"Systems Engineering applied to Urban Transportation"

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Preface

Over the past four decades and more, over 40 Personal Rapid Transit (PRT) systems have appeared, some with substantial funding, and then disappeared. As Chairman of four International Conferences on PRT, I carefully studied each of them and found that, while they accepted and indeed promoted the basic PRT concept – off-line stations, small vehicles, and automatic control – they fell down because they either did not understand how to design the control system or they neglected some important requirements in the design of the guideway. The only PRT concept that I found fully acceptable is the one designed by The Aerospace Corporation, quite likely because, having been formed in 1960 to manage ballistic missile programs for the United States Air Force, they have the best Systems Engineering team in the World. The system I propose (ITNS) has drawn heavily on their work and has been improved by further analyses and by advances in technology not available when they initiated their work on PRT in 1968 or even in 2005 when I was forced to leave Taxi 2000 Corporation.

Many years ago, I was privileged to hear a lecture by Cal Tech Astrophysics Professor Fritz Zwicky on his concept of Morphology, which was based on his work during World War II in the design of jet engines. He wrote a book he called *Morphology of Propulsive Power*,[1] but his ideas can and should be applied to any design. He stressed design *without prejudice,* and wrote: ". . . the indomitable determination to investigate any complex of problems without any prejudice is not trivial at all, and it perhaps has never been fully realized in practice. Prejudices stemming from personal weaknesses and limited experience, from stupidity, inertia, aversions, superstitions, sympathies, love and fear, neuroses, from taboos and conventions, from influence of pressure groups and from restrictions imposed and suppressions practiced by dictators . . . have in the past poisoned and falsified much of the thinking of man."

From the experience of my own design work, from teaching mechanical-engineering design, from studying the work of other design professionals, from being influenced by Professor Zwicky, and from observing all of the mistakes a certain company made in designing its own PRT system, I wrote a paper I called "16 Rules of Engineering Design," which anyone can obtain from information given on page 7 of this document. On that same page I summarize the basic morphological ideas in one large slide.

The Power Point presentation that is the content of this paper is based on over 40 years of involvement in PRT politics, planning, development, design, and study of almost every PRT system proposed. It is the briefest summary of my work, which on several occasions I have presented in 10 two-hour lectures, each followed by a 3-hour Q&A period. The HUD Director for Sustainable Cities called my system "an essential technology for a sustainable world." Details are given in the book announced on page 7 of this presentation.

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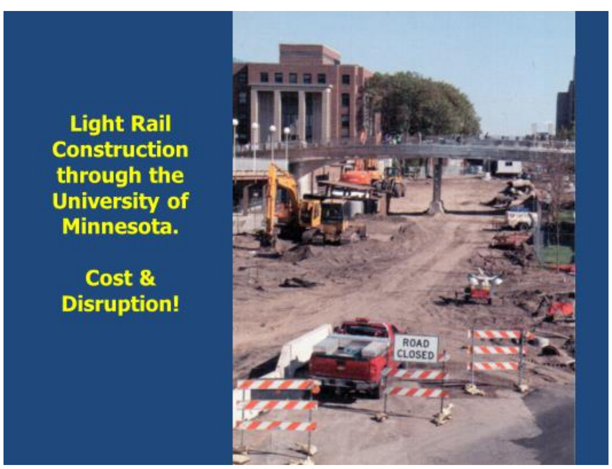
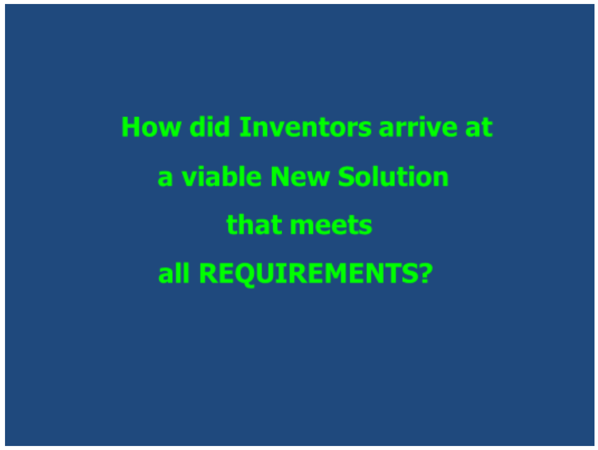
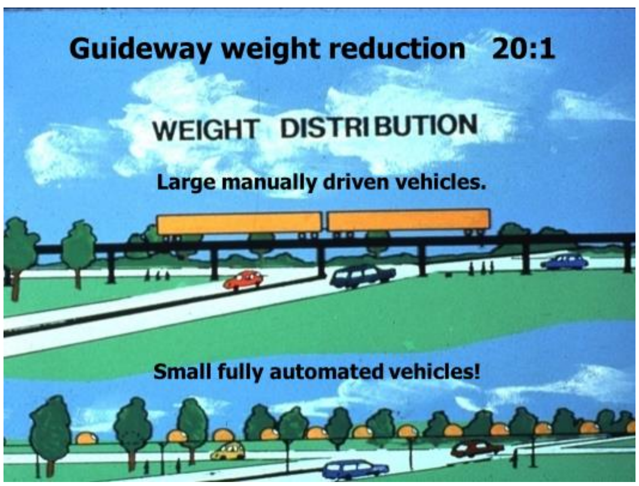
[1] Society for Morphological Research, Pasadena, California, 1962.

According to an article entitled "Light-Rail Tragedies Raise Safety Alarms" in the December 20, 2015 issue of the *Sunday St. Paul Pioneer Press*, "In a little more than a year, the Green Line, which runs down the center of University Avenue in St. Paul, MN, has registered 59 crashes of all types, from pedestrian to vehicle collisions."

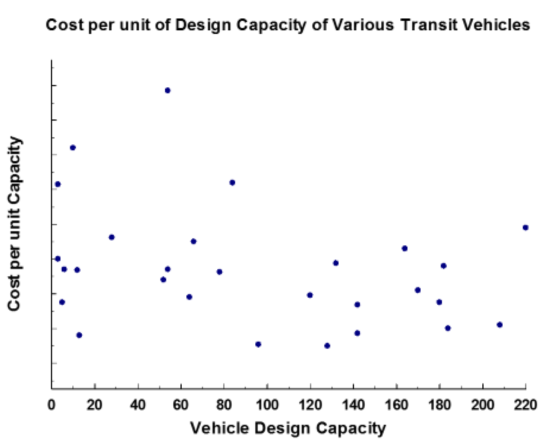




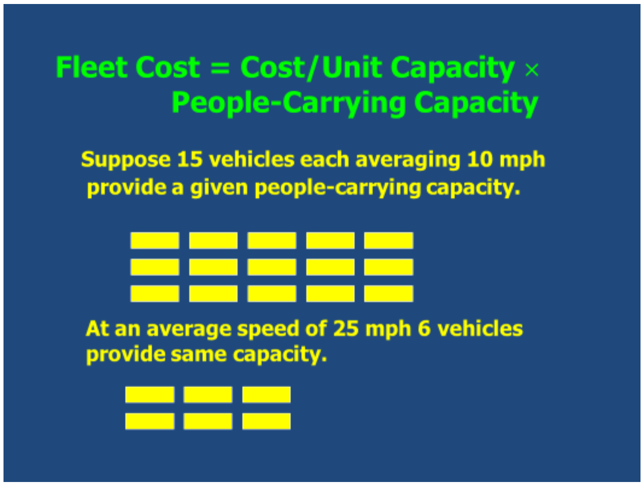


In the 1890s congestion got so bad in Boston, New York, Philadelphia, Cleveland, and Chicago that planners began thinking about going to a new level, either elevated or underground. At great expense they planned and built both, underground when there was no room for elevate trains. In those days, the trains were large and manually driven.

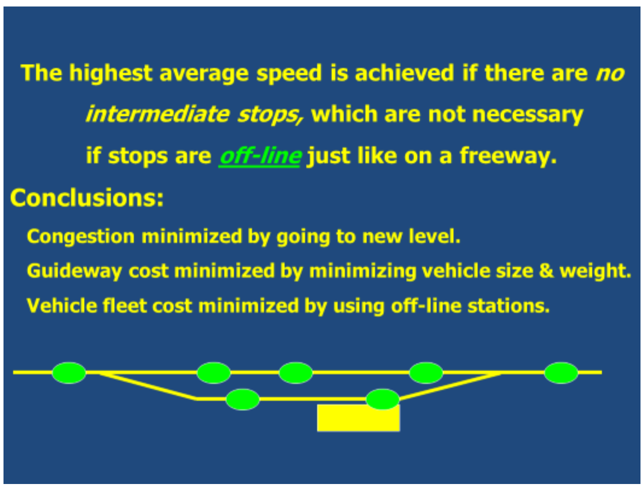
In 1953, Donn Fichter of Chicago and Ed Haltom of Dallas dreamed that if they would split the load into many vehicles of the smallest practical weight and automated them, they could reduce the weight of the guideway needed to support them by at least 20:1!



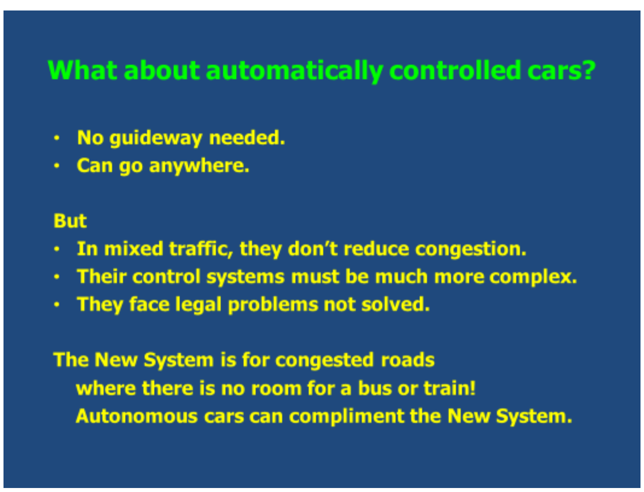
Next point: Here is a plot of the Cost per Unit Capacity of transit vehicles against Vehicle Design Capacity. Each dot on the chart represents a transit vehicle and the costs are normalized to take into account inflation. While there is a great deal of scatter in the chart, one can see that it is possible to design a transit vehicle of any size for about the same cost per unit of capacity, i.e., Cost per Unit Capacity does not have to depend on the size of the vehicle.



Thus, the cost of a fleet of transit vehicles depends not on vehicle size (capacity) but on the required people-carrying capacity of the system, which depends mainly on the average speed of the vehicles.



Thus, to minimize the cost of the vehicle fleet, all stations must be placed on bypass guideways off the main line. Note that we have already reached three basic conclusions on the path to minimizing system cost and maximizing ridership.



Automated automobiles are much in the news, but they are no substitute for going to a new level on an exclusive guideway. According to an article in the Wednesday, March 16, 2016 issue of the St. Paul *Pioneer Press*: "Self-driving cars aren't yet able to handle bad weather, including standing water, drizzling rain, sudden downpours and snow, Missy Cummings, director of Duke University's robotics program, said . . . and they certainly aren't equipped to follow the directions of a police officer."

Imagine stopping in a freeway lane, letting someone out of your car and another person in before you accelerate back to line speed. How far behind would the next car have to be to make that safe? It's minutes behind – that is the way buses and streetcars must operate, while autos on freeways operate seconds apart, and often less than a second apart. With offline stations, this also applies to PRT.

With offline stations, vehicles need run only on demand rather than on a schedule. This procedure markedly reduces the vehicle-miles per day needed to meet a given demand. A computer reroutes empty vehicles from stations where there are too many to stations where they are needed, thus enabling the service to be always available. Off-peak wait time is zero and on-peak waits average not more than a minute. With on-line stations, the closer the station spacing, the lower will be the average speed – access must be sacrificed for speed or speed for access. With off-line stations, the system has both speed and access! With nonstop trips, the time required to wait for a random passenger wishing to go to your destination increases as the square of the number of stations, and after only a few stations is too long to be of interest.[2]

Many studies[3] show that these features will enable a transit system in the United States to attract at least 10 times the ridership attracted to conventional transit.

In the presentation, this illustration is a video that shows the operation of a PRT system as the cars merge into and out of stations, and from line to line. The system does not interfere with cross traffic of any kind. We have developed programs to calculate curved guideways of any configuration and to operate systems of any configuration.

[2] J. E. Anderson, *Transit Systems Theory*, page 89. Available on www.advancedtransit.org.
[3] *Contributions to the Development of PRT*, 1.5.2 "PRT Ridership Studies." Available on www.advancedtransit.org.

The video showed the basic PRT Concept, but there are many ways to design such a system!

I found 46 issues each with several alternatives.

Suppose 2 alternative ways to resolve each issue.

$2^{46} = 10^{13} \times 10^{.847} > 70{,}000{,}000{,}000{,}000$.

More than 70 trillion ways to design a PRT system!

Systems Engineering is needed to show the way!

A Rigorous Systems Engineering Process is needed to Develop an Optimum System

Thoroughly understand the *Problem* and the *Requirements* for solution.

Let System Requirements dictate the technologies.

Identify all alternatives in all issues without prejudice and with absolute objectivity.

Thoroughly analyze all reasonable alternatives in each issue until it is clear which best meets all technical, social, and environmental requirements.

This is hard work and requires the best of the Engineering Sciences and Engineering Mathematics!

"16 Rules of Engineering Design"

Tradeoffs?

1. Dual Mode vs. Single Mode
2. Switch: On Board or at Wayside
3. Vehicles: Supported or Hanging
4. Suspension: Maglev, Air, Wheels
5. Propulsion: Rotary or Linear Motors
6. LMs: Synchronous or Induction
7. LIMs: On Board or at Wayside
8. Power Source: On Board or at Wayside
9. Control: Synchronous, Quasi-Synchronous, Asynchronous
10. Guideway: Wide or Narrow
11. Cabin Considerations

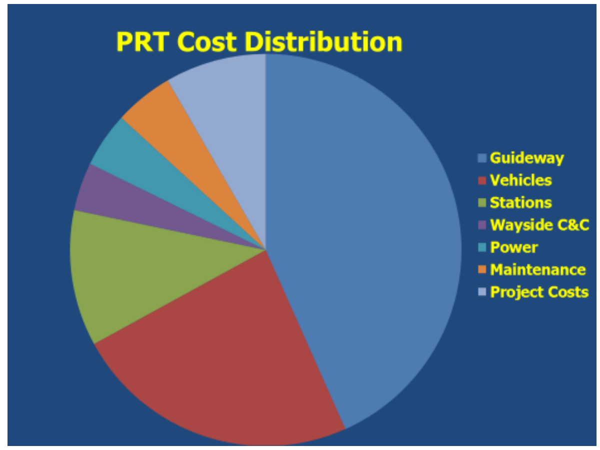
35 more tradeoff considerations!

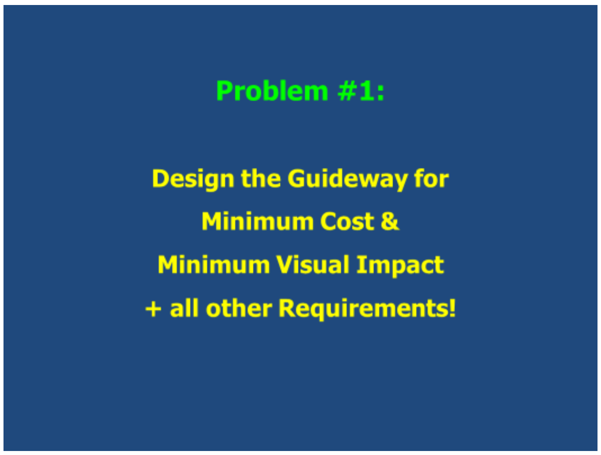
Details, including "16 Rules of Engineering Design," can be found in my new Book:

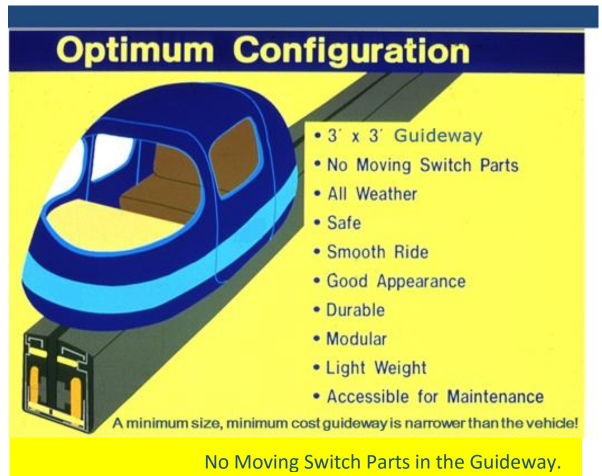
"Contributions to the Development of Personal Rapid Transit"

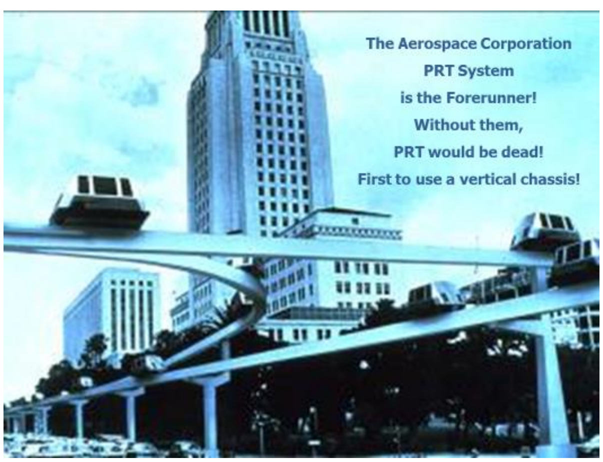
1500 pages in 3 Volumes

Volume #1 can be downloaded from www.advancedtransit.org





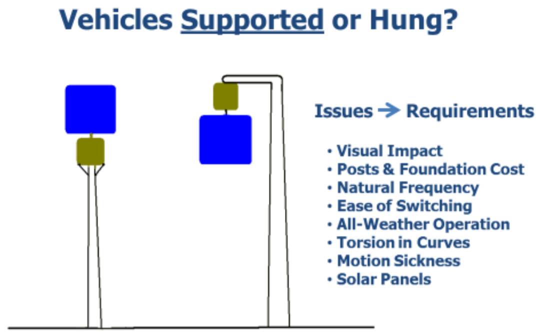




The slide above shows 10 of the requirements, with the top requirement being guideway size. The analysis given in Section 10.2 of my book *Transit Systems Theory,* which is available on www.advancedtransit.org, shows that the beam of minimum weight and hence cost is narrower than it is deep, and is narrower than the vehicle. We therefore cannot use an ordinary auto-type chassis and instead must go to something novel: a vertical chassis. The Aerospace Corporation[4] had already reached this conclusion.[5] They gave me the courage to go with a totally new concept, which is one of the fundamental ideas that lead to minimum system cost.

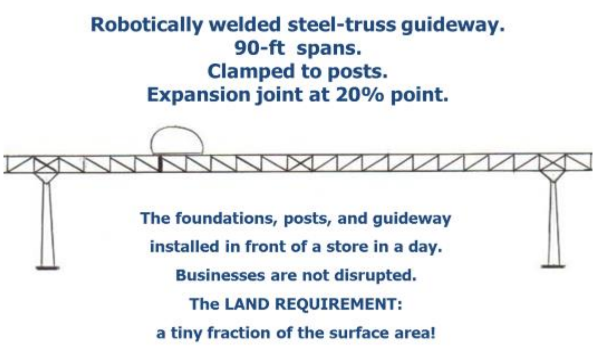
[4] Irving, J. H., Bernstein, H., Olson, C. L., and Buyan, J. 1978. *Fundamentals of Personal Rapid Transit,* Lexington Books, D. C. Heath and Company, Lexington, MA. Available on www.advancedtransit.org.

[5] The German Cabinentaxi system came to the same conclusion, but placed the wheel supports outside the beam, which markedly complicates and increases the cost of the merge and diverge sections.



SV = Supported vehicles, HV= Hung vehicles.

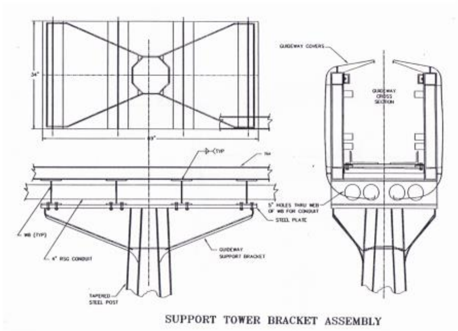
-It is easy to see that SV has the least visual impact.
-With unbalanced vehicle load and longer lever arm, the maximum bending moment at the foundation of HV, and hence its cost, is about twice that in SV.
-The *Natural Frequency* (*NF*) of the guideway is important because the maximum comfortable speed is proportional to *NF*, which is proportional to the square root of the cross-sectional moment of inertia of the guideway and hence to the square root of its weight. With SV, we can clamp the guideway to the posts[6], which more than doubles *NF* from that with simple supports, which will result with HV. Thus, to obtain the same *NF* with HV as with SV, the guideway of HV will weigh almost four times as much as the guideway of SV.
-Switching is straightforward with SV, but requires a special mechanism with HV.
-All weather operation clearly favors HV and with SV requires the special attention given below.
-Planners of HV often think of the vehicles freely swing out in curves. However, Swedish railroad engineers designed tilting bogies to permit their trains to go faster in curves, but found that many passengers got motion sickness, so they had to slow the trains substantially. Thus, with HV the vehicles will have to be restrained in curves just as they are with SV.
-One group chose HV so that they could place solar panels on the top of the guideway. With our SV design, shown below, we can do nearly as well.



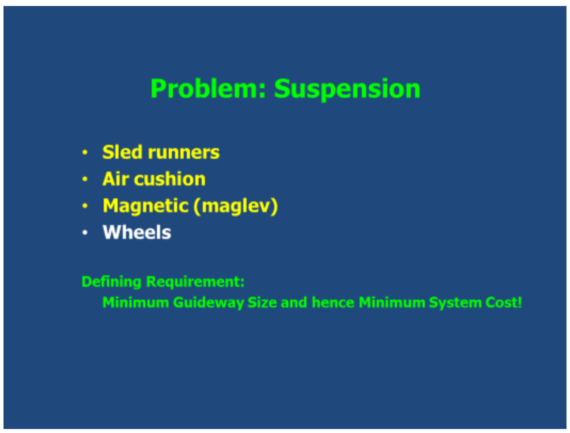
Computer analysis by Stone & Webster Engineering Company independently confirmed the design of our Guideway.

The clamped support substantially increases both bending and torsional stiffness. The bending moment in a clamped beam under uniform load is zero at the 21% point in the beam. Placing the joint there means that it takes mostly shear and little bending,[6] which simplifies the joint design. We found from planning studies done in our Chicago RTA study that the minimum span length must be at least 90 feet.

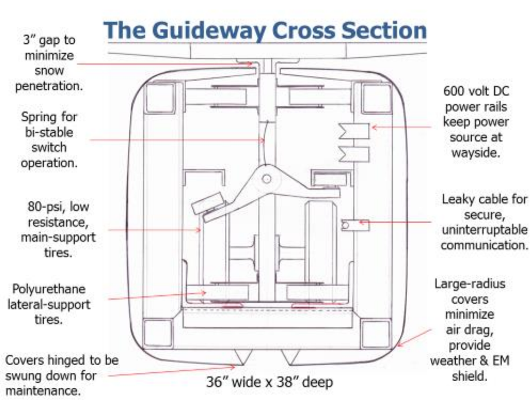
[6] First recommended by The Aerospace Corporation.



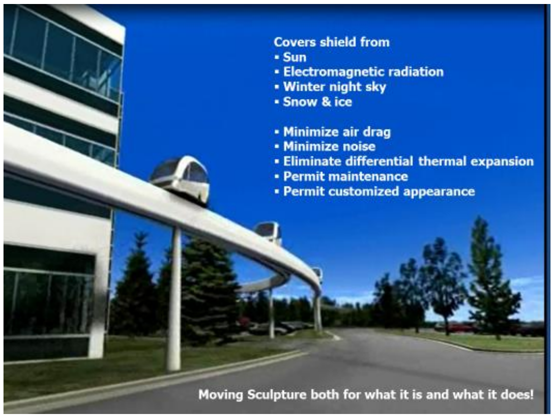
Here is the post-bracket assembly designed by Stone & Webster to cause the guideway and post to bend together. It will be modified by finite-element analysis before being released to production.



Here are four possible ways to suspend the vehicles. Air cushion suspension requires a wide guideway. Several groups chose Maglev and then proceeded to design a PRT system around that concept. In almost all cases that turned the program into permanent R&D. Wheeled support leads to a minimum-size guideway and hence minimum system cost.

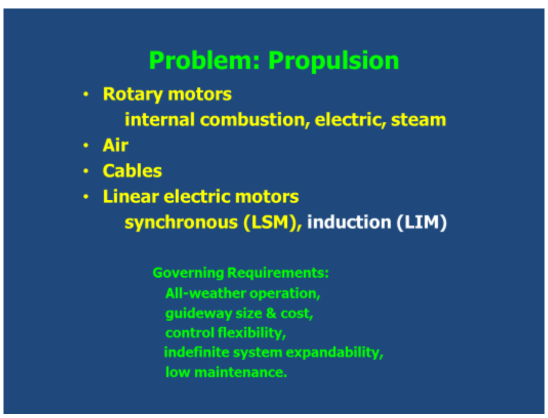


Here is the cross section of our guideway. The vertical steel chassis is only 2 inches wide and the slot in the cover is 3 inches wide, thus permitting very little snow to enter. Finite-element analysis shows how to design the joint with the cabin to be conservative. The bottom is opened 6 inches. The support tires are either 80 psi pneumatic or the new airless tire with the same dynamic properties. They run on smooth steel angles. Auto tires are usually rated at 35 psi because they must be designed to run over chuckholes and curbs. The switch is an arm with polyurethane-tired wheels at each end, one of which grabs a rail located at the guideway merge and diverge areas. It is made bi-stable by means of a leaf spring. The guideway is covered for nine reasons, one of which is that with curve radii at the top and bottom at least one-sixth the height, wind-tunnel tests show that the drag coefficient on the guideway is only a little more than

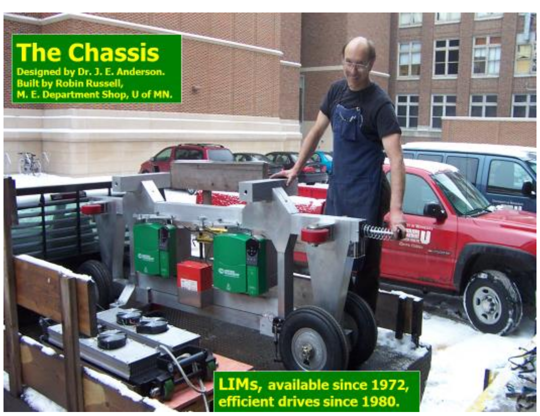


one half.[7] Without the covers, the drag coefficient goes to two, thus the covers reduce the wind load on the guideway by a factor of almost four. Communication with wayside computers is via a leaky cable, and to minimize external EM interference, the cover will be made of composite material with a thin layer of aluminum sprayed on the inside.

The covered guideway without the necessary brackets is shown here. The covers shield the interior of the guideway from the sun, so that the tires operate in the most benign environment possible – in the shade of the sun with no chuckholes or curbs to run over. In PRT systems with the power rails in view of the night sky, even in Texas, on a clear winter night sky frost forms on the power rails, which in one case required spraying the power rails with ethylene glycol each morning before beginning operations. The covers completely eliminate this problem. If there were no covers and the sun shines on one side of the guideway, with the other side in the shade, differential thermal expansion puts extra stress on the guideway. The covers completely eliminate this problem. Altogether, the covers resolve nine requirements.

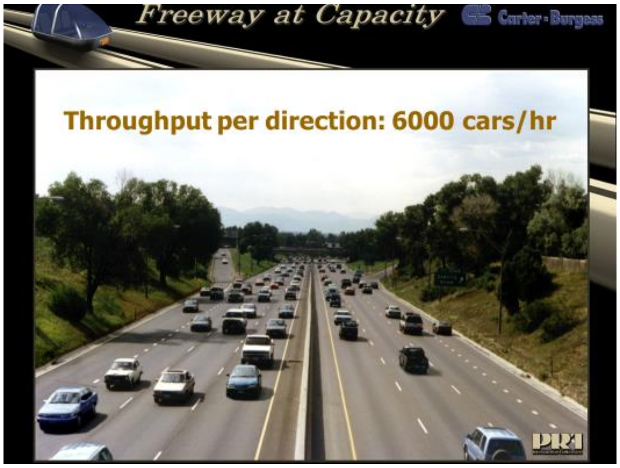


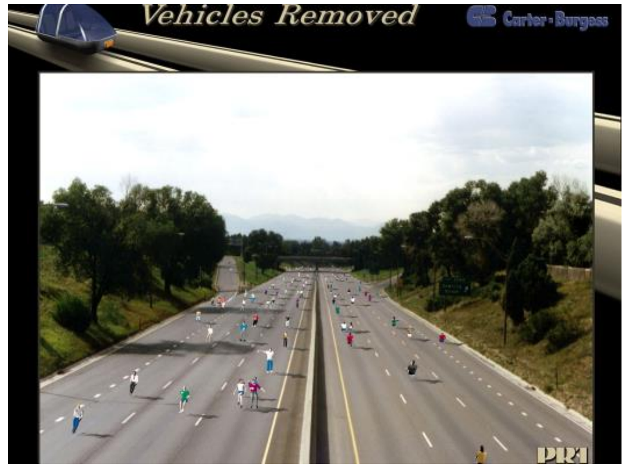
Most of the many PRT designs use rotary electric motors and thus depend on friction to provide acceleration and braking. Studies show, however, that to increase friction sufficiently in wet-weather, the guideway must be roughened; but then if the brakes must be applied in dry weather the deceleration is sufficient to throw passengers into the windshield. Neither the use of air propulsion or pulling vehicles with cables works well in a large PRT system. Linear synchronous-motor propulsion is suitable only for very high speeds and long headways.



Here is the first vertical chassis I designed with the man who built it. The LIMs with their cooling fans, off on the side, are not yet installed. The green boxes are variable-frequency drives, each to run one of the two motors. Variable frequency is extremely important because for each speed there is a frequency that minimizes the current and the losses are proportional to the square of the current. The red box is a battery that provides power for auxiliary functions on the vehicle.

[7] C. Scruton and E. W. E. Rogers, “Steady and Unsteady Wind Loading,” Philosophical Transactions of the Royal Society of London A. 269(1971) 353-379.

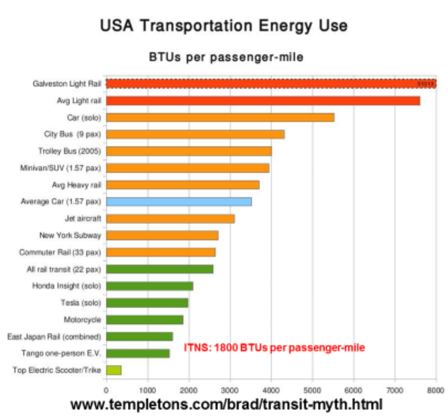




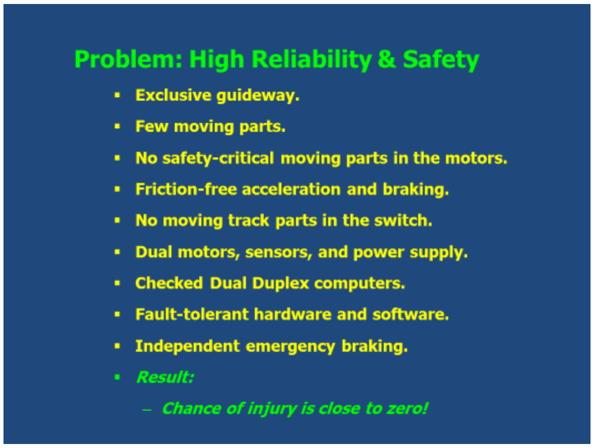
The 3-lane freeway shown here (the 4th lane is an acceleration lane) can handle about 6000 cars an hour. Likewise, if LIMs are used, which means that braking is independent of friction, the PRT system shown, with the same number of people, can handle 6000 cars per hour while reducing the land requirement from a 300-ft width to only 15 feet – a 20:1 reduction.

The PRT guideway shown here, which is only 3-ft wide, can barely be seen from the air, yet it can handle much more traffic than the arterial streets below. A former parking lot can become a park or a garden!

To attain a high average speed, planners of surface-level rail systems like to place the stations at least a mile apart and they accelerate the trains to 60 mph between stations. A three-car train weighs empty about 330,000 lb. The peak kinetic energy of such a train, without passengers, is about 15 kW-hr and, because of finite efficiency, the input energy is several times that. This amount of energy is added and then turned into heat every mile. Some energy can be recovered through regenerative braking, but because of efficiencies not much. With off-line stations, it is not necessary to go to such a high maximum speed. On the same line, 35 mph will achieve a higher average speed. Moreover, every quantity that increases with speed increases as the square of speed.



Brad Templeton wondered how much energy various modes of transportation use. He went to several government websites where he mined the necessary data. To his astonishment, he found that LRT topped the list. There are two reasons for this: 1) Accelerating to a high speed and then braking to a stop at every station, and 2) the inherently low vehicle occupancy averaged over a day that occurs with scheduled service. The director of transit planning for the MTC told me many years ago that the daily average occupancy on their 60-passenger city buses was only 2.5 people. No wonder these systems are so energy intensive. ITNS energy use per passenger-mile is less that an average motorcycle and only about a quarter of light rail.



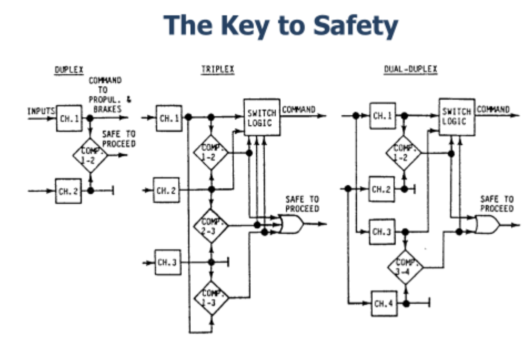
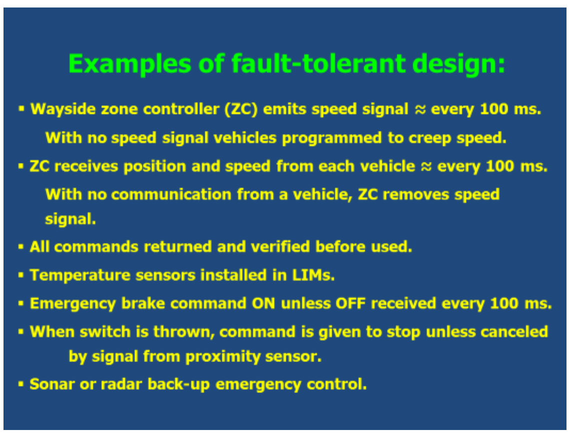
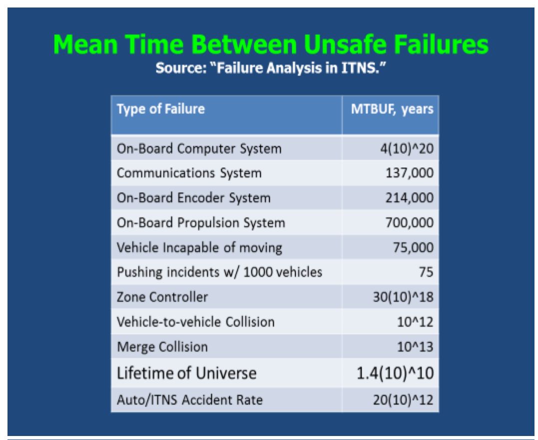


FIGURE 3: MICROPROCESSOR REDUNDANCY CONFIGURATIONS

In Figure 3, the diagram on the left is of a pair of identical microprocessor control systems. There is a command to apply the brakes approximately every 100 millisec, which must be canceled by a "Safe to Proceed" command, which requires an exact match between the two computers. If they don't agree, the brakes are applied and the vehicles stop. Not liking this outcome, engineers at both Honeywell and Boeing considered the above-shown triplex and dual-duplex configurations. A Boeing paper[8] shows why they chose dual-duplex, which in PRT enormously lengthens the mean time between unsafe failures.





Type of Failure	MTBUF, years
On-Board Computer System	4(10)^20
Communications System	137,000
On-Board Encoder System	214,000
On-Board Propulsion System	700,000
Vehicle Incapable of moving	75,000
Pushing incidents w/ 1000 vehicles	75
Zone Controller	30(10)^18
Vehicle-to-vehicle Collision	10^12
Merge Collision	10^13
Lifetime of Universe	1.4(10)^10
Auto/ITNS Accident Rate	20(10)^12

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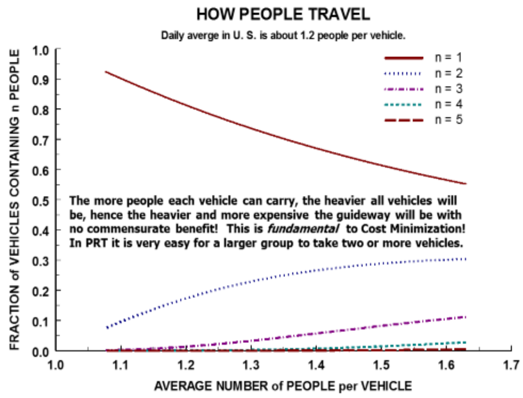
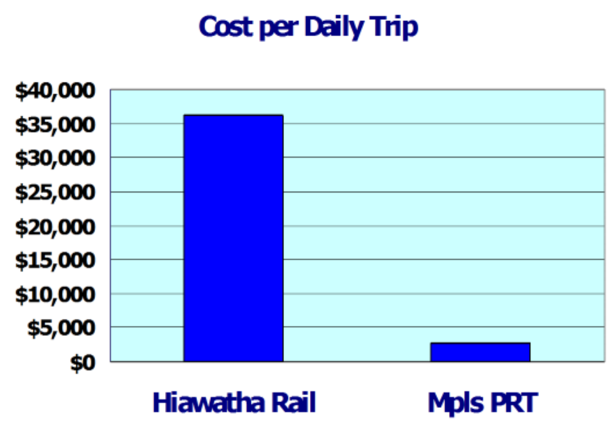
[8] R. C. Milnor & R. S. Washington, 1984. "Effects of System Architecture on Safety and Reliability of Multiple Microprocessor Control Systems," IEEE Conference Paper.

Since 13,200 vehicles per hour has already been demonstrated, why did I show 6000 vehicles per hour? Because many studies[9] have shown that that flow is sufficient for a very wide variety of applications. We have a comfortable margin of safety!



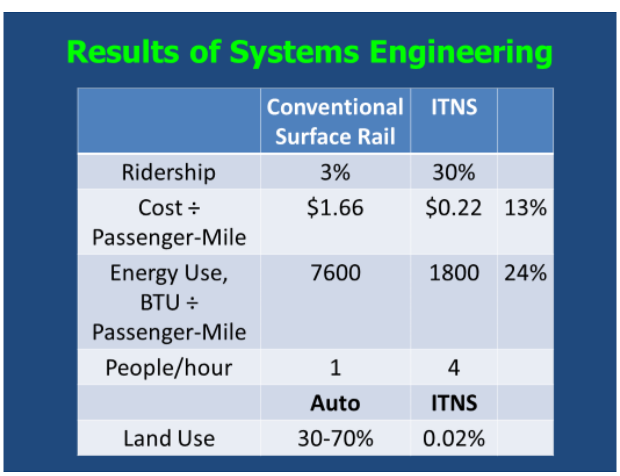
The system I designed with its LIM control, propulsion and braking, worked exactly as designed!

[9] *PRT I, PRT II, PRT III*, University of Minnesota, 1972, 1974, 1976.



By "transit mode" in the above slide, I mean a transit system that uses manually driven vehicles or trains, vehicles large enough to amortize the wages of the driver, and stopping at every station. Data shows that a mode with these characteristics in the United States attracts only about 3 to 4 percent of urban travel.

From Metro Transit data, the Hiawatha LRT cost $720,000,000 and attracts 20,000 trips a day, giving $36,000 per daily trip. We laid out an 8-mile PRT system for downtown Minneapolis and estimated its cost at $100,000,000. A transportation consultant operating independent of us estimated the ridership to be about 74,000 daily trips. Since our system has not been built, double its cost, in which case the cost per daily trip is less than $3000 – even then a reduction of more than a factor of 10!

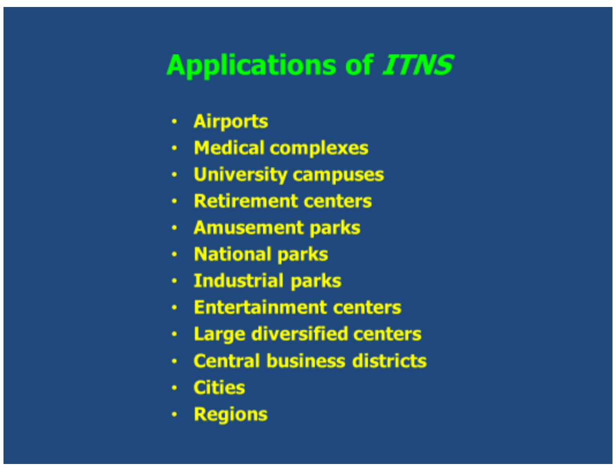


Results of Systems Engineering

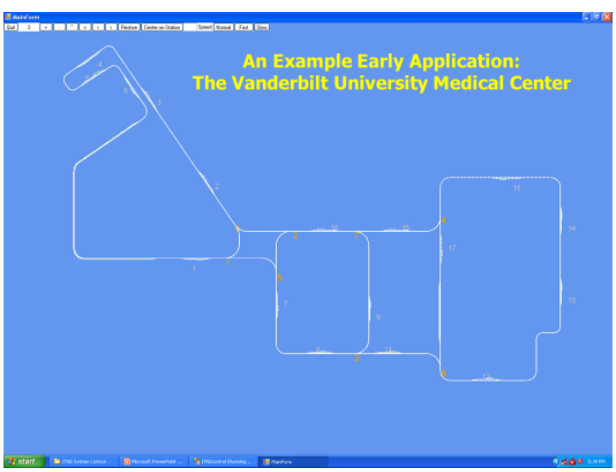
	Conventional Surface Rail	ITNS	
Ridership	3%	30%	
Cost ÷ Passenger-Mile	$1.66	$0.22	13%
Energy Use, BTU ÷ Passenger-Mile	7600	1800	24%
People/hour	1	4	
	Auto	**ITNS**	
Land Use	30-70%	0.02%	

We enjoy modern aviation, telecommunications, computers, the Internet, etc., all of which came out of military industry. Since there has been no military application for buses and streetcars, we still use systems introduced well over a century ago.

In his *Encyclical on the Environment*, Pope Francis said: *"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."* Alas, we have been stuck with 19th Century urban transportation concepts!



We have studied all of the types of applications listed here in considerable detail. The Manager of Parks Operations Research at Disney World visited me in my office at Boston University. He had heard a presentation of my system given by a retired Four-Star Air Force General, to whom I had given a set of my slides. That Disney manager told me of many applications of my system at Disney World and then went through a long list of technical questions, the last of which was "Who will build it?" We had no answer and Disney had no interest in getting back in the transit business. They are still waiting!



Here is an application of ITNS at the Vanderbilt University Medical Center. Many medical facilities are located in the area covered by this network, but the roads are too narrow for the large intrastate buses that carry people here from many towns in Tennessee. The VMC planners envisioned having the buses park in a Park in the upper left corner of this layout and there transfer to ITNS. I have been told that congestion is getting critical around VMC and that they desperately need a new solution.

Will it Work?

ITNS

is a new arrangement

of ordinary components

all of which work every day

in other ways!

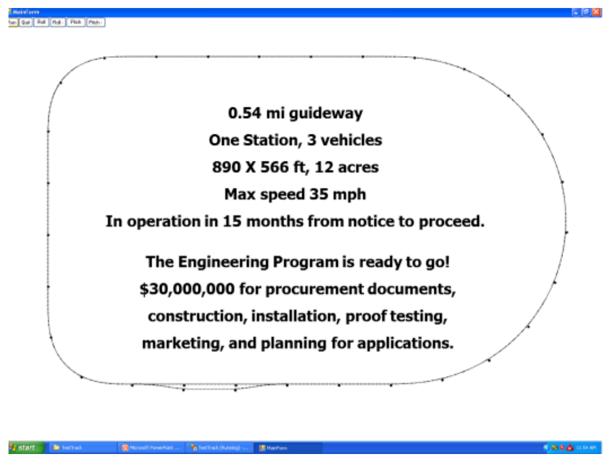
Nothing exotic!

We will operate as a

private business

with revenue exceeding costs!

The Next Step:



The Engineering Program consists of Parallel Tasks.
Each can be accomplished
by engineers with available skills:

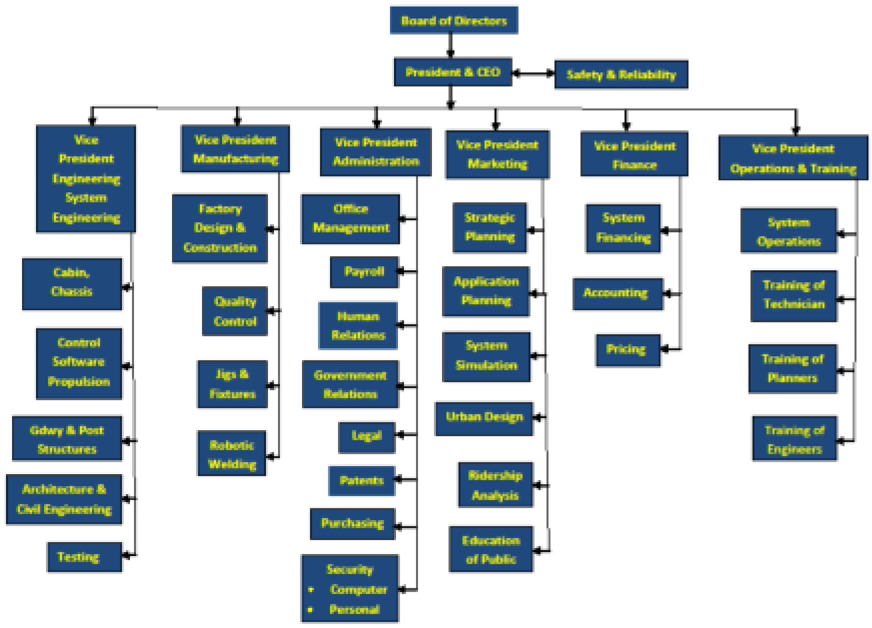
Task #1: Management and Systems Engineering.
Task #2: Safety and Reliability.
Task #3: Cabin.
Task #4: Chassis.
Task #5: Guideway and posts.
Task #6: Guideway covers.
Task #7: Control system.
Task #8: Propulsion and braking.
Task #9: Wayside power.
Task #10: Civil works – stations, maintenance, foundations.
Task #11: Test program.
Task #12: Application Planning & Marketing.

Team Work can accomplish remarkable results!

The project will start as a

Lockheed "Skunk Works"

and in time will ramp up to . . .



Market:

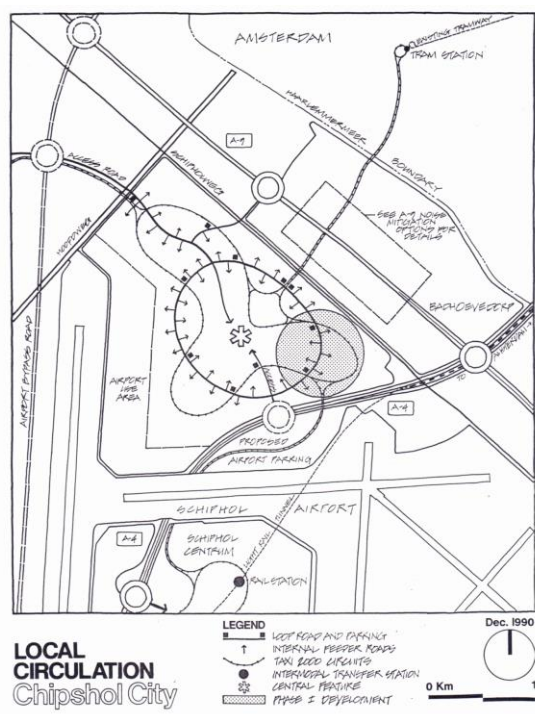
Requirement: No Controversy!

Dozens of such applications above $200,000,000 each are available that can be financed privately !

An investor, with conditions, will finance the needed $30,000,000!

The Vision . . .

This illustration was prepared at the direction of the Dutch company Chipshol Forward, which was planning the development at Schiphol International Airport in Amsterdam shown here served by Taxi 2000, the system I designed. They wanted to fund the test system we needed and we negotiated with them for over two years, following which we accepted an offer from the Raytheon Equipment Division.



In June 1993, the Chicago RTA selected our team for their Phase II Test Program, following which I receive the letter shown on the next page from the President of the University of Minnesota. Then two terribly unfortunate events happened: The General Manager of the Equipment Division retired and the Chairman of the RTA resigned. Both knew me from many meetings and had insisted that I be involved in a significant way. The new Raytheon managers decided that they could do better in a year with only their engineers and thus locked up all of our information. The system they designed, *with not a shred of Systems Engineering*, was four times as expensive as the system that came out of the Phase I design study led by Stone & Webster Engineering Corporation, as a result of which the RTA walked away from the project and said nothing more about PRT – a tragedy! Notwithstanding this event, the Chicago project caused many people to renew interest in PRT, and in particular the Swedish government sponsored a series of application studies that went on for over 15 years. PRT systems running at Heathrow Airport in London, in the United Arab Emirates, and in South Korea were directly inspired by the Chicago project. The mistakes made by the Raytheon team were the major inspiration for "*16 Rules of Engineering Design*," almost all of which that great company ignored.

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June 25, 1993

Professor J. Edward Anderson
Taxi 2000 Corporation
40 Salem Street
Lynnfield, Massachusetts 01940

Dear Professor Anderson:

I am writing to offer you both my personal congratulations and the congratulations of the University of Minnesota on the announcement that Chicago and Raytheon are proceeding with the development of your PRT system. Tony Potami has, over the past several years, kept me informed of continuing efforts by Taxi 2000, the University, and others to commercialize this technology. There have been many advances and setbacks over that period, but the decision by the Chicago RTA is a major breakthrough. We anticipate now that the Taxi 2000 system is on its way to commercial development and application!

Your singular efforts and commitment over an extended period of time deserve most of the credit for this event. I hope that you feel a great amount of pride and satisfaction in the results of your efforts. We at the University take satisfaction in our support for and participation in an endeavor that may prove to be one of the most successful and far reaching technology transfers from a university.

Sincerely,

Nils Hasselmo

Nils Hasselmo
President