"Systems Engineering applied to Urban Transportation"

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Professor of Mechanical Engineering
University of Minnesota & Boston University

Why the Need for Systems Engineering?

"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, Encyclical on the Environment

Problem: Congestion

Problem: Accidents

A wreck a week!

Light Rail Construction through the University of Minnesota.

Cost & Disruption!

The New Transit System Must

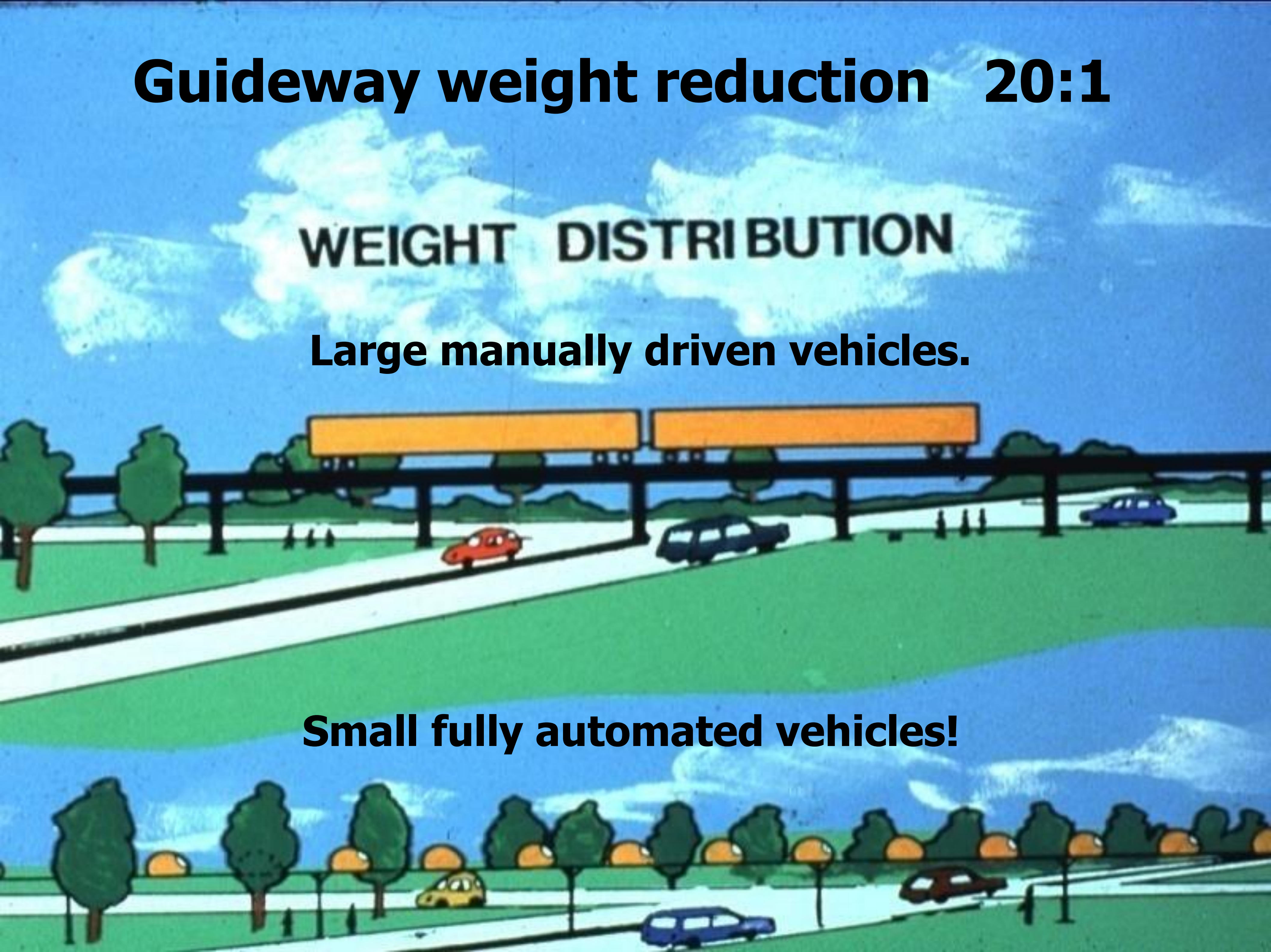
- Attract many more riders
- Have adequate capacity
- Reduce congestion
- Be safe and reliable
- Produce minimum disruption during installation
- Minimize Capital & Operating Costs
- Increase access to the Community
- Operate where conventional transit can’t
- Not Pollute the Environmental
- Save Energy
- Operate in all kinds of Weather
- 26 more Requirements!

How did Inventors arrive at

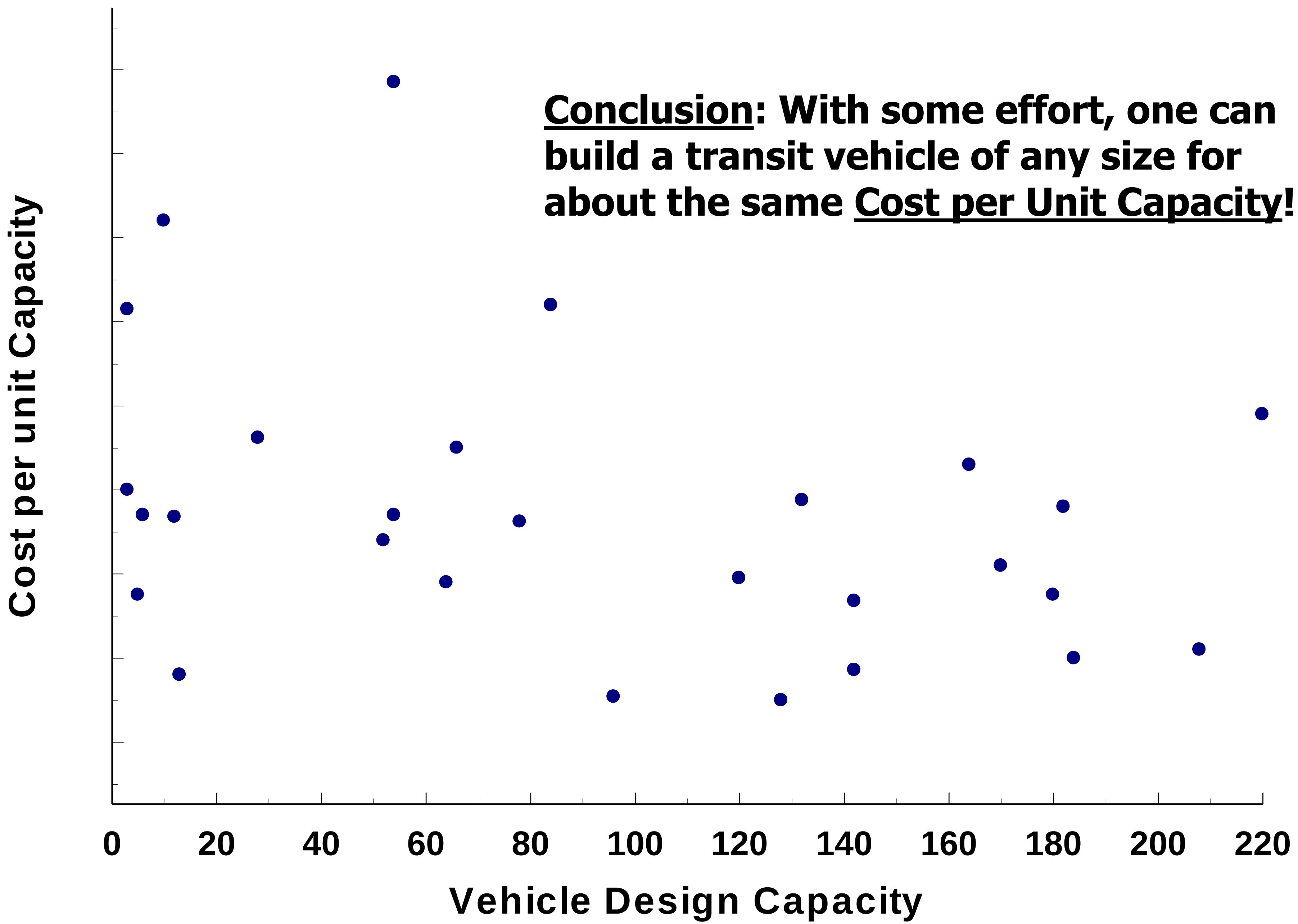
a viable new Solution

that meets

all REQUIREMENTS?

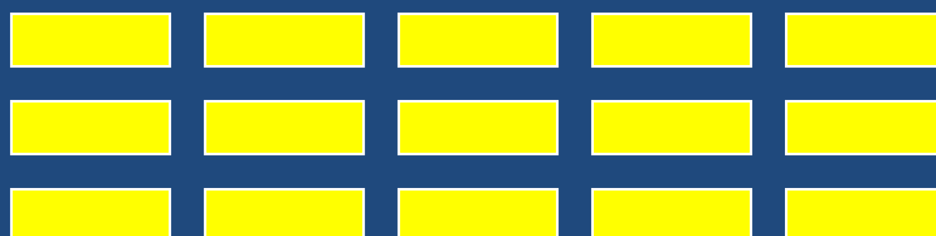

Guideway weight reduction 20:1
WEIGHT DISTRIBUTION
Large manually driven vehicles.
Small fully automated vehicles!

Cost per unit of Design Capacity of Various Transit Vehicles



Fleet Cost = Cost/Unit Capacity × People-Carrying Capacity

Suppose 15 vehicles each averaging 10 mph provide a given people-carrying capacity.



Then at an average speed of 25 mph 6 vehicles provide same capacity.

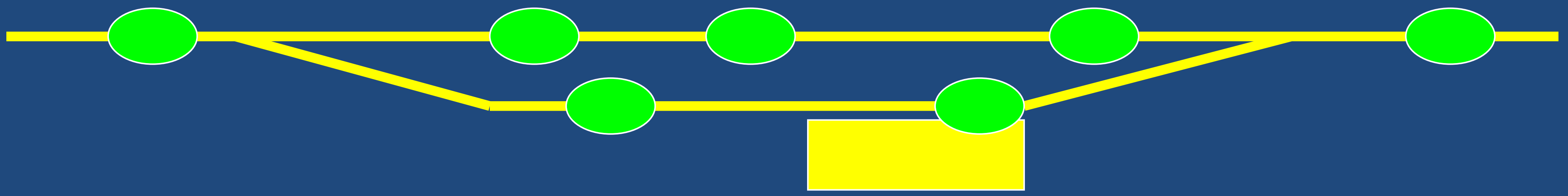
The average speed is highest if there are *no intermediate stops,* which are not necessary if stops are <u>*off-line*</u> just like on a freeway.

Conclusions:

Guideway cost is minimized by minimizing vehicle weight.

Vehicle fleet cost is minimized by using off-line stations.

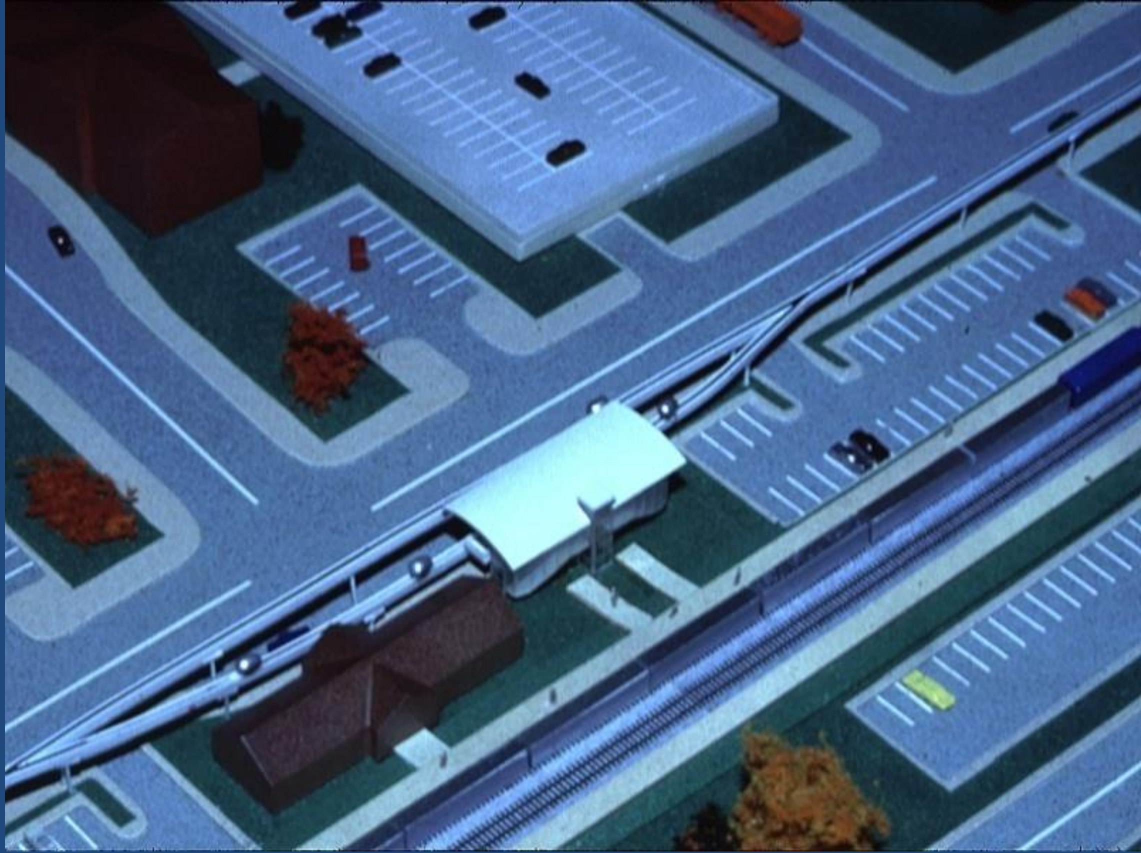
The New Solution requires full automation!



Off-Line Stations

Permit:

- Nonstop trips
- Highest average speed
- Minimum fleet size & cost
- High throughput
- Small vehicles
- Small, low-cost guideway



There are more benefits:

- Vehicles run only on demand, not on a schedule.
- Service is always available, the wait is short to none.
- Adding stations does not reduce the average speed.
- Stations can be sized to demand.
- You ride with chosen companions or alone.

All of these benefits increase ridership and reduce costs!

Off-line stations and small vehicles attract many riders!

- Available to anyone anytime 24/7.
- No need to understand system.
- Short walk in wider service area.
- Short or zero wait.
- A seat for everyone.
- Ride alone or with chosen companions.
- An enjoyable, nonstop ride.
- Can make use of time while riding.
- No transfers.
- Short, predictable trip time.
- Competitive fare.


Morgantown "PRT"
No S. E. apparent here!

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 must show the way!

Development of an Optimum System Requires a Rigorous Systems-Engineering Process:

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

Let <u>System Requirements</u> dictate the technologies.

Identify all alternatives in all issues <u>without prejudice</u>

and with <u>absolute objectivity</u>.

<u>Thoroughly analyze</u> all reasonable alternatives in each issue

until it is clear which best meets all technical, social,

and environmental requirements.

Requires the best of

The Engineering Sciences and Engineering Mathematics!

The Key Point:

Therefore <u>unattached ever</u> perform action

that must be done;

For performing action <u>without attachment</u>

man attains the highest.

The Bhagavad Gita

Written 2500 to 5000 years ago!

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!

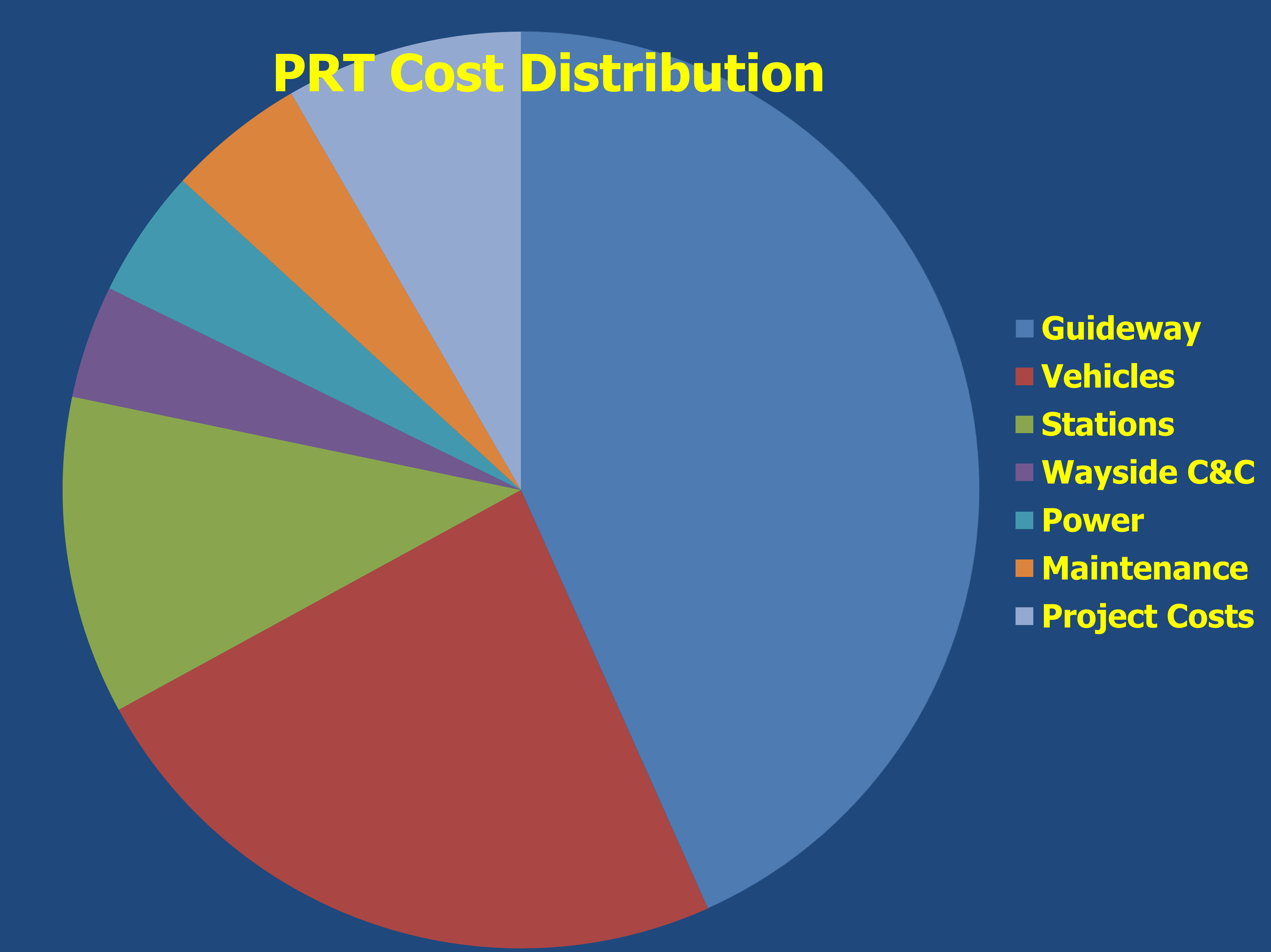
Details are in my Book:

"Contributions to the Development of Personal Rapid Transit"

1500 pages in 3 Volumes

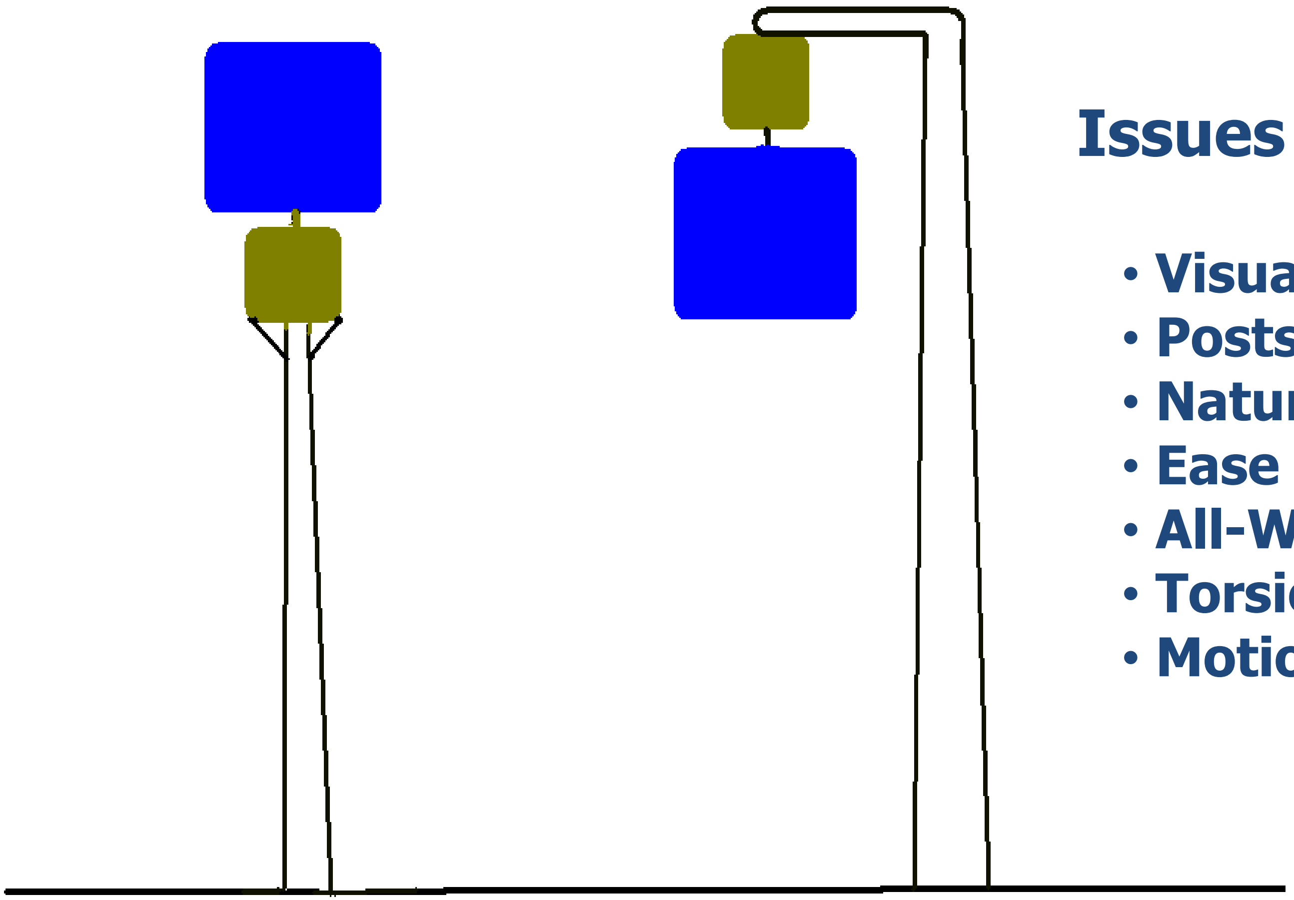
Volume I can be downloaded from www.advancedtransit.org

How to Minimize Cost while Maximizing Ridership?


PRT Cost Distribution
Guideway
Vehicles
Stations
Wayside C&C
Power
Maintenance
Project Costs

#1 Problem:
Design Guideway for Minimum Cost & Minimum Visual Impact:

Issue: Vehicles Supported or Hung



Issues → Requirements

- Visual Impact
- Posts & Foundation Cost
- Natural Frequency
- Ease of Switching
- All-Weather Operation
- Torsion in Curves
- Motion sickness

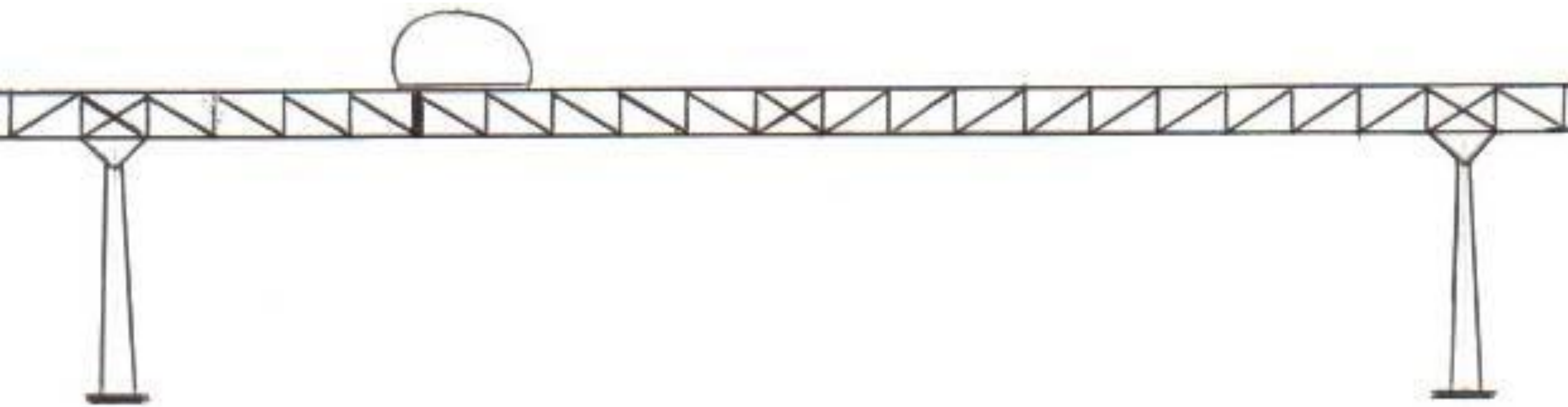
Optimum Configuration

- 3′ x 3′ Guideway
- No Moving Switch Parts
- All Weather
- Safe
- Smooth Ride
- Good Appearance
- Durable
- Modular
- Light Weight
- Accessible for Maintenance

A minimum size, minimum cost guideway is narrower than the vehicle!


The Aerospace
Corporation
PRT System

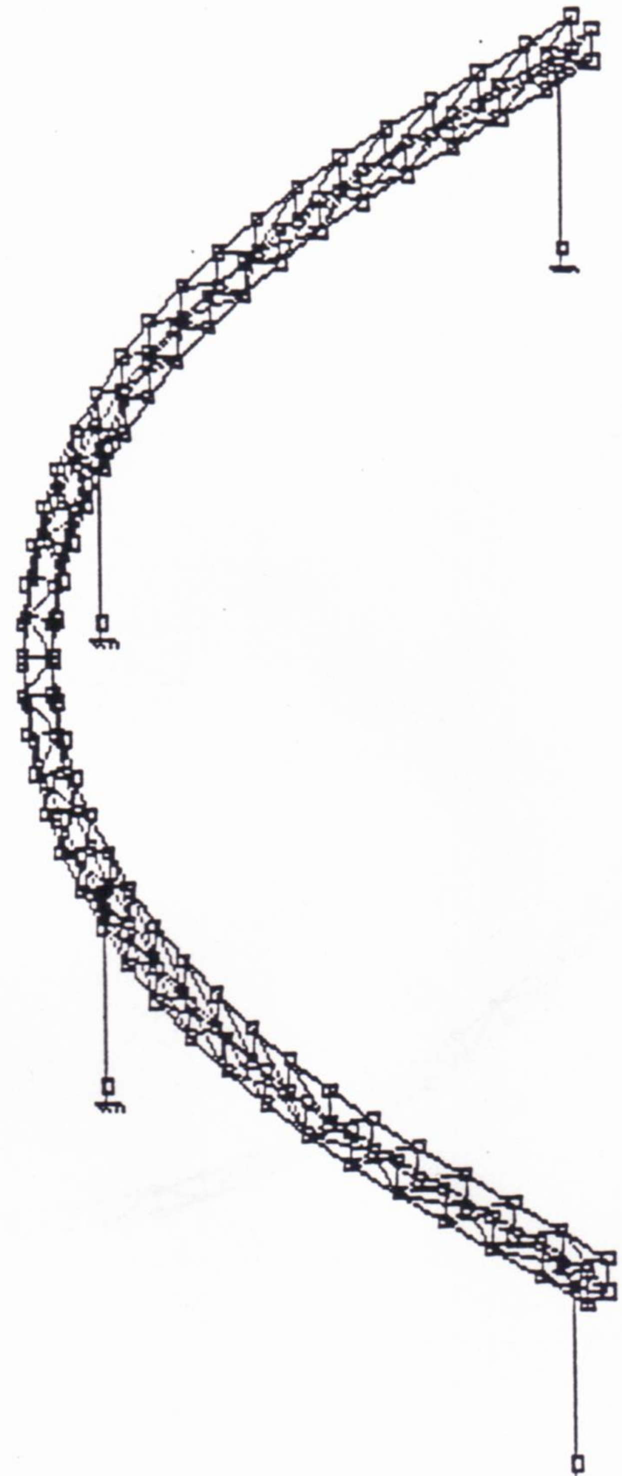
Robotically welded steel-truss guideway.
90-ft spans.
Clamped to posts.
Expansion joint at 20% point.

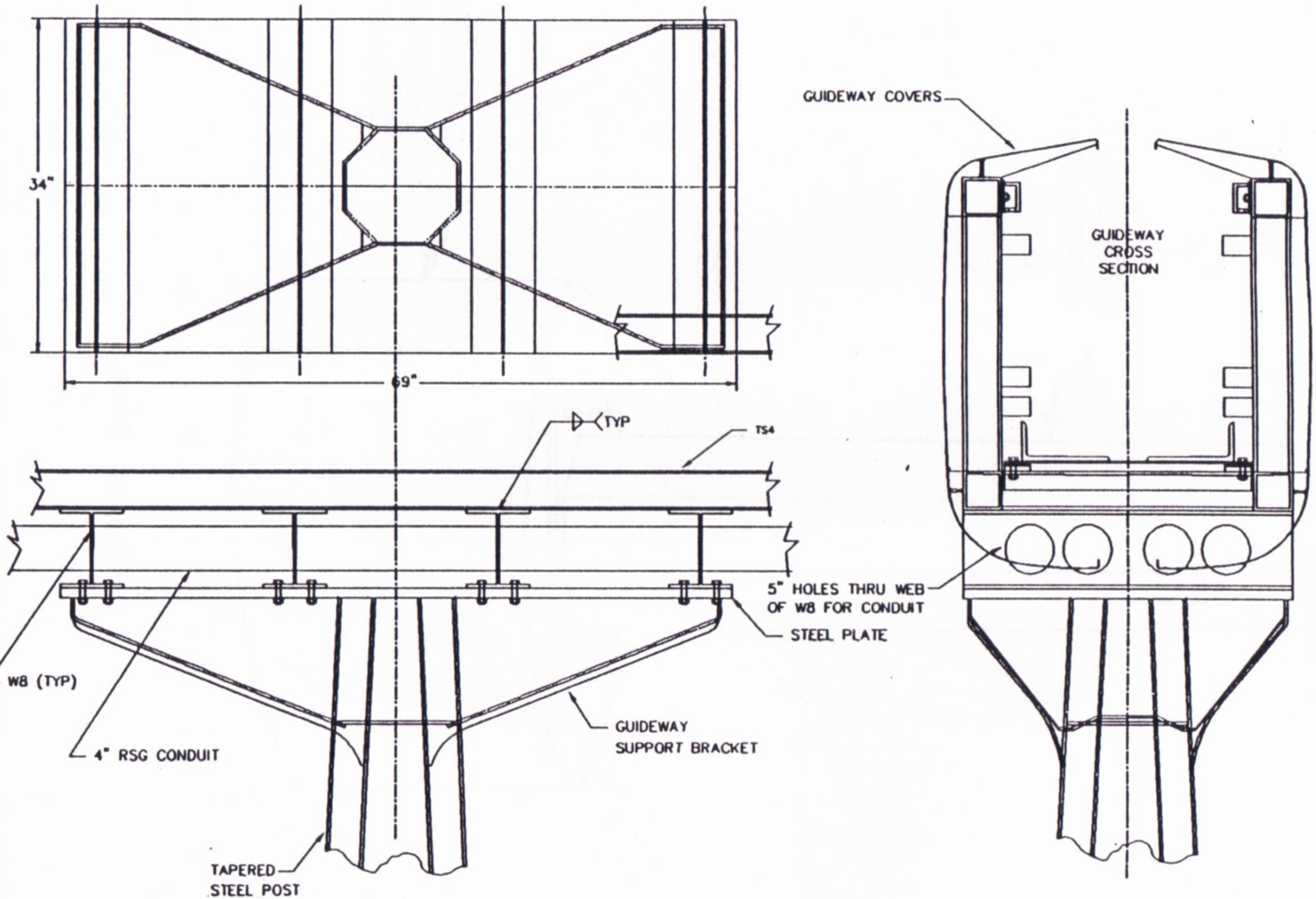


The foundations, posts, and guideway can be installed in front of a store in a day or two.
Businesses are not disrupted.
The LAND REQUIREMENT is a tiny fraction of the surface area!

Computer analysis by Stone & Webster Engineering Company has confirmed the design of the ITNS Guideway.

A 67-page paper "The Guideway for an Intelligent Transportation Network System" provides up-to-date details.





SUPPORT TOWER BRACKET ASSEMBLY

Issue: Suspension

- Sled runners
- Air cushion
- Magnetic (maglev)
- Wheels

Defining Requirement:

Minimum Guideway Size and hence Cost!

The Guideway Cross Section

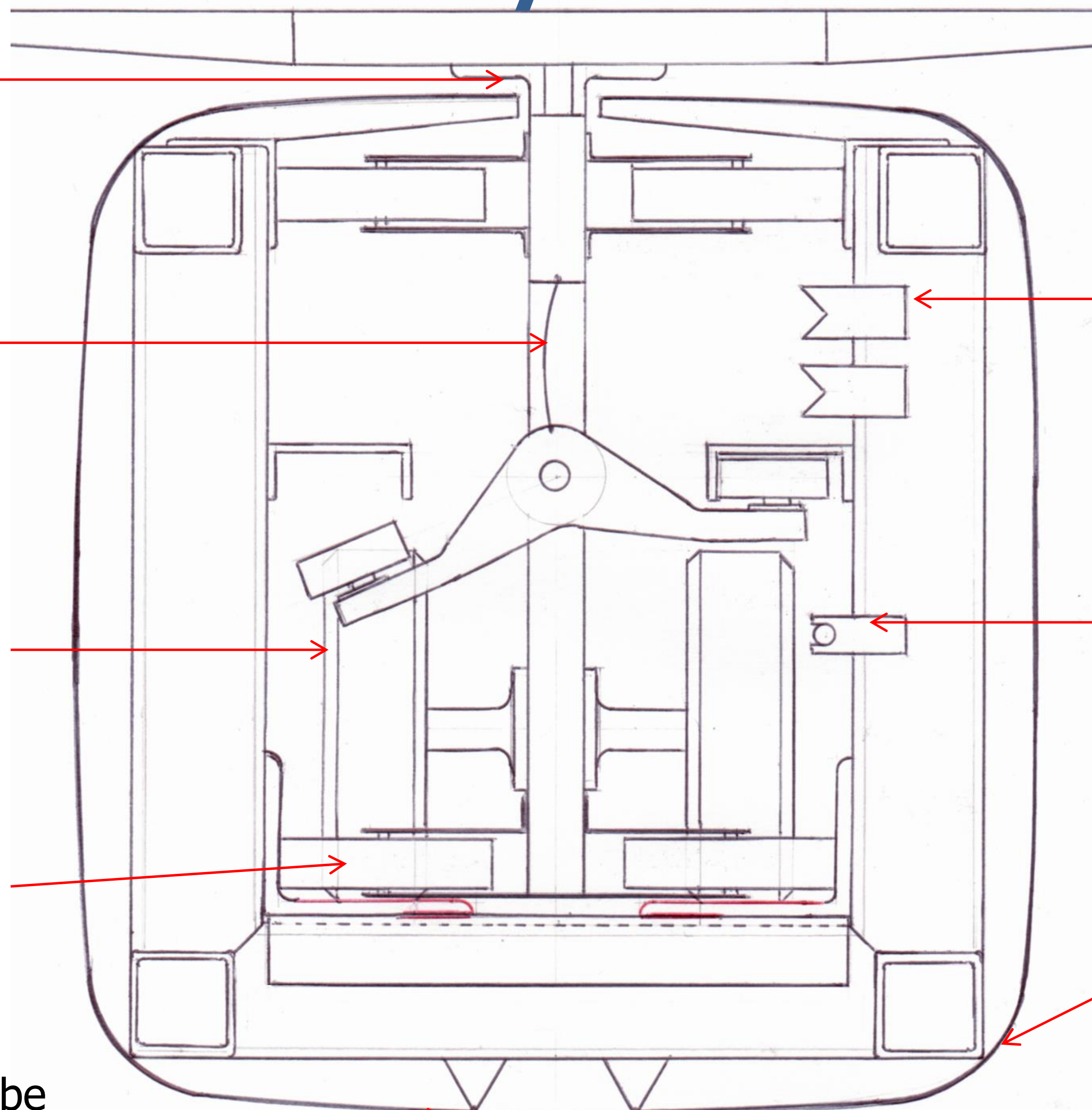
3″ gap to minimize snow penetration.

Spring for bi-stable switch operation.

80-psi, low resistance, main-support tires.

Polyurethane lateral-support tires

Covers hinged to be swung down for maintenance.

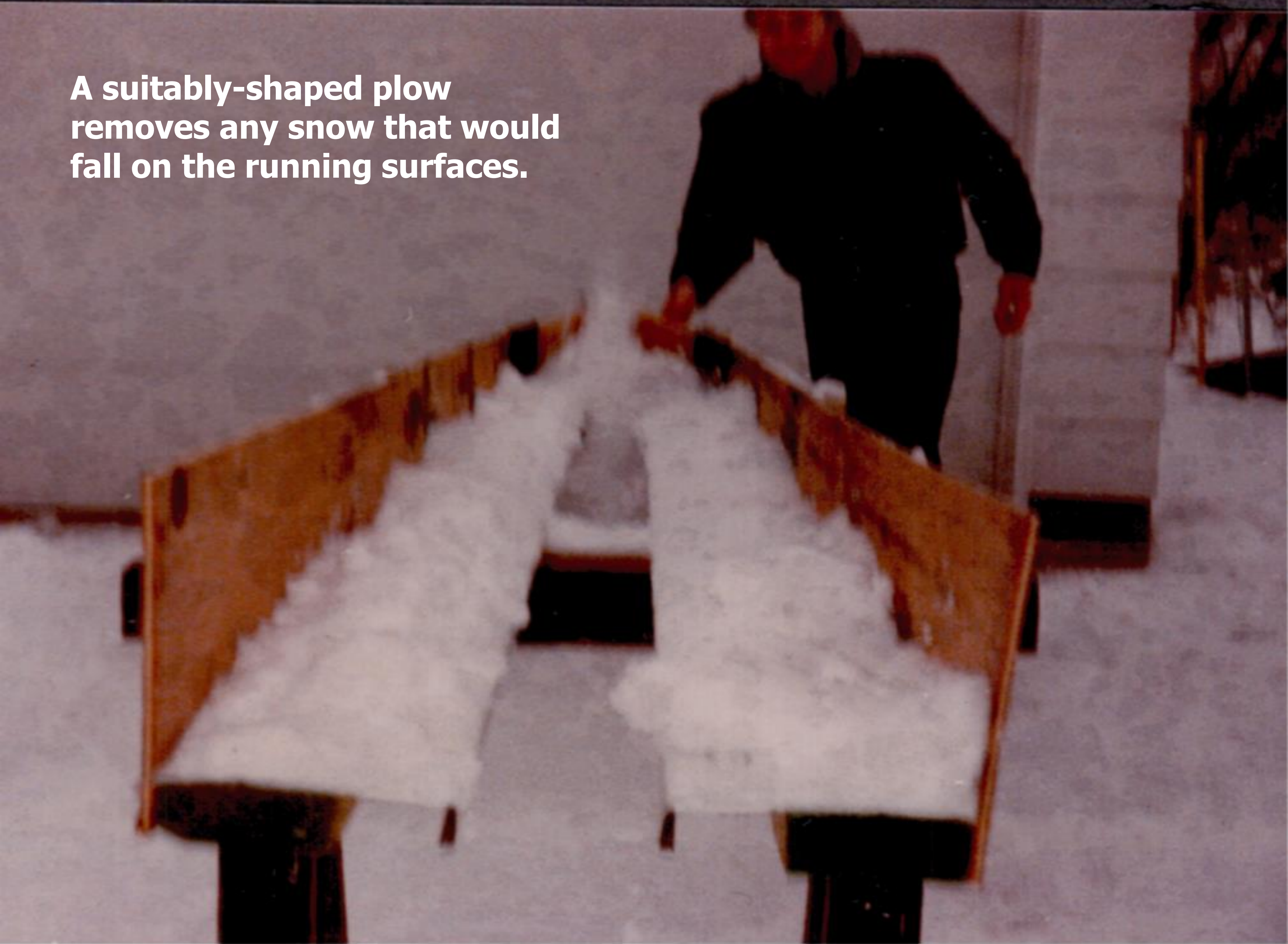


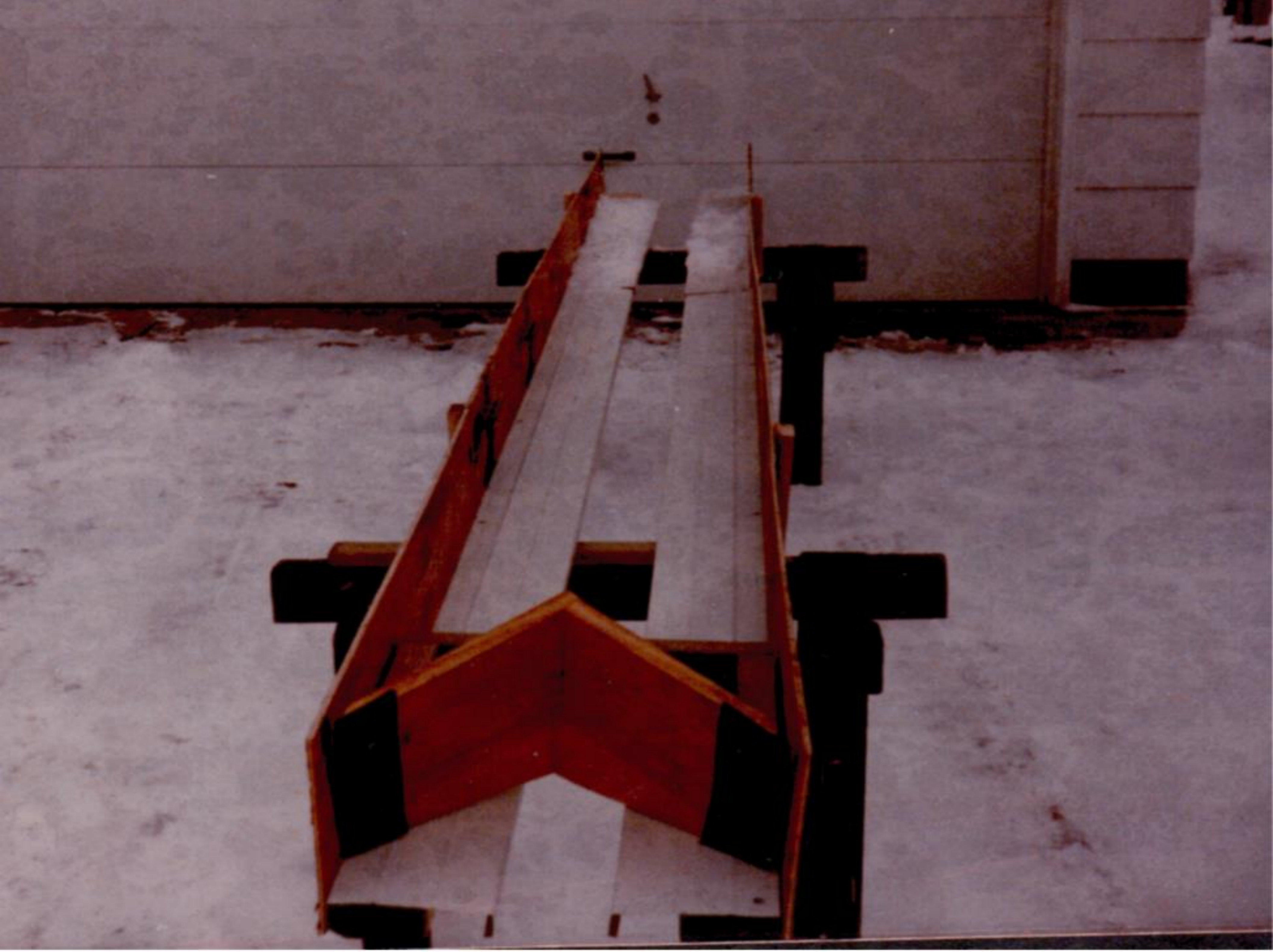
600 volt DC power rails keep power source at wayside.

Leaky cable for secure, uninterruptable communication.

Large-radius covers minimize air drag, provide weather & EM shield.

36″ wide x 38″ deep


A suitably-shaped plow
removes any snow that would
fall on the running surfaces.




Covers shield from
▪ Sun
▪ Electromagnetic Radiation
▪ Winter night sky
▪ Snow & ice
▪ Minimize Air Drag
▪ Minimize Noise
▪ Eliminate differential thermal expansion
▪ Permit maintenance
▪ Permit customized appearance
Moving Sculpture both for what it is and what it does!

Issue: Propulsion

- Rotary motors
  - internal combustion, electric, steam
- Air
- Cables
- Linear electric motors
  - synchronous (LSM), induction (LIM)

Governing Requirements:
All-weather operation,
guideway size & cost,
control flexibility,
low maintenance.

For safe, all-weather fractional-second headway use *Linear Induction Motors:*

- Braking rate
  - Wheel braking depends on
    - Friction, grade, tail wind – must assume the worst case.
  - LIM braking independent of
    - Friction, grade, tail wind.
- Reaction time
  - Wheel braking > 500 milliseconds
  - LIM braking almost instantaneous
- Moving parts
  - Propulsion and braking through wheels: Many
  - LIM propulsion and braking: Fan motor only
- How to obtain adequate braking?
  - Wheel braking
    - Need rough surface
    - Braking rate on dry surface too high
    - Tire material imbeds in surface
  - LIMs: braking independent of friction
    - Want smooth surface
    - Wheels only rollers – no braking through wheels

The Chassis

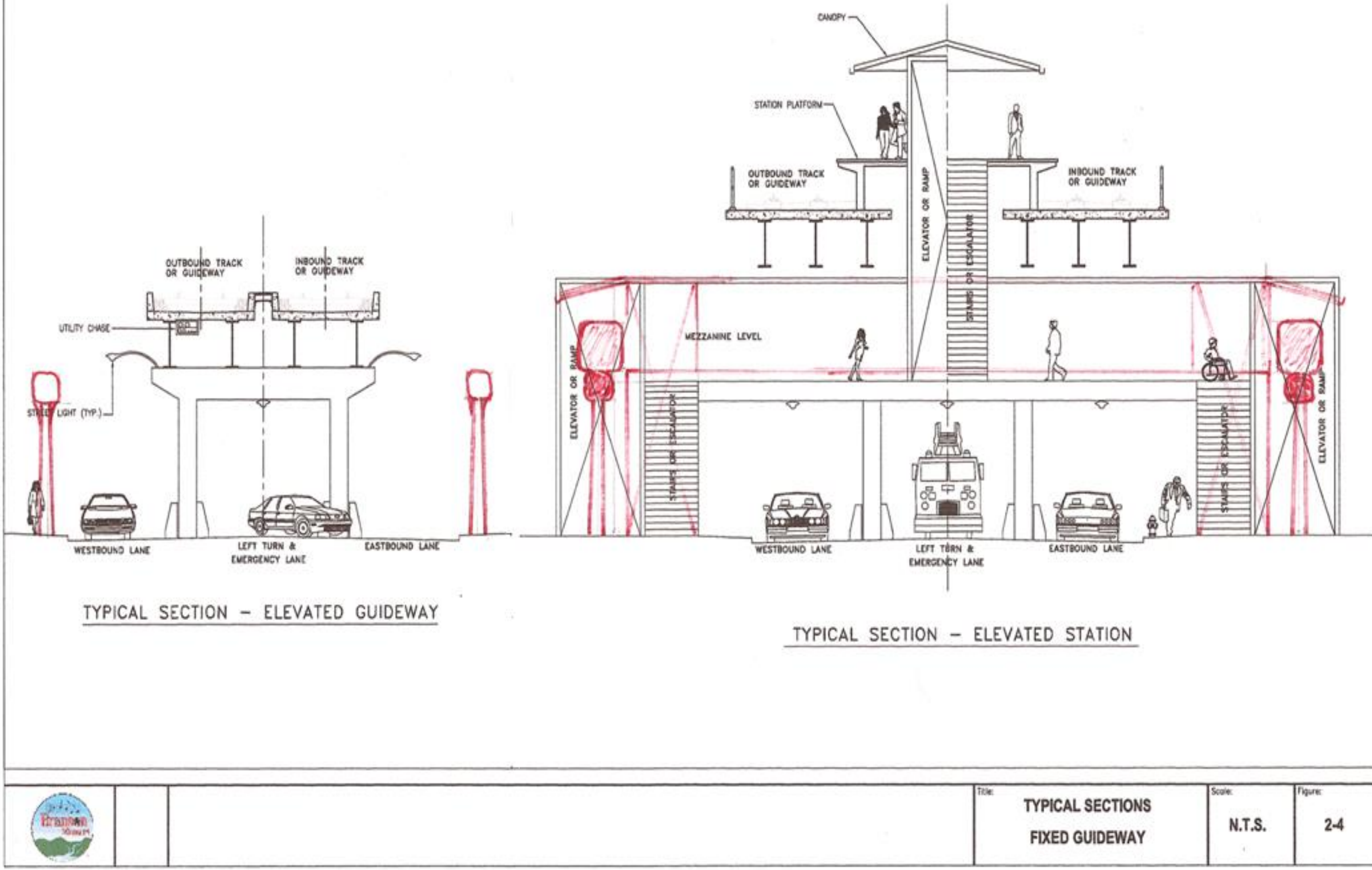
Designed by Dr. J. E. Anderson.
Built by Robin Russell,
M. E. Department Shop, U of MN.

LIMs, available since 1972,
efficient drives since 1980.

We call our version of this new system
an Intelligent Transportation Network System (*ITNS*).

It is a form of High-Capacity Personal Rapid Transit (PRT).

ITNS vs. Conventional Rail



Freeway at Capacity

Carter Burgess

Throughput per direction: 6000 cars/hr

Vehicles Removed

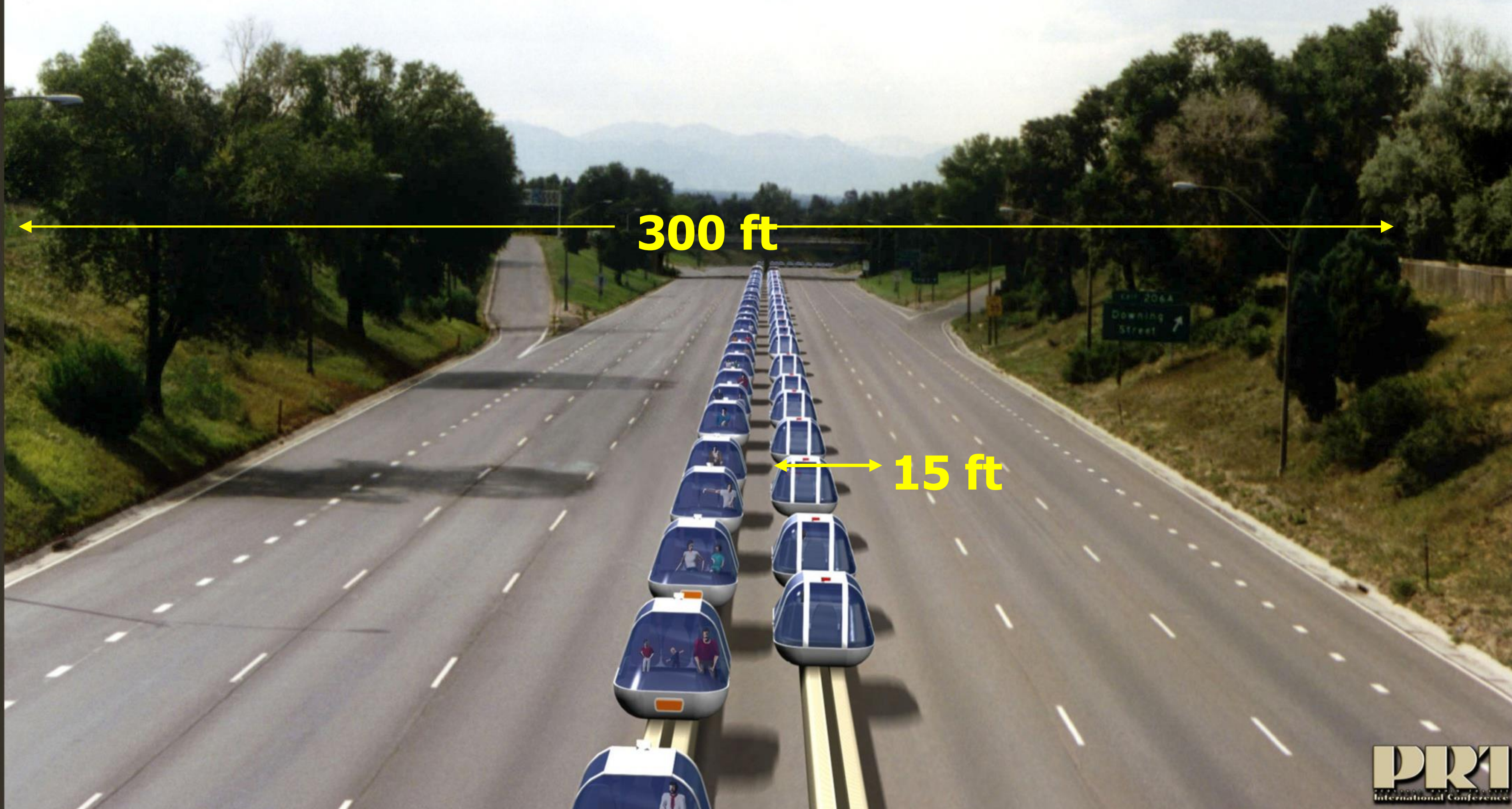
Carter::Burgess

PRT Passengers

Carter Burgess

Carter Burgess

Throughput per direction> 6000 cars/hr




A former parking lot!

Enormous Land Savings!

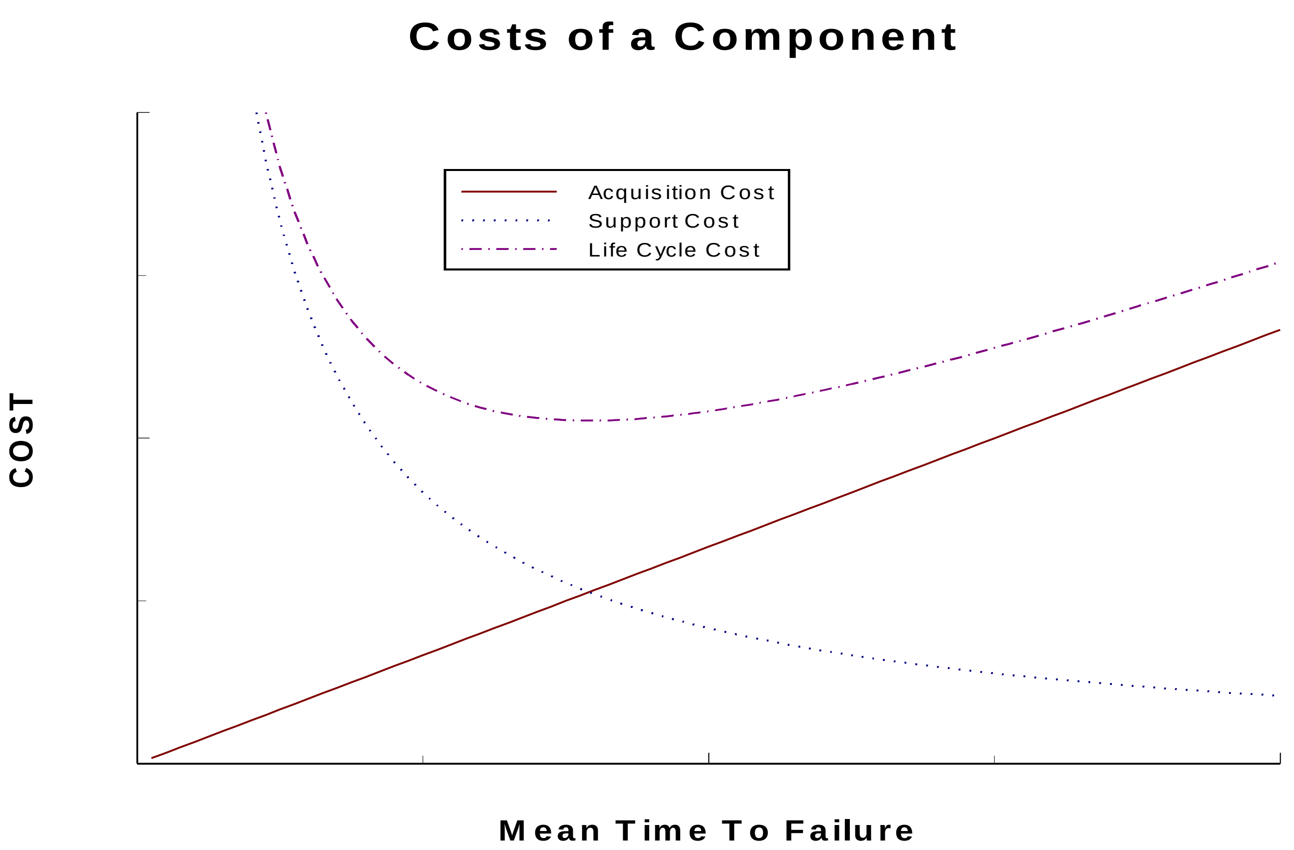
- **Land is required only for posts and stations,**
  only 1/5000th or 0.02% of city land.
- **Auto system requires**
  - **30% of land in residential areas**
  - **50% to 70% in downtown**

This is the REASON for CONGESTION!

Problem: Find MTBF of each Component that Minimizes System Life Cycle Cost subject to given Dependability.

Solution: Lagrangian constrained minimization problem solved in paper "Life-Cycle Costs and Reliability Allocation in Automated Transit"

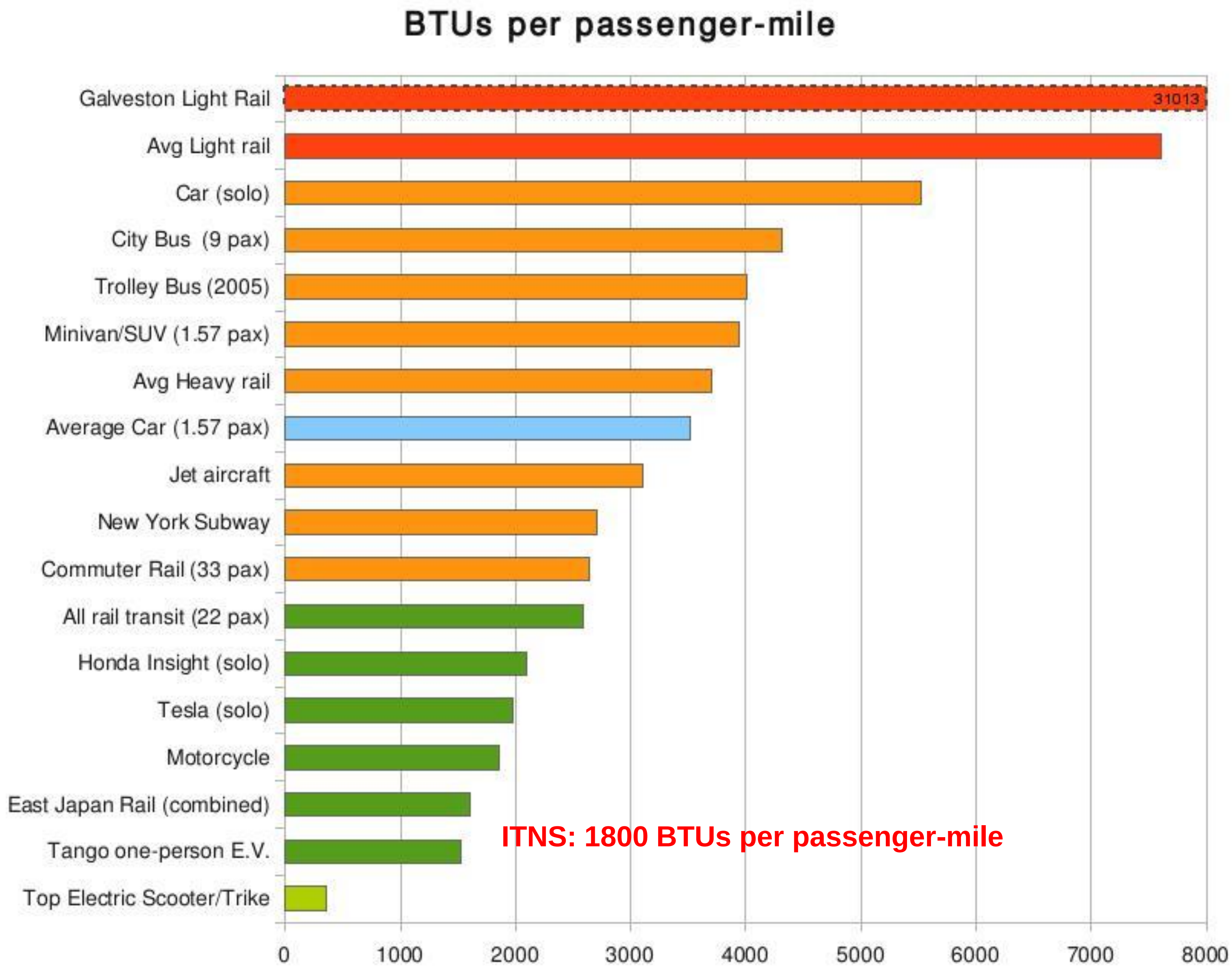
$$MTBF_j = \frac{1}{U}\left(\frac{\alpha_j v \tau_j}{LCC'_j}\right)^{1/2} \sum_{i=1}^{E} \frac{r_i}{N_v}(\alpha_i v \tau_i LLC'_i)^{1/2}, \qquad j = 1, 2, \ldots, E$$



How to Minimize Energy Use:

- Run Vehicles only when needed.
- Eliminate intermediate stops.
- Lower maximum speeds.
- Use each vehicle over and over again.
- Use very light-weight vehicles.
- Minimize material use.
- Use smooth, stiff tires for low road resistance.
- Streamline for low air drag.
- Make propulsion efficient.
- Provide enough but not too much insulation.

USA Transportation Energy Use



www.templetons.com/brad/transit-myth.html

How to Achieve High Reliability & Safety

- **Exclusive guideway.**
- **Few moving parts.**
- **No safety-critical moving parts in motors.**
- **Friction-free acceleration and braking.**
- **No moving track parts in switch.**
- **Dual motors, sensors, and power supply.**
- **Checked Dual Duplex computers.**
- **Fault-tolerant hardware and software.**
- **Independent emergency braking.**
- ***Result:***
  - ***Chance of injury is close to zero!***

The Key to Safety

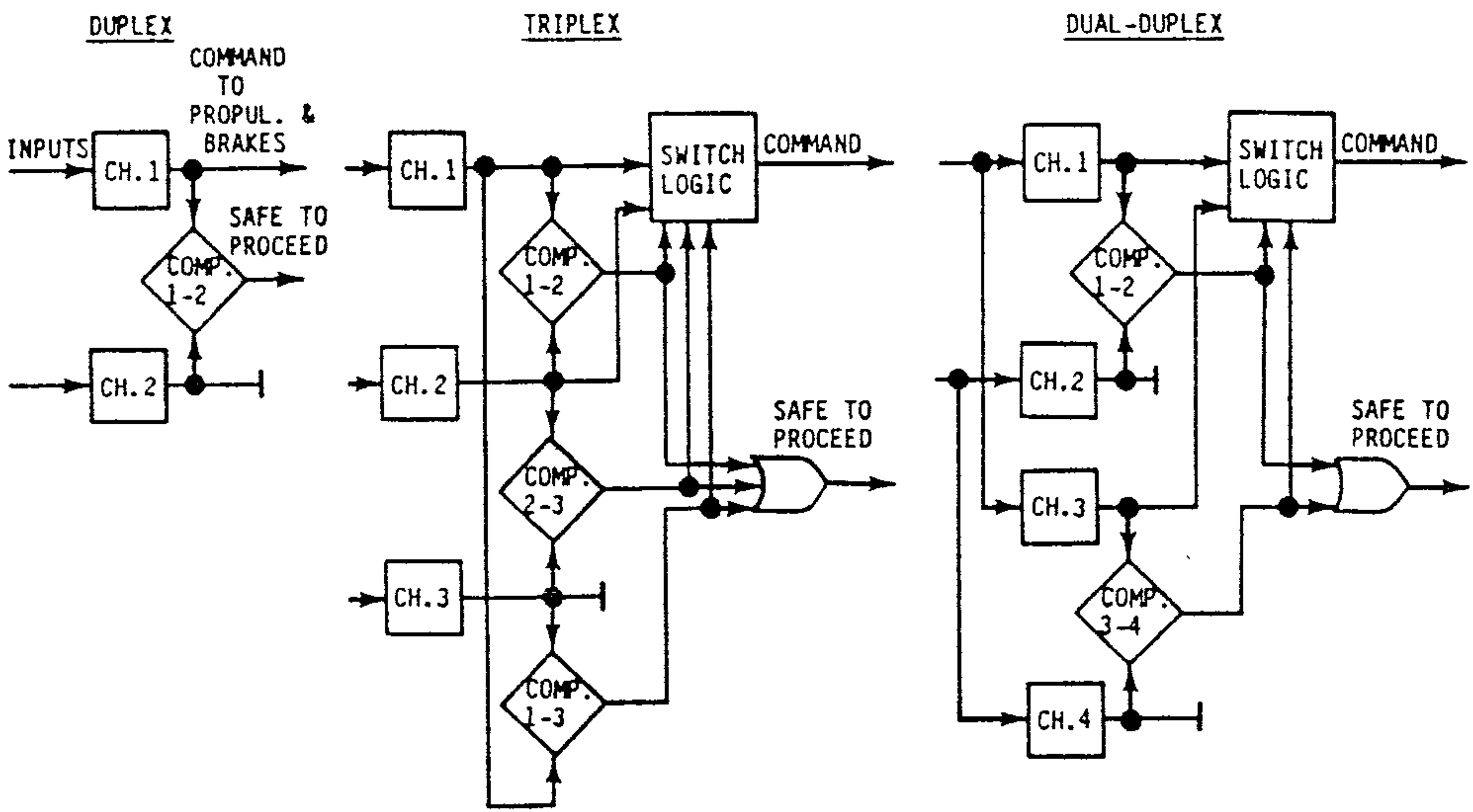


FIGURE 3: MICROPROCESSOR REDUNDANCY CONFIGURATIONS

Examples of fault-tolerant design:

- Wayside zone controller (ZC) emits speed signal every 50 ms.
  - With no speed signal vehicles programmed to creep speed.
- ZC receives position and speed from each vehicle every 50 ms.
  - With no communication from a vehicle, ZC removes speed signal.
- All commands returned and verified.
- Temperature sensors installed in thrusters.
- Emergency brake command ON unless OFF received every 50 ms.
- When switch is thrown, command is given to stop unless canceled by signal from proximity sensor.
- Sonar or radar back-up emergency control.

Mean Time Between Unsafe Failures

Source: "Failure Modes and Effects Analysis and Minimum Headway in PRT."

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/ 500 vehicles	150
Zone controller	30(10)^18
Vehicle-to-vehicle collision	10^12
Merge collision	10^13
Lifetime of Universe	13.8(10)^9
Auto/PRT accident rate	20(10)^12

Measure and Calculate System *Dependability*

"Dependability as a Measure of On-Time Performance of PRT Systems"

Dependability **= (1 - Person-Hours of Delay due to Failures ÷ Person-Hours of Operation)×100**

Analysis shows > 99.97% independent of system size!

The method permits *Dependability* to be both calculated in advance and measured in real time as a basis for contract specification.

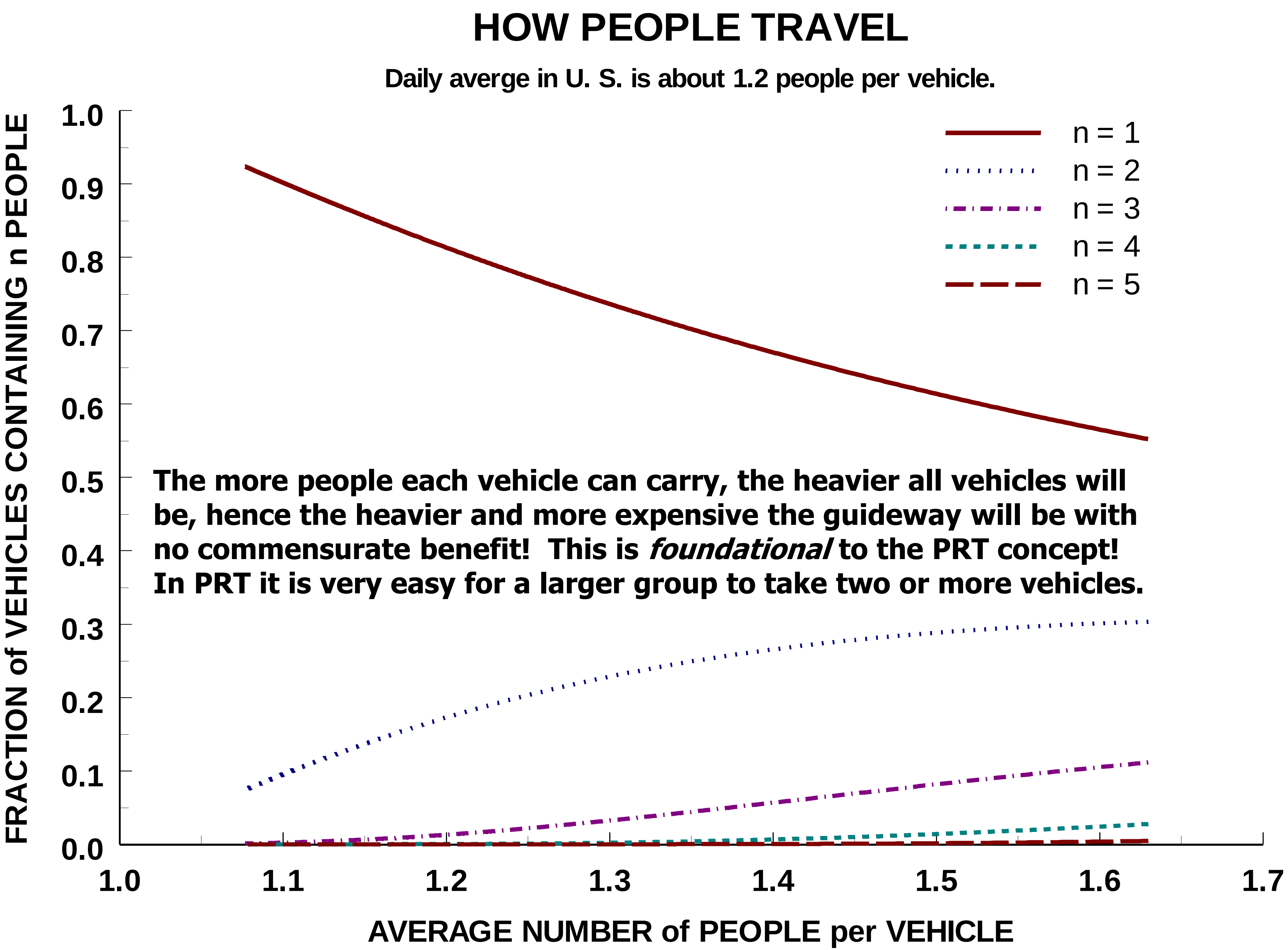
High *Dependability* results in high Safety!

1990's PATH Project: 60 mph on freeway near San Diego at 0.273 sec Headway.

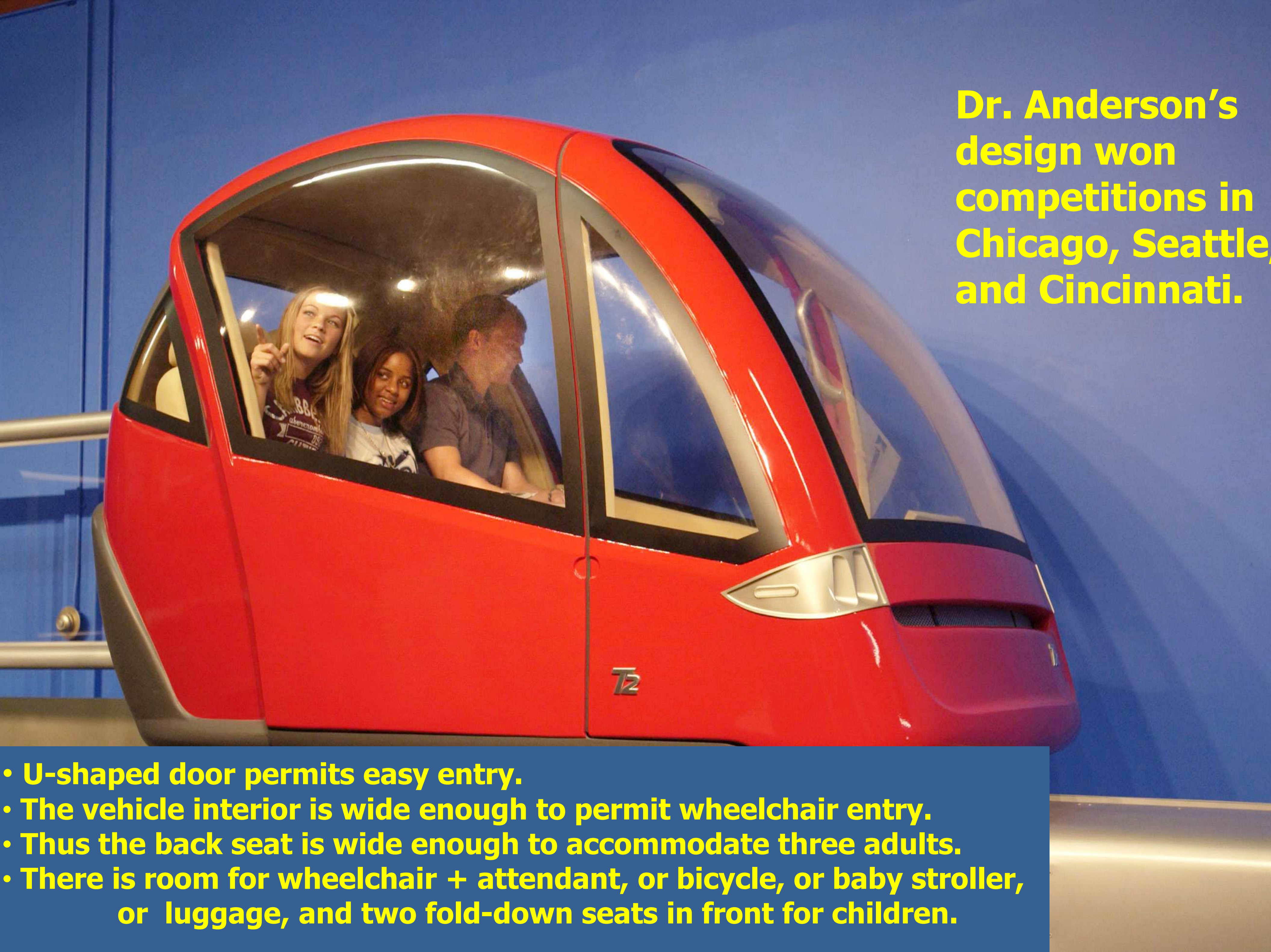
Monitored by National Highway Traffic Safety Board

Issue: Vehicle Design

- Accommodate a small family.
- Easy access by person using walker.
- Easy access by wheelchair + attendant.
- Accommodate bike or stroller or luggage.
- Minimize air drag.
- Provide not too much and not too little emergency braking.
- Conform to the way people travel.



HOW PEOPLE TRAVEL
Daily averge in U. S. is about 1.2 people per vehicle.
FRACTION of VEHICLES CONTAINING n PEOPLE
AVERAGE NUMBER of PEOPLE per VEHICLE
n = 1
n = 2
n = 3
n = 4
n = 5
The more people each vehicle can carry, the heavier all vehicles will be, hence the heavier and more expensive the guideway will be with no commensurate benefit! This is *foundational* to the PRT concept! In PRT it is very easy for a larger group to take two or more vehicles.
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7


Dr. Anderson's design won competitions in Chicago, Seattle, and Cincinnati.
T2
• U-shaped door permits easy entry.
• The vehicle interior is wide enough to permit wheelchair entry.
• Thus the back seat is wide enough to accommodate three adults.
• There is room for wheelchair + attendant, or bicycle, or baby stroller, or luggage, and two fold-down seats in front for children.


Working for You

Thousands of smooth rides given at 2003 Minnesota State Fair. No Redundancy. No Failures. Almost 4000 people petitioned the Legislature!

High Capacity with Small Vehicles?

Surface-level rail: 6 min between trains in rush period

At capacity: 450 people per train or
$450 \times 10 = 4500$ people per hour

ITNS: 6000 vehicles per hour

At capacity: 3 people per car or
$3 \times 6000 = 18{,}000$ people per hour

ITNS capacity/Rail capacity = 18,000/4500 = 4:1

The common belief that small vehicles mean small capacity is a myth!

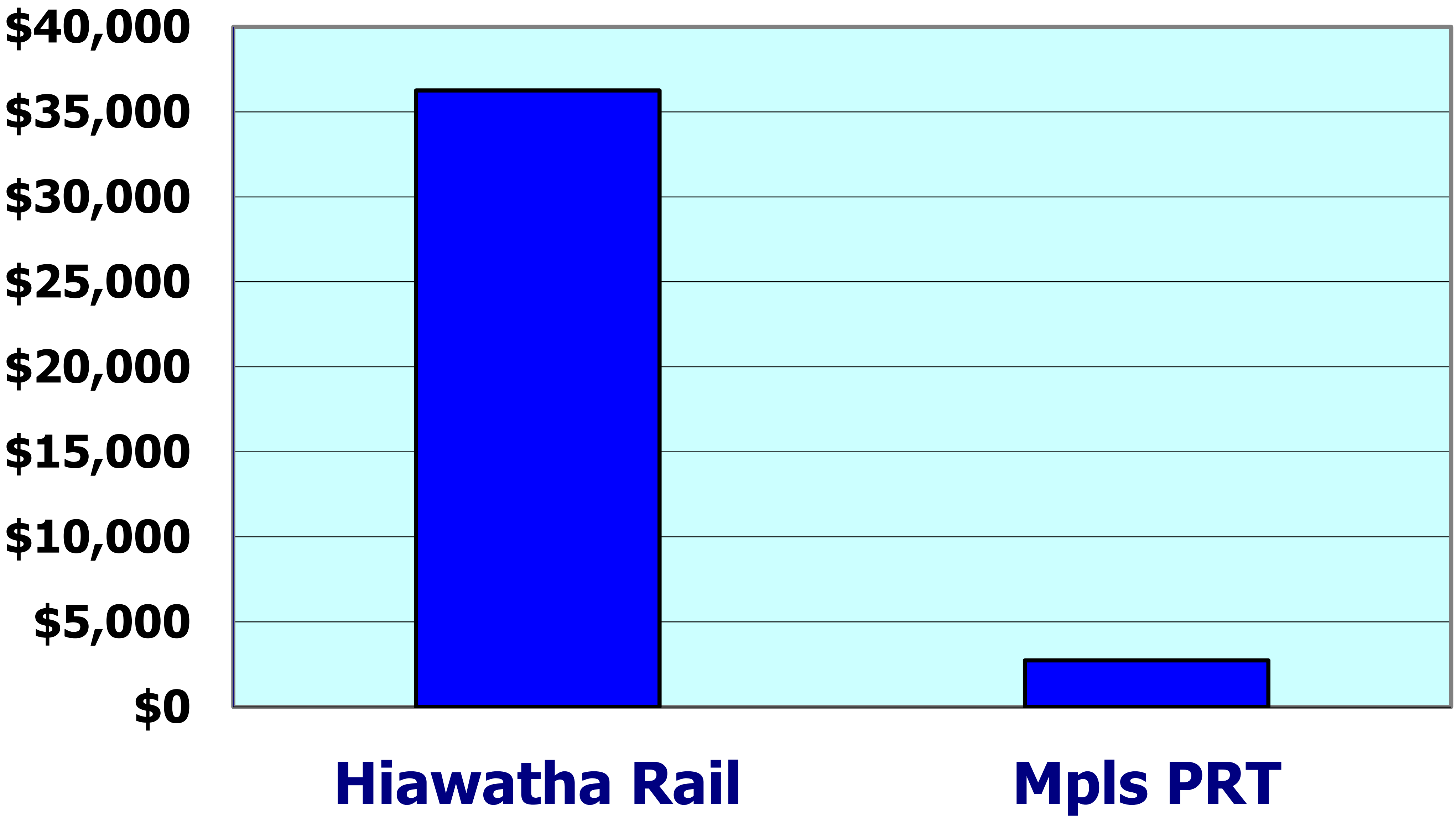
"PRT: Matching Capacity to Demand"

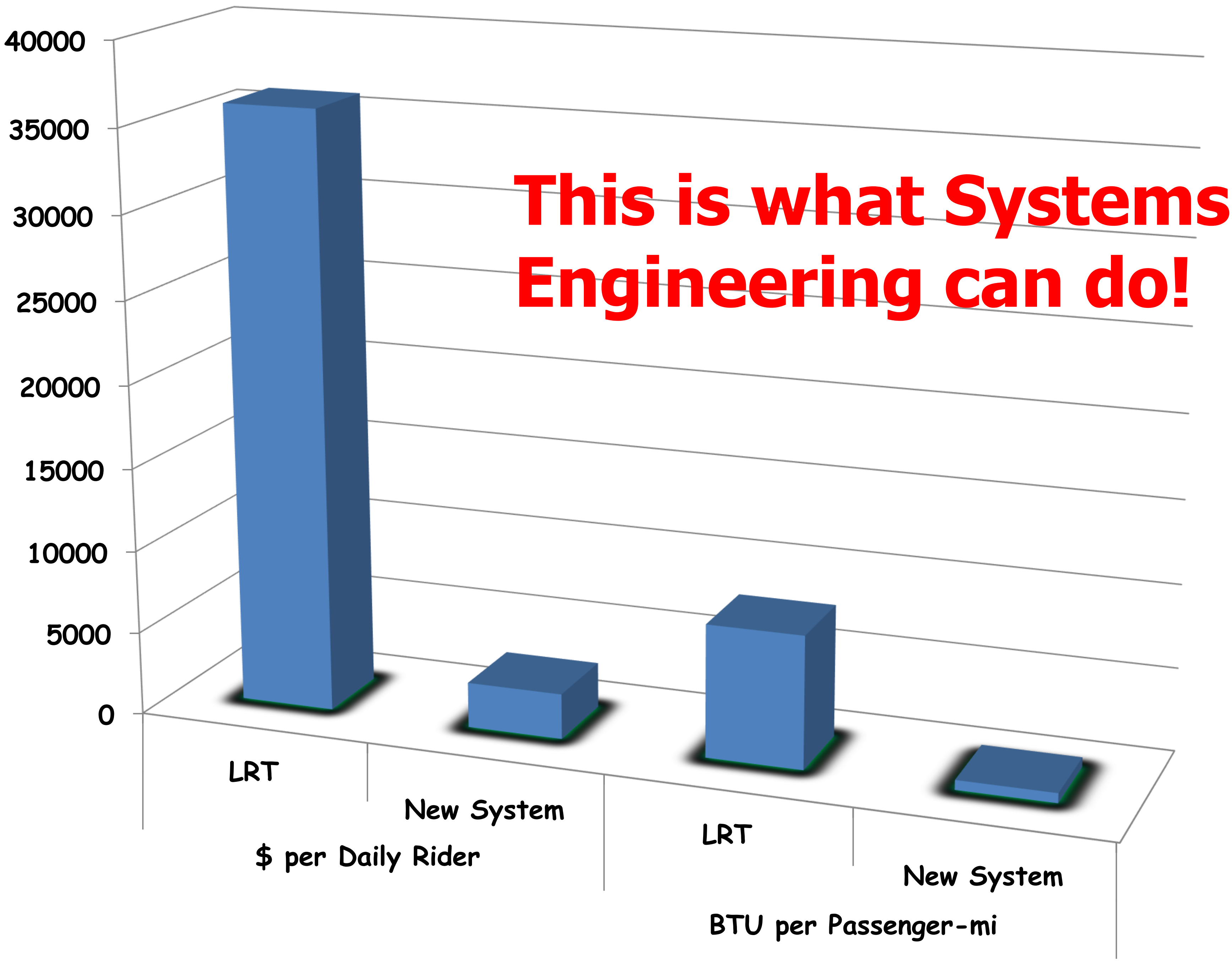
"The Capacity of High-Capacity PRT Systems"

How do Costs Compare?

“Light” Rail.
A transit mode first introduced in 1886.

Cost per Daily Trip




40000
35000
30000
25000
20000
15000
10000
5000
0
This is what Systems Engineering can do!
LRT
New System
$ per Daily Rider
LRT
New System
BTU per Passenger-mi

We will operate as a private business with revenue exceeding costs!

ITNS provides

Huge land savings + low cost + high ridership

permits safe, reliable, zero-pollution,

energy-efficient, environmentally friendly living

to an extent not possible

with conventional transportation.

“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.”

Bill Ford, Chairman,
Ford Motor Company

See Bill Ford on TED talks!

“Four billion clean cars on the road are still four billion cars!”

With these features,

why has it been difficult

to introduce PRT

in the United States?

Thomas S. Kuhn,

The Structure of Scientific Revolutions

Factors of jealousy, fashion, not-invented-here , greed have delayed new ideas.

Military industry – fear drives innovation.

Civil industry – fear inhibits innovation.

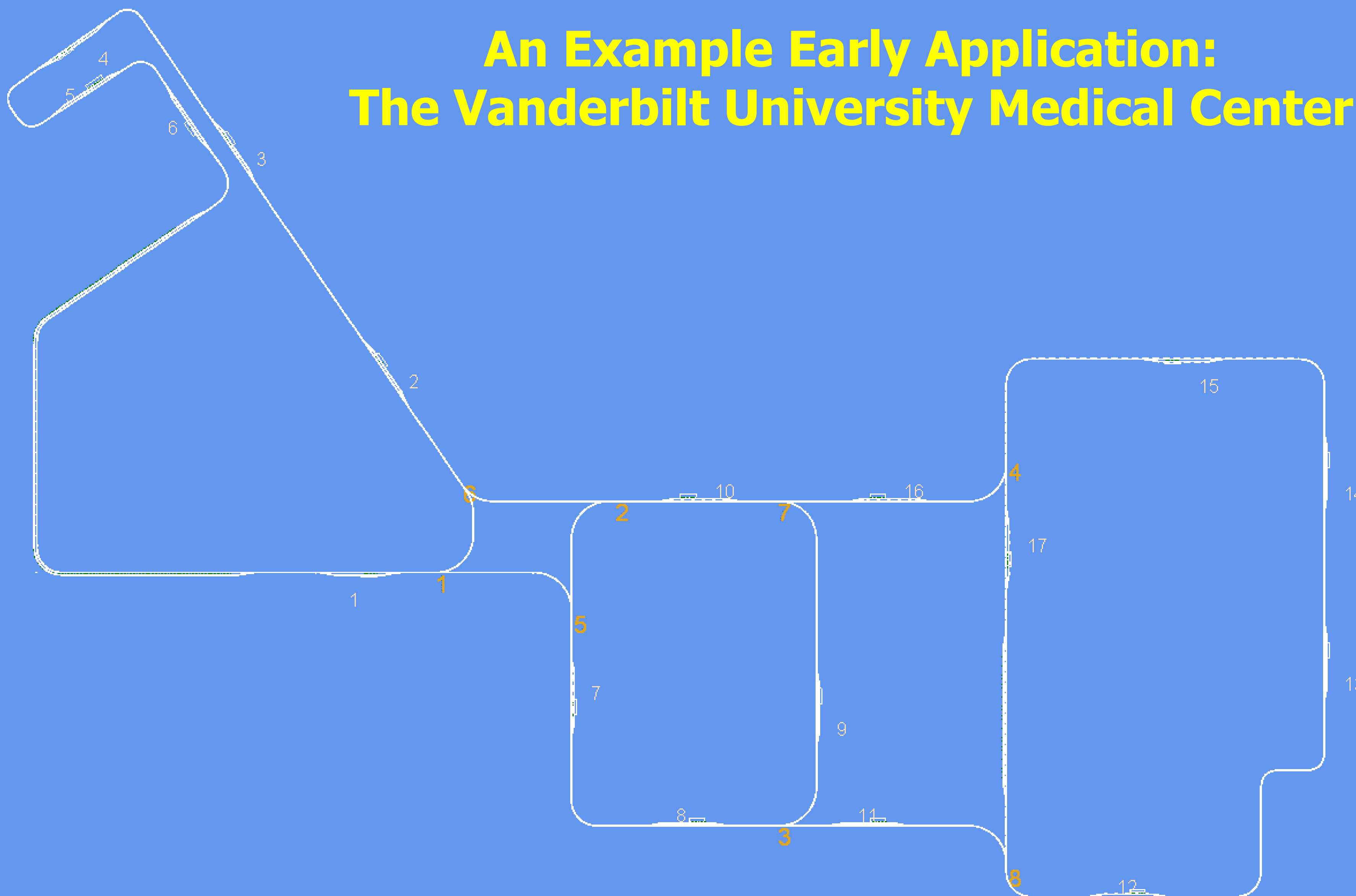
Applications of *ITNS*

- **Airports**
- **Medical complexes**
- **University campuses**
- **Retirement centers**
- **Amusement parks**
- **National parks**
- **Industrial parks**
- **Entertainment centers**
- **Large diversified centers**
- **Central business districts**
- **Cities**
- **Regions**

MainForm

Quit 3 + - ^ v < > Restore Center on Station Speed Normal Fast Slow

An Example Early Application:
The Vanderbilt University Medical Center



start ITNS System Control Microsoft PowerPoint ... ITNScontrol (Running... MainForm 5:39 PM

ITNS

is a new arrangement

of ordinary components

all of which work

in other ways!

The Next Step:

0.54 mi guideway
One Station, 3 vehicles
890 X 566 ft, 12 acres
Max speed 35 mph
In operation in 15 months from notice to proceed.

The Engineering Program is ready to go!
$30,000,000 for procurement documents, construction, installation, proof testing, marketing, and planning for applications.

The Engineering Program

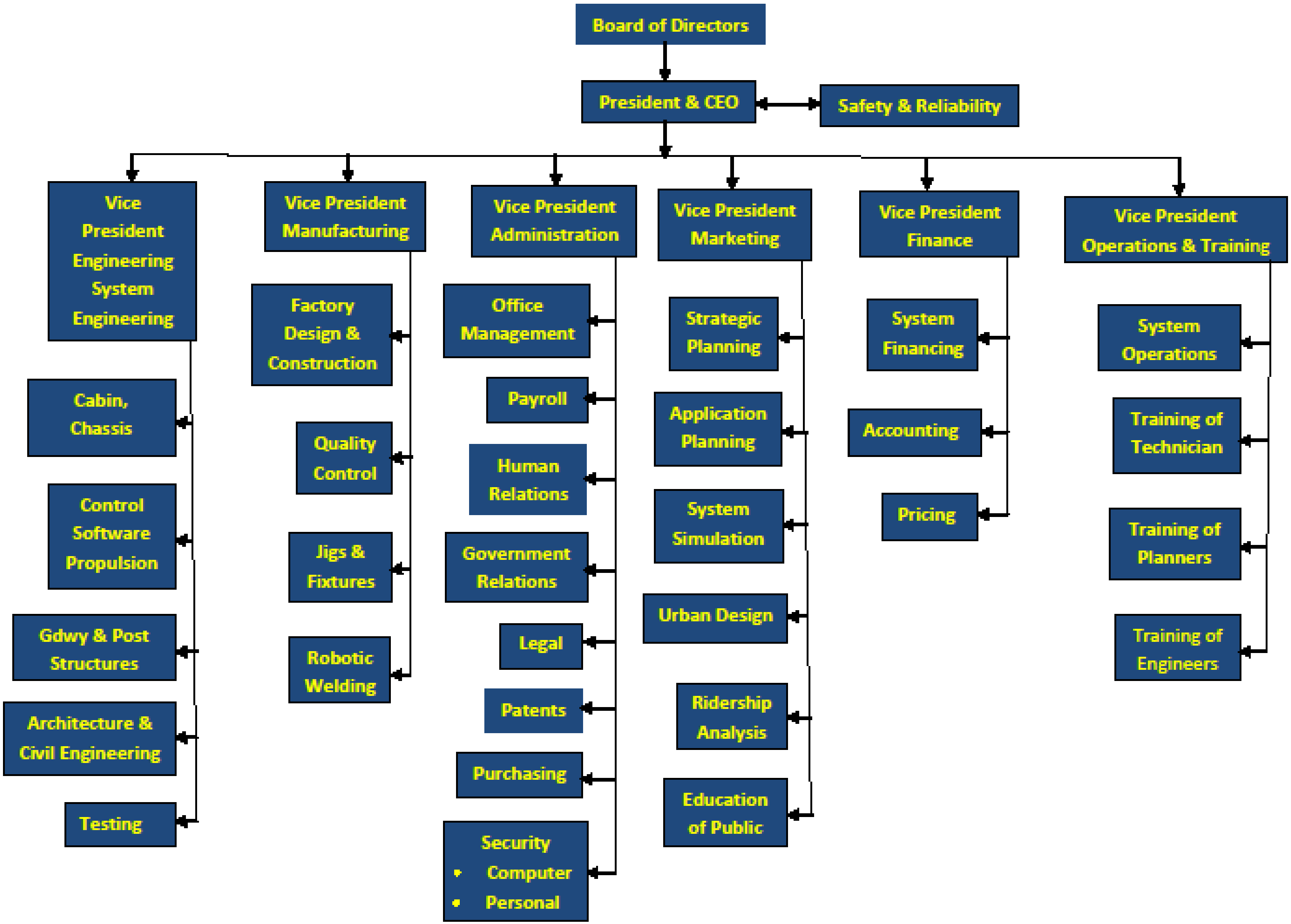
Task #1: Management and Systems Engineering.
Task #2: Safety and Reliability.
Task #3: Cabin.
Task #4: Chassis.
Task #5: Guideway and posts.
Task #6: Guideway covers.
Task #7: Control system.
Task #8: Propulsion and braking.
Task #9: Wayside power.
Task #10: Civil works – stations, maintenance, foundations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

Team Work is Essential!

The project will start as a

Lockheed "Skunk Works"

and in time will ramp up to . . .



Board of Directors
President & CEO
Safety & Reliability
Vice President Engineering System Engineering
Cabin, Chassis
Control Software Propulsion
Gdwy & Post Structures
Architecture & Civil Engineering
Testing
Vice President Manufacturing
Factory Design & Construction
Quality Control
Jigs & Fixtures
Robotic Welding
Vice President Administration
Office Management
Payroll
Human Relations
Government Relations
Legal
Patents
Purchasing
Security
• Computer
• Personal
Vice President Marketing
Strategic Planning
Application Planning
System Simulation
Urban Design
Ridership Analysis
Education of Public
Vice President Finance
System Financing
Accounting
Pricing
Vice President Operations & Training
System Operations
Training of Technician
Training of Planners
Training of Engineers

ITNS is "An Essential Technology for a Sustainable World"

Andrew Euston

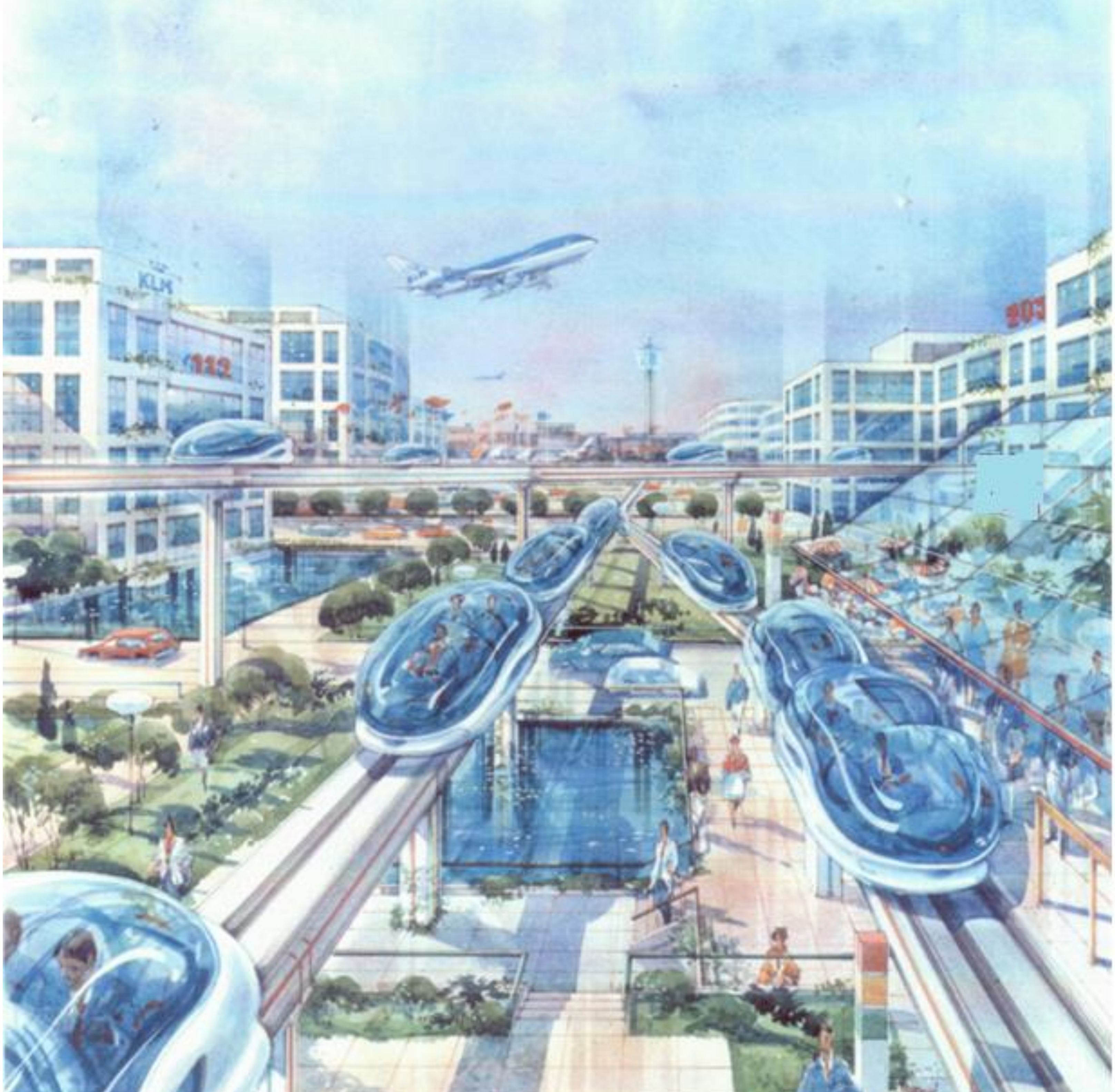
Retired Director for Sustainable Cities

U. S. Department of Housing and Urban Development

Market:
We know of several dozen applications each at $200,000,000 and up!

We have an investor who, with conditions, will invest the needed $30,000,000!

The Vision . . .


KLM

Thanks to Chiphol Forward, Amsterdam!