system, we can assume lf_i to be a constant equal to lf_m.

6. Station Dwell Time

Let LR_v be the loading or unloading rate per vehicle or train in people per unit of time. Obviously, LR_v depends on the width and number of doors. If t_{D_i} is the station-dwell time at station i, that is, the time each vehicle or train is stopped at station i, $LR_v t_{D_i}$ is the total number of people who can unload and load during the time the vehicle is standing in the station. The number of people who must load onto and unload from each vehicle or train at station i is proportional to T_{s_i} $(=T$ in on-line-station systems) and depends on whether the unloading and loading occurs in sequence or simultaneously. If the process occurs in sequence, i.e., if people first unload and then load through the same doors,

$$LR_v t_{D_i} = \beta\left(D_{i\sigma} + D_{\sigma i}\right)T_{s_i} \tag{15}$$

If loading occurs simultaneously with unloading, as would be the case if people load through one door and unload through another (e.g. past the driver at the front of the vehicle and out through middle doors),

$$LR_v t_{D_i} = \beta \max\left(D_{i\sigma}, D_{\sigma i}\right)T_{s_i} \tag{16}$$

In both of these equations β is a dimensionless factor greater than or equal to one included to account for uneven loading through several doors and for surge loading of more than the average number of people onto a given vehicle or train. Note, in both cases, that LR_V must be large enough so that $t_{D_i} > T_{s_i}$. If we do not satisfy this inequality, we must increase LR_v by adding more vehicles to each train, or by using more or wider doors on each vehicle.

With *on-line-stations*, from equation (13) $T_{s_i} = T$. Thus, for *sequential* unloading and loading

$$t_{D_i} = \beta \frac{\left(D_{i\sigma} + D_{\sigma i}\right)T}{LR_v} \tag{17}$$

and for *simultaneous* unloading and loading

$$t_{D_i} = \beta \frac{\max\left(D_{i\sigma}, D_{\sigma i}\right)T}{LR_v} \tag{18}$$

With off-line stations, sequential unloading and loading will be almost always used because this case almost always applies to automated, single-door vehicles. Thus, substituting equation (14) into equation (15),

$$t_{D_i} = \frac{\beta C_v l f_i}{LR_v} \frac{D_{i\sigma} + D_{\sigma i}}{\max\left(D_{i\sigma}, D_{\sigma i}\right)} \tag{19}$$

7. Minimum Safe Headways

The minimum safe time headway between vehicles or trains stopping each at the same position in a station and then passing through the station is

$$T_{\min} = t_{D_{\max}} + \frac{L}{V_L} + \left(1+\alpha\right)\frac{V_L}{A} \quad if \quad L \geq (1-\alpha)\frac{V_L^2}{A} \tag{20}$$

or

$$T_{\min} = t_{D_{\max}} + 2\left[\frac{L}{\left(1-\alpha\right)A}\right]^{1/2} \quad if \quad L \leq \left(1-\alpha\right)\frac{V_L^2}{A} \tag{21}$$

in which V_L is the line speed, L is the length of the vehicles or trains, A is the normal acceleration and deceleration, and

$$\alpha = k\frac{A}{2A_e} \tag{22}$$

where A_e is the emergency braking rate and k is the safety factor, that is, the ratio of minimum distance between vehicles to the stopping distance of one vehicle. These equations are from Anderson (1978). In a conventional train system, it is common to take $A_e = A$ and $k = 2$, in which case $\alpha = 1$. In this case, equation (20) is applicable. In small-vehicle automated systems in which all passengers are seated, it is possible to take A_e □ $2A$. Then $\alpha < 1$ and usually $L < (1-\alpha)V_L^2 / A$. Always use equation (21) in such an instance.

The end stations of a line-haul rail system are often back-up stations. In this case, Anderson (1978) showed that when a = 1 the minimum safe headway is

$$T_{\min} = t_{D_{\max}} + 2\frac{L + L_{swx}}{V_L} + \left(1+\alpha\right)\frac{V_L}{A} \tag{23}$$

in which case L_{swx} is the track length needed for one incoming train to clear the last outgoing train.

The simplest expression for minimum line headway, i.e., minimum headway along a line away from stations, is

$$T_{\min} = t_c + \frac{L}{V_L} + \frac{V_L}{2}\left(\frac{1}{A_e} - \frac{1}{A_f}\right) \tag{24}$$

in which t_c is the time required to initiate braking at a rate A_e and A_f is the emergency braking rate. Anderson (1978) or McGean (1976) supply more complex equations accounting for velocity differences and jerk; however, equation (24) accounts for the principal effects. The brick-wall stopping criterion is obtained by taking $A_f = \infty$.

There can be only one value of system headway throughout the loop. It is therefore the maximum of the various $T_{\min}$. With a given line speed, equation (23) gives a larger value than equation (20) and determines the system minimum headway. However, if we reduce the speed approaching the end stations, then it is possible to reduce the back-up station $T_{\min}$ to the straight-through station $T_{\min}$ given by equation (20). In on-line-station systems, the values of station $T_{\min}$ are greater than the line $T_{\min}$, given by equation (24). However, in off-line-station systems, by use of multiple berths and batch loading as described by Irving (1978), it is possible to increase station throughput to almost any desired value.

8. Round-Trip Time

The general formula for round-trip time is

$$t_O = \frac{l_O}{V_L} + ns_O\left(\frac{V_L}{A} + \frac{A}{J}\right) + \sum_i t_{D_i} \tag{25}$$

in which ns_O is the number of stops per round trip, $\left(V_L/A + A/J\right)$ is the excess time required for each stop at a comfort level of acceleration A and comfort level of jerk J, and the third term is the sum over the station delays at the stations at which the vehicles or trains stop.

For an *on-line-station system* in which the vehicles stop at all of *n* stations

$$t_O = \frac{l_O}{V_L} + nT_{ex} \tag{26}$$

where

$$T_{ex} = \frac{V_L}{A} + \frac{A}{J} + t_{D_{av}} \tag{27}$$

is the average excess time required to stop at a station with the comfort level of acceleration A, comfort level of jerk J, and average dwell time

$$t_{D_{av}} = \frac{1}{n}\sum_{i=1}^{n} t_{D_i}. \tag{28}$$

For *off-line-station systems* in which all trips are nonstop,

$$ns_O = \frac{l_O}{\langle L_t \rangle} \tag{29}$$

and equation (25) becomes

$$t_O = \frac{l_O}{V_L}\left(1 + \frac{V_L T_{ex}}{\langle L_t \rangle}\right) \tag{30}$$

in which equation (27) gives T_{ex}.

9. Fleet Size

In a loop system, the required number of vehicles in operation in the peak period is

$$N_{op} = \frac{t_O}{T} \tag{31}$$

where we find t_O from the above section and T from equation (13). Since N_{op} is an integer, we must round off the value given by t_O / T to an integer. If at the next integer $T = t_O / N_{op} > \max T_{\min}$, take N_{op} as that integer. If this value produces a line headway less than $\max T_{\min}$, take as N_{op} the value of t_O / T rounded to the next lower integer.

The total fleet size is

$$N = \frac{t_O}{T} + N_s + N_m \tag{32}$$

where N_s is a number of extra vehicles that may be required at some stations of a personal rapid transit system to minimize wait time (for other types of systems $N_s = 0$), and N_m is the maintenance float. If the rush period time is t_{rush}, if the vehicle mean time to failure is $MTBF$, and if the mean time to restore $(MTTR)$ a vehicle into service is less than the time between rush periods,

$$N_m = N_{op}\frac{t_{rush}}{MTBF} \tag{33}$$

9. The Revised Time Headway, Round-Trip Time and Load Factor

In equation (31), T comes from equation (13) based on an estimate of lf_m and then for on-line-station systems we computed t_{D_i} from either equation (17) or equation (18) based on this value of T. Since N_{op} in equation (31) must be an integer, we must modify T and, hence t_O. To do so, consider equation (25). Let $t_O = N_{op}T$ where N_{op} is the integer determined below equation (31) and the correct value of T is to be determined. Then in equation (25), substitute $P = l_O / V_L + ns_O \left(V_L / A + A / J \right)$, a known value, and $Q = (1/T_{old})(\sum_i t_{D_i})_{old}$, the value computed as indicated above. Then equation (25) becomes

$$N_{op}T = P + QT$$

or

$$T = \frac{P}{N_{op} - Q}. \qquad (34)$$

This is the operating headway. The round-trip time is then

$$t_O = N_{op}T \qquad (35)$$

and, from equation (13), the peak-link load factor is

$$lf_m = \frac{F_m T}{C_v}. \qquad (36)$$

In *off-line station systems,* line headway does not affect the t_{D_i}. Therefore, after rounding N_{op} in equation (31), equation (30) still gives t_O. Thus the operating headway is

$$T = \frac{t_O}{N_{op}} \qquad (37)$$

where N_{op} is the integer found from equation (31). Using equation (37) for T, equation (36) gives the peak-link load factor.

10. Average Trip Speed, Trip Time, and Stops per Trip

In a loop system, the average speed is

$$V_{av} = \frac{l_O}{t_O} \tag{38}$$

The average trip time is then

$$t_{av} = \frac{\langle L_t \rangle}{V_{av}} \tag{39}$$

But, in analogy to equation (26), t_{av} is also

$$t_{av} = \frac{\langle L_t \rangle}{V_L} + ns_{av} T_{ex} \tag{40}$$

Hence the average number of stops per trip is

$$ns_{av} = \left(\frac{V_L}{V_{av}} - 1 \right) \frac{\langle L_t \rangle}{V_L T_{ex}} \tag{41}$$

For nonstop trips, $ns_{av} = 1$. That the equations are consistent with this result may be seen by substituting t_O from equation (30) into equation (38) and then the resulting value of V_L / V_{av} into equation (41).

11. Vehicle Miles per Hour and per Day

In a loop system, the number of vehicle-miles in the peak hour is

$$VMPH = N_{op} \frac{l_O}{t_O} = \frac{l_O}{T} = \frac{l_O F_m}{C_v l f_m} \tag{42}$$

In a *demand-responsive system*, the number of vehicle-miles per day $VMPD$ is directly proportional to demand. Therefore,

$$VMPD = VMPH \, \frac{TR / DAY}{TR / PKHR} \tag{43}$$

in which the ratio of peak hour to daily travel, $(TR / PKHR)/(TR / DAY)$ ranges, from data reported by Pushkarev and Zupan (1978), from about 0.08 for fully demand-responsive systems up to the range of 0.10 to 0.24 for scheduled systems.

In a *scheduled system,* $VMPD$ can be written in the form

$$VPMD = l_O \sum_k \frac{(H/D)_k}{T_k}$$

in which $(H/D)_k$ is the number of hours per day the vehicles run at headway T_k. But, from equation (35), the peak headway is t_O / N_{op}, and , using equation (38), we have

$$VMPD = N_{op} V_{av} \sum_k \frac{(H/D)_k}{C_k} \tag{44}$$

where

$$C_k = \frac{T_k}{T_{peak}}. \tag{45}$$

If the data is available, it may be more convenient to find *VMPD* from the equation

$$VMPD = l_O(Vehicle\ round\ trips / day). \tag{46}$$

12. Average Peak-Hour and Daily Load Factor

The average number of people per vehicle in the peak hour is the passenger-miles of travel per peak hour divided by the vehicle-miles of travel per peak hour. Thus, if lf_{av} is the average peak-hour load factor,

$$C_v lf_{av} = \frac{PMPH}{VMPH} = \frac{F_{av}}{F_m} C_v lf_m$$

where the right-hand equality is found by substitution from equation (10) and (42). Then

$$lf_{av} = \frac{F_{av}}{F_m} lf_m \tag{47}$$

Equation (47) also gives the daily average load factor in a loop system if the headways throughout the day are adjusted according to demand, i.e., according to equation (13), and the ratio of average to maximum line flow remains the same. We can expect this in a completely demand-responsive system such as a personal rapid transit system. In a scheduled system, however, headway cannot be adjusted exactly according to demand because: (1) the schedules must be published and adhered to; and (2) increasing headway as demand decreases according to equation (13) increases waiting time and, thus, reduces demand more than would be the case if shorter headway were maintained. Thus, in a scheduled loop system we express the number of vehicle-miles per day $(VMPD)$ by either equation (44) or equation (46). From equation (10), the number of person-miles per day $(PMPD)$ is

$$PMPD = l_O F_{av_d} \tag{48}$$

where F_{av_d} is the weighted average daily link flow in people per day. Dividing by equation (46), the daily average load factor for *scheduled loop systems* is

$$lf_d = \frac{F_{av_d}}{C_v(Vehicle\ Round\ Trips\,/\,day)} \tag{49}$$

It is instructive to find lf_{av} by observing that the operating fleet size can be expressed as

$$\begin{aligned} N_{op} &= \frac{number\ of\ \ people\ on\ system\ at\ one\ time}{average\ number\ of\ \ people\ \ per\ vehicle} \\ &= \frac{(Peak\ hour\ \ flow,\ people\,/\,hr)(Av\ trip\ time,\ hrs)}{C_v lf_{av}} \\ &= \frac{D\langle L_t\rangle / V_{av}}{C_v lf_{av}} = \frac{t_O}{T} = \frac{t_O F_m}{C_v lf_m} \end{aligned} \tag{50}$$

where the middle expression is from equation (31), and the right-hand expression from equation (13). Using equation (12),

$$\frac{F_{av} l_O}{lf_{av} V_{av}} = \frac{t_O F_m}{lf_m}.$$

Using equation (38), equation (47) follows, which shows that the equations we developed are consistent.

13. Station Wait Times

In an on-line-station system, the average station wait time is one half the line headway, $T/2.$ In an off-line-station system in which no extra vehicles are assigned to stations, the average station wait time is, similarly, $T_s/2,$ but varies from station to station depending on the station flow. In a personal rapid transit system, if we determine that the wait time at a specific station is too long, we can decrease it by arranging requisitions for empty vehicles in such a way that an extra empty vehicle is nominally present at the station. (This is not practical with group rapid transit since people on vehicles may be required to pass through the station without getting off. Thus, the extra vehicle would frequently be pushed through empty.)

The average wait time in the station of a personal rapid transit system that is assigned one more empty vehicle than needed to meet demands for service can be estimated by assuming that vehicles arrive at the station at the rate of λ vehicles per unit of time, where $\lambda(=1/T_s)$ is the arrival rate needed to meet demands for service, but that the passenger arrivals are randomly distributed. (For purposes of this analysis, the passenger is either one individual or a small group traveling together.) If one passenger arrives within the time interval $1/\lambda$ since the last vehicle left, the presence of the empty vehicle insures that there is no wait. If there are two passenger arrivals in $1/\lambda$, the first party need not wait, but the second party must wait an average of $1/2\lambda$. Thus, the average wait time considering both parties is $1/4\lambda$. If there are three passenger arrivals in $1/\lambda$, the second party waits an average of $1/2\lambda$, but the third party must wait an average of $3/2\lambda$. Thus, the average wait time of the three parties is

$$\frac{1}{3}\left(0+\frac{1}{2\lambda}+\frac{3}{2\lambda}\right)$$

If there are n arrivals in $1/\lambda$, the average wait time for these n parties is

$$\frac{1}{n}\left(0+\frac{1}{2\lambda}+\frac{3}{2\lambda}+\frac{5}{2\lambda}+\ldots+\frac{2n-3}{2\lambda}\right)=\frac{(n-1)^2}{2\lambda n}$$

With randomly distributed passenger arrival rates occurring at an average arrival frequency of λ passenger groups per unit of time, the probability of n arrivals in time t is given by the Poisson distribution function:

$$P_n(t)=\frac{e^{-\lambda t}(\lambda t)^n}{n!}$$

Thus, the probability of n arrivals in time $t=1/\lambda$ is

$$P_n(1/\lambda)=\frac{1}{en!}$$

The average wait time assuming one extra empty vehicle is therefore

$$T_{wait_1}=\sum_{n=1}^{\infty}\frac{(n-1)^2}{2\lambda n}\cdot\frac{1}{en!}=\frac{0.2206}{2\lambda}$$

With no extra vehicles, the wait time is $0.5T_s=1/2\lambda$. Therefore, addition of one additional empty vehicle reduces the average wait time to 22% of its value with no extra vehicle.

A similar calculation shows that with two, then three extra vehicles in the station, the average wait time is

$$T_{wait_2}=\sum_{n=2}^{\infty}\frac{(n-2)^2}{2\lambda n}\cdot\frac{1}{en!}=\frac{0.04295}{2\lambda} \tag{52}$$

$$T_{wait_{13}} = \sum_{n=3}^{\infty} \frac{(n-3)^2}{2\lambda n} \cdot \frac{1}{en!} = \frac{0.00725}{2\lambda}$$

14. The Travel-Time Matrix

Determination of patronage requires knowledge of the time patrons wait at stations and the travel time between all station pairs. Let t_{ij} be the travel time between station i and station j. Then, if the trip is *nonstop*, i.e., there are no intermediate stops,

$$t_{ij} = \frac{l_{ij}}{V_L} + T_{ex} \tag{53}$$

where T_{ex} is given by equation (27). Strictly, $t_{D_{av}}$ is the average of the time delays at stations i and j, but it is often usually as the average for the system. For an *all-stop* system such as a rail transit system,

$$t_{ij} = \frac{l_{ij}}{V_L} + (j-i)\left(\frac{V_L}{A} + \frac{A}{J}\right) + \sum_{k=i+1}^{j} t_{D_k} \tag{54}$$

in which $(j-i)$ is the number of stops, assuming the stations are numbered consecutively in the direction of flow. Equation (41) gives the average value of $(j-i)$.

We make the initial calculation of D_{ij} with values of t_{ij} assumed from experience. Having then gone through all of the above calculations, we find a new trip time matrix and a new set of station wait times, which form the basis of a revised estimate of the D_{ij}. The process must be repeated until it converges.

15. Extension to Networks

Conventional bus systems consist of a group of interconnected, usually line-haul or collapsed-loop system or routes, each designated by its own route number. The formulas derived apply without modification if we keep in mind the fact that the link flows, station flows, headways and wait times apply specifically to each route. For patronage analysis, the only additional factor is transfer time. Guideway systems, such as conventional rail transit system or the newer automated group rapid transit systems, also operate vehicles on designated routes that sometimes overlap. We can treat these systems in the same way.

In true personal rapid transit systems, however, each vehicle trip occurs over the most direct route nonstop from an origin i to a destination j. The vehicles are not confined to fixed routes. Because of this operational procedure, we must modify some of the above formulas, as we discuss in the following paragraphs.

In analysis of network systems, links between stations cannot be used to calculate trip times because there is not a unique link between each station pair. As shown in Figure 1, the flow from station 1 splits into two flows downstream of a branch point. We define, instead, the link as used in network personal rapid transit systems as the link between line-to-line branch points, as shown in Figure 2. We will not refer to the points of divergence into and convergence out of off-line stations as branch points. A link between branch points defined in this way may contain any number of stations including zero. If the length of link i is l_{bp_i}, the sum of the l_{bp_i} is the total length of guideway not counting off-line-station guideway.

If the flow just downstream of the branch point initiating link i is known, we can find the flows downstream of stations on link i from equation 8. Let F_i be the flow just downstream of the branch point initiating link i. Calculation of the F_i requires specification of the path through the network as well as the D_{ij}. If none of the links is overloaded when the minimum-length paths are in use, the minimum-length path is the logical choice and is always the logical choice for the first iteration. Within each link between branch points, designate the sublink from the first branch point to the first station as sublink $i1$, the sublink between the first and second stations as sublink $i2$, etc. Then designate the path between each set of station pairs as the sequence of links and sublinks traversed. If we set up a group of initially zeroed memory registers in a computer program corresponding to the links and sublinks, we can find the sublink flows by adding D_{ij} for every i, j pair to each of the link-sublink registers included in the path from station i to station j. This procedure substitutes for equation 8. Equation 9 is valid if l_i becomes l_{ik}, the sublink corresponding to flow F_{ik}. Then l_O becomes the sum of the l_{ik}, and with this meaning, equations (10) and (12) are valid.

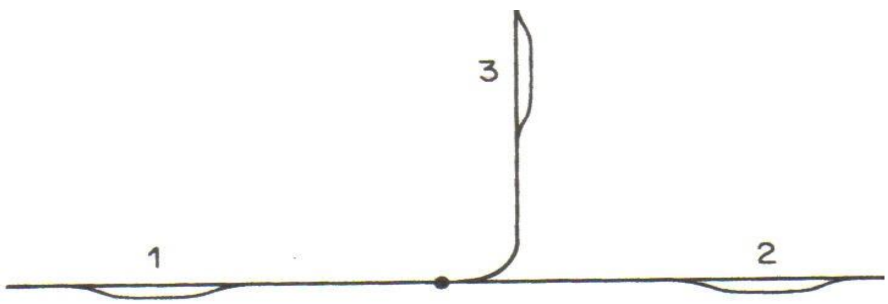

Figure 1. A branch point

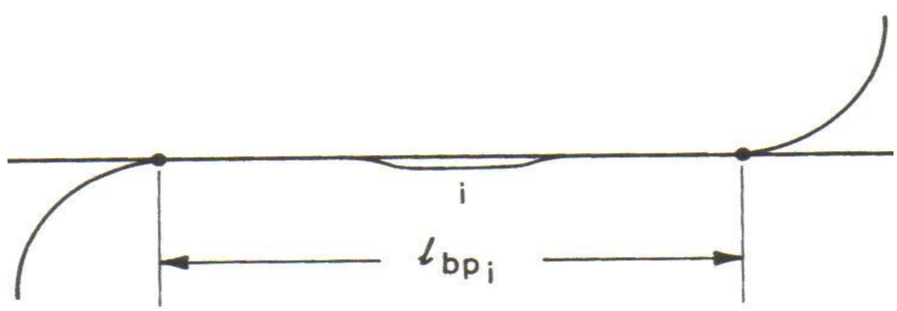

Figure 2. A link between branch points in a network system

We can determine the *fleet size* (counting empty vehicles required to balance the flows) based on the maximum total system demand D, which for this purpose we can assume to be constant in time. The first step in determining fleet size is to identify the maximum flows of people per unit of time in all of the links between branch points. The total flow of vehicles per unit of time in link i must be at least as high as $1/T_i$, where T_i is the operating headway given by equation (13) with F_m the maximum flow in link i and lf_m the average load factor of an occupied PRT vehicle. In general these T_i are different in different links. Find the actual flows in the links including empty vehicles by adjusting the flows upward by adding empty vehicle flows so that, in each link such as shown in Figure 2, the sum of two merging vehicle flows equals the sum of the two downstream diverging flows, in analogy to Kirchhoff s Law of electric circuits. Once we find these adjusted T_i values by applying this continuity principle throughout the network, we can find the fleet size.

If there are no station stops in link i, the number of vehicles found in link i at any instant of time during the period of peak demand is the adjusted vehicle flow, $1/T_i$, multiplied by the time l_{bp_i}/V_L required to traverse the link: $l_{bp_i}/V_L T_i$. For every station in the link, the extra vehicles needed as a result of requiring an excess time T_{ex} (see equation (27)) to pass through the station is T_{ex}/T_{s_i}, where T_{s_i} is given by equation (14). Thus, the total fleet size (see equation (32)) is

$$N = \frac{1}{V_L}\sum_{link}\frac{l_{bp_i}}{T_i} + T_{ex}\sum_{station}\frac{1}{T_{s_i}} + N_s + N_m$$

in which the first sum is over all links between branch points, and the second sum is over all stations. Using equation (14) the total *fleet size* is

$$N = \frac{1}{V_L}\sum_{link}\frac{l_{bp_i}}{T_i} + \frac{T_{ex}}{C_v lf_m}\sum_{station}\max(D_{i\sigma}, D_{\sigma i}) + N_s + N_m \tag{55}$$

By analogy with equation (53), in a personal rapid transit system the *average trip time* is

$$t_{av} = \frac{\langle L_t \rangle}{V_L} + T_{ex} \tag{56}$$

Then, using equation (39), the *average speed* is

$$V_{av} = \frac{V_L}{1 + V_L T_{ex}/\langle L_t \rangle} \tag{57}$$

In a network system, it is simplest to compute the *vehicle-miles per peak hour* from the equation

$$VMPH = V_{av} N_{op} \tag{58}$$

in which, from equation (55), $N_{op} = N - N_s - N_m$. Since the system is completely responsive to demand, we can compute the vehicle-miles per day from equation (43).

Finally, the *rush-period average load factor* counting empty vehicles follows from the first form of equation (50):

$$lf_{av} = \frac{Dt_{av}}{C_v N_{op}} \tag{59}$$

in which equation (56) gives t_{av}. In a fully demand-responsive system, N_{op} varies throughout the day in direct proportion to *D*. Therefore, equation (59) applies at any time of day and gives also the *daily average load factor*. In a PRT system, passengers occupy vehicles with an average load factor lf_m unless they are empty. Denoting the occupied vehicles by N_o and the empty vehicles by N_e

$$N_{op} = N_o + N_e$$

and

$$C_v lf_{av} N_{op} = C_v lf_m N_o$$

Thus

$$N_o = \frac{lf_{av}}{lf_m} N_{op} \tag{60}$$

where we find lf_{av} from equation (59) and $C_v lf_m$ is the average size of a group of people traveling together.

17. Summary Remarks

The methodology this paper develops reduces the performance analysis of transit systems to simple analytical procedures that can be readily programmed on a computer or worked through by hand. The resulting equations are particularly useful in estimating the cost per trip from an equation derived by Anderson (1981). A number of application studies have found hand calculation with the method to be simple and instructive. To obtain simplicity, I have based the methodology on the assumptions that, to calculate the required fleet size and potential bottlenecks where capacity limits are reached, the maximum flow can be treated as steady state and the spacing between vehicles is uniform, having no stochastic component. The maximum steady-state flow can be determined over any period desired such as an hour or fifteen minutes; the shorter the period, the larger will be the fleet size calculated, but the closer will the conditions of maximum crowding in vehicles approach a pre-set requirement. Since the actual flow in the system will generally not remain at the maximum for very long and may occur at different times in different parts of the system, the actual number of vehicles required will not be more than computed by the method. Stochastic variations in vehicle headways around the calculated expected values will cause some vehicles in all but the PRT systems to be more crowded than calculated, and the wait times in PRT systems to fluctuate more widely than calculated. Thus the method is useful as a preliminary calculation of performance, but is not a substitute for a comprehensive computer analysis of the behavior of the system throughout the day or in the rush period with unavoidable fluctuations in demand and vehicle spacing. We can, however, justify comprehensive computer analyses only in detailed stages of system planning. It is useful to guide them by an analytical procedure such as the one described.

18. Notation

A	Comfort level of acceleration
β	Vehicle load-unevenness factor
C_v	Design capacity of a vehicle or train, people
D	Total demand, people per hour
$D_{i\sigma}$	Total demand entering system at station i, people per hour
$D_{\sigma i}$	Total demand leaving system at station i, people per hour
D_{ij}	Demand from station i to station j, people per hour
F_i	Link flow just downstream of station i, people per hour
F_{av}	Average link flow, people per hour
F_m	Maximum link flow, people per hour
J	Comfort level of jerk
L	Length of vehicle or train
LR_v	Loading rate of vehicle or train
lf_{av}	Average load factor
lf_i	Load factor in i-th link
lf_m	Maximum load factor
l_{ij}	Distance from station i to station j
l_{bp_i}	Length of link between branch points
l_O	Length of loop transit system
$\langle L_t \rangle$	Average trip length
N	Total fleet size
N_{op}	Number of operating vehicles
N_m	Size of maintenance float
N_s	Number of extra vehicles at off-line stations
n	Number of stations in a loop
ns_O	Number of stops per round trip
ns_{av}	Average number of stops per trip
$PMPH$	Passenger miles of travel per hour
$PMPD$	Passenger miles per day
T	Time headway between vehicles (front to front)
T_{s_i}	Time headway through i-th station
$T_{\min}$	Minimum safe time headway
T_{ex}	Excess time required to stop at a station

t_{D_i} Time delay at *i*-th station

t_O Trip time around a loop transit system

V_{av} Average speed

V_L Line speed

VMPH Vehicle-miles per hour

VPMD Vehicle-miles per day

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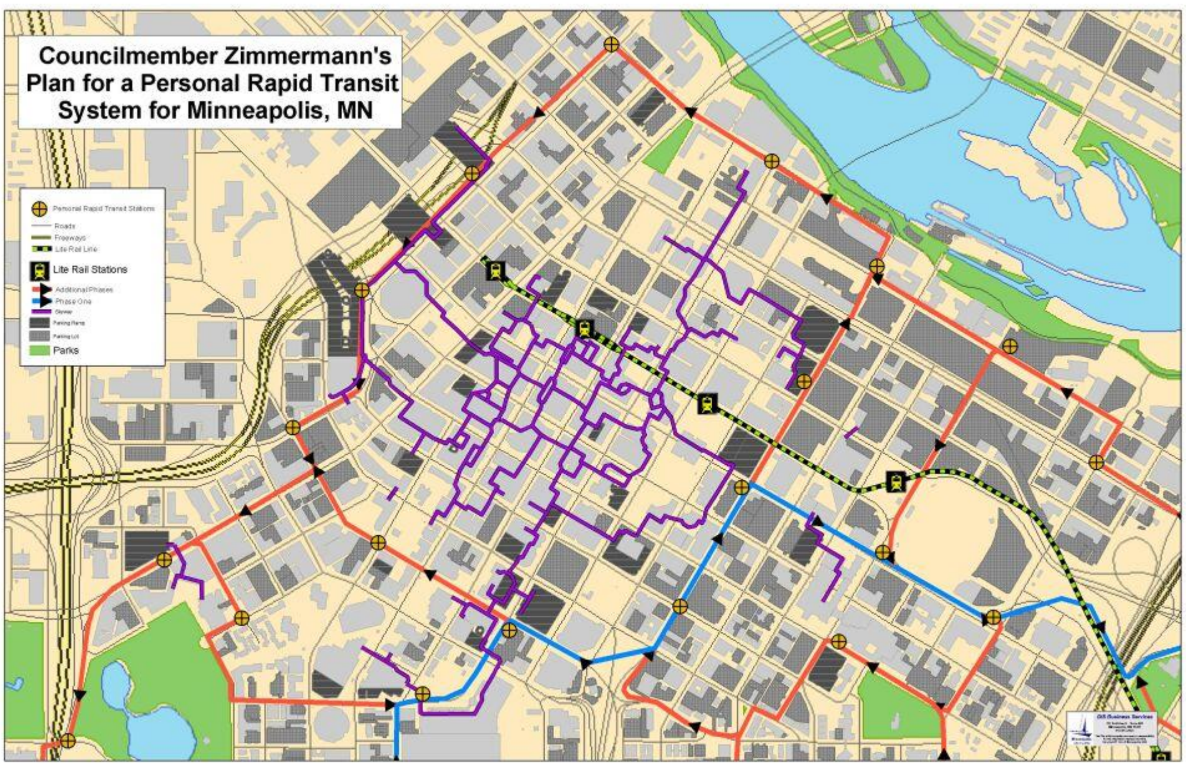


1.4.5 Matching Capacity to Demand

An ATRA Information Paper

PERSONAL RAPID TRANSIT:
MATCHING CAPACITY to DEMAND

J. Edward Anderson, Ph.D., P. E.

A publication of the Advanced Transit Association (ATRA)
a 501(c)(3) organization

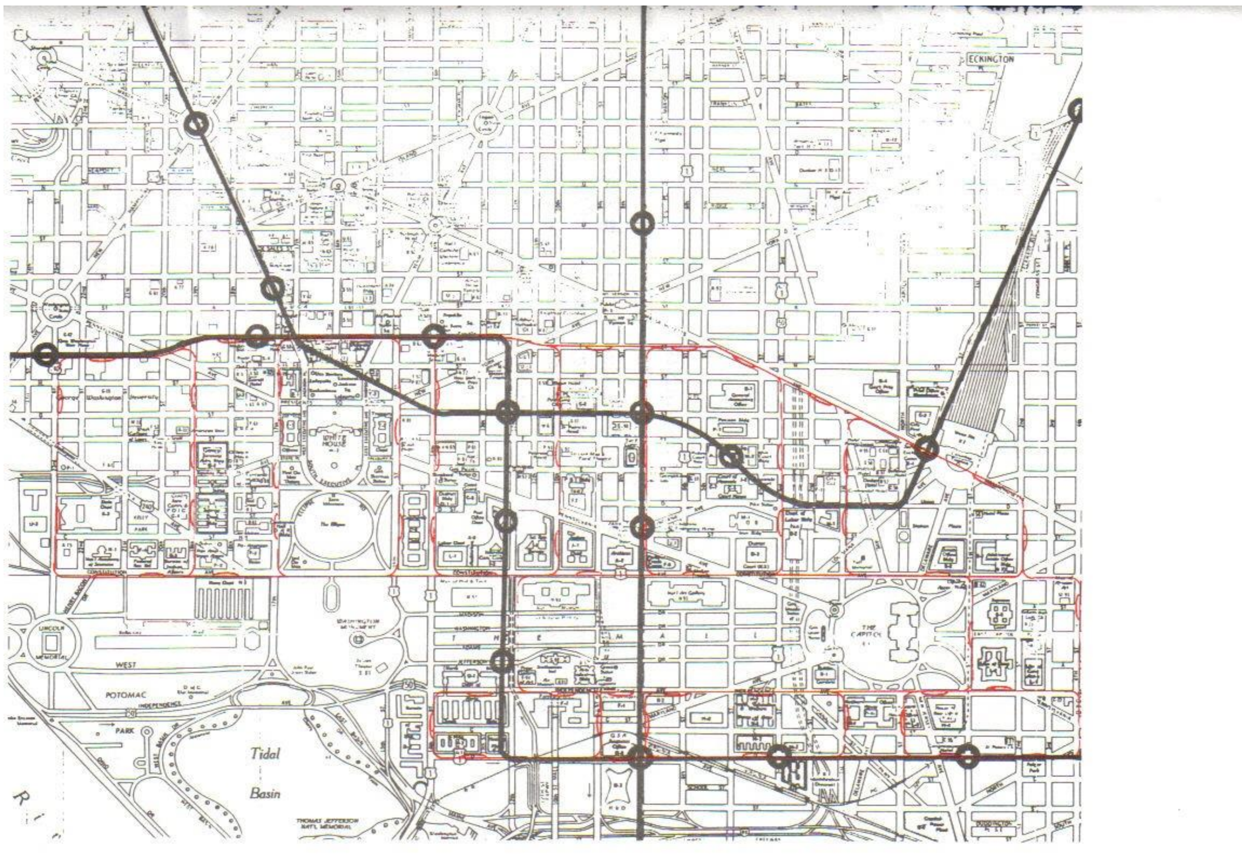
Illustrative PRT Networks

PRT is a fully automated network transit system in which the vehicles are sized to hold no more than a small group traveling together by choice nonstop to their destination. Each of the two PRT networks illustrated is in red with its many off-line stations shown, and is superimposed upon a street map on which the conventional fixed-guideway transit system is shown by heavy black lines. To maximize the capacity of these networks, the merges and diverges alternate to prevent unusually high flows on any line.

By placing PRT networks in central-city areas such as shown here, significant additional channels of non-road movement of people and goods at average speeds exceeding that of the automobile is provided while using very little land. By thus decreasing the need for auto circulation in peak-traffic hours in the downtown area, congestion, noise, air pollution, and energy use are decreased. The price is the generally elevated guideway, which must be designed to be as unobtrusive as possible. One famed sculptor, having studied the impact PRT could have, referred to it as *Moving Sculpture*. By thus improving the inner-city environment, more people can be attracted to live within the city. So doing they would reduce urban sprawl.

Following Page

This illustration shows how a PRT system could improve circulation in downtown Washington, D. C. and how it could interface with and increase the utility of the Washington Metro, an existing underground heavy-rail system. Stations of the PRT system can be placed as close as one block apart. In sensitive areas such as the Mall, the line can be placed underground. The PRT system shown has 58 off-line stations.



Last Page

This illustration shows how a PRT system could improve circulation in downtown Minneapolis and in the adjacent University of Minnesota Campus. The heavy black line coming from the south and terminating at the Humphrey Dome is a proposed transit-way that would go to the airport and the Mall of America. The PRT system shown has 52 off-line stations.

Acknowledgment

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Foreword

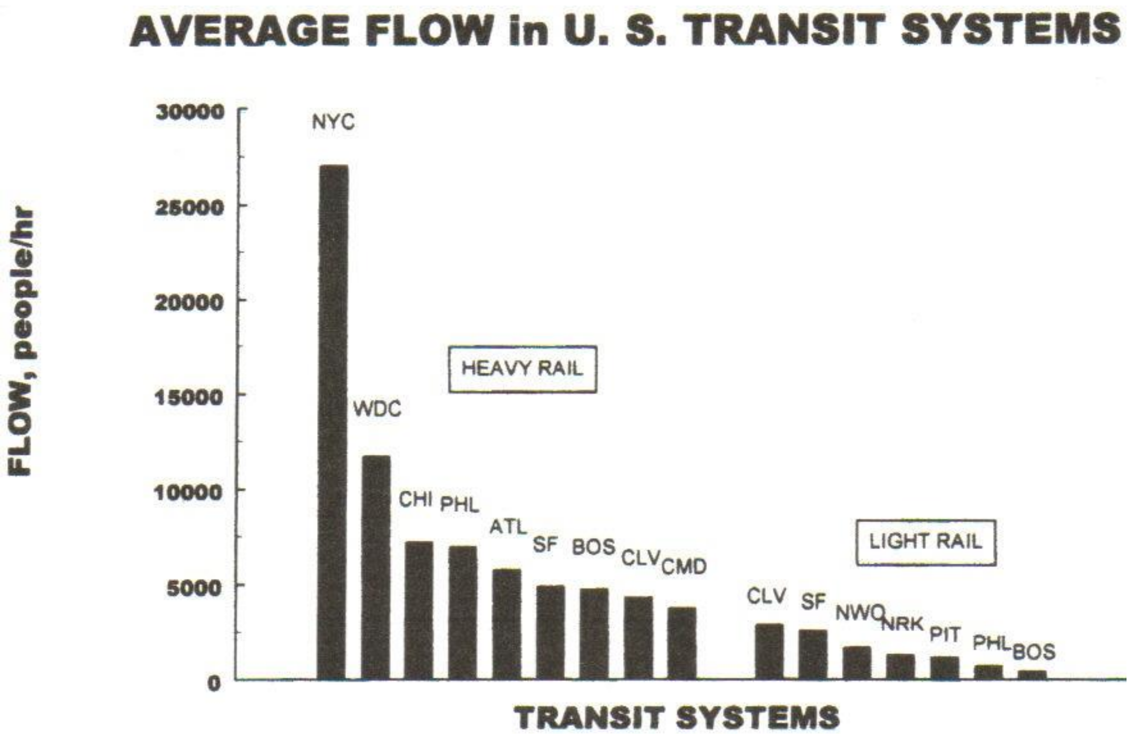
Over many years, backers of the personal transit concept (PRT) have stressed its projected special values as compared to conventional transit modes and many of the heavy forms of automated guideway transit (AGT). These values include: (1) Very low construction and operations/maintenance costs, which would become more advantageous as PRT service networks expand into more parts of communities; (2) Relative ease and flexibility of installation and adaptability to widely varying urban and suburban physical conditions and service needs; (3) Simplicity of use by all age groups and availability under all weather conditions; (4) Closer proximity of numerous PRT stations to traveler origins and destinations; (5) Nonstop, faster trips from origin to destination; and (6) Privacy and greater personal security while traveling.

Obviously, a transit concept with such values would have a great impact on urban and suburban planning generally and on land uses. As expected, however, the claimed values for PRT made it much debated. Yet, the focus of arguments has been shifting. Over the past 10 years, many earlier engineering and control questions raised about the feasibility of the PRT concept have been answered through extensive analytical and design work by Dr. J. Edward Anderson (University of Minnesota and Boston University) and others. ATRA's own widely circulated PRT study report in 1988 examined its overall feasibility and concluded the no critical design, engineering, or service barrier blocked its development, and that PRT could be developed and deployed at very low costs compared to other transit modes. With these conclusions in hand, the Northeast Illinois Regional Transportation Authority and Raytheon Company jointly funded a project to create and test a working PRT system (PRT 2000). That effort, to be completed in the spring of 1998, has answered many practical engineering, software, and control questions debated over the years, and are expected to lead to a working PRT demonstration in Rosemont, Illinois, USA.

Notwithstanding growing recognition that PRT is technologically feasible, a persistent question remains about its capacity to carry the necessary passenger loads. The obvious importance of capacity to transit planning requires that the capacity capabilities of PRT be illuminated. While the Advanced Transit Association (ATRA) does not sponsor any particular form of advanced transit, its members recognize the critical need for communities to have better options than now exist for meeting mobility needs in far-flung, traffic-congested, and increasingly environmentally sensitive metropolitan areas. ATRA also recognizes the needs of urban planners and developers to have highly service- and cost-effective circulators for major activity centers and linkages to other systems of transportation. However, ATRA finds the whole subject of capacity is rife with questionable assumptions and presumptions. This paper raises issues about such capacity assumptions and presumptions and discusses approaches to analyzing their implications for transit planning and action.

In the interest of improving the discussion of various transit modes, ATRA is encouraging preparation of carefully reasoned papers that present new findings and facts that help identify and join issues and that examine possible misconceptions about PRT and other transit modes. Drafts of such papers will be circulated for comment to ATRA members and others, and revised as necessary. Completed drafts will then be submitted to ATRA's directors for decision. If approved, they will be widely circulated. This PRT capacity paper has been through this process and was approved as an ATRA Information Paper by ATRA's Board of Directors in January 1998.

Jarold Kieffer
ATRA Chairman



PERSONAL RAPID TRANSIT:
MATCHING CAPACITY to DEMAND

Introduction

Descriptions of Personal Rapid Transit (PRT) have been given in papers published in various sources over the past quarter century. Some systems called PRT have been disappointing because of their cost and size. Yet there is ample evidence that properly designed PRT will be a major breakthrough in urban transportation and is worthy of serious consideration. The purpose of this pamphlet is to show why the capacity of an optimally designed PRT system is adequate to meet a wide variety of demands. PRT can in time reduce congestion and can realize major improvements in the urban environment.

When first exposed to PRT, the reaction of many people is that, with such small cars, it cannot possibly carry enough people to make it worthwhile. This view is held even though we experience daily that great masses of people travel in urban areas in automobiles with rush-hour occupancies averaging less than 1.1 persons per vehicle. With the roads overcrowded, rush-period travel time has increased to the point that congestion is a topic of major concern and the comment that everything should be examined is more frequently heard.

PRT is a fully automated network system such as shown in the examples on the inside front and back pages of this pamphlet. The trips are nonstop and there are no transfers. Promoters of conventional transit argue that their system also is a network system, called a "family-of-vehicles," in which people ride a bus to a train and then from a train to a bus, thus covering the area of a city.

Unfortunately, however, the resistance to transferring is very high. In a PhD thesis at the University of Minnesota, F. P. D. Navin showed by regression analysis on actual ridership data that people consider one minute of transfer time to be equivalent to six to ten minutes of riding time.[84] The result is that very few transit riders regularly transfer from one transit line to another, thus vastly restricting the range of destinations available to them. Moreover, because of frequent stops, the average speed on conventional transit is much lower than on PRT. High average trip time and time uncertainty due to transfers are the major reasons transit ridership in the U. S. is less than three percent of total travel. Because PRT roughly doubles average speed and eliminates the need for transfers, it will attract a much larger proportion of urban travel.

It is common to compare the line capacity of PRT with the line capacity of heavy rail, which is in the range of 40,000 persons per hour, and to thereby argue that PRT has inadequate capacity. This argument is pointless, at least in the United States outside of New York City, because the peak flows actually achieved are far lower. Moreover, as shown in this paper, by networking, the line throughput a PRT system must deliver to meet reasonable demands for service is much lower than the maximum throughput of heavy rail. Because of networking, PRT will as a whole be able to attract and manage a much larger fraction of the trips than is possible with a high-capacity conventional light or heavy rail system operating with bus feeders, and is much more closely matched in capacity and economics to actual needs.

This document was written as a part of the argument needed to persuade the reader to consider seriously the role PRT can play in diverting meaningful amounts of traffic from congested roads, and to invite opportunities for us to answer any and all questions about it. This is not the whole story—there are other aspects of PRT that need to be understood—but it is one of the most important. In this document I explain the line and station throughput a PRT system must have to meet demands for service and the capacity of these lines and stations. I also make flow comparisons with conventional bus and rail transit systems and with the automobile.

The line-flow capacity or maximum throughput a transportation system must have if it is to meet demands for service depends on population density, line spacing and average trip length, and, as shown in the Appendix, is proportional to all three. The line-flow capacity a transportation system can deliver depends on the size of the vehicles and trains and on the minimum headway (time between vehicles) at which the system can operate safely and reliably day in and day out. The minimum safe headway of a PRT system has been a point of contention. It is key to the discussion of the capacity of a PRT system and is considered below.

Another meaning of transit-system capacity is not a flow but the total number of people-carrying places (seats plus standing places) on all of the vehicles. To move a given number of people per unit of time this capacity is proportional to demand and to average trip time. The longer the average trip time, the more places are needed to move a given number of people per hour, and hence the greater is the congestion. By using switchable vehicles sized for a single person or small party traveling together by choice and by placing all stations off the main lines the trips can be nonstop, in which case in congested urban areas the average trip speed becomes competitive with

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[84] Navin, F. P. D. 1974. Time Costs in Personal Rapid Transit. *Personal Rapid Transit II*. Audio Visual Library Services, University of Minnesota, Minneapolis, Minnesota.

and even exceeds that of automobiles and the required number of vehicles is minimized.

The guideway size and cost of a PRT system are dependent on vehicle weight. By proper design, the size and cost can be low enough so that it is practical to deploy a PRT system widely in networks even in less dense regions of a city, thus vastly increasing accessibility as compared with a conventional rail system. For the rider, the additional advantages of PRT are travel in seated comfort with one's own companions or alone nonstop to the destination at any time of day or night. Optimized PRT provides a combination of accessibility, high service level, and low cost far beyond that possible with existing transit modes and will attract many more riders than regularly use conventional transit. In contrast, the cost of a conventional rail system is so high that, for it to be economical, it is necessary to arrange higher-density living along a number of lines more limited than most Americans prefer or that is socially desirable. Attempts at area-wide coverage by arranging bus lines to feed the rail line fail because too few people will transfer regularly—the travel time and time uncertainty is too great.

Transit Capacity Needed to Meet Demands for Service

Demands Determined by Observation

To obtain a feeling for the capacity required of or needed by a transit system, consider people walking through a revolving door. The average spacing between individuals is rarely closer than about four feet, and average walk speed going through revolving door is somewhat less than the average speed walking down a sidewalk, which is about three feet per second. So, suppose the average speed through a revolving door is two feet per second. With four-foot spacing between people, the average time headway would be 4 ft/2 ft/sec or two seconds, or an average of 1800 people per hour. If you actually time people going through a door, you find that the average time headway is usually no less than about three seconds, or 1200 people per hour. I measured the average time headway between people debarking a loaded 747 aircraft and found it to be close to three seconds (300 people in 15 minutes). If you time cars coming out of a parking ramp, you find again an average of about one car every three or four seconds if they don't have to pay a fee upon exit. If they do, the average headway is of course much longer.

When exposed to the concept of PRT, the first question most people ask is how it would handle the people leaving a stadium at the end of a major event. Being interested in the question, I have observed what usually happens now as people leave an event. They walk to their cars in a parking lot or ramp and they wait, sometimes for 30 to 40 minutes, while the cars leave at a rate of about one every three to five seconds. I once timed cars coming out of a full parking lot onto an arterial street after a hockey game in a 20,000-seat stadium and found again a headway in the range of three to four seconds. So, typically over an hour is required for 1000 cars to leave. I once watched people coming out of Fenway Park in Boston after a baseball game. Many go to the Kenmore Square subway station where they must walk slowly about four or five abreast through a tunnel to two ticket booths and two turnstiles, through which about one person every two to four seconds can pass. If Fenway Park were serviced by a PRT system, there could be a station on each of its four sides, each of which would handle as many people per hour as the Kenmore Square rail line.

I once taught a class in transportation engineering to Boston University freshmen and on the first day described PRT. One question was how PRT could handle the people coming out of the John Hancock Tower where 5000 people work. I had the students do various kinds of traffic surveys and one group of three decided to count the people coming out of that building at the busiest time in the evening, around 5 pm. They talked to the guards to be sure that they covered all of the exits. They found, to their surprise, that only 1200 people came out in the busiest hour, or an average of one every three seconds. *People don't all rush into or out of a building at once!*

So, it seems that a transportation system that can move approximately 1200 people per hour on a given line is quite significant. Today in most cities in the U. S. transit handles only a small fraction of the trips. Even into and out of central business districts, a mode split to transit of 20% is high. If a PRT system were to do so well as to attract half the trips, it could cover a wide range of demands if it could only handle 600 people per hour from given points onto a single line. Yet, as we will show, a PRT system can handle far more than this.

Demands Determined by Theory

Another way of examining travel demand on transit lines and into and out of stations begins by considering a city of uniform population density. In typical American cities the average person takes about three trips in a vehicle during each weekday of which about 10% occur in the peak hour. Thus, the total number of peak-hour vehicle trips/sq-mi is about 0.3 times the population/sq-mi.

While every PRT network will be shaped to conform to existing or desired topography, it is useful for general systems analysis to assume, for mathematical simplicity, that the network is a square grid. Figure 1 illustrates a portion of a square PRT network having east-west and north-south lines, each in alternating directions.

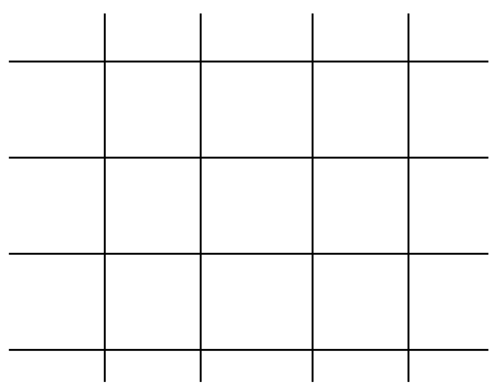


Figure 1. A Portion of a Square-Grid PRT Network

As an example, assume the lines are spaced half a mile apart. This is a typical distance between major streets and a spacing that places everyone within a quarter mile of a station if the stations are at the midpoints between each pair of intersections. Let the population density be 12,000 persons/sq-mi, which is high for most auto-oriented U. S. cities. Then, within one of the quarter-square-mile squares between PRT lines there would be 3000 people and, in the busiest hour, 0.3(3000) = 900 trips. But each of the four stations on the lines bounding a square serve two squares, so there are two stations per square, giving an average peak-period station flow of 450 persons per hour if all trips were on PRT. If a PRT system were to be so successful as to attract half of the trips, the average station-flow requirement would be only 225 persons per hour. Such a flow can be handled by a one-berth PRT station; however, as described below, a PRT station may practically have up to about 12 berths.

If the spacing between transit lines in a square grid is denoted by L, the number of vehicle trips generated within one square is the trip density multiplied by the area, L^2, and that half of each of four stations are within the square grid. Thus, as a formula, we have

$$Average\ station\ flow = \frac{1}{2}\left(Trip\ density\right)L^2$$

Since the peak-period trip density is roughly 30% of the population density, we have

$$Peak-Hour\ Average\ Station\ Flow = 0.15\left(Population\ Density\right)L^2$$

In the Appendix it is shown that the formula for the average peak-hour line flow is obtained by substituting the average trip length, which we shall call L_{trip}, for one of the $L's$. L_{trip} is the demand-weighted average distance from the origin station to the destination station. Thus

$$Peak-Hour\ Average\ Line\ Flow = 0.15\left(Population\ Density\right)LL_{trip}$$

The average bus trip in a typical U. S. city is in the range of three to four miles long, and the average auto trip is typically seven to ten miles long. Suppose the average PRT trip length is in the middle, say $L_{trip} = 5$ miles. Then with 50% of the trips on PRT, as in the above example, the peak-hour average line flow would be the average station flow multiplied by the ratio L_{trip} / L or, in the above example, 225(5/.5) = 2250 people per hour. If there were say an average of 1.2 people per vehicle in a PRT system (increased over rush-hour auto occupancy by charging a fare per vehicle), the vehicle flow would be 2250/1.2 = 1875 vehicles per hour, corresponding to an average headway of 3600/1875 = 1.92 sec. This would be the required capacity if the travel demand were uniform; however, it is almost never uniform, so the capacity required of some lines will be higher. Also, as mentioned below, some of the vehicles are empty so to achieve 1875 occupied vehicles per hour, the average headway between vehicles must be less.

Considering that in the U. S. the average mode split to transit is less than 3%, the above-described PRT system would be wildly successful, but it could quite likely not be able to attract as many as 50% of the trips, nor would that be necessary to make a huge difference in congestion. It is interesting to observe that the line flow thus calculated is only a little more than the maximum exit flow from a parking structure. By comparison, the flow on an expressway lane under uncongested conditions does not exceed the range of 1800 to 2000 vehicles per hour. Thus, an extremely successful PRT system in a city of 12,000 persons/sq-mi need handle on each line no more than about one expressway lane of traffic. As mentioned, there of course will always be points where the flow will be higher—two to three times higher but most U. S. cities have substantially lower population density, which proportionately lowers the line and station flows.

Rapid-Rail Capacity vs. Demand

As mentioned above, it is often commented that a rapid rail system can handle up to about 40,000 trips per hour, which corresponds to about 20 expressway lanes of traffic under the best conditions. Where does one need such capacity? During the 1970s, it was stated by Denver transit promoters that there was a transit requirement in Denver for 14,400 people per hour in each direction, which is more than seven expressway lanes of traffic in one direction under ideal flow conditions! Denver had a population density of about 5000 persons/sq-mi, so why would there have been a need for such a high flow on a transit system in a city that had, at the time, a mode split to transit (buses) of about 2%? Can the reader guess what is going on? Such total traffic flows occur only in dense cities in which the flow from about a quarter of the city is concentrated onto a single corridor. And even then there are few cities in which the freeways have seven lanes in each direction. In the Twin Cities, in the early 1970s, it was stated by rail advocates that there was a transit requirement for 15,000 persons per hour in each direction, which "just happened" to be the capacity of a rail system then being promoted. Actually, these extraordinary demands occur only in very dense cities such as New York, in which transit ridership is very high. With a transit system capable of networking, the demand on each line is, as shown, substantially less.

The Capacity of a PRT System

The Brick-Wall Stop

In railroad practice, the minimum nose-to-nose time headway between trains (called simply the "headway") is determined by the requirement that a train can stop before a collision occurs if the train ahead stops instantly. This is called a "brick-wall stop." To provide a margin of safety, the minimum headway is usually taken to be at least two of such stopping distances. Since the station stops are on-line, each stopped train waiting to unload and load will block the train behind. Hence the minimum headway is determined by on-line station stopping. The station delay, train length, and stopping kinematics combine to give a minimum urban-rail headway usually more than one minute. As a result, train engineers have been baffled by statements that PRT systems could run safely at fractional second headways.

PRT Safety Philosophy

In a PRT system, all of the stations are on by-pass guideways, off the main line. Thus, station stopping is not involved in determining the safe main-line headway. As mentioned, in railroad practice the safety philosophy is that if a brick-wall stop occurs, the train behind must stop before colliding. But, if a train stops instantly or close to it, people have already been killed. A PRT system runs on an exclusive guideway, usually elevated. Its safety philosophy must and can be that it must be designed in such a way that even if there is only one vehicle moving on the system there is no reasonable way for it to stop suddenly. One would like to say that it would be impossible for a vehicle to stop suddenly; however, it is not practical to design any transit system so that there can be no serious event if two or more major failures occur in close proximity in space and time. As an example, if the brakes on a train fail just as the train ahead derails, the conditions for a collision are set up. In technical jargon this is called "simultaneous major failures." They can happen, but the probability of such a combined event is so low that we live with it, notwithstanding occasional collisions.

Failure Modes and Effects

Analysis of potential failures and ways to reduce their consequences is fundamental to the design of PRT systems and in a successful PRT design will have been given major emphasis. Careful analysis of failure modes in a PRT system shows that it is practical to design the system in such a way that the conditions for a sudden stop can be set up only if at least two major failures occur simultaneously. In such a system the mean time between such combined failures is measured in millions of years. Using failure-modes-and-effects analysis (FMEA), it has been shown that it is practical to design a PRT system in which the minimum safe headway is well under one second. Such a system will use checked redundant computers and monitoring of every reasonable cause of a failure. Over the past two decades, serious PRT designers have designed for headways at least as small as a half second.

Experimental Evidence

As an example of the state of the art, consider that in August 1997 the National Automated Highway System Consortium tested ten Buick LeSabres running on a special highway near San Diego at 50 mph at a bumper-to-bumper spacing of only six feet. This corresponds to 0.3-sec headway. They would not have openly announced such an event if they had not been very sure that it could be done safely. At 30 mph, a more reasonable urban PRT speed, half-second headway corresponds to a nose-to-nose spacing of 22 feet. With nine-foot-long PRT vehicles, a practical length, the minimum bumper-to-bumper spacing is 13 feet. Thus a position tolerance of a few feet would be satisfactory, yet with today's control systems it is practical to control the spacing to a few millimeters.

PRT Line Capacity Compared

If the minimum headway is half a second, the average headway in the rush period will usually be no less than about one second. Thus an average PRT line flow of 3600 vehicles past one point in an hour is practical, which is roughly equivalent to two expressway lanes operating under ideal conditions in which a speed of at least 30 mph is maintained. Because of the vagaries of human drivers, however, expressways all too often do not operate under ideal conditions. When the speed on an expressway falls off, as it does every day in congested areas, its throughput drops rapidly. By comparison with bus systems, if a PRT system averaged only one person per vehicle, a system of 60-passenger buses each full of passengers would have to operate one minute apart to achieve the same capacity. Such a headway with buses can be attained in and out of busy stations only if cascades of buses unload and load simultaneously.

Movement of Empty Vehicles

Attempts to understand the capacity of PRT systems raises questions about how the movement of empty vehicles is handled. Many simulations of PRT systems have shown that about one third of the operating vehicles will be empty. By comparison, according to federal data, the average bus or streetcar in the U. S. operates at a daily average of only 10 to 20 percent of vehicle capacity. PRT vehicles are automatically rerouted to stations where they are needed without having to have patrons call for them. At each station there is a checked redundant computer that observes and manages the station flow. When an empty vehicle parked in the first berth in a station is not needed, the station computer commands it to go to the next downstream station that needs a vehicle. On the incoming side of each station, at a predetermined command point, the station computer checks each approaching vehicle. If a vehicle is occupied and is destined for its station, it commands the switch to throw in the direction of the station if there is room. In a properly designed PRT system, the chance that there is no room is very small, but if there is none, the vehicle is switched away and automatically returns in a few minutes. If the approaching vehicle is empty, the station computer, knowing if its station needs an empty, determines, in cooperation with the central computer, if it is to be switched in. Knowing how many passengers are waiting at each station and their wait times, the central computer may request that a particular empty vehicle bypass a particular station for another in which the passengers have waited longer.

Just upstream of a point of divergence between main lines there is a diverge-point computer that determines which way each vehicle, empty or occupied, should switch. This computer is also in communication with the central computer, where knowledge of the number and wait time of waiting passengers at all stations is known, and the whereabouts of all vehicles in the network, empty and occupied, is known. This knowledge, which improves as the computer "learns," permits empty vehicles to switch to meet demands in an optimum way, taking into account pending congestion in the system. Near the end of the day, when fewer vehicles are needed, excess empty vehicles, over and above those needed to supply each station, are switched into storage stations. Since it is not necessary to get a specific vehicle out of storage at a certain time, as is the case with automobiles in parking structures, the volume required for storage is surprisingly modest. One or more vehicles will always be kept at each station to meet demands at any time of day or night.

By these means of recycling empty vehicles, many simulations of PRT systems have shown that the average wait time during peak periods will be well under three minutes, and during the off-peak periods there will be no waiting at all.

PRT Station Capacity

The simplest PRT station has one by-pass guideway branching in and out of the station and a number of loading berths, usually varying from two to about 12, used for both boarding and debarking. A disadvantage of such a station is that if someone is slow to enter or leave a vehicle everyone behind is delayed. But the important variable is the statistical average, which is reasonably short, particularly in the rush periods where people move quickly to work or home. Additional station guideways in any of several configurations could be added if necessary, but usually have an unfavorable ratio of added benefit to cost.

Numerous analyses and simulations have verified that the capacity of PRT stations with a single bypass guideway varies from about 300 vehicles per hour through a 2-berth station to about 1300 vehicles per hour through a 12-berth station. As shown above, such stations, sized to demand, will serve a very wide range of needs in all cities except those of very high density; however, in such cities, system capacity can be at least doubled by placing lines every two blocks instead of every four blocks apart. An advantage of PRT is that each station can be sized to its own demand, whereas, in a conventional rail system all stations must be sized to the length of the longest train, thus producing a significant increase in station costs.

Conclusions Critical to Considerations of Transit Capacity

- A PRT system can be sized to meet peak demands much higher than usually attained by conventional transit, with average peak-period waiting times of less than three minutes. In off-peak periods, automatic recycling of empty vehicles eliminates waiting entirely.

- PRT provides great flexibility and speed in deploying the vehicle fleet to match hour-by-hour demands for service, thus reducing operating costs.

- Because of relatively low costs and ease of installation, more lines and stations at more geographically dispersed locations are possible with PRT than with conventional rail transit. Consequently, PRT becomes more accessible for a much larger fraction of urban and suburban trips. Because the stations of conventional rail transit are on-line and, to maintain speed, the stations must be widely spaced, these systems require the aggregation of travelers in a few places. To handle these aggregations, conventional rail must have large, costly vehicles, station platforms and guideways. High cost then limits them to a few corridors. Since PRT uses off-line stations, the vehicles can be very small, which means that the guideway can be inexpensive and the trips nonstop. PRT can therefore have more dispersed lines and more numerous and closer-spaced stations without reducing average speed. Its ability to generate and manage significant passenger loads does not depend upon aggregating large numbers of people in a few places. Indeed, the demand per station is reduced while accessibility is further increased.

- The capacity of conventional rail transit systems is well beyond the need in all but very high-density cities such as New York City. Assumptions that lead to building overcapacity are counterproductive in three ways: (1) Much capacity is unused during most of the day; (2) costly oversizing of vehicles and stations drains transportation resources and prevents other transportation needs from being met; and (3) new approaches to meeting transit needs, such as PRT, are ruled out at the planning stage because they are presumed to have inadequate capacity potential.

- Planners need to judge from a fresh perspective the ability of PRT to handle capacity needs, and thus to solve pressing problems of urban mobility.

- The advantages of PRT can become fully understood only if it is included in planning studies. Such studies are needed to encourage manufacturers to provide optimized PRT systems.

Appendix

The Formula for Line Flow

The number of vehicles in any transit system can be expressed in two ways:

1) The number of people riding the system at any one time divided by the average number of people per vehicle.

2) The total one-way line length divided by the average distance between vehicles.

By equating these two ways of expressing the number of vehicles, the formula for line flow, with some algebraic work, results.

The number of people riding the system at any one time is the total demand in people per unit of time multiplied by the average trip time in the same time units. This may not be obvious. To clarify suppose there is a flow of 60 people per minute from the street into station P. Suppose all of these people travel to station Q and that it takes 10 minutes to travel from station P to station Q. Then in 10 minutes 600 people would have left station P on the way to station Q. But in exactly 10 minutes the first person would just be arriving at station Q. So 600 people are riding the system. In general, the number of people riding from station P to station Q is the flow multiplied by the trip time. But station P and station Q are any pair of stations in a system. Thus by summing over the flow multiplied by trip time for all pairs of stations, one has the number of people riding the whole system at any one time. This quantity is the same as the total system demand in people per unit of time multiplied by the *demand weighted* average trip time in the same time units. The demand-weighted average trip time is the demand-weighted average trip length divided by the demand-weighted average speed.

In algebraic notation, let

D	=	system demand, person-trips/unit time
L_{trip}	=	average trip length
V	=	average speed
p	=	average number of people per vehicle
L_{line}	=	total one-way line length
h	=	average time headway, i. e., the average time per vehicle
H	=	average distance between vehicles $=Vh$

Then

$$Number\ of\ vehicles = \frac{DL_{trip}}{pV} = \frac{L_{line}}{H} = \frac{L_{line}}{Vh} \tag{A-1}$$

Isolate the second and fourth forms of equation (A-1), multiply the resulting equation by pV and divide by L_{line}. The result is

$$\frac{p}{h} = Average\ line\ \ flow = \frac{DL_{trip}}{L_{line}} \tag{A-2}$$

Note that $p/h =$ people/vehicle $\div$ time/vehicle $=$ people per unit of time, i.e., line flow. But, the total demand D is the demand density in person-trips per unit of time per unit of area multiplied by the area covered. If we define

$d =$ trips/hr/sq-mi = trip density
$A =$ area covered by the system, sq-mi

we can write

$$D = dA \tag{A-3}$$

If, as in Figure 1 in the main text, we assume a square grid of PRT lines of spacing L then each square in the grid has an area L^2. Since each of the four line segments on the sides of the square, each of length L, is shared with a similar square, the total line length associated with one square is $\frac{1}{2}(4L)=2L$, and the total line length in a much larger area A is

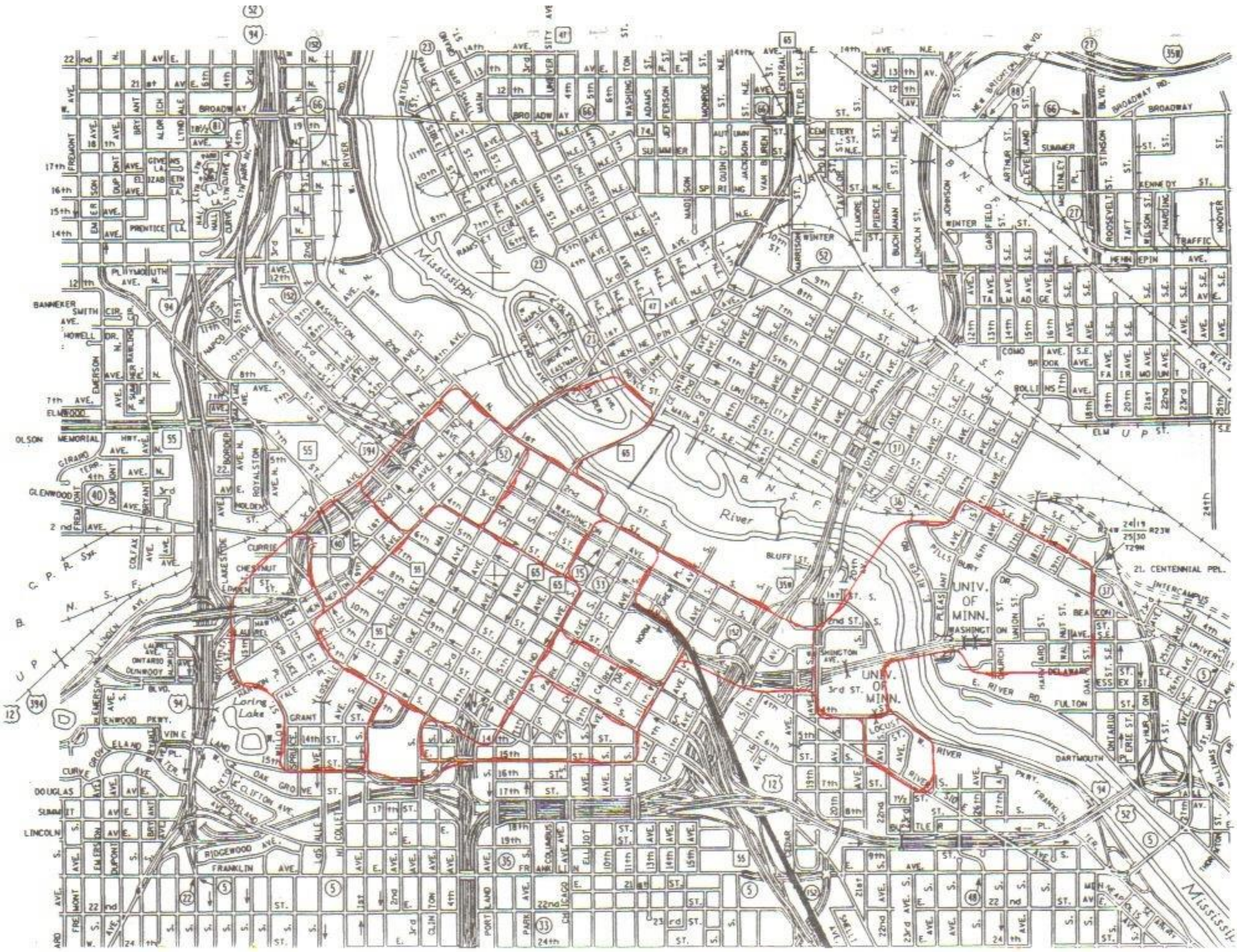
$$L_{line} = 2L\frac{A}{L^2} = \frac{2}{L}A \tag{A-4}$$

Substituting equations (A-3) and (A-4) into equation (A-2), the area A divides out and the result is

$$Average\ Line\ Flow = \tfrac{1}{2}dLL_{trip} \tag{A-5}$$

As shown in the text,

$$Average\ Station\ Flow = \tfrac{1}{2}dL^2. \qquad \text{(A-6}$$


Mississippi
River
UNIV. OF MINN.
Loring Lake

1.4.6 The Capacity of High-Capacity Personal Rapid Transit Systems

For purposes of this paper, capacity is defined as the maximum flow in people per hour. This is in contrast to the capacity of a vehicle in terms of the number of people it can carry. Three types of capacity must be considered: line capacity, station capacity and system capacity; and in all cases it is necessary to compare the capacity with the required capacity in various applications. I have examined the question of capacity, but here my objective is to summarize and update the results in fewer pages.

<u>Line Capacity</u>

In considering line capacity, we will have to distinguish between the maximum flow in the busiest link in a system and the maximum flow averaged throughout the system. As a specific example, consider the capacity of the Minneapolis rail line, in which the maximum flow carried between the two airport terminals far exceeds the peak-period flow averaged over the whole system. According to Metro Transit (www.metrotransit.org) the cars hold a maximum of 186 people and they operate in three-car trains at a minimum schedule frequency of one train every 7.5 minutes. This corresponds to a theoretical maximum flow of 3(186)(60/7.5) = 4464 people per hour.
PRT cars hold typically from 3 to 5 persons, but on the average fewer. In a 1990 survey taken in Minneapolis and St. Paul, it was found that the peak-period auto occupancy was only 1.08 people per vehicle and the daily average was 1.2. We assume that in PRT a fare per vehicle rather than per person will be charged, which will encourage group riding. However, on the same basis as calculated for a conventional rail line, assume 5 people per vehicle and the "brick-wall" headway of 2 second between vehicles. Then the PRT system could handle 2.5 people per second or 9000 people per hour or about twice as many people per hour as the rail system. However, the easily achievable headway using linear induction motors for propulsion and braking is 0.5 sec or, with 5 people per vehicle 36,000 people per hour. Using the above-mentioned average vehicle occupancy of 1.2, the maximum throughput is 8640 people per hour, or about 1.9 times the theoretical capacity of surface-level rail. The true comparison depends on proving in daily practice the safety and reliability of sub "brick-wall" headways.

During the 1990s, the Automated Highway Consortium (AHC) demonstrated 0.27 second headway at 60 mph, which corresponds to 3600/0.27 = 13,333 vehicles per hour or, with an achievable average of 1.5 people per vehicle, 20,000 people per hour. This is a maximum flow equivalent to about 10 freeway lanes of travel – much higher than needed in a well-designed network. The AHC program was conducted under the supervision of the National Highway Safety Board. Moreover, it used vehicles in which braking depends on the friction of the running surface, whereas in the best PRT systems braking and acceleration is via linear induction motors, which can be applied in a few milliseconds rather than in a few tenths of a second, and braking does not depend on the coefficient of friction of a running surface.

Notwithstanding these findings, some people are puzzled by the assertion that very small cars can have greater line capacity than large conventional-rail cars. <u>The clear answer is on-line vs. off-</u>

line stopping. Imagine yourself travelling in an automobile on a freeway lane. Imagine stopping in the lane, letting a person out and then another person in. How far behind will the next automobile have to be to make this maneuver safe? The answer is minutes behind. This is the way conventional rail and bus systems operate. *They stop on line*, as a result of which they must be placed minutes apart, whereas it is well known that autos travel on freeways seconds apart and often less than a second apart. How can this be? Simply by stopping only after one has steered out of the freeway lane.

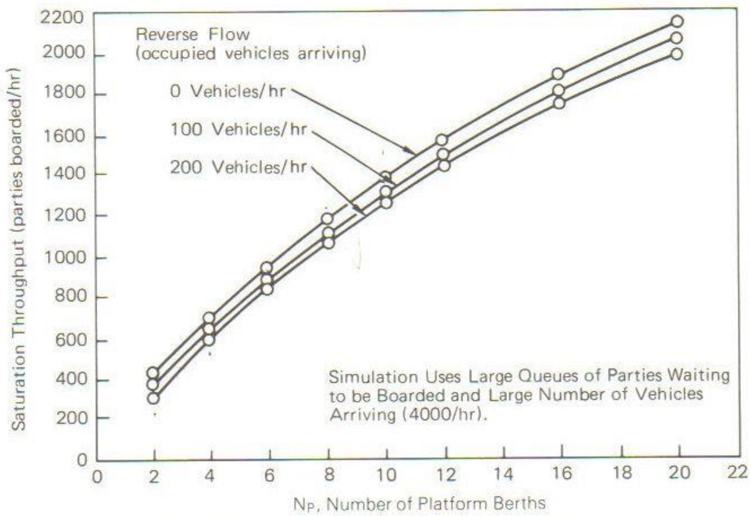


Fig. 3-12. Saturation Throughput for Evening Rush Hours

How many people per hour do conventional rail systems in the United States actually carry? Data from federal sources for peak-period flow averaged over a whole system are shown in Figure 1. In 1973, after extensive investigations by its systems engineers, the UMTA Administrator told congress that "high-capacity PRT could carry as many passengers (per hour) as a rapid rail system." We see in Figure 1 that, with the numbers used above, a high-capacity PRT system can carry more people per hour than carried by any U. S. transit system except the New York subway. The UMTA engineers compared the flow in seats or units of vehicle capacity and for a PRT system assumed 4 seats per vehicle at half-second headway, or 28,800 seats per hour. They compared this figure with the Washington Metro with trains carrying 648 seats every 2 minutes, or 19,440 seats per hour.

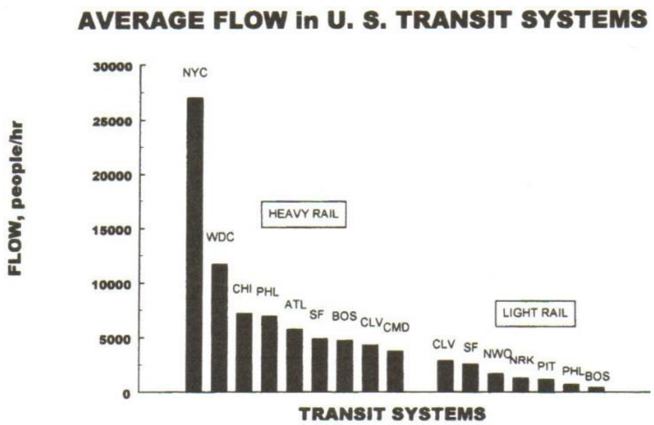
Station Capacity

The above Figure 3-12 is taken from page 77 of Jack H. Irving, et al, *Fundamentals of Personal Rapid Transit*, Lexington Books, D. C. Heath and Company, 1978, which is based on a Program of Research at THE AEROSPACE CORPORATION. This figure gives a good representation of the capacity of PRT stations.

In Reference 2, I reported on the observed flow of people per hour from a large office building, a just-landed 747 aircraft, a hockey arena, and people leaving a baseball park walking to a streetcar station, and found that the maximum of these flows to be about 1200 people per hour, or about one person every 3 seconds, which according to the above figure would require a 10-berth PRT station. These observations can easily be repeated.

Also in Reference 2 I calculate average flows to the stations in a square grid of guideways half a mile apart north-south and east-west. I found that with a population density of 12,000 people per square mile, if half the trips were taken on the PRT system, the average peak hour station flow is only about 225 people per hour, which from Figure 3-12 can be handled by a two-berth PRT station. Much larger station flows are of course possible, for example from the stations of a commuter rail system carrying people home from work. The largest example I have worked on is the peak-hour flow of people leaving Chicago's Union Station into the Chicago Loop. I was given the fraction of those people who would appreciate a ride to their jobs and found that that flow can be handled with a 12-berth station on each of the four sides of Union Station.

System Capacity



The previous paragraph gives an example of the average peak-period demand when there is a network of guideways spread over an area, in this case with 8 stations per square mile. It is seen that even with a population density of 12,000 people per square-mile the average peak-period demand is remarkably small. The reasons the flows to and from a conventional rail system are so much higher are 1) because of the large right-of-way required there can be many fewer lines, and 2) to maintain a reasonable average speed the stations must be placed much farther apart. These two factors combine to result in large numbers of people standing at stations waiting for trains in peak-load periods. Observing this, it is often remarked that PRT cars could not accommodate such large numbers of people, not taking into account that if the flow of people were carried away quickly in PRT cars, such large numbers would not be found standing at the stations. Moreover, since a PRT system can have more stations without reducing the average speed, there would be even less reason for such large crowds to accumulate at one place.

In any specific example, the station sizes and line layout can be determined accurately only by means of an accurate simulation of the system's operation, and then only as accurately as the ridership analysis can be performed. A number of analysts including the author have developed computer programs needed for this task.

1.4.7 Station Throughput

See Section 9.8 for our reasons for considering the type of station shown in Figure 1.4.7.1.

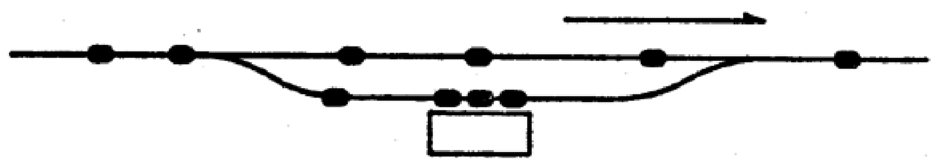


Figure 1.4.7.1. Layout of a Serial-Loading Off-Line Station

Basic Throughput Formula

The cycle time T_c is the time required for a group of *N* vehicles to move forward a distance of *N* berths from rest to rest and then to unload and load passengers. T_c is given by the equation

$$T_c = T_{door} + T_{dwell} + T_a \tag{1}$$

in which T_{door} is the time to open and close the vehicle door, T_{dwell} is the time required for passengers to leave and then enter a vehicle, and T_a is the time to advance from rest to rest a station length L_s ahead. It is given by one of the following three equations, which are derived in Appendix A:

$$\begin{aligned} T_a &= \frac{1}{2}\left(\frac{L_s}{J_c}\right)^{1/3} && \quad if\ 0 \le L_s \le D_1 \\ &= \sqrt{\frac{4L_s}{A_c} + t_J^2} + t_J && \quad if\ D_1 \le L_s \le D_2 \\ &= \frac{L_s}{V_s} + \frac{V_s}{A_c} + t_J && \quad if\ D_2 \le L_s \end{aligned} \tag{2}$$

in which

$$D_1 = 2A_c t_J^2$$

$$D_2 = V_s\left(\frac{V_s}{A_c} + t_J\right)$$

and

$A_c =$ comfort acceleration

$J_c =$ comfort jerk

$t_J = A_c / J_c$
$L_b =$ berth length
$V_s =$ station speed
$L_s = NL_b =$ station length

Under ideal conditions, a group of N vehicles can advance every T_c units of time, so that, if T_c is in seconds, the maximum throughput is

$$Maximum\ Throughput = \frac{3600N}{T_c} \quad vehicles\ per\ hour. \tag{3}$$

Mean Dwell Time

Station throughput is most strongly affected by dwell time, which is a stochastic variable dependent on human behavior, and approximately follows a normal distribution. The basic parameters of dwell time are the mean dwell time and the variance in dwell time. In computer simulations, we must also specify minimum and maximum dwell times. By means of simple experiments, it is possible to obtain reasonable values of these parameters.

In simulating system performance, a random number *R* from zero to one is generated and must be used to pick a value of dwell time from the distribution function. It is thus necessary to take the inverse of the distribution function, which leads to a log function. We have found satisfactory results with the formula

$$T_{dwell} = T_{mean} + T_{\mathrm{var}} \ln\left(\frac{R}{1-R}\right) \tag{4}$$

in which T_{mean} is the mean value of dwell time and T_{var} is its variance. Note that as *R* varies from 0 to 1, ln[*R*/(l - *R*)] varies from $-\infty$ to $+\infty$ and that when *R* = 1/2, the most probable value, the log function is zero. Let the minimum dwell time be $T_{\min}$ and the maximum dwell time be $T_{\max}$. Then for the values T_{mean} = 4.5 sec, T_{var} = 2 sec, $T_{\min}$ = 2 sec, and $T_{\max}$ = 20 sec, the distribution of dwell times was calculated by means of the program of Appendix B and is shown in Figure 2. It can be seen that the distribution of dwell times follows approximately the expected normal distribution. It is assumed that the dwell time calculated from equation (4) applies to passengers either entering or leaving a vehicle. When both occur at one vehicle, the total dwell time is the sum of the two dwell times.

In an *N*-berth station, the cycle time depends on the longest of *N* dwell times. Using the above parameters, the mean value of the longest of *N* dwell times was calculated and averaged for 100,000 randomly determined dwell times for *N* = 1 to 15 by means the program of Appendix B. The results are shown in Figure 3, and can be easily revised if new values of the four dwell-time parameters are found from further observation.

Consequences of Statistical Variation in the Input Flow

If the vehicles arrive in the station exactly every T_c seconds and there are no merge conflicts on departure, the station throughput is exactly as given by equation (3). In reality, vehicles arriving at an average rate of $1/T_c$ vehicles per second are randomly distributed. Thus, sometimes an (N + l)th or (N + 2)th waiting berth will be needed, and sometimes the waiting-time queue will not have filled at the time the vehicles must advance into the loading berth.

A sequence of random arrivals characterized by a fixed average rate λ is described by the Poisson distribution function

$$P_n(t) = \frac{e^{-\lambda t}(\lambda t)^n}{n!} \tag{5}$$

in which $\lambda = 1/T_c$, n is the number of arrivals, and t is a time interval. We need to know the probability of n arrivals in the time interval $t = T_c$, where $n = 0,1,2,...$ This probability is

$$P_n(1/\lambda) = \frac{1}{en!} \tag{6}$$

$P_2(1/\lambda)$ is the probability that two vehicles want to fill the last waiting position in time T_c. If there is no room for the second one, it must either slow down at more than the comfort rate on entering the station or it must by-pass the station, i.e., it must be "waved off." The probability of wave off if there is the same number of waiting positions as loading positions is the sum of the probabilities of arrival of any number of extra vehicles, i.e.,

$$\sum_{n=2}^{\infty} \frac{1}{en!}$$

But e, the base of natural logarithms, can be represented by the infinite series

$$e = 2 + \sum_{n=2}^{\infty} \frac{1}{n!}$$

Therefore

$$P_{waveoff} = \frac{e-2}{e} = 0.2642 \tag{7}$$

If there are $n+1$waiting berths, a second vehicle may arrive early without having to be waved off. Then the probability of wave off is

$$P_{waveoff} = \sum_{n=3}^{\infty} \frac{1}{en!} = \frac{1}{e}\left(e - 2 - \frac{1}{2}\right) = 0.0803 \tag{8}$$

If there are $n+2$ waiting berths, the probability of wave off is

$$P_{waveoff} = \sum_{n=4}^{\infty} \frac{1}{en!} = \frac{1}{e}\left(e - 2 - \frac{1}{2} - \frac{1}{6}\right) = 0.0190 \tag{9}$$

In this way we can construct the following table:

Number of waiting positions	Percent Wave offs
n	26.42
$n+1$	8.03
$n+2$	1.90
$n+3$	0.37
$n+4$	0.06

The probability that no vehicles arrive in T_c is $P_o(1/\lambda) = 1/e = 0.3679$. Thus, if there were *n* waiting positions, in 368 times out of 1000 the waiting vehicles would have to move forward with the last position empty. The person or group waiting at the last berth position would be denied a vehicle and would have to wait for the next one to arrive. But, to minimize wave offs, there must be more than *n* waiting positions. Experience with simulations shows that at least $n+3$ waiting positions are needed. Thus, if in one cycle, no vehicle appears, but in the previous cycle more than one appeared, there would still be *n* vehicles that could move into the unloading and loading berths. Consequently, on the average, the results of equation (3) may still be reasonable.

Modification due to Line-Flow Choking

Headway is the time between vehicles. Let the minimum safe headway on the mainline be $T_{\min}$ and let the actual headway be T_h. The flow rate at minimum headway is $1/T_{\min}$ and the actual flow rate is $1/T_h$. Thus the flow rate of "slots" or potential openings for vehicles from a station is $1/T_{\min} - 1/T_h$. The mean time between slots is the reciprocal of this quantity and the mean time a vehicle ready to leave a station must wait for a slot is half the mean time between slots. Ideally, the cycle time must be increased by just this mean time, but that implies that a vehicle is ready to leave the station every time a slot is available. Because of statistical variations, this can never be true. It is more realistic to assume that only every other available slot can be filled. In this case throughput equation (3) must be modified to the following form:

$$Maximum\,Throughput = \frac{3600n}{T_c + \dfrac{T_{\min}}{\left(1 - T_{\min}/T_h\right)}} \tag{10}$$

A reasonable design condition is that the average peak-period line flow is about half the flow at minimum headway, in which case the throughput equation becomes

$$Maximum\,Throughput = \frac{3600n}{T_c + 2T_{\min}} \tag{11}$$

Conclusions

Simulation results reported by Lioprios (1974) show in a few cases a maximum throughput of about 77 percent of that given by equation (10), which is in approximate agreement with results of the author's station simulation with the same operational strategies. Therefore, as a recommendation for practical maximum throughput, equations (10) and (11) should be multiplied by a factor of about 3/4. Equation (11) multiplied by 3/4 is plotted and tabulated in Figure 4 for $V_s = 9$ meters/sec, $L_b = 2.9$ meters, $A_c = 0.2\,g$, $J_c = 0.25\,g/s$, $T_{door} = 3$ sec, T_{dwell} from Figure 3, for from 1 to 15 station berths, and for minimum headways from 0.5 to 5 sec. The results shown take into account that the maximum station throughput in vehicles per hour physically cannot exceed $3600/T_{\min}$. This limit is evident for $T_{\min} \geq 3$ sec for the larger numbers of station berths.

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Figure 2. Dwell Time Frequency Distribution

in intervals of 0.1 sec

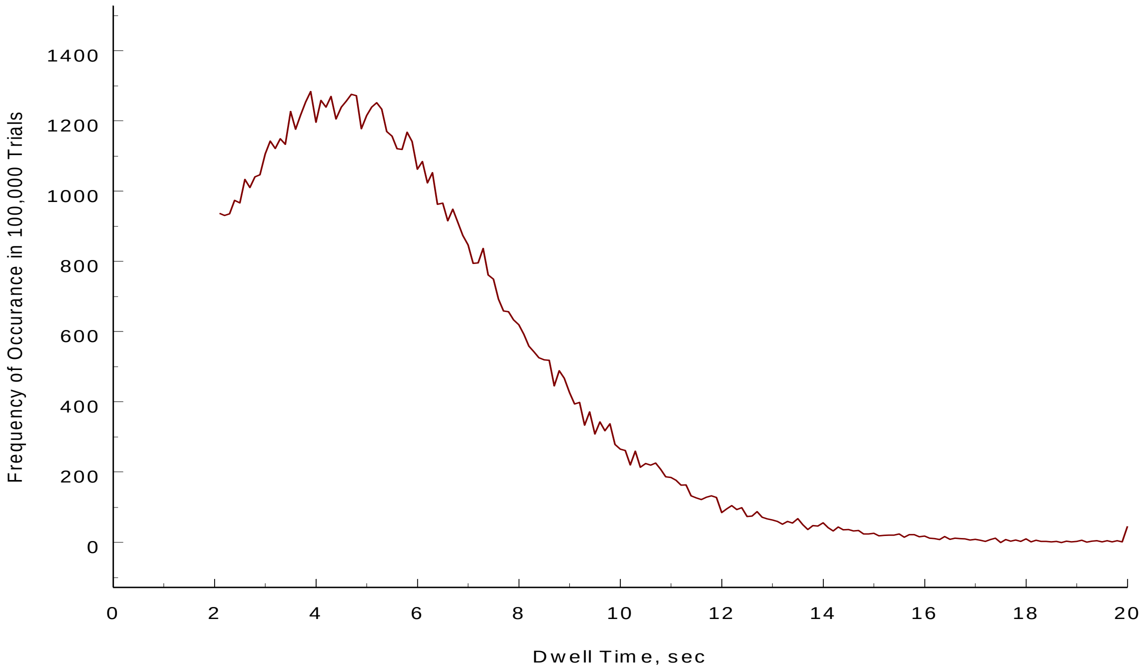


Figure 3. Mean Dwell Time

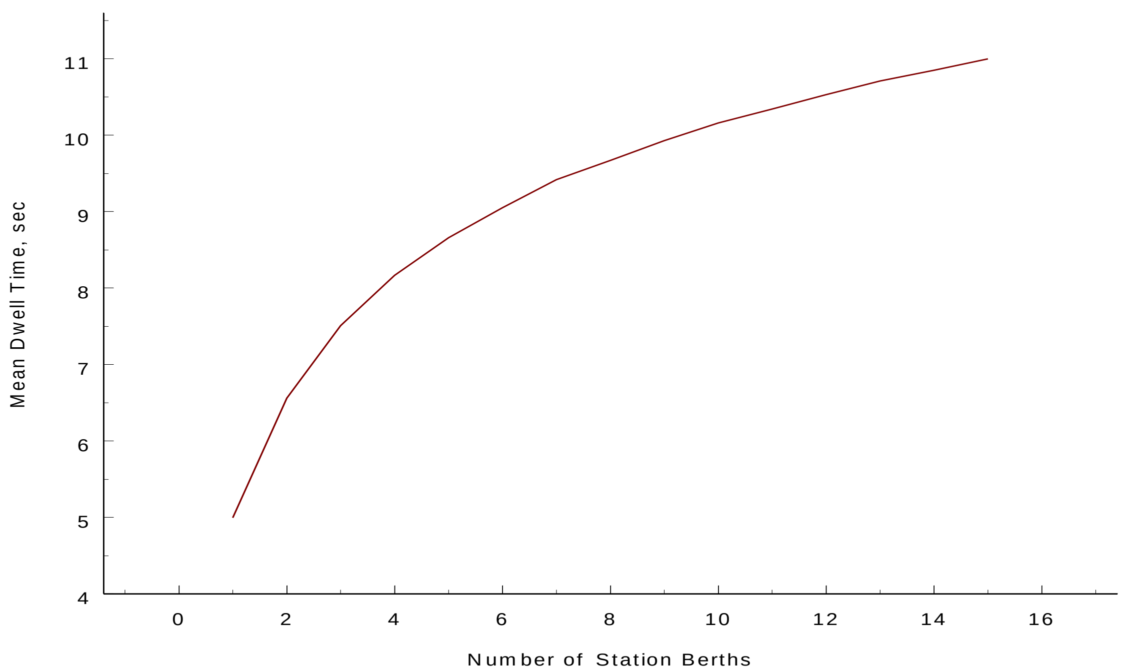
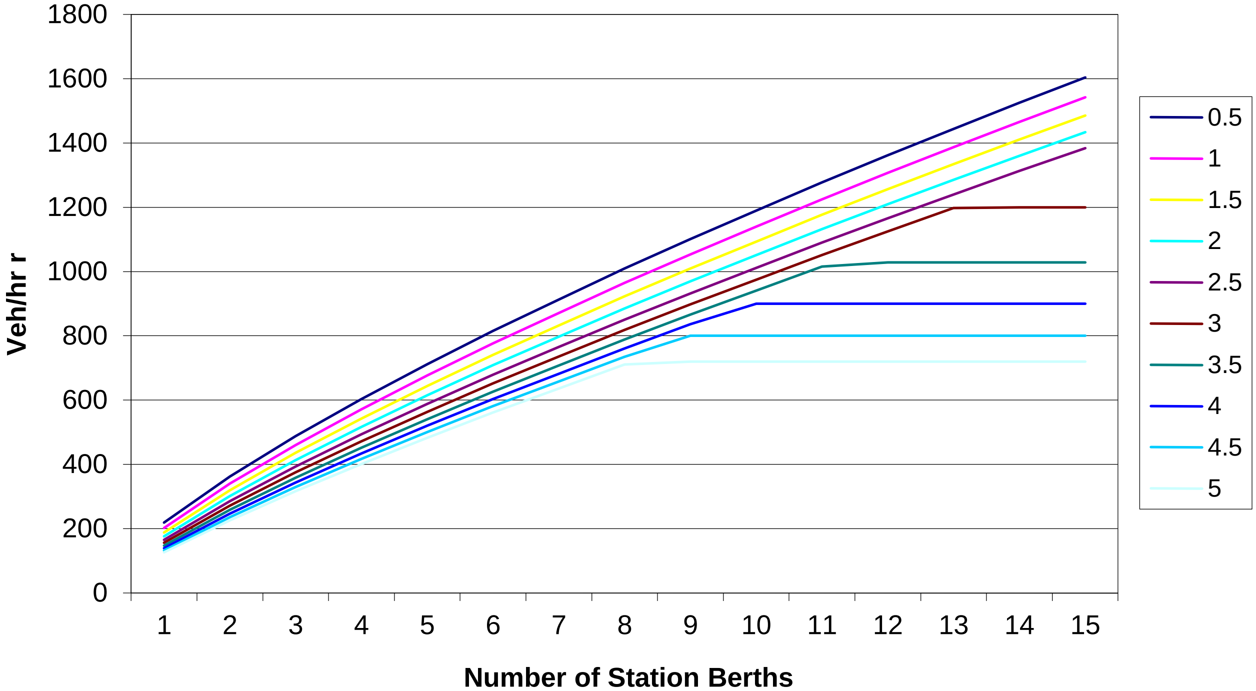


Figure 4. Maximum Throughput of an Off-Line Station



Throughput of an Off-Line Station in Vehicles per hour

Maximum Station Speed is 9 m/s, Tdoor = 3 sec

Minimum Line Headway, sec -->

	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5
1	218	202	188	176	165	156	147	139	133	126
2	363	340	320	302	286	271	258	247	236	226
3	488	460	436	413	393	375	358	343	329	316
4	603	571	543	517	493	472	452	434	417	401
5	712	676	644	615	588	564	541	520	501	483
6	816	777	741	709	679	652	626	603	581	561
7	913	871	832	797	765	735	708	682	658	636
8	1010	965	923	885	851	818	788	761	735	711
9	1101	1053	1010	969	932	898	866	836	800	720
10	1190	1140	1093	1051	1012	975	941	900	800	720

11	1278	1225	1176	1132	1090	1051	1016	900	800	720
12	1362	1307	1256	1209	1166	1125	1028	900	800	720
13	1444	1387	1334	1285	1240	1197	1028	900	800	720
14	1525	1466	1411	1360	1313	1200	1028	900	800	720
15	1604	1543	1486	1433	1384	1200	1028	900	800	720

Appendix A

Derivation of Equations 2 for T_a

We assume that the speed of a vehicle begins from rest at constant jerk J_c up to an acceleration A_1. Then if x is the distance variable

$$\dddot{x} = J_c, \quad \ddot{x} = J_c t, \quad \dot{x} = \frac{1}{2} J_c t^2, \quad x = \frac{1}{6} J_c t^3. \tag{A-1}$$

Let this motion proceed until $\ddot{x} = A_1 \ at\ t = t_1$. At this point

$$t_1 = \frac{A_1}{J_c}, \ V_1 = \frac{A_1^2}{2J_c}, \ x_1 = \frac{A_1^3}{6J_c^2} \tag{A-2}$$

At $t = t_1$ apply negative jerk of the same magnitude until $\ddot{x} = 0 \ at\ t = t_3$. Then

$$t_3 = 2t_1 = 2\frac{A_1}{J_c}, V_3 = 2V_1 = \frac{A_1^2}{J_c} \ so\ \frac{A_1}{J_c} = \frac{V_3}{A_1} \ and\ t_3 = \frac{V_3}{A_1} + \frac{A_1}{J_c}. \tag{A-3}$$

By symmetry

$$x_3 = x_1 + (V_3 t_1 - x_1) = \frac{V_3}{2}\left(\frac{V_3}{A_1} + \frac{A_1}{J_c}\right) = \frac{A_1^2}{2J_c} \cdot \frac{2A_1}{J_c} = \frac{A_1^3}{J_c^2}. \tag{A-4}$$

Now, in advancing through a station, the vehicles accelerate to a speed we call here V_3 and then decelerate in the same way to zero speed. If $V_3 < V_s$, the designated maximum station speed, and if $A_1 < A_c$, the designated maximum comfort acceleration, then the distance traveled, L_s is

$$L_s = 2x_3 = 2\frac{A_1^3}{J_c^2}. \tag{A-5}$$

So, if $L_s \le 2\frac{A_c^3}{J_c^2}$ then $\frac{A_1}{J_c} = \left(\frac{L_s}{2J_c}\right)^{1/3}$. We have designated the time to advance a distance L_s from rest to rest as T_a, which we see in this case is $2t_3$. Thus, if

$$L_s \le 2\frac{A_c^3}{J_c^2} = 2A_c t_J^2 \equiv D_1, \tag{A-6}$$

where
$$t_J = A_c / J_c \tag{A-7}$$

then
$$T_a = 4\left(\frac{L_s}{2J_c}\right)^{1/3} = \frac{1}{2}\left(\frac{L_s}{J_c}\right)^{1/3}. \tag{A-8}$$

If the vehicle reaches $A_1 = A_c$ *but* $V_3 < V_s$, which is always the case since we will always have $V_s > A_c^2 / J_c$, we must introduce a new intermediate time t_2 , which is the time from rest to the end of a region of constant acceleration A_c. Then, from symmetry,

$$t_3 = 2t_1 + \frac{V_2 - V_1}{A_c} = 2\frac{A_c}{J_c} + \frac{1}{A_c}\left(V_3 - V_1 - V_1\right) = \frac{V_3}{A_c} + 2\frac{A_c}{J_c} - \frac{A_c}{J_c} = \frac{V_3}{A_c} + \frac{A_c}{J_c} \tag{A-9}$$

which is the same as the previous formula given by equations A-3. From symmetry, the distance x_3 is the same as given by equations A-4 with $A_1 = A_c$. Thus

$$L_s = 2x_3 = V_3\left(\frac{V_3}{A_c} + \frac{A_c}{J_c}\right) \tag{A-10}$$

which can be written in the quadratic form

$$V_3^2 + \frac{A_c^2}{J_c}V_3 - A_c L_s = 0$$

the solution of which is

$$V_3 = \frac{1}{2}\left[-\frac{A_c^2}{J_c} + \sqrt{\left(\frac{A_c^2}{J_c}\right)^2 + 4A_c L_s}\right]$$

which can be written in the form

$$2\left(\frac{V_3}{A_c} + \frac{A_c}{J_c}\right) = \sqrt{\frac{4L_s}{A_c} + \left(\frac{A_c}{J_c}\right)^2} + \frac{A_c}{J_c}. \tag{A-11}$$

So now, from equation A-10, if

$$L_s \le V_s\left(\frac{V_s}{A_c}+\frac{A_c}{J_c}\right)\equiv D_2 \tag{A-12}$$

then

$$T_a = 2t_3 = 2\left(\frac{V_3}{A_c}+\frac{A_c}{J_c}\right)=\sqrt{\frac{4L_s}{A_c}+t_J^2}+t_J\,,\quad t_J=\frac{A_c}{J_c}\,. \tag{A-13}$$

Now, if $L_s \ge D_2$ we have

$$L_s = 2\left(\frac{V_s}{A_c}+\frac{A_c}{J_c}\right)+V_s\Delta t$$

so

$$\Delta t = \frac{L_s}{V_s}-\frac{V_s}{A_c}-\frac{A_c}{J_c}. \tag{A-14}$$

In this case

$$T_a = 2\left(\frac{V_s}{A_c}+\frac{A_c}{J_c}\right)+\Delta t = \frac{L_s}{V_s}+\frac{V_s}{A_c}+\frac{A_c}{J_c} \tag{A-15}$$

The three cases derived in this Appendix agree with equations (2). QED

Appendix B

```
'This program LOADING.BAS calculates the mean loading and unloading time
'in an N-berth HCPRT system

DEFDBL A-Z
DIM Tave(15) AS DOUBLE
DIM Ndwell(200) AS INTEGER
DIM N, I AS INTEGER
DIM NN, J AS LONG

Tmean = 4.5  'mean loading time not counting door opening and closing time
Tvar = 2     'variance in loading time
Tmin = 2     'minimum loading time
Tmax = 20    'maximum loading time
NN = 100000  'number of trials calculated

CLS

'Calculate the frequency distribution of loading and unloading times
OPEN "LOADFREQ.ASC" FOR OUTPUT AS #1
FOR J = 1 TO NN

  'Calculate a loading time
  R = RND
```

```
  IF R > 0 AND R < 1 THEN Tload = Tmean + Tvar * LOG(R / (1 - R))
  IF R = 0 THEN
    Tload = Tmin
  ELSEIF R = 1 THEN
    Tload = Tmax
  END IF
  IF Tload > Tmax THEN
    Tload = Tmax
  ELSEIF Tload < Tmin THEN
    Tload = Tmin
  END IF
  'Count the number of dwells in each 0.1-sec interval
  FOR I = 10 * Tmin TO 10 * Tmax
    IF INT(10 * Tload) = I THEN Ndwell(I) = Ndwell(I) + 1
  NEXT I
NEXT J
'Record the dwell frequency distribution
FOR I = 10 * Tmin TO 10 * Tmax
  PRINT I / 10, Ndwell(I)
  WRITE #1, I / 10, Ndwell(I)
  count = count + 1
  IF count = 40 THEN count = 0: SLEEP
NEXT I
SLEEP
CLOSE #1

'Calculate the mean of N dwells, where N=1 to 12
OPEN "LOAD.ASC" FOR OUTPUT AS #1
FOR N = 1 TO 15
  Tav = 0
  FOR J = 1 TO NN
    TmaxN = 0
    FOR I = 1 TO N
      'Calculate a dwell time
      R = RND
      IF R > 0 AND R < 1 THEN Tload = Tmean + Tvar * LOG(R / (1 - R))
      IF R = 0 THEN
        Tload = Tmin
      ELSEIF R = 1 THEN
        Tload = Tmax
      END IF
      IF Tload > Tmax THEN
        Tload = Tmax
      ELSEIF Tload < Tmin THEN
        Tload = Tmin
      END IF
      'Find the largest of N dwells
      IF Tload > TmaxN THEN TmaxN = Tload
    NEXT I
    Tav = Tav + TmaxN   'Accumulate the load times to find the average
  NEXT J
  Tave(N) = Tav / NN    'Average loading time
  PRINT N;
  PRINT USING "####.##"; Tave(N)
  WRITE #1, N, Tave(N)
NEXT N
CLOSE #1
```

1.4.8. Units

Since the United States still used the foot, pound, second (FPS) system of units, while almost all of the rest of the world uses the meter, kilogram, second (MKS) system, we in the United States must know how to quickly convert from one of these system of units to the other.

The weight *W* of an object is equal to its mass *m* multiplied by the acceleration of gravity, g. Thus

$$W = mg$$

In FPS units, a mass of 1 lb will under standard gravity weigh 1 lb, which seems to be ambiguous, and can be solved by only using the pound force.

We can illustrate by considering the force applied to an object by wind. A wind speed *V* applied to a surface applies a force of

$$F = \frac{1}{2}\rho V^2 C_D A$$

in which ρ is the mass density of air, C_D is the dimensionless drag coefficient and A is the area on which the wind is applied. In FPS units, we use the weight density of air, and so write the force equation as

$$F = \frac{\rho g}{2g} V^2 C_D A$$

in which the standard value of ρg = 0.075 lb weight/ft^3.

In MKS units, the kilogram, kg, is the unit of mass. The unit of force is the Newton, *N*, and one *N* is required to move a mass of one kg at an acceleration of 1 meter/sec^2. Sir Isaac Newton stated as his third law of motion, a law proven to be true by almost 400 years of experience if the speed is not close to the speed of light, that a force *F* is required to move a mass *m* at an acceleration *a*, where

$$F = ma$$

In metric units, standard g = 9.80665 m/sec^2, and there are 0.0254 meters per inch, or

$$0.0254 \frac{m}{in} \times 12 \frac{in}{ft} = 0.3048 \frac{m}{ft}.$$

Thus, in English units,

$$g = \frac{9.80665}{0.3048} = 32.1740 \frac{ft}{sec^2}.$$

The accepted standard relationship between pounds mass, lb, and kilograms, kg, is

$$2.2046 \text{ lb mass} = 1 \text{ kg.}$$

In the MKS system, as mentioned, it takes a force of 1 N to accelerate a mass of 1 kg at 1 m/sec^2. Thus a mass of 1 kg weighs 9.80665 N, i.e.

$$1\, kg \times 9.80665\ \frac{m}{sec^2} = 9.80665\, N$$

or

$$2.2046 \text{ lb mass} \times \text{g} = 9.80665 \text{ N}$$

Thus

$$1 \text{ lb mass} \times \text{g} = \frac{9.80665}{2.2046} = 4.4483\, N = 1 \text{ lb force}$$

In the case of the force of an air stream on a surface,

$$\rho = 0.075\frac{lb}{ft^3} \times \left(\frac{1\, ft}{0.3048\, m}\right)^3 \times \frac{1\, kg}{2.2046\, lb} = 1.201\frac{kg}{m^3}$$

The value of g in FPS units is 9.80665 m/sec^2 /0.3048 m/ft = 32.174

Assume that V = 30 mph = 44 ft/sec = 13.411m/sec, A = 20 ft^2 = 1.858 m^2, C_D = 1. Then

$$F = \frac{0.075}{64.35}44^2(1)(20) = 45.13\, lb = \frac{1.201}{2}(13.411)^2(1)(1.858) = 200.7\, N = 45.12\, lb$$

Acknowledgements

A serious problem with finding funds needed to build High-Capacity PRT has been that, after the Raytheon debacle no large industry has been willing to step forward with support. It is natural and responsible for city planners to look only at systems they can purchase and are supported by companies with a sufficiently solid reputation that they could be confident that the system would be supported into the indefinite future. A small company like Taxi 2000 was not able to establish such a record. Even with Shef Lang alive and active we looked weak, and without him weaker. I first met Dick Daly in 1974 when he was Director of Government Marketing for the Raytheon Company, and it took 19 years and a special circumstance before the Raytheon CEO decided to enter the market, and even then the project did not succeed. Getting a new large company involved, which means getting their engineers involved – engineers their top management would trust, but who would have had no experience in PRT – likely would mean another flop.

In 1971 the Ford Motor Company CEO, Henry Ford II, having read about interest in PRT, decided to enter the automated transit market. As would any similar CEO, he assigned a group of his engineers to the project, again engineers with no understanding of PRT technology. They designed an automated system they called ACT for Automatically Controlled Transportation. It used 24-passenger vehicles supported by standard truck chasses and riding on a wide, concrete-trough elevated roadway. The operating and maintenance costs were off the chart. Ford built a demonstration at the Fairlane Town Center in Dearborn, Michigan, and built the guideway for a second system at the Hartford, Connecticut, Airport. Its operating-cost estimate was so high that the Connecticut Governor refused to fund the deficit, which required Ford, at great embarrassment, to tear it down. The basic problem was that the engineers involved were not given the time and resources to thoroughly understand the theory and practice of PRT before they started to design, and they violated basic rules of Engineering Design. They thought the problem was simple.

Another example was McDonnell Douglas. They decided to enter the automated transit field by in 1974 by licensing a maglev system being developed by Krauss-Maffei of West Germany. There could have been no systems engineering in either McDonnell Douglas or Krauss-Maffei because, due to shockingly high operating-energy use, the German government stopped funding the project even after it was promised for a Fair in Canada. I was visiting Krauss-Maffei in Munich the day the plug was pulled.

After the Chicago PRT project collapsed, it was difficult to see any other U. S. city taking the lead again anytime soon unless a significant number of its political leaders could become informed while inevitable flak from conventional rail supporters would try to shoot the new idea down. These leaders would need to understand why light rail, even with a federal construction grant, would be such a bad choice that they would be willing to investigate a new idea. We got Chicago interested because we were working with Raytheon, with the high expectation that, since one of their managers, Dick Daly, was involved, the company must have been involved. Decision makers don't seem to understand the freedom of initiative middle managers are often given in large corporations.

In at least one incidence, however, government did the right thing. In 1990 Congress decided to fund a program to develop 300-mph magnetically levitated trains. As the first phase they awarded \$28M of contracts to four maglev concept systems. Instead of requiring these design studies to be led by large companies, the National Maglev Initiative Office gave each prime contract to the developer of a specific maglev concept with Raytheon, Grumman, Hughes, and Bechtel as subs. What a concept! Let the people who understand the problem lead! If that had happened in Chicago, PRT would have been running by 1995.

Dick Daly wrote to me shortly after the 2003 State Fair was over. Somehow he had learned what we had done. The letter was most gracious and led me to recall that without his involvement with me for two decades, we likely could not have advanced anywhere near as far as we did, and likely would have had to give up long ago. The PRT field is full of people who have provided essential assistance for a time, then for one reason or another had to drop out or died. I have written eulogies to four of the most outstanding – Dr. Larry Goldmuntz, Dr. Byron Johnson, A. Scheffer Lang, and Dr. Jack Irving. The current state of PRT, with projects now outside of the United States, is due to efforts of a great many people. For me, beyond the excellent team I had at the University of Minnesota including Professors Jack Dais, Bill Garrard, Alain Kornhauser & Harold York, I think of my department head Dr. Richard Jordan, Conference Coordinator Gordon Amundson, Donn Fichter, Ed Haltom, The Aerospace Corporation with the outstanding leadership of Dr. Jack Irving, Dr. Jerry Kieffer, Dr. Larry Goldmuntz, Minnesota Senators Mel Hanson & Robert North, Congressman Bill Frenzel, Dick Daly, Dr. Byron Johnson, Professor Catherine Burke, Barton Aschman Vice President Mike Powells, German one-man UMTA Hermann Zemlin, Klaus Becker, Morse Wade, Professor Jerry Schneider, Duncan MacKinnon, Professor Lonnie Haefner, Dick Willow of Congressman Frenzel's staff, Indiana Assemblymen Dick Doyle and Dr. Ned Lamkin, Dr. Larry Dallam, Ferrol Robinson, LIM-Developer Alan Foster, Professor Syed A. Nasar, Ray MacDonald, Kim In Key, University of Minnesota Associate Vice President for Technology Transfer Tony Potami, former Dean of the University of Minnesota Institute of Technology Roger W. Staehle, Joe Schuster, Davy McKee President Bob Perry, Mike Loffel, Ike Glicker, Paul Hoffman, Scott Gaff, Professor Phil Lewis, my pro-bono legal counsel Bert Press, Dick Gehring, Jim Carley, Boston University Board of Trustees Chairman Arthur G. B. Metcalf, Thomas Watson's grandson Stuart Watson, Judd Berlin, Boston University President John Silber, Harvard Professor Charles Harris, HUD Director for Sustainable Cities Andy Euston, Raytheon Senior Vice Presidents Dr. George Sarney and Walter Stowell, Larry Jack, Jan Poot who provided the illustration on the title page, George Billman, Chicago RTA Chairman Gayle Franzen, Tom Riley, John David Mooney, Professor Ted Galambos, Dr. Ingmar Andréasson, Göran Tegnér, Jan Eric Nowaski, John Martinson, Dr. Ray Warner, Bill Wilde, A. Sheffer Lang, Dr. Charles Roth, Dr. Harold Cates, Charles Michael, David Gow, Liz Sroufe, Roy Moore, Tom Goff, Jake Solomon, Ed Porter, John Braff, Ed Rydell, Richard Broms, Kurt Allen, Attorney's Chuck Shreffler and Jack Clifford, Minneapolis City Councilman Dean Zimmerman, Minnesota State Representatives Mark Olson and Bruce Anderson, Minnesota State Senators Gen Olson and John Marty, Minnesota Transportation Commissioner Tom Sorel, Rev. R. Alan James, New Zealand website developer Will Wilson, 747-pilot

Richard Gronning, Bruce Haydu, Fred Brody, Laura Stuchinsky, Tom Paige, Scott Spaeth, many individuals in ATRA and Citizens for PRT, many other individuals who have assisted in many ways, some of whom I have mentioned in this document, and by a supportive family including my three children, Candy, Jim and Stan, and my wife, Cindy.

In my autobiography I have mentioned that in 1968 while in the Soviet Union on an exchange program sponsored jointly by the United States Academy of Sciences and the Soviet Academy of Sciences, I became increasingly unhappy with the way my career was going. The subject was so complex that I felt that no more than a half dozen scientists in the world would care about my work. I thought of the time I had spent at Honeywell working on projects that required the coordinated activity of many engineers. While brooding about it, suddenly from nowhere I recalled a statement of Jesus: "He who shall lose his life for my sake shall find it and find it in abundance." I immediately interpreted that to mean: "He who shall become deeply involved in a cause of fundamental need for mankind shall find his life in abundance." That was it! I found my life, thus far in spiritual abundance through the many, many friends and acquaintances who have joined with enthusiasm over the past four and a half decades for a new mode of urban transportation. It has been worth the effort and it is still worth the effort. Now, more than a decade after the 2003 State Fair and after many more figurative roller-coaster rides, we are positioned to reach the dream we have worked on for so long.

To those who have in one way or another resisted these efforts, I try to understand that each person has his or her own agenda and that these different agendas often clash. For those who feel they will lose their jobs if PRT takes hold, I hope that PRT advances at a rate that will permit career adjustments to be made. But resistance to a system that can be built for less than 10% of the cost per passenger-mile of light rail, will require less than 15% of the energy per passenger-mile of light rail, will release no greenhouse gases, will occupy no more than 0.02% of the surface land, and will attract around ten times the ridership of light rail while our country faces huge deficits and while the need to conserve energy and reduce greenhouse gases becomes more and more apparent cannot for long persist.

We will contribute by introducing a system that is badly needed for urban societies everywhere. We can do well by doing good. I have been blessed by wonderful parents, the education I received from Mom, in grammar school, high school, North Park College, Iowa State University, the University of Virginia, the University of Minnesota, and the Massachusetts Institute of Technology; while working at the NACA (now NASA) Structures Research Laboratory at Langley Field, VA, and the Honeywell Aeronautical Division; and while a professor at the University of Minnesota and Boston University. All have been relevant to every important phase of PRT development. Finally, I have been blessed by being the son of missionary parents who found their lives in helping others.

About the Author

Fyi

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DEPARTMENT OF ECONOMICS

August 5, 1986

Dean Louis Padulo,
College of Engineering
Boston University
110 Cummington St.
Boston, Mass. 02315

My dear Dean:

It has been my good fortune to know J. Edward Anderson for at least 15 years. It grew out of his working here as a consultant for the Regional Transportation District, shortly after I had been Chairman of the Mayor's Committee on Mass Transit, and then served on the HUD Advisory Committee on Mass Transit. In the years since then, We have met frequently, and corresponded much. I have been privileged to read many of the fine papers Ed has written, and to share with him our common concern that public transit needs to be small, automated, on-call (demand-responsive), elevated, quiet, attractive, serving urban goods movement as well as people.

Having hosted or attended a number of national conferences on public transit, I can attest that Prof. Anderson is viewed throughout the profession as one of the most imaginative, thoughtful, sensitive, thorough-going, inventive and creative minds--not only in the US, but in Germany, England, and Japan. In visits to Minneapolis, I have met a few of his studetns, who have great respect and affection for him. You will be fortunate to have him on your faculty. He has a great deal to contribute.

While my contacts have been with his work in transportation, I know from our conversations and his resume that his earlier work in engineering is equally impressive.

Sincerely yours,

Byron L. Johnson

Byron L. Johnson, Professor-Emeritus
Chairman, Denver RTD Board, 1984
Regent, U. of Colorado, 1970-1982

Davy

Davy McKee

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August 5, 1986

Dean Louis Padulo
School of Engineering
Boston University
110 Commington St.
Boston, MA 02215

Re: Dr. E. Anderson
Letter of Recommendation

Dear Dean Padulo:

I have been associated with Dr. Anderson for over a year in Davy McKee's efforts to assist in the development of the TAXI 2000 personal rapid transit system which he conceived.

My work with Ed has been a most rewarding experience. He is truly a man of utmost integrity and capability and his interpersonal attributes are only exceeded by his excellent oral and written communication skills.

Technically, Ed is superbly qualified in a multitude of technical disciplines and is additionally gifted with an ability to convey his highly sophisticated knowledge and reasoning in an understandable way for those who do not have his training, experience or aptitude in technology. Since such skills are in my opinion the essence of the teaching profession, it is appropriate that Ed should dedicate part if not all of his time to teaching especially at a university as renowned as Boston University.

Ed's attributes have dimensions of such breath that he is able to function with great advantage in many diversified non academic roles. This is witnessed in business leadership roles in developing and promoting the TAXI 2000 Company and the management tasks he successfully accomplished while located here in our Chicago office.

There is no doubt in my mind and in that of my associates that Ed's technical and communication skills are far above the norm. However, his greatest asset is his unrelenting personal commitment and dedication to

Dean Louis Padulo
Boston University
August 5, 1986
Page Two

personal rapid transportation system technology which I sincerely believe will revolutionize the transportation industry. Even more significant is his loyalty to those individuals and organizations who have supported him in his endeavors even when such loyalty was not in his best personal interest.

Dr. Anderson is indeed a professional of the highest capability and integrity and will surely be a significant asset to Boston University. I highly recommend him for the position he is seeking.

Very truly yours,

DAVY McKEE CORPORATION

M. W. Loeffl

M. W. Loeffl
Vice President - Projects

MWL/kb

ROGER W. STAEHLE
24 Ardmore Drive
Minneapolis, MN 55422
(612) 374-9606

August 9, 1986

Dr. Louis Apadulo
Dean
College of Engineering
Boston University
110 Cummington Street
Boston, Massachusetts 02215

Dear Dean Padulo:

I understand that you are considering Dr. J. Edward Anderson for your faculty. I have known Ed in two primary connections.

First, when I was Dean of the Institute of Technology at Minnesota, he was a member of the Mechanical Engineering faculty. I knew him then as a committed teacher since his course on technology and ecology was well known and one of the more popular courses for students who were not in the Institute of Technology. Every so often I would receive a note from a student commenting on the high quality of Professor Anderson's course as well as a great personal meaning to the student.

In fact, one of these notes from a student came exactly at the time when another institution was trying to lure Ed away from Minnesota. I am sure you understand very well the tricks that deans must play in keeping outstanding faculty without giving pay raises. My only option at the time was to forward a recent student's note to Professor Anderson's department chairman, Richard Goldstein, and arrange for Professor Anderson to be made aware of the student's note.

There was another occasion I recall where we had to exert ourselves to keep Professor Anderson.

Another important part of Professor Anderson's teaching talent lies in his great personal commitment to social progress; thus, he is committed not only to his major research programs but he is also committed to projects which make net social advances.

I have also worked with Professor Anderson in getting the business started associated with personal rapid transit and have contributed slightly over two years as President of the company. I also helped get the company started in 1983. Thus, I came to know Ed in detail.

Dr. Louis Apadulo
August 9, 1986
Page 2

Another of his talents besides teaching is his great analytical capability. Ed is certainly head and shoulders above most faculty in the area of analysis as well as the enthusiasm with which he approaches analysis. He is competent in a broad range of analytic procedures and technical areas. Further, those areas with which he is now familiar usually break under his assault in a relatively short time.

Finally, it is my general opinion that Professor Anderson understands the field of ground transportation probably better than anybody in the world and, for this reason alone, he should be a great asset to your faculty.

I would be pleased to supply whatever other information you need.

Sincerely,

Roger W. Staehle

Roger W. Staehle
Professor of Chemical Engineering
and Materials Science
University of Minnesota

RWS:mls

RAYTHEON COMPANY

WAYLAND. MASSACHUSETTS 01778

RICHARD F. DALY
MANAGER OF MARKETING

12 August 1986

Dean Louis Padulo
College of Engineering
Boston University
110 Cummington Street
Boston, MA 02215

Dear Dean Padulo:

Dr. J. Edward Anderson asked me if I would write you and recommend his appointment as a Visiting Professor at Boston University. I am pleased to do so without reservation.

I have known Ed Anderson for more than ten years. In the early-mid seventies Raytheon began investigating the application of technology to urban transit. I soon learned that academic work in that field was in process at the University of Minnesota and that Professor Anderson was recognized as the most knowledgable expert in the world. I visited him at Minnesota and later we went to Europe together to review technical efforts then underway in France and Germay. Subsequently he spent a sabbatical year here at Raytheon working on transit system concepts.

I have attended a number of lectures by Dr. Anderson and have spent hundreds of hours with him in creative working sessions. He is an excellent lecturer, an enormously competent engineer, and a patient, pleasant and effective instructor. Based on my direct knowledge, I am confident that Professor Ed Anderson will be an outstanding addition to the faculty of Boston University.

Sincerely yours,

Richard F. Daly
(MA Physics B.U. 1949)

/mf

UNCLASSIFIED AIR POUCH

OPERATIONS MEMORANDUM

TO: USIA WASHINGTON FOR: ICS/S DATE: April 19, 1973

FROM: USIS STOCKHOLM

SUBJECT: Volunteer Speaker J. Edward Anderson

REF: -

Stockholm seems recently to have had more than its fair share of speakers who fell below the grade. Some of these were gotten through the Volunteer Speaker Service and we have duly reported on them. Having been assiduous in writing up the negative, we feel it only fair now to write up the positive: Mr. J. Edward Anderson, Professor of Mechanical Engineering, University of Minnesota.

Mr. Anderson was practically a model speaker. His topic was personal rapid transit systems and he came extremely well prepared with slides, a film and his own printed material for distribution to members of the audience. A relaxed style accentuated his total expertise on his subject, and his presentation was both lucid and absorbing. In the discussion which followed, Mr. Anderson proved more than capable of handling all questions.

In sum, a speaker who was nearly perfect. We wish all speakers could match his standard of excellence and recommend him most highly to all posts.

USIS:CD:JHudson:WBPetty:abs

UNCLASSIFIED

IA-5D (11-73)

FIELD - MESSAGE

U. S. INFORMATION SERVICE

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Classification

FROM: USIS Bonn

TO: USIA WASHINGTON

MESSAGE NO. 88

REF:

DATE November 30, 1977

E.O. 11652: N/A

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DEC 5 11 14 '77

USIA A-

SUBJECT: New Transportation Technologies Discussions in Düsseldorf

AGENCY USE 305

ACTION IOP/D

INFO. IEU ICS IOP/G IOP/R DFS State COMM DOT

SUMMARY: VOLUNTARY SPEAKER J. EDWARD ANDERSON, PROFESSOR OF MECHANICAL ENGINEERING, UNIVERSITY OF MINNESOTA,AND PROMINENT SPOKESMAN FOR NEW TRANSPORTATION TECHNOLOGIES HAD INFORMAL LUNCHEON DISCUSSION WITH NORTH RHINE-WESTPHALIA'S AND DUESSELDORF CITY'S LEADING TRANSPORTATION OFFICIALS. EXPERT EXCHANGES WERE PROFITABLE. COMPLEXITY OF U.S. PROBLEMS STRESSED AS WERE IMAGINATIVE RANGE OF SOLUTIONS BEING DEVELOPED.

A group of nine senior German officials concerned with planning and implementation of state and city transportation systems met on November 22, 1977, with Dr. Anderson, a personable and, as far as the post could judge, totally informed researcher now specializing in the field of new transportation technologies.

USIS Duesseldorf, during the past few years, has had a variety of occasions to bring together experts in the field of urban planning and, particularly, new transportation systems-- primarily because the state of Northrhein Westphalia has taken a leading position in the construction of new vehicles and systems.

These expert discussions,so called, were often less than fulfilling, from the post's point of view, because German experts' attitudes toward our experts lay somewhere between bemusement and condescension. The negative aspects of our transportation planning were all too well known-- BART, electric car failures and immense public transportation system deficits provided the grist for horror stories at our expense.

The discussions with Anderson and the planners went a little differently and the post feels satisfied that a slight dent was made in upper level smugness. First of all, Anderson was impressive in showing that easy solutions are not always best. He had also calculated costs, deficits, etc. comparatively and

DRAFTED BY: USIS Duesseldorf:PJReuss:un

DATE: Nov.23, 1977

APPROVED BY: John P. Clyne

USIS AND OTHER CLEARANCES: USIS:FC:RVGildea

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PAGE 1 OF 2

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FROM USIS Bonn

was able to show that systems currently in vogue in Europe are not necessarily the most effective, either aesthetically or cost effectively. Our planners became aware, we hope, that considerable intelligence and imagination exists in the U.S. planning process, that political considerations need not always be crass, and that the best of all possible transportation worlds has not yet been reached, but would be more reachable if more substantive interchanges could take place between people working on similar problems.

The atmospherics of the brief but intense session reflected this change from genial scepticism through alertness toward a final flurry of name and address exchanges, requests for additional information and thanks for an unusual exposure.

for [signature]

Alexander A. Klieforth

Country Public Affairs Officer