An Intelligent Transportation Network System:

Rationale, Attributes, Status, Economics, Benefits, and Courses of Study for Engineers and Planners

J. Edward Anderson, Ph.D., P. E.
Minneapolis, Minnesota, USA

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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.

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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 (www.wbcsd.org), 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 that was 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][1]. 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. A March 2006 European Union Report concluded: “The overall assessment shows vast EU potential of the innovative PRT transport concept” [2].

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[1] [n] is the nth reference in the list at the end of this paper.

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 all 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 [37], 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 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 are summarized in a DVD[2]. We begin by diagramming all combinations of system attributes without prejudice toward pet solutions. We then analyzed thoroughly 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 a vital one.

3. The Problems to be Addressed

- Increasing congestion.
- The use of oil in transportation. "The era of cheap oil is over."[3]
- Air pollution.

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[2] Available on request.

[3] *World Energy Outlook 2008*, International Energy Agency.

- 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. Requirements of the New System

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.

These and other requirements are discussed in Appendix A. A series of 18 criteria are discussed in Appendix B.

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.

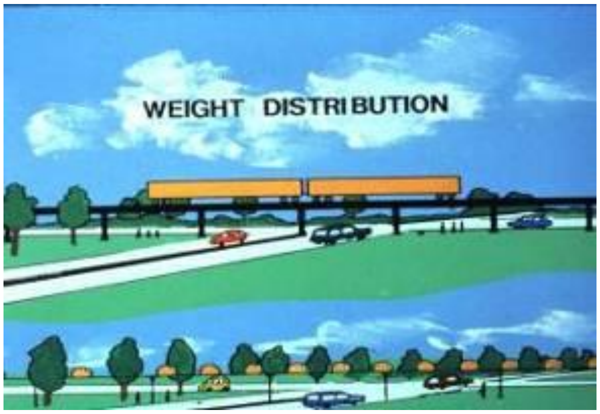

Figure 5.1. Guideway Weight and Size.

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 the data in Figure 5.2 show, however, that this is not so. Each point in Figure 5.2 represents a transit system, with the 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 conclusion is that a higher rate of production reduces unit costs.

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.

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.

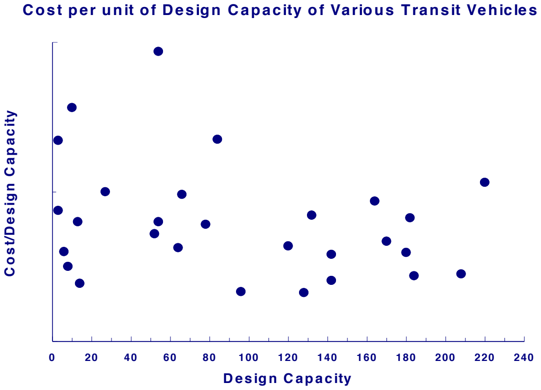

Figure 5.2.

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 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].[4]

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[4] 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

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 apart, whereas on freeways cars travel seconds apart, and often less than a second apart. An example is given in Section 9.

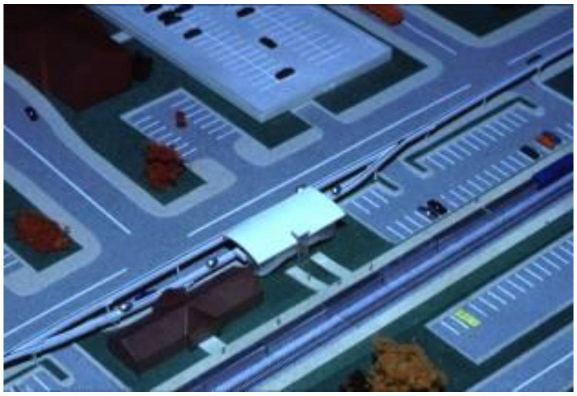

Figure 6.1. An Off-Line Station

- 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.

- Practical use of the nonstop trip means that the average waiting time for a second party is generally too long to be of interest.[5] 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

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generally avoid the busiest hours, the statistical average peak flow will not be much decreased by the occasional presence of such persons. If system studies show a need for such stations, there is nothing in our design that would prevent us from including them.

[5] Reference 19, page 89, equation 4.5.22.

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.

7. Tradeoffs

Following is a series of tradeoffs that defined *ITNS,* on each of which a paper is available to the interested reader.

Dual Mode vs. Single Mode [46]
Supported vs. Hanging Vehicles [6]
Air cushions vs. maglev vs. wheels [47]
Rotary motors vs. linear motors [11]
Linear induction motors vs. linear synchronous motors [48]
Motors on board vs. motors in guideway [49]
Power source on board vs. power source at wayside [50]
Synchronous vs. quasi-synchronous vs. asynchronous control [13]

The Vehicle's Cabin Configuration

The minimum-sized cabin of a High-Capacity PRT System 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:

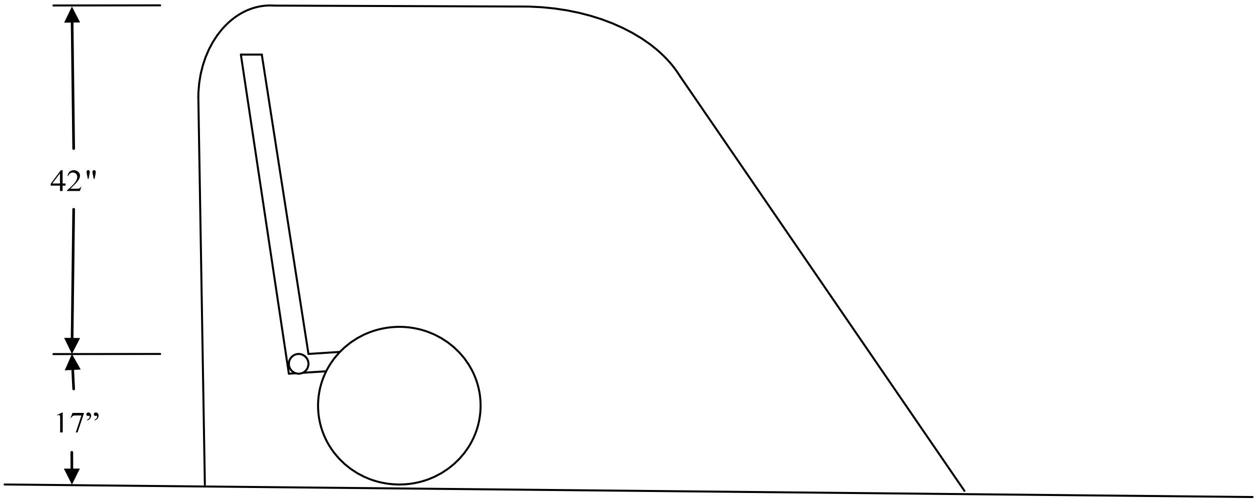

Figure 7.1. Sketch of Minimum-Size Vehicle.

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.

How many people will ride in a PRT vehicle?

Let n be the number of people riding in a vehicle, and let $f(n)$ be the fraction of vehicles that contain n people. From the statistical theory of the normal distribution

$$f(n) = ce^{-\lambda n^2} \tag{7.1}$$

Then, by definition of $f(n)$, we have

$$1 = c\sum_{n=1}^{\infty} e^{-\lambda n^2} \tag{7.2}$$

Hence

$$f(n) = \frac{e^{-\lambda n^2}}{\sum_{n=1}^{\infty} e^{-\lambda n^2}} \tag{7.3}$$

Now, the average number of people per vehicle is

$$N_{ave} = \frac{\sum_{n=1}^{\infty} ne^{-\lambda n^2}}{\sum_{n=1}^{\infty} e^{-\lambda n^2}} \tag{7.4}$$

Given N_{ave} this is a transcendental equation for λ. Once λ. is found by iteration, we can find *f(n)* from Equation 7.3. The calculations have been performed in a simple computer program with the results shown in Figure 7.3 and Table 7.1.

In 1990 the Twin Cities Metropolitan Council did an 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 7.3 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 assume 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 carpeted floor. In calculation of operating costs, we have assumed the vehicles will be cleaned daily. We noted that in PRT it is easy to take two or more vehicles if there is a larger group than would be comfortable in one vehicle, and they can communicate with each other via the cell phones they likely carry. Such vehicles would leave the origin station seconds apart and similarly arrive at the destination station seconds apart. Note that the larger each vehicle is, the heavier the guideway must be and the more expensive the system will be; however, if a client were to insist on a larger vehicle, it can be supplied, but at additional system cost.

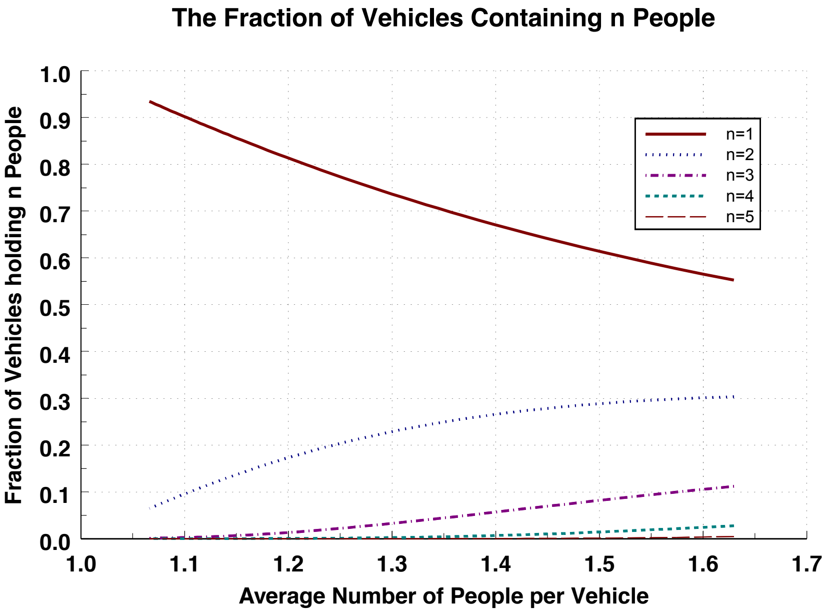

Figure 7.3

Table 7.1. Some numerical results of equation 7.4.

Average	n=1	n=2	n=3	n=4	n=5
1.6	0.565	0.301	0.105	0.024	0.004
1.4	0.671	0.266	0.057	0.007	0.0004
1.2	0.814	0.173	0.013	0.0004	-
1.08	0.921	0.078	0.0013	-	-

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. 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,[6] 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 (see Section 10.5).
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. [40]
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.
9. To permit the community to select the color and texture of the exterior surface of the guideway covers.

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[6] [19], Chapter 10; [5] and [39].

8. The Attributes of *ITNS*

A system that will meet the requirements of Section 3 will have

- Off-line stations.
- Minimum-sized, minimum weight vehicles.
- Adequate speed, which can vary with the application and the location in a network.
- Fully automatic control.
- Hierarchical, modular, asynchronous control to permit indefinite system expansion.
- Dual duplex computers for high dependability and safety.
- Accurate, dual position and speed sensors. Today's sensors are much more accurate than needed.
- Smooth running surfaces for a comfortable ride.
- Rubber-tired wheels for suspension to minimize guideway cross section and weight.
- All-weather propulsion and braking by means of linear induction motors.
- Switching with no moving track parts to permit no-transfer travel in networks.
- Small, light-weight, generally elevated guideways.
- Guideway support-post separations of at least 90 ft (27 m).
- Vehicle movement only when trips are requested.
- When trips are requested, empty vehicles are rerouted automatically to fill stations.
- Nonstop trips with known companions or alone.
- Propulsive power from dual wayside sources.
- Well lit, television-surveyed stations.
- Planned & unplanned maintenance *within the system*.
- Full compliance with the Americans with Disabilities Act.

9. The Optimum Configuration

During the 1970s I accumulated 37 requirements for design of a PRT guideway. They are given in Appendix A. 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 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 [6].

Figure 9.1. The Optimum Configuration

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 as calculated. 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 [30] that I presented at the 2009 APM Conference. In the 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. In the paper I give the above-mentioned requirements and also 19 design criteria, which are included in Appendix B.

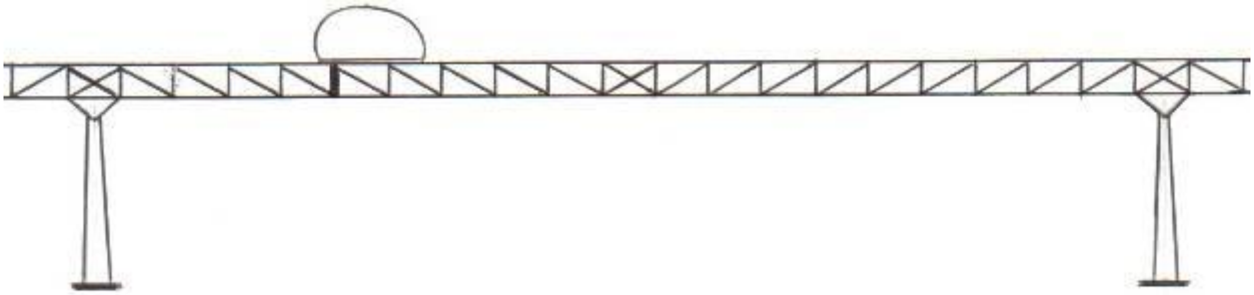


Figure 9.2. A Low Weight, Low-Cost Guideway

As shown in Figure 7.4 and 9.1 the guideway will be covered. A slot only three inches wide at the top permits the vertical chassis to pass and a slot six inches wide at the bottom permits snow, ice, or debris to fall through. We have designed and tested a plow that can be attached at the bottom of the chassis if needed. The plow is angled in such a way that any snow or other debris on the running surfaces will be thrown down the slot between the pair of steel-angle running surfaces. The covers permit the system to operate in all weather conditions. They minimize air drag, prevent ice accumulation on the power rails, prevent differential thermal expansion when the sun is shining on one side of the guideway, serve as an electromagnetic shield, a noise shield, and a sun shield, permit access for maintenance, and permit the external appearance to be whatever the local community wishes. The covers thus enable the system to meet nine of the guideway design requirements. They will be manufactured from composite material with a thin layer of aluminum sprayed on the inside surface to provide electromagnetic shielding.

Figure 7.4 shows the guideway cross section, with one of a series of U-frames, each of which is placed at a position of one of the vertical lines 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 with its attachment to the cabin above. Comprehensive finite element analysis has been performed on the joint to insure that it is very strong and conservatively designed. The main support wheels are shown. They run on a pair of 8×6×9/16 inch steel angles. The side support wheels are shown in Figure 7.4. These tires are polyurethane of stiffness determined from a dynamic simulation 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 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.

The Americans with Disabilities Act requires the vehicle to be wide enough so that a wheelchair can enter and face forward with room for an attendant. Such a vehicle is wide enough for three adults to sit side-by-side and for a pair of fold-down seats in front for small people, making it a five-person vehicle. Without the wheelchair, such a size cabin can accommodate a person and a bicycle, a large amount of luggage with two people, a baby carriage plus two adults, etc. [7]

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 9.3. An Application in Downtown Chicago

Figure 9.3, 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.

10. Control

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 [11 – 15]. I add to this collection of papers a paper [31] 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 10 times a second. 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 [31]. The methodology we use was obtained from Boeing papers developed during their work on AGRT [4].

Three types of computers are needed for vehicle control: 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. 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 [33].

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 optimizes recycling of empty vehicles, 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 [32] 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 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 [29]. The zone controllers similarly talk to and from the leaky cable, which is commercially available. This type of communication is completely secure and cannot be interfered with by hackers. Our computers need not and will not have Internet capability.

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 two hundred times per second. 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 times each second. Code has been developed to control any number of vehicles in networks of any size or configuration]26]. 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. System Features Needed for Maximum Throughput Reliably and Safely

The features needed are illustrated in Figure 11.1.

1. All weather operation: 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 200 times per second.
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.

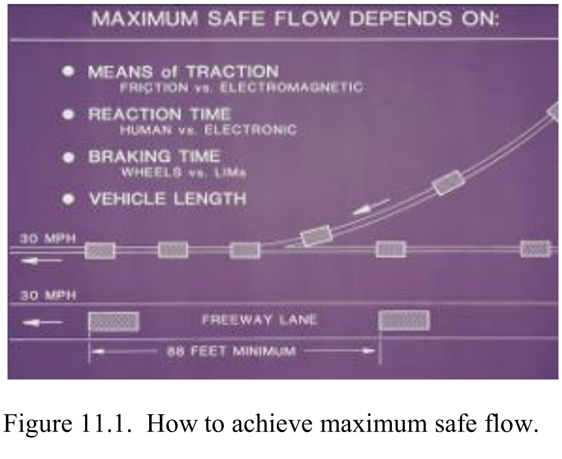


Figure 11.1. How to achieve maximum safe flow.

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 [11], i.e., 6000 vehicles per hour. During the Phase I PRT Design Study for Chicago, extensive failure modes and effects analysis [12], 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 [13]. Combined with redundant power sources, fault-tolerant software, and exclusive guideways; our studies performed during our Chicago PRT Design Study showed that there will be no more than about three person-hours of delay in ten thousand hours of operation [14]. A method [15] 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 about 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 [8]. 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.

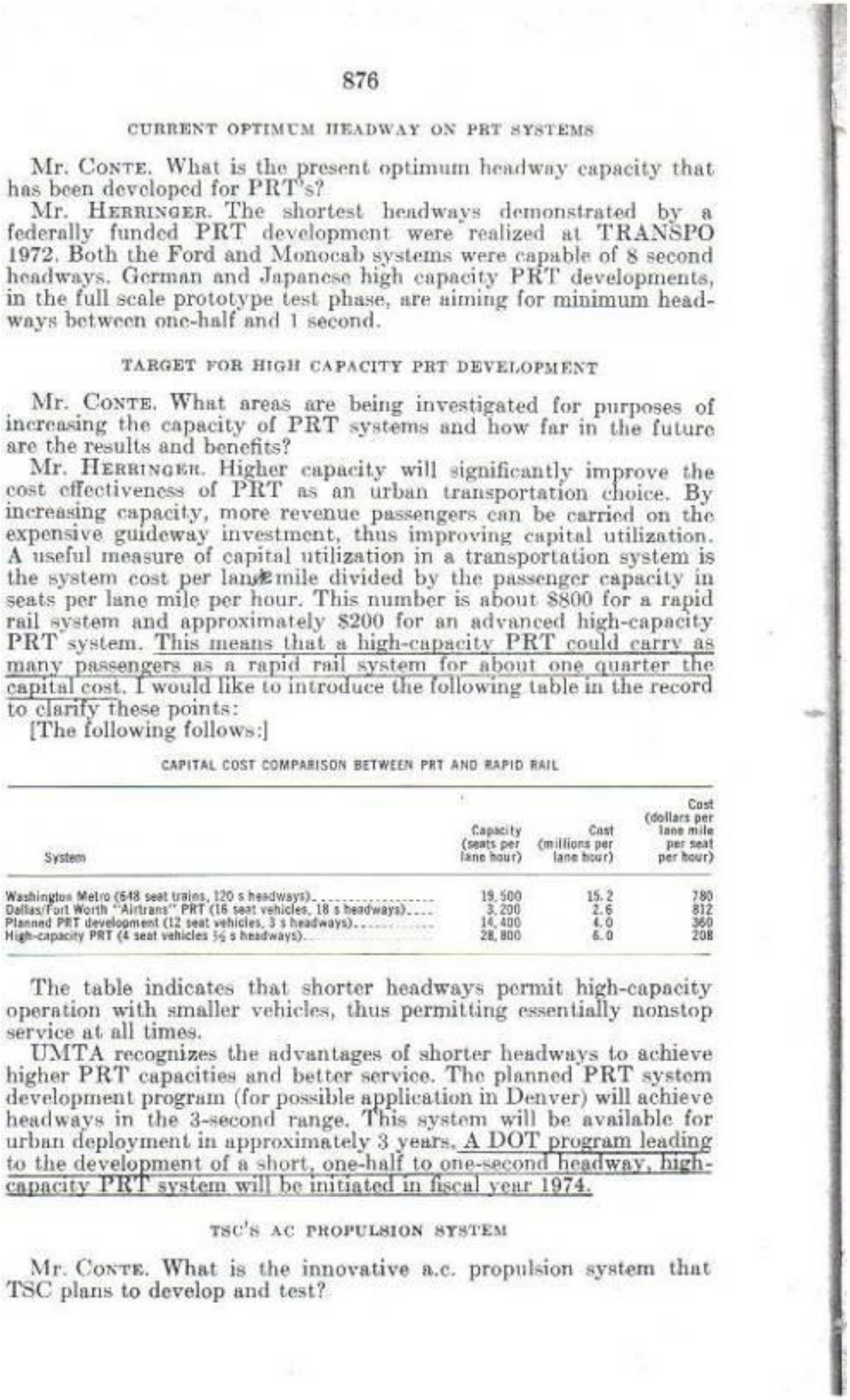
In 1973 Urban Mass Transportation Administrator Frank Herringer told Congress that "a high-capacity PRT could carry as many passengers as a rapid rail system for about one quarter the capital cost" (see Figure 12.2). Notwithstanding that this pronouncement was backed up by the work of a competent R&D 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, 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 [10]. 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.

Figure 12.1. Automated Highway Experiment.

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.

I discuss this in some detail in References [13] and [31]. 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.



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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].

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 [16] 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% [17], 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.

15. History and Status

All of the technologies needed to build *ITNS*, including all of the control hardware and software, have been developed. All we need is the funds required to build the small, full-scale pilot system described in Section 23 – a sum lower than many people estimate, but practical because of the advanced state of our development work. Such programs are already underway overseas. *ITNS* is a collection of components proven in other industries. The only new thing is the system arrangement: The system control software has been written [45] and excellent software tools are available from many sources for final design verification and development of the final drawings needed for construction. But, because there has been no U. S. federal funding to support the development of PRT during the past three decades, few people in the United States have been able to continue to study and develop these systems. The immediate question is this: Why the lack of federal support? While the full answer is complex, the driving reason was that HCPRT was too radical for an industry suddenly confronted with it and with no real chance or desire to understand it. The human reaction was to lobby to kill it, which the lobbyists accomplished by September 1974. Today, the situation is different. Transformative technologies like HCPRT are essential to maintaining mobility in an age of declining oil availability and the need to markedly reduce pollution.

The two leading HCPRT development programs during the 1970s are illustrated in Figures 15.1 and 15.2. The Aerospace program ended in the mid 1970s because of the lack of federal support, and the Cabintaxi program (DEMAG+MBB) ended in 1980 when the Federal Republic of Germany had to divert substantial funds to NATO programs. These programs provided the bulk of the background needed to continue PRT development during the next decades.

Without these programs, I don't believe we would be talking about PRT in any form today. The world owes them thanks for their pioneering efforts.

Figure 15.1. The Aerospace Corporation PRT System [1]

Figure 15.2. Cabintaxi [18]

A third important PRT-related development program conducted during the 1970s still operates in Morgantown, West Virginia. It is shown in Figure 12.3. I call it "PRT-related" because its fully automatic operation is similar to PRT but it uses 20-passenger vehicles, and thus is more correctly classified as Group Rapid Transit. Contracts were let in December 1970 to get the system operating only 22 months later. Since there was almost no knowledge of the theory of PRT systems [19] in 1970, many decisions were made that increased size, weight, and cost. Yet, this system has been in continual daily operation since the mid 1970s with no serious accidents of any kind, which attests to the safety of fully automated transit systems. The gross (fully loaded) vehicle weight is about 11,800 lb and the operating headway is 15 seconds.

Figure 15.3. Morgantown

Through these years we studied carefully the work of others on the PRT concept and studied how to optimize the design of a PRT system. Before our hardware was built, we won competitions in Chicago, SeaTac and Cincinnati. In 2001-3 I directed the design and construction of the system shown in Figure 7.2. It was fully automatically controlled and propelled and braked by linear induction motors. It was opened to the public in April 2003 and thousands of rides were given flawlessly to an enthusiastic public on a 60-ft section of guideway at the 2003 Minnesota State Fair. The fully loaded vehicles have a maximum gross weight of about 1800 lb and the control system is designed so that multiple vehicles can operate at half-second headways.

Figure 15.5. ULTra, Vectus, and 2getthere PRT Systems

Figure 15.5 shows three new PRT systems. The picture on the left is ULTra (www.ultraglobalprt.com), which has been developed at Bristol University in the United Kingdom. This system is in operation at Heathrow International Airport and is moving people from parking lots into the terminals. From papers on their web page, it is clear that this system is restricted to relatively small, low-speed, low-capacity applications in areas with very little ice and snow. The center system is Vectus, which is being developed by the Korean steel company Posco (www.vectusprt.com). Since September 2007 they have been operating a test system in Uppsala, Sweden, and in September 2009 they announced that they will build a system in Suncheon, South Korea. It is now in operation. Vectus uses LIMs in the guideway, which increases guideway weight and cost, and has a guideway similar to that in the failed Raytheon system. The picture on the right is the Dutch PRT system (www.2getthere.com). It was selected for the first phase of the famous Masdar project in Abu Dhabi, United Arab Emirates, as a means for providing non-polluting, non-oil-using transportation and is now in operation. This system uses wire-guided vehicles operating on a surface, and thus does not require a guideway. None of these systems meets the full range of requirements given in Section 3 and Appendix A.

16. Economics of *ITNS*

Based on a system-significant equation for cost of any transit system per passenger-mile, I have shown [21] 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%,[7] 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 [22]. 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.

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[7] 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 – 26% of conventional light rail.

Figure 16.1. Minneapolis-Airport (Hiawatha) light rail.

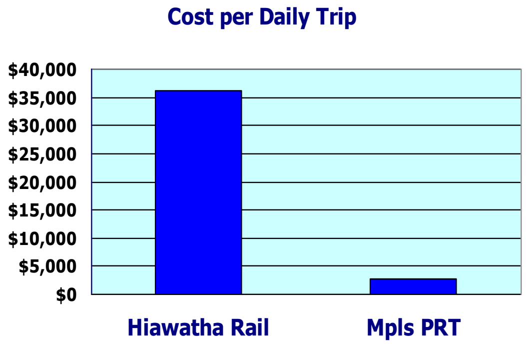

Figure 16.2. Cost Comparison

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 [16] 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.

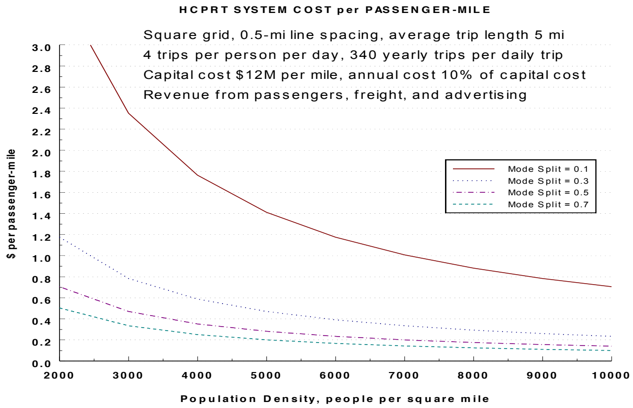

Figure 16.3. Cost per passenger-mile.

17. Land Savings.

Figure 17.1 shows a freeway running on the left side at capacity – about 6000 cars per hour [23]. 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 an *ITNS* system, 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 [21]. 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 as many trips per day as about 10 automobiles, thus saving the energy of construction of at least nine automobiles, each of which weighs roughly twice the weight of an *ITNS* vehicle.

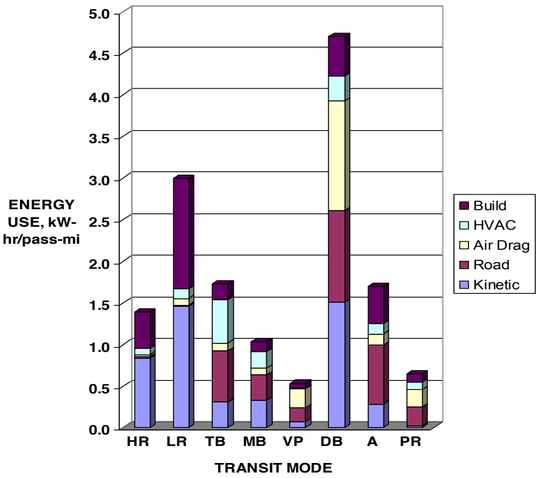

Figure 18.1. Energy use per passenger-mile.

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 [24]. 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 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. Benefits for the Riding Public

- The system will be easy for everyone to use. No driver’s license needed.
- Vehicles will wait for people, rather than people for vehicles.
- Travel is cost competitive.
- The trips are short, predictable, and nonstop.
- There is minimum or no waiting.
- 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, or watch the scenery.
- 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.

20. Benefits for the Community

- Energy use is very low.
- The system can use 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.
- Land savings is huge – 0.02% is required vs. 30-70% for the auto system.

- 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 [12] 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 will be no significant high-value targets for terrorists.
- Transit subsidies will be reduced.
- More livable high-density communities will be 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 are 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.
- Fewer tendencies to urban sprawl.

21. Reconsider the Problems

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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.

And the solution: 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*.

22. 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 is 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[8] – 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.

- 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.

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[8] Swedish name for Personal Rapid Transit.

- 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 has 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]

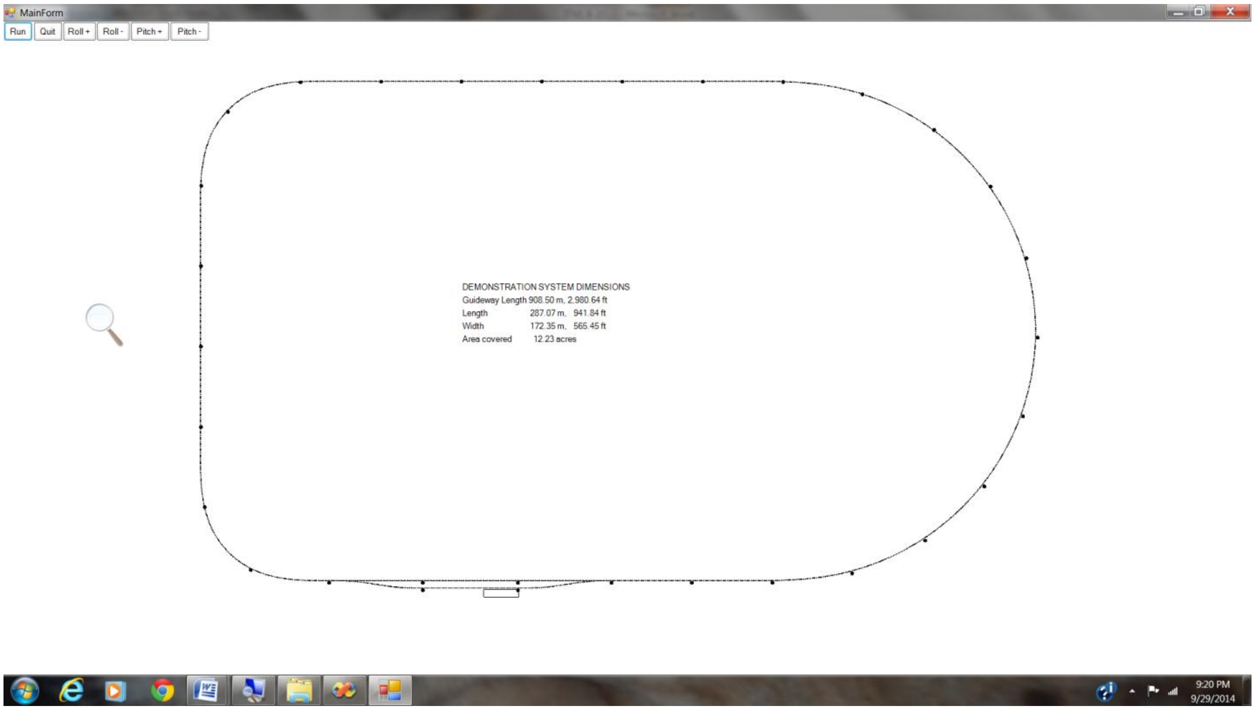
- In 1998, after a year of study, the Advanced Elevated Rail Committee of a Cincinnati businessmen's organization called Forward Quest recommended my design over 50 other elevated rail systems, some of which existed in hardware and others were paper designs.

- 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.

23. 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 (see Appendix E) need to be recruited to work with the company as soon as the needed funds are available. Our approach is as follows:

1. 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:



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DEMONSTRATION SYSTEM DIMENSIONS
Guideway Length 908.50 m, 2,980.64 ft
Length             287.07 m,   941.84 ft
Width              172.35 m,   565.45 ft
Area covered         12.23 acres
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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. A minimum of one off-line station and three vehicles is needed. 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.

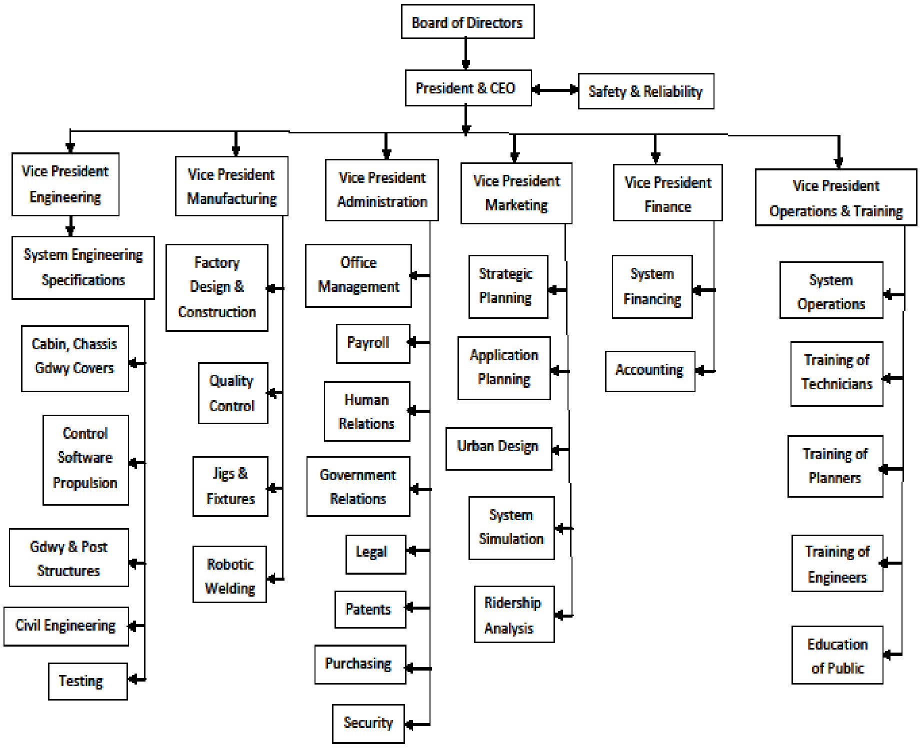

Figure 23-2. Project Management.

2. With a group of investors interested in applications, fund first a full-scale pilot project on an easily selected site using a loop guideway large enough to achieve speeds of at least 35 mph comfortably and having at least one station, a maintenance facility, and three vehicles, recognizing that all stations, all vehicles, and all merges and diverges are alike. Such a 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."

3. In cooperation with others, continue to inform consultants, planners, and financiers.

4. Perform planning studies for specific applications.

5. Teach and promote the teaching of the engineering, economic, and planning sciences of *ITNS* per the syllabus given in Appendix C. A wide range of transportation consultants need to know the details if they are to be able to evaluate and plan these systems.

6. Realize that in time *ITNS* will become similar to other public works such as bridges, roads, rail systems, etc. on which companies bid and win projects based on competence, design superiority, and by giving the buyer assurance of multiple sources of supply. Investors who see the potential of *ITNS* now will reap substantial profits before the field saturates.

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Appendix A

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 structure, which minimizes guideway size and weight.
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 electrical-power losses are minimized.
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 the switch becomes 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 design 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 -45°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 almost 0.5. 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 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 for the foundations and posts to resist a side inertia load. The truss guideway is the lightest possible. In an 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 clamped to the posts.
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 pow-	By hinging the covers at the bottom and by use of quick fasteners at the top, they can be swung down to reach the guideway interior for any maintenance task,

	er 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.	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 result in 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. 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.	The covers eliminate this 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 or top of the guideway posts. It is practical to 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 clamped to its posts gives 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 a ground power rail.
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 coating 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.
33	The design must permit the appearance to be varied to suit the community.	The composite covers can be colored and textured to suit the community.
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 zinc-based paint or galvanizing should be specified for 50-year life.

Appendix B

Design Criteria

1. Vertical and Lateral Design Loads. One must consider dynamic loading due to vehicles moving at speed, wind loads, earthquake loads, longitudinal loads due to braking vehicles, and loads due to street vehicles crashing into the support posts, if that is to be permitted. The best study I have seen on dynamic loads is one done in the M. I. T. Mechanical Engineering Department by Snyder, Wormley, and Richardson [44]. In their computer studies, they simulated vehicles of various weights operating at various speeds and various headways, and running over guideways of various span lengths. By placing their results in dimensionless form, the usefulness of their results is extended considerably. I studied their results [19, Chapter 10] and noted that the shorter the minimum headway the smaller was the difference between dynamic and static deflection, and in the theoretical limit of zero spacing between vehicles the dynamic and static deflection are the same, i.e., the guideway cannot tell the difference. Assuming PRT vehicles operating at a minimum headway of half a second, I found that the maximum dynamic guideway deflection and stress with vehicles operating at line speed was less than the maximum deflection and stress with vehicles nose-to-tail on the guideway. Therefore the maximum possible vertical load becomes a uniform load and it is easiest to calculate. The likelihood, however, that every vehicle on a span would have the maximum payload is vanishingly small. It is more realistic to take the maximum weight of a vehicle to be the empty weight plus the maximum payload weight divided by the square root of two. Call this the root mean square or rms load. Thus we take the design load on a span to be

    1) RMS loaded vehicles nose to tail on span + 30 m/s (70 mph) crosswind.
    2) No vehicles + 80 m/s (180 mph) crosswind.

   The maximum wind load on a guideway can be substantially reduced by reducing its drag coefficient based on known wind-tunnel data [42, 43].

1. Longitudinal loads. The criterion is based on vehicles operating at minimum headway all stopping simultaneously at 0.5 g. I found this load to be less than the maximum wind load.

2. Earthquake load. There is debate on the maximum horizontal acceleration measured due to an earthquake. In a presentation at a Society of American Military Engineers conference in San Diego in the last week of March, 1994, shortly after the Los Angeles earthquake, an Army Major General who had been placed in charge of rebuilding the Los Angeles freeways told his audience that the maximum horizontal acceleration measured was 1.6g, which is higher than any figure I have seen in print. The bottom line, though, is that the lighter the elevated structure, the easier it is to design foundations to withstand such loads. I have found that for the guideway I designed a horizontal acceleration of the ground of 0.86 g[9] is equivalent to a wind load of 80 m/s (180 mph). A PRT guideway must be designed to the

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[9] By mounting the guideway posts on suitable springs, I found that this value increases to 1.6 g.

local earthquake code, which varies considerably from one region to another. In areas prone to earthquakes, structures are often designed not with rigid foundations but with foundations that can flex and absorb horizontal shock loadings. Similarly, the foundations for the posts of a PRT guideway can be built with heavy springs near the lower end to take up the shock of a sudden horizontal acceleration.

3. Design stress – The designer must use standard values for the selected material.
    a. Specify corrosion protection for the life of the structure.
    b. Prevent water accumulation.
    c. Plan to clean out any bird droppings, which are corrosive.
    d. Design to account for material fatigue over the specified life.
    e. Design to relieve thermal stresses.

4. Maximum allowable deflection. The standard for steel transit guideways is span**/10**00 whereas the AASHTO bridge standard has been span/800.

5. Minimum allowable span. The Chicago PRT design study conclusion: 28 m (90 ft) except in curves, where a center support can be used.

6. Ride Comfort
    a. Observe the ISO standards for acceleration vs. frequency
    b. Observe the ISO standard acceptable constant acceleration and jerk for normal and emergency operation, which are also given in the ASCE APM Standards.
    c. Crossing frequency of vehicles should be out of phase with natural frequency of guideway to prevent resonance, which is achieved with asynchronous control.
    d. Reduce incidents of motion sickness by limiting the bank angle in turns. The ASCE APM Standards specify a maximum bank or superelevation angle of 6^o. There is no ISO standard here, but experience in Swedish railroads with tilting bogies has shown that motion sickness has limited the speed at which these trains can negotiate curves.

7. System Life. The Chicago RTA specified 50 years for the fixed facilities.

8. Compliance with the Americans with Disabilities Act (ADA).
    a. Must accommodate a wheelchair with an attendant.
    b. In the Chicago study, the disability community strongly demanded access to every vehicle, with the wheelchair facing forward.
    c. Must provide for visual and hearing disabilities.

9. The minimum line headway needs to be specified at the beginning of the design program based on detailed site-specific planning studies. When it is not, as has usually been the case, the system may be destined for a limited range of applications. Based on many independent studies we have designed for a minimum headway of half a second. [11, 31]

10. Design for the expected environment
    a. Rain, ice, snow of a given rate of accumulation.

   b. Ambient temperature range, typically -40°C to +55°C.
   c. Lightning protection.
   d. Sun.
   e. Dust, sand, salt.
   f. Nesting bees, birds, squirrels, etc.
   g. Earthquakes – Design to maximum expected horizontal acceleration at the site.
   h. Fire. [NFPA 130]
   i. Vehicles crashing into posts. [12, Appendix A]
   j. Interference from other elements of the urban scene.
   k. Ice build up on power rails due to clear winter night sky.

11. <u>Speed range</u>. Select the cruising speed to minimize cost per passenger per unit of distance. Consider that turn radii, stopping distance, kinetic energy, and the energy needed to overcome air drag all increase as the square of speed; and that energy use also depends on streamlining, low road resistance, and propulsion efficiency. Consider that the maximum operational speed for acceptable ride comfort is proportional to the guideway natural frequency, which depends on guideway stiffness and the type of support. [41]

12. <u>Costs</u>. The design team should aim for costs sufficiently low to be recoverable in fares, i.e., the system should be designed to be a profitable private enterprise. Such a conclusion cannot be reached without a strong systems-engineering effort, but by striving for this goal the design team will insure its future.

13. Require a small amount of <u>vibration damping</u> in the guideway.

14. <u>Acoustical noise</u> should be less than the noise of automobiles on streets.

15. <u>Electromagnetic noise</u> generated cannot interfere with existing devices.

16. <u>Communication</u> means must be accommodated.

17. <u>Expansion</u>. Design so that the system can be expanded indefinitely.

18. Design to minimize the effects of <u>vandalism and sabotage</u>.
    a. Assign young engineers to study ways to vandalize the system and how to prevent it.
    b. The spread-out nature of a PRT system provides no high-value targets.

Appendix C

Courses of Study to prepare for work on PRT Design and Planning

I. Systems Engineering applied to PRT Systems

Optimization of Transit-System Characteristics

A system-significant equation for the cost per passenger-mile is developed and from it, using available data, it is shown that the system that minimizes cost per passenger-mile has all the characteristics of the true PRT concept.

The Future of High-Capacity PRT

High-capacity personal rapid transit (HCPRT) is a concept that has been evolving for over 50 years. Notwithstanding lack of institutional support, 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 thoroughly thought-through requirements and 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 could not have maintained interest in the field.

After deriving the HCPRT concept, work is reviewed 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. Once PRT systems are in operation we can expect that universities will teach courses on HCPRT design and planning and that a number of competent firms will be involved in manufacturing HCPRT systems. HCPRT is close to moving to mainstream and can bring about a brighter future for mankind.

Intelligent Transportation Network System

A review of the derivation of a high-capacity PRT system; its physical characteristics, economics, energy use, and benefits to both the user and the community; the status of development; requirements and criteria for design, and development strategy.

A Review of the State of the Art of Personal Rapid Transit

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. The author summarizes arguments that 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 the author discusses 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, calculation of curved guideways, operational simulation, power and energy. The paper concludes with a listing of the implications for a city that deploys an optimized PRT system.

Automated Transit Vehicle Size Considerations

Nine considerations are developed that will assist an analyst desiring to determine the optimum size of an automated transit vehicle. These considerations are travel behavior, network operations, personal security, treatment of disabled riders, social considerations, safety, dependability, capacity, and cost.

The Structural Properties of a PRT Guideway

Calculation of the structural properties of a U-shaped truss guideway in both bending and torsion. Determination of the guideway natural frequency and the critical speed.

Safe Design of Personal Rapid Transit Systems

The safety of PRT systems involves careful attention to all features of the design such as the use of a hierarchy of fault-tolerant redundant control system, 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. The paper describes the relevant features in a new transit system and the principles of safe design required.

Control of Personal Rapid Transit Systems

Overcoming Headway Limitations in PRT Systems

The problem of precise longitudinal control of vehicles so that they 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. The preferred control strategy is one that could be called an "asynchronous point follower." Such a strategy requires no clock synchronization, is flexible in all unusual conditions, permits the maximum possible throughput, requires a minimum of maneuvering and uses a minimum of software. Since wayside zone controllers have in their memory exactly the same maneuver equations as the on-board computers, accurate safety monitoring is practical.

Synchronous or Clear-Path Control in Personal Rapid Transit

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

Dependability as a Measure of On-Time Performance of Personal Rapid Transit Systems

Dependability is defined as the percentage of person-hours of operation of a PRT system completed with a delay less than a prescribed value. Such a definition, while desired in conventional transit, cannot be measured without asking every patron the destination of his or her trip, which is impractical. This definition is practical in PRT systems. Both how to calculate Dependability in advance of deployment of a PRT system and how to measure it while the system is in operation are developed. The method provides the basis for precise contract language by which to measure on-time performance.

Life-Cycle Costs and Reliability Allocation in Automated Transit

In any system composed of many subsystems and components there is a performance requirement that must be met and it should be met at minimum life cycle cost. It is generally possible to manufacture each component to fail less frequently but at higher cost. The acquisition cost of each component increases as the mean time to failure (MTBF) increases but the support cost decreases as the MTBF increases, so the life-cycle cost of each component is a bathtub curve as a function of MTBF with a single minimum point. If all of the components were selected at their minimum points, the system life cycle cost would be minimized, but generally the performance would be less than required. To minimize the life-cycle cost at a higher level of performance the MTBF of each component must be select at a longer time than the value that minimizes the life-cycle cost for that component. This is a constrained minimization problem, i.e., the problem of finding the values of the MTBF of each component that meets the performance requirement at minimum life cycle cost. This problem is solved and results in an equation for optimum MTBF of each component in terms of the normal and emergency operation of the system and the life-cycle-cost characteristics of each component. The method is a useful tool to guide the development of any system.

The Capacity of Personal Rapid Transit System

A comprehensive discussion of the question of both required and obtainable capacity in PRT system based on both observation of the behavior of people and on theory. It is shown that once a network of PRT guideways is laid down rather than the few widely spaced lines of conventional rail system the required capacity of both lines and stations is remarkably modest. As a result a modern PRT system will exceed the maximum practical throughput of most conventional rail systems.

Energy Use in Transit Systems

The energy use of heavy rail, light rail, trolley bus, motor bus, van pool, dial-a-bus, auto, and PRT are compared. The energy needed to overcome air drag, rolling resistance, and inertia; the energy needed for heating, ventilating, air conditioning; and the energy needed for construction are calculated. The factors used for the conventional transit systems are averages given in federal data.

II. Planning of PRT Systems

Policy Issues that will guide the design of the system.

Safety and Security issues, handicapped access, passenger comfort and convenience, operational convenience, ticketing, weather, loading, performance, and standards.

The Capacity of Personal Rapid Transit System

Energy Use in Transit Systems

Simulation of the Operation of Personal Rapid Transit Systems

A simulation program is necessary for accurate quantitative evaluation of PRT systems. The steps needed to set up and operate such a program for any PRT system are developed.

Equations needed to compute the properties of curved guideways

Each curve requires first a region in which the curvature increases from zero to the maximum comfort value, then generally a section of constant curvature, and finally a section in which the curvature deceases from the maximum value to zero. In general the curve is superelevated. The differential equation of the curve are developed and solved for any curve, horizontal or vertical.

The Transition to an Off-Line Station

Generally applicable differential equation for the transition curve. Equations for constant-speed transition. The transition to an off-line station. Limits. Quarter and half point values. Transition with variable speed. The Curvature. The Slope of the Transition Curve. The Transition Curve. The Length of the Transition. The Station Speed. Solution for large lateral displacement. Collection of the Equations for the Transition. Calculation of the Speed into a Station. How does the Station Throughput change with Station Speed? A Program to Compute the Transition. Numerical Solution for the Transition for an Arbitrary Speed Profile.

Layout of a PRT Network

Quantitative layout of a PRT network including properties needed for vehicles and passengers. List of constant values for the system. Programs to calculate and plot the system.

Stopping Distance vs. Transition Length

Derivation of the relationship between stopping distance and the transition length to an off-line station.

Ridership Analysis

III. The Simulation and Control of PRT Systems

Longitudinal Control of a Vehicle

Generally applicable formulae for the gain constants in a proportional plus integral controller required for stable control of the speed of any vehicle in terms of natural frequency, damping ratio, vehicle mass, and thruster time constant. An example, based on a simulation of the controller and vehicle, is given. The theory shows that only speed and position feedback are needed. Acceleration feedback is unnecessary.

Control of Personal Rapid Transit Systems

Simulation of the Operation of Personal Rapid Transit Systems

Failure Modes and Effects

A wide range of failure modes in PRT systems are treated with estimates of the mean time to failure of each and the degree of redundancy needed to meet requirements of performance and safety. In developing the results, many details of the control system required are explained.

The Geometry of a Vehicle Moving in 3-D Space

The Reference Frames and the Velocity Vector. Components of Acceleration. Maximum Speed based on Comfort Acceleration. The components of Jerk. The Differential Equations of the Spiral Transitions. Plane Transition Curves at Constant Speed. The Transition Curve with no Region of Constant Curvature. The Transition Curve with a Region of Constant Curvature. The Roll-Rate Limit. Nonlinear Effects. Yaw-Pitch Coupling. Large Yaw Angles. Superelevation.

The Throughput of an Off-Line Station

Layout of a PRT Network

Quantitative layout of a PRT network including properties needed for vehicles and passengers. List of constant values for the system. Programs to calculate and plot the system.

Kinematics of motion of PRT vehicles

A simple means of calculating all of the required maneuvers is developed.

IV. The Design of a PRT System

The Future of High-Capacity PRT

Design requirements and criteria.

Policy Issues that will guide the design of the system.

Systems Engineering and Safety

A great deal of systems engineering work has been done to arrive at the current configuration of a PRT system. The team needs to be sure that the hardware and protocols selected for system control take advantage of the current state of the art. A major part of any automated guideway transit engineering program is to insure that the system will be safe.

The Structural Properties of a PRT Guideway

Calculation of the structural properties of a U-shaped truss guideway in both bending and torsion. Determination of the guideway natural frequency and the critical speed.

Dynamic simulation of a vehicle passing through a merge or diverge section of guideway

The purpose of this dynamic simulation is to determine maximum loads on the wheels and the tire stiffness required to insure passenger comfort.

Analysis of a Bi-Stable Switch

The Optimum Switch Position

Conditions for a Vehicle to Tip

Coasting Tests

LIM Clearance in Vertical Curves

Design of:

- Guideway and Posts
- Guideway Covers
- Chassis
- Cabin
- Control software and hardware
- Propulsion System
- Wayside Power and Guideway Electrification
- Test Program

Appendix D. The Linear Induction Motor and its Efficiency

The basic principles of electromagnetic induction upon which a linear induction motor operates are illustrated in Figure D-1. If a magnet moves at a speed *V* the magnetic flux ahead of the magnet increases in time with respect to a fixed surface and the magnetic flux behind the magnet decreases with time. The way Mother Nature works, a time varying magnetic field induces an electric field perpendicular to the magnetic field and proportional to its rate of change. If the magnet moves along a conducting surface, the induced electric field causes a current in the plate proportional to it. With the North and South poles as shown in Figure D-1, the current is counterclockwise ahead of the moving magnet and clockwise behind. Under the middle of the magnet the induced currents come out of the paper towards the left in Figure D-1 and here the magnetic field is of maximum strength and is downward. This is the principle of electromagnetic induction, which was discovered in 1820.

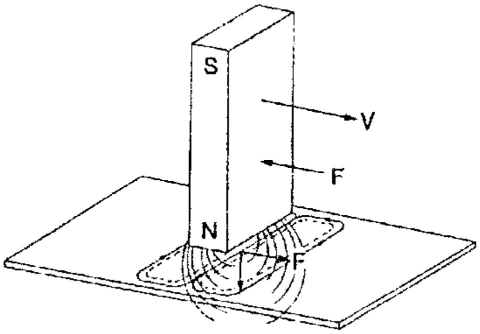

Figure D-1. Current induced by a moving magnet.

A property of nature is that when an electric current passes across a magnetic field a force is produced perpendicular to both the current and the magnetic field. James Clerk Maxwell, in the mid 1850s, derived the laws under which these phenomena work in a set of equations now called Maxwell's equations. The remarkable fact is that these equations have proved time and again to be exact. In Figure D-1 the force on the plate is to the right. If the conducting plate is resting on a low-friction surface, the plate will be dragged along with the magnet.

To achieve the speed *V*, the person or object moving the magnet must overcome the force F on the magnetic, which force is equal and opposite to the force induced in the conducting plate. If the conducting plate is fastened down and above it there is a vehicle containing a traveling magnetic field moving to the right, the force *F* moves the vehicle to the left. It is thus necessary to devise a way to produce such a traveling magnetic field.

A means for producing a traveling magnetic field is illustrated in Figure D-2. In the middle illustration, the elongated object containing slots is one of a stack of thin iron sheets stamped out with a die. The bottom view shows the same iron sheets in edge view stacked up as in a transformer. Three sets of coils are wound as indicated and are connected as shown in either the illustration on the left or on the right. The left illustration show what is called a "delta" connection after the Greek letter Δ that it resembles, and the one on the right is a "Y" connection. A three-phase alternating voltage is applied to the three windings with a frequency that increases with speed, with the voltages phased as shown in the top diagram. With the delta connection the voltage is applied directly across each set of coils. With the Y-connection each phase of the voltage is applied across two coils. The delta connection may therefore be used for high thrust and the Y connection for moderate thrust.

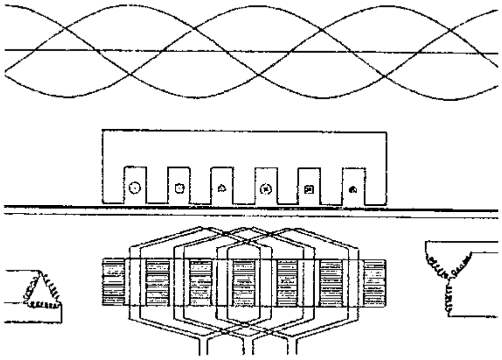

Figure D-2. A means for producing a travelling magnetic field.

There is a frequency of oscillation of the voltage that minimizes the current and that frequency increases linearly with speed. This is important because the electrical resistance losses are proportional to the square of the current, and thus the surface needed to dissipate the heat generated is proportional to the square of the current. The drive's volume increases as the three halves power of its surface area. Hence the required volume of the drive must increase in portion to the cube of the maximum current. For this reason, maintaining the frequency of oscillation of the voltage close to optimum is very important. Linear induction motors have been under development for many decades and several books have been written describing them in technical detail.

The Efficiency of Linear Induction Motors

Energy is lost in operation of an induction motor in proportion to the square of the current. Thus, as described under Figure D-2, it is extremely important in their design and operation to determine how to achieve the required thrust at minimum current. Study of linear induction motors shows that at every speed there is a frequency that minimizes current, and that that frequency increases linearly with speed. The numerical values are determined from detailed study of the motor. Without knowledge of the minimum current, the LIM may be quite inefficient.

Acceleration power per unit of mass is acceleration multiplied by speed, and the electric current that must be supplied increases as acceleration power increases. Thus, in accelerating a vehicle from rest to line speed, if the maximum acceptable acceleration were to be applied until the vehicle reaches line speed, the acceleration power increases in proportion to speed and then suddenly drops to zero. This practice would maximize the electrical current that must be supplied. There is very little disadvantage to a practice in which, as illustrated in Figure D-3, once the vehicle reaches about half its line speed a small constant negative jerk is applied until the acceleration is about half the maximum value at which point maximum negative jerk must be applied to enable the vehicle to reach line speed at zero acceleration. Analysis shows that this practice reduces the maximum acceleration power to about 55% of the value it would have if maximum acceleration were applied right up to line speed, and $0.55^2 = 0.30$. Thus the maximum electrical losses are reduced to 30% of the value they would have if maximum acceleration were applied right up to line speed.

By applying these to practices, one to design and one to operation, a LIM efficiency of between about 55% and 60% is achieved. The energy use of *ITNS* per passenger-mile in this case is about 600 Btu, which is less than 10% of the energy use per passenger-mile of the average light rail system. It would be ideal if higher efficiency was possible, but the advantages of the LIM in increasing both all-weather reliability and throughput are so great [31] that the LIM is the key to maximizing the cost-effectiveness of automated guideway transportation.

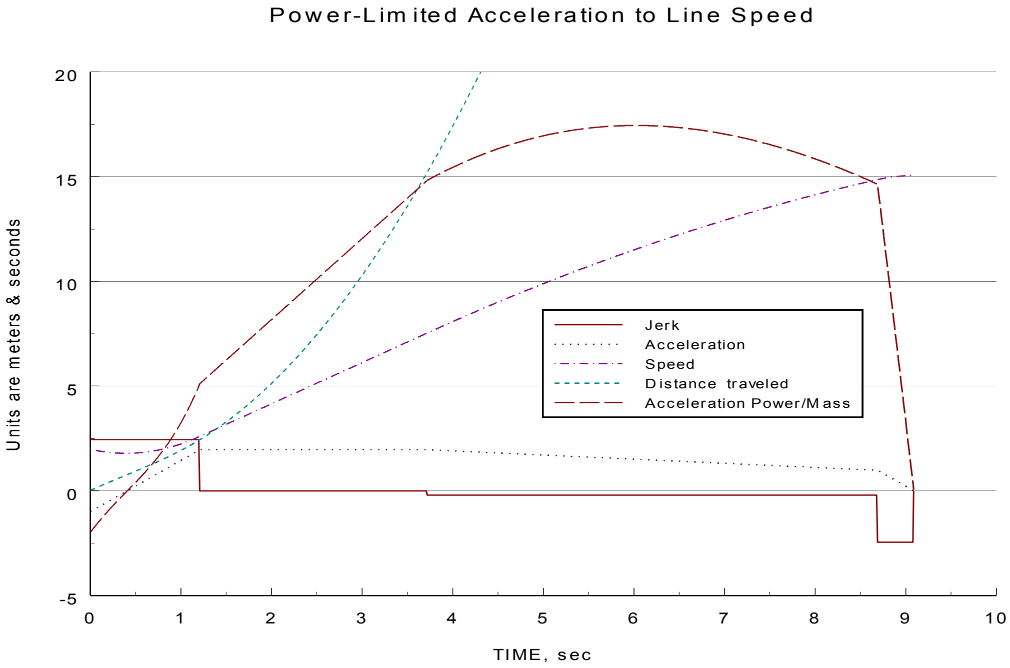

Figure D-3. Performance of a LIM.

Appendix E. 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. 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 1959 he received a Convair Fellowship under which, with a half-salary grant from Honeywell, he went to M. I. T. to study for a Ph. D. degree. He became fascinated with magnetohydrodynamics and wrote a thesis entitled *Magnetohydrodynmaic 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 in 1962 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, 1972. 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, from which 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, Sweden, 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, 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.

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 short segment of 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 in Figure 7.2. In 2005 he began on his own 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 its highest honor: 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.