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.
PRT International, LLC
Minneapolis, Minnesota, USA

www.prtinternational.com/cms

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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 service safely and reliably over an urban area of any extent in all reasonable weather conditions without the need for a driver's license, and in a way that minimizes cost, energy use, material use, land use, and noise. Being electrically operated it does not emit carbon dioxide or any other air pollutant.

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.

With these physical characteristics and in-vehicle switching ITNS is much more closely comparable to an expressway on which automated automobiles would operate than to conventional buses or trains with their on-line stopping and large vehicles. We now call this new system ITNS rather than High-Capacity Personal Rapid Transit, which is a designation coined over 35 years ago.

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PRT International, LLC
Minneapolis, Minnesota 55421 USA

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 a 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 had been developed, Figure 13, *was* developed by rocket scientists at The Aerospace Corporation between 1968 and 1972 [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].

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, an update 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. There is more and more evidence today that *ITNS* will solve many urban problems.

2. The Problems to be Addressed

- Increasing congestion
- High and rising oil prices
- Global warming
- 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
- Large transit subsidies

3. 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
- Operational 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

4. 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 Boston, New York, Philadelphia, Cleveland, and Chicago. A serious concern, though, was the size and cost of the elevated structures. We have found that if, as illustrated in Figure 1, the units of capacity are distributed in many small units, practical now with automatic control, rather than a few large ones, and by taking advantage of lightweight construction practical today, we can reduce guideway weight per unit length 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.

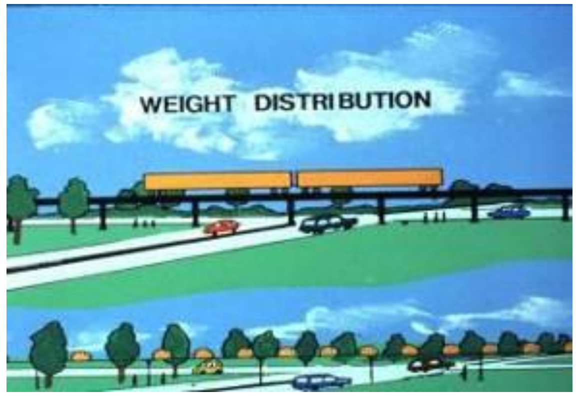

Figure 1. Guideway Weight and Size.

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 2 show, however, that this is not so. Each point in Figure 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 is independent of capacity.*

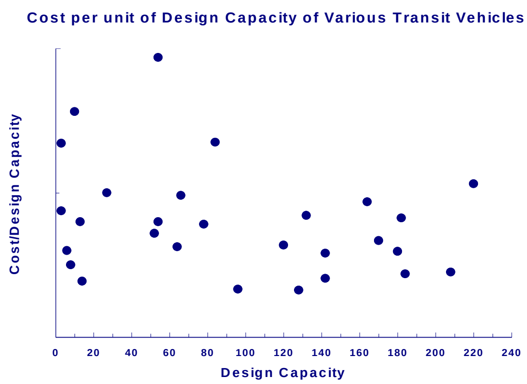

Figure 2. Vehicle Cost per Unit Capacity

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 a constant, 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 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*.

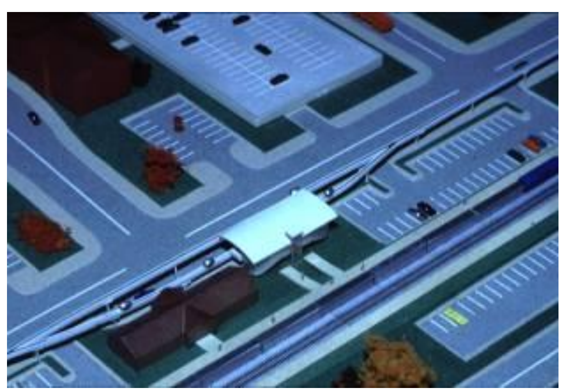
Figure 3. An Off-Line Station

The trips can be nonstop if all of the stations are on bypass guideways off the main line as shown in Figure 3.

5. Off-Line Stations are the Key Breakthrough!

Figure 3 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 15 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].[1]

The advantages of off-line stations are as follows:

- Off-line stations minimize the fleet size and hence the fleet cost because they maximize the average speed. This was discussed in Section 4.
- 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 8.
- 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.
- Off-line stations permit a person to travel either alone or with friends with minimum delay.
- Off-line stations permit the vehicles to wait at stations when they are not in use instead of having to be in continuous motion as is the case with conventional transit. Thus, it is not necessary to stop operation at night – service can be available at any time of day or night. Moreover, compared with conventional 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.

[1] To allow for the case in which one party takes an extraordinary amount of time to enter or exit a vehicle, some PRT designers have designed stations in which each parked vehicle can enter or exit the station independent of other vehicles. Three factors cause us to recommend against such stations: 1) Due to interference, the throughput of these stations is disappointing, 2) these stations require much more space and cost much more than the single-by-pass design, and 3) because elderly or disabled people generally avoid the busiest hours, the statistical average peak flow will not be much decreased by the occasional presence of such persons. If system studies show a need for such stations, there is nothing in our design that would prevent us from including them.

- With off-line stations there is no waiting at all in off-peak hours, and during the busiest periods empty vehicles are automatically moved to stations of need. Computer simulations show that the peak-period wait will average only a minute or two.

- Stations can be placed closer together than is practical with conventional rail. With conventional rail, in which the trains stop at every station, the closer the station spacing, the slower is the average speed. So to get more people to ride the system, the stations are placed far enough apart to achieve an average speed judged to be acceptable, but then ridership suffers because access is sacrificed. The tradeoff is between speed and access – getting more of one reduces the other. With off-line stations the system provides both high average speed and good access to the community.

- Off-line stations can be sized to demand, whereas in conventional rail all stations must be as long as the longest train.

All of these benefits of off-line stations lead to substantially lower cost and higher ridership.

6. 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-redundant computers for high dependability and safety.
- Accurate position and speed sensors. Today's sensors are much more accurate than we need.
- Smooth running surfaces for a comfortable ride.
- 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.

7. Optimum Configuration

During the 1970s I accumulated a list of 33 requirements for design of a PRT guideway [4, 5]. As chairman of three international conferences on PRT, I was privileged to visit all automated transit work on this planet, talk to the developers, and observed over a decade both the good and the bad features. The requirements listed in Figure 4 are the most important, and, from structural analysis [5] I confirmed The Aerospace Corporation's conclusion that the minimum-weight guideway, taking into account 150-mph crosswinds and a maximum vertical load of fully loaded vehicles nose-to-tail, is a little narrower than it is deep. I compared hanging, side-mounted, and top-mounted vehicles and found ten reasons to prefer top-mounted vehicles [6].

Figure 4. The Optimum Configuration

Such a guideway has minimum visual impact. It also has minimum weight if it is a truss as shown in Figure 5, which is scaled to posts 90 ft apart. 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 least expensive to manufacture, transport and erect. The analysis reported in [5] has produced the properties need to meet all 33 requirements. I observed over decades that whenever a PRT program died, and there have been many of them, the major reason could almost always 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 tried to point out in the limited space I was allotted 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 33 requirements and also 19 design criteria.

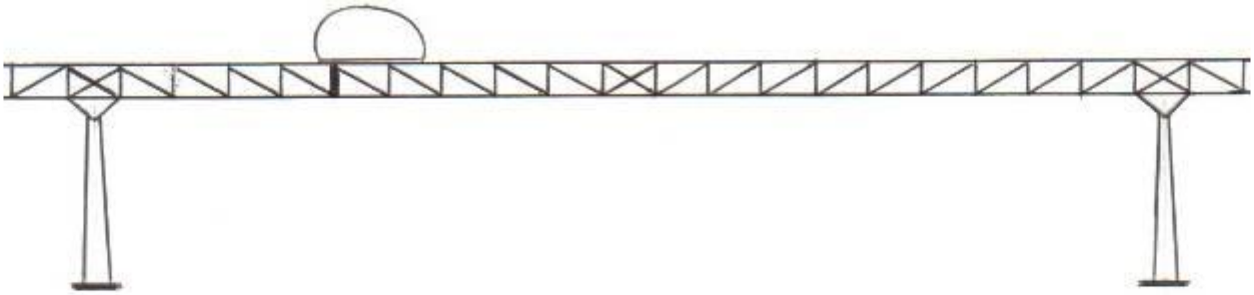

Figure 5. A Low Weight, Low-Cost Guideway

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. Such a size can also accommodate a person and a bicycle, a large amount of luggage with two people, a baby carriage plus two adults, etc. [7] See Figure 17.

As shown in the figure on the cover and Figure 4, the guideway will be covered. A slot only four 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. The covers permit the system to operate in all weather conditions, minimizes air drag, prevents ice accumulation on the power rails, prevents differential thermal expansion, serves as an electromagnetic shield, a noise shield, and a sun shield, permits access for maintenance, and permits the external appearance to be whatever the local community wishes. The covers enable the system to meet nine of the 33 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 6, in which north is to the left, shows how PRT could begin to serve a portion of Downtown Chicago. The PRT guideway is shown in red.

Figure 6. An Application in Downtown Chicago

8, Control

Control of PRT has been investigated at many organizations since the 1960s. The author has published [4] a bibliography of papers on control of PRT that have been useful as he and his colleagues developed the control system for *ITNS*. His detailed papers related to control are listed [11 – 15] and may be found with other papers on www.prtnz.com. The *ITNS* control hardware consists of computers, sensors, and a communications medium.

8.1 Computers

All computers in *ITNS* are dual redundant, which means that each "computer" is two pairs of computers. The outputs of each pair of computers are compared 20 times a second, and likewise the common outputs of the two pairs are compared 20 times a second. Any error detected causes the vehicle to be directed to a maintenance shop directly upon completing its trip. With this arrangement the mean time between serious events is extremely long, longer than anyone will believe without checking the calculations [12]. The methodology I used 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. The zone controllers command specific maneuvers to specific vehicles as needed and each individual vehicle computer responds to these commands. The algebra needed to command every one of the maneuver a vehicle can make has been worked out by several organizations. 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 the position of a vehicle can be controlled almost as closely as we can measure it, which is substantially closer than necessary.

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. 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.

8.2 On-Board Position and Speed Sensing

The position and speed of each vehicle is measured on board each vehicle by means of digital encoders placed in the main bearing of each of the four wheels. Averaging the left and right output gives the correct measurement in curves. Having encoders in both the fore and aft wheels provides redundancy. These encoders register at least 4096 pulses per revolution, or with the 336.6 mm (13.25") OD tires we plan to use about 0.26 mm (0.010") per pulse. With this accuracy, experimental evidence has shown that we can differentiate to obtain accurate speed measurements. If, however, the assumed OD was in error by say 1%, the distance measurement would be in error by 1%. Thus, we will calibrate each vehicle as it leaves a station by means of fixed magnetic markers. In this way we will know the position of each vehicle to an accuracy of less than 25 mm (one inch).

8.3 Wayside Position and Speed Sensing

The position and speed of each vehicle is measured by suitably placed pairs of wayside 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.

8.4 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 affected by solar storms [29]. The zone controllers similarly talk to and from the cable. Such cables are commercially available. This type of communication is completely secure and cannot be interfered with by hackers.

8.4 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 today to measure position and speed are much more accurate than we need. Wayside zone controllers monitor the motion of each vehicle at least 10 times each second. Code has been developed to control any number of vehicles in networks of any size or configuration.[2] 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 redundant, 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.

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[2] J. E. Anderson, "Some History of PRT Simulation Programs," 2008, www.prtnz.com.

9. <u>System Features Needed to achieve Maximum Throughput Reliably and Safely</u>

The features needed are illustrated in Figure 9.

1. All weather operation: Linear induction motors (LIMs) provide all-weather acceleration and braking independent of the slipperiness of the running surface.

2. Fast reaction time: For LIMs the reaction time is a few milliseconds. With human drivers the reaction time is 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.

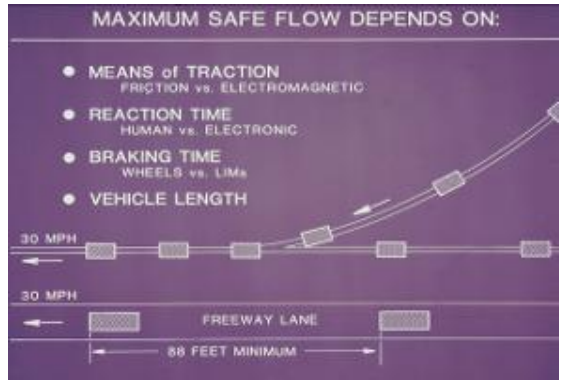

Figure 9. How to achieve maximum safe flow.

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 redundant computers [13]. Combined with redundant power sources, fault-tolerant software, and exclusive guideways; studies show 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 has been developed and used during the design process.

10. <u>Is High Capacity Possible with Small Vehicles?</u>

Consider a surface-level streetcar or so-called "light rail" system. A typical schedule frequency is 6 minutes, or 10 trains per hour. The new "light" rail cars have a capacity of about 200 people. With two-car trains the system then can move up to 400 people every 6 minutes. A high-capacity PRT or *ITNS* system can operate with a maximum of 120 vehicles per minute or 720 in 6 minutes carrying up to five people per vehicle. However, even with only one person per vehicle, the *ITNS* system would carry 720 people in 6 minutes, which is 80% more than the number of people per hour light rail can carry. Since the light-rail cars in a whole system are virtually never full, *ITNS* has an even higher throughput margin over a light-rail system. A comprehensive discussion of the throughput potential of *ITNS* lines and stations is given in reference [8].

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 7). The effect of this pronouncement was to ridicule and kill a budding federal HCPRT program. PRT was a threat to conventional systems, but 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.

During the 1990's the Automated Highway Consortium 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 6 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 6. Automated Highway Experiment.

Thus the 1973 UMTA claim was more than proven in the 1990s. Because of problems associated with automated highways that are not relevant to PRT 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 7, 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 Reference [13]. Early PRT systems, which must be small, 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 7. Thus, at the present time, the safety of fractional-second headways need not be a subject of debate – we must and will prove it.

Model PRT Vehicle and Guideway built in Raytheon Model Shop in January 1993 18 months before the fatal decision to go to the configuration shown in Figure 16.

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 7. Page from the 1974 Congressional Record [9]

11. How Does a Person Use an *ITNS* System?

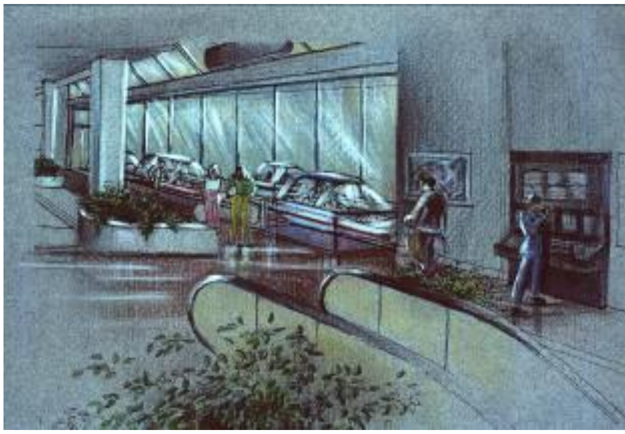

Figure 10. Pick a Destination and Pay the Fare

Figure 11. Transfer Destination to Vehicle

As shown in Figure 10 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. The memory of the destination is then transferred to the prepaid card and the fare is subtracted. To encourage group riding, we recommend that the fare be charged per vehicle rather than per person. As shown in Figure 11, 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 12, 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.

Figure 12. Riding Nonstop to the Destination

12. 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, and can use a cell phone.
- 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 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 practical for the vast majority of urban residents. , indicating that scheduled, all-stop transit is not practical for the vast majority of urban residents.Accurate methods for calculating ridership are needed because the system needs to be designed but not over-designed to meet anticipated ridership.

13. 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 (about $US20 million) to build a full-scale test system. 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 [26] 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. This problem is likely the major factor that caused the collapse of the Chicago RTA PRT program. We hope to correct this deficiency by means of the courses described in the Appendix. 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 they accomplished by September 1974.

The two leading HCPRT development programs during the 1970s are illustrated in Figures 13 and 14. 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 a substantial amount of money to NATO programs. These programs provided the bulk of the background that was needed to continue PRT development during the next two 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 13. The Aerospace Corporation PRT System [1]   Figure 14. Cabintaxi [18]

A third important PRT-related development program conducted during the 1970s still operates in Morgantown, West Virginia. It is shown in Figure 15. I call it "PRT-related" because its fully automatic operation is like 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. The gross (fully loaded) vehicle weight is about 11,800 lb and the operating headway is 15 seconds.

Figure 15. Morgantown

In Section 1, I mentioned work of the Northeastern Illinois Regional Transportation Authority (RTA). It led, beginning in 1993, to a public/private partnership between the RTA and Raytheon Company. Figure 16 shows the Raytheon PRT system that was developed. Unfortunately, lack of appreciation for relevant experience resulted in a vehicle four times the weight and a guideway twice as wide and twice as deep as necessary. The resulting capital cost of a system proposed for Rosemont, Illinois, more than tripled and the operating costs were correspondingly high and uncertain. As a result Rosemont wisely declined to proceed and the program died. The gross weight of the four-passenger Raytheon vehicle was about 6600 lb and the operating headway was about 3 seconds.

Figure 16. Raytheon PRT 2000

Finally, consider the system shown in Figure 17. In 2001-2 I directed its design and construction for Taxi 2000 Corporation. It opened to the public in April 2003 and thousands of rides were given flawlessly to an enthusiastic public over 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 I designed the control system so that multiple vehicles can operate at half-second headways. There are no intellectual-property issues that would prevent PRT International from using the information obtained in this program. The system shown in Figure 17, as we understood it in 1989, was the basis for the winning proposal in the RTA program. Unfortunately, when the Phase II program got underway in October 1993, prior work, including work done in the Phase I program, was ignored, which resulted in major weight and cost overruns and program cancellation.

Figure 17. An Optimum HCPRT Design

Figure 18 shows the gross weights of the systems shown in Figures 15, 16, and 17. Cost data were available on the cost per mile of each of these systems. Deflating these costs to the same year I found that *system cost was very nearly proportional to vehicle gross weight*. Cost minimization requires use of the smallest, lightest-weight vehicles practical. They permit the smallest, lowest-cost guideways and are fully practical with today's technology.

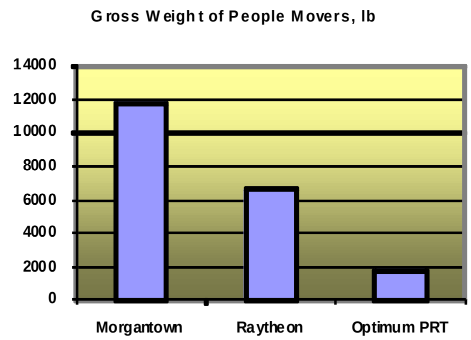

Figure 18. Vehicle weight comparison.

Figure 19 shows three PRT system currently under development. The picture on the left is ULTra (www.atsltd.co.uk), which is being developed at Bristol University in the United Kingdom. This system is currently under test at Heathrow International

Figure 19. ULTra, Vectus, and 2getthere PRT Systems

Airport to move 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. This system uses LIMs in the guideway, which increases guideway weight and cost, and uses a guideway similar to that in the failed Raytheon system. The picture on the right is the PRT Dutch 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 of providing non-polluting, non-oil-using transportation. 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.

14. Economics of *ITNS*

The author has shown [21], based on a system-significant equation for cost of any transit system per passenger-mile, that the system that minimizes this cost has all the characteristics of the true PRT concept. Figure 20 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 its capital cost was $715,300,000 and its ridership has been 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 operating cost was $19,850,000. Amortizing the capital cost at the OMB-specified 7%,[3] 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. 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.

Figure 20. Minneapolis-Airport (Hiawatha) light rail.

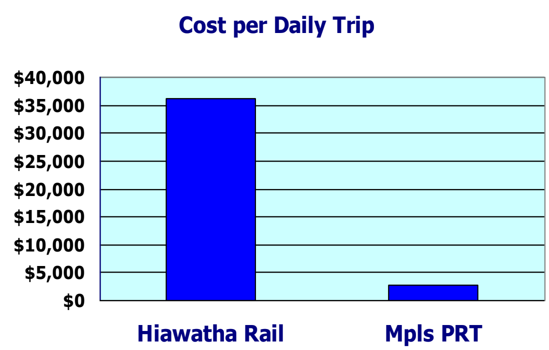

Figure 21. Cost Comparison

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 21. Our estimate was about $100 million capital cost 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. 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.

[3] The web page of the federal Office of Management and Budget directs that capital costs be amortized at 7%.

What would be the cost per passenger-mile on a built-out PRT system? Figure 22 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 22 the relationship between population density, mode split, and the fare needed for a PRT system to break even. As mentioned in Figure 22, 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 22.

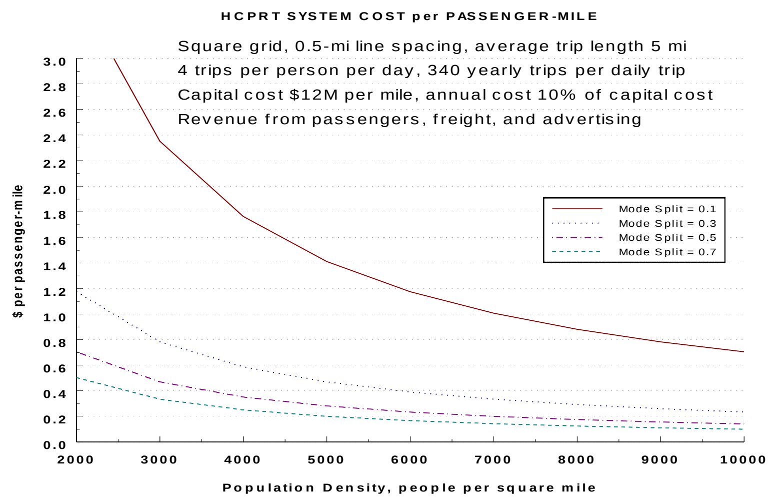

Figure 22. System cost per passenger-mile.

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.

15. Land Savings.

Figure 23. A Freeway Running at Capacity.

Figure 24. The People Riding.

Figure 23 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 24 shows the people riding. In over 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 25 shows all of the people moved to the center and Figure 26 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. The two *ITNS* lines in the middle of Figure 26 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 the 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 the land in residential areas 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 25. The people moved to center.

Figure 26. All riding *ITNS*.

Figure 27 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 release it as heat, whereas plants soak up solar energy as they grow, and while growing absorb carbon dioxide from the air.

Figure 27. A restored park thanks to *ITNS*

16. 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 will be designed into *ITNS*. Moreover, 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]. An additional point is that when a 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 vehicle will serve as many trips per day as about 10 automobiles, thus saving even more energy.

Figure 28 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 the averages from federal sources. The energy use for kinetic energy, road resistance, air drag, heating-ventilating-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.

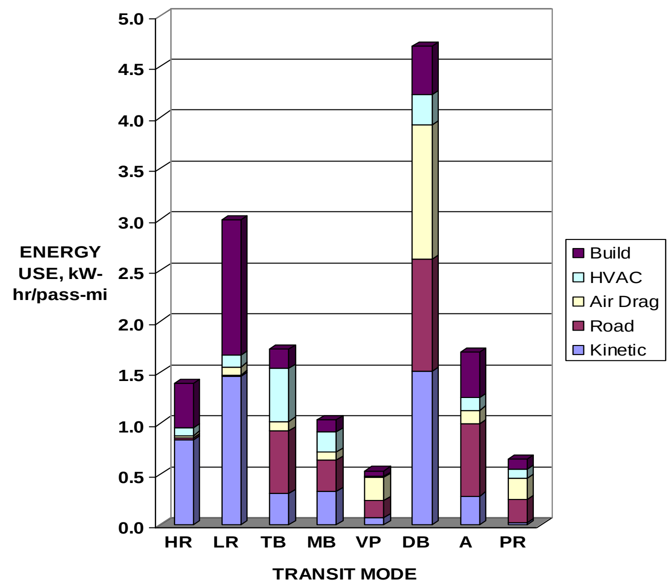

Figure 28. Energy-use comparison.

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 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 are likely to 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.

17. <u>Benefits for the Riding Public</u>

- 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.

18. <u>Benefits for the Community</u>

- 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 can 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.
- *ITNS* provides safe, swift movement of mail, goods and waste.
- *ITNS* provides easier access to stores, clinics, offices and schools.
- *ITNS* provides faster all-weather, inside-to-inside transportation.
- More efficient use of urban land becomes practical.
- There will be fewer tendencies to urban sprawl.

19. <u>Reconsider the Problems</u>

.

ITNS addresses all of the problems listed in Section 2, of which congestion, dependence on oil, and global warming are much in the news [25]. 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, yet they observe that the characteristics of scheduled, all-stop transit are such that building more of such systems will not attract enough auto drivers to make much difference. On the other hand, 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 about 10 automobiles and markedly reduces the land required for parking, and 3) can attract at least ten times the ridership experienced on scheduled, all-stop transit. This, with its high energy efficiency and ability to use non-polluting energy sources *ITNS* is *the clear answer to a serious problem of industrialized civilization.*

20. <u>Significant related Activity</u>

- A series of studies of PRT in Sweden in 1990's resulted in the statement: "Our recommendation is therefore clear—a PRT system provides such a broad range of desired qualities that it should be given highest priority in research, development, testing, and demonstration for implementation in the urban environment." Göran Tegnér, Business Manager International, TRANSEK Consultants Company, Solna, Sweden. *Infrastructure,* Vol. 2. No. 3, (1997).

- The British Airport Authority has a PRT system under test at Heathrow International Airport to move people and their luggage from parking lots to terminals.

- The Korean steel company Posco has built and is operating a demonstration of their PRT system, called Vectus, in Uppsala, Sweden.

- The Masdar project in Abu Dhabi is actively engaged in installing a PRT system using the Dutch system 2getthere for a first-phase system, which is to be operational in 2009.

- The Cities of Santa Cruz and San Jose, California, have invited potential PRT suppliers to submit qualifications to build PRT systems.

- The New Jersey State Legislature has funded a study very favorable to PRT, which was released in April 2007. It is available on several web sites including www.prtnz.com.

- The City of SeaTac, Washington, spent about $1 million on studies of PRT during the 1990s and awaits 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.

- In 1998, after a year of study, the Advanced Elevated Rail Committee of a Cincinnati businessmen's organization called Forward Quest recommended Taxi 2000 over 50 other elevated rail systems, some of which existed in hardware and others were paper designs.

- Official research by the European Union concluded in March 2006: "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 which 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 December 2008 Frost & Sullivan [28] released ar 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."

21. Development Strategy

PRT International, LLC,[4] has entered the HCPRT field with a new design, improved over prior work, and now called *ITNS*. Experienced systems engineers and engineering companies are ready to work with the company as soon as the needed funds are available. Our approach is as follows:

- Seek first a modest-sized application where the decision process is relatively easy, and find investors who see that we can best meet their requirements. This first real people-moving demonstration must convince a skeptical transportation community that *ITNS* will work as projected.

- With a group of investors interested in applications, fund first a full-scale pilot project 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. Such a facility will enable us to prove the specifications needed to assure success of the first people-moving application and will provide a test bed for proving for many years new design features apart from applications. Drawing on many years of experience in theory, development, planning, design, and construction, we estimate that we can complete this program in 24 to 30 months for no more than US$20 million. We have completed sufficient planning for such a program to enable us to proceed immediately, and today's design tools will enable us to ready the final designs for manufacture much more quickly than formerly possible. In today's term, we are "shovel ready."

- In cooperation with others, continue to inform consultants, planners, and financiers about *ITNS*.

- Perform planning studies for specific applications.

[4] 5164 Rainier Pass NE, Minneapolis, Minnesota 55421-1338, USA, (763) 586-0877.

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

- 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 becomes saturated.

The reader is invited to view our summary power-point presentation "Solving Urban Transportation Problems through Innovation," which can be watched on or downloaded from the web page http://www.prtinternational.com/cms.

22. References (Papers indicated by * can be found on www.prtnz.com)

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Figure 19. www.atsltd.co.uk, www.vectusprt.com, www.megarail.com

Figure 20. www.metrocouncil.org

Figures 23, 24, 25, 26. William A. Wilde [23]

Figure 27. Minneapolis Architectural Illustrator7

Figure 28. Author's paper [24]

Figure 29. www.prtinternational.com

Appendix

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

I. Systems Engineering applied to PRT Systems

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 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.

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.

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.

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

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. The paper discusses the functions of vehicle control; the control of station, merge, and diverge zones; and central control.

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 in this paper 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 a PRT system. The paper shows both how to calculate Dependability in advance of deployment of a PRT system and how to measure it while the system is in operation. 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 is desirable to meet it at minimum life cycle cost. It is generally possible to manufacture each component to fail less frequently but at higher cost. Thus the acquisition cost of the component increases as the mean time to failure (MTBF) increases but the support cost decreases as the MTBF increases, so the life-cycle cost 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.

Calculation of Performance and Fleet Size in Transit Systems

A consistent, analytic approach to the calculation of the parameters needed to analyze the performance and cost of transit systems of all types including network systems. The method developed is a

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 report "National Urban Mass Transportation Statistics."

High-Capacity Personal Rapid Transit

1. Introduction
2. The problems to be addressed
3. Rethinking transit from fundamentals

4. Derivation of the new system
5. Off-line stations are the key breakthrough
6. The attributes of high-capacity PRT
7. The optimum configuration
8. Is high capacity possible with small vehicles?
9. System features needed to achieve maximum throughput reliably and safely
10. How does a person use a PRT system?
11. Will PRT attract riders?
12. Status
13. Economics of PRT
14. Land savings
15. Energy savings
16. Benefits for the riding public
17. Benefits for the community
18. Reconsidering the problems
19. Significant PRT activity
20. Development strategy

II. Planning of PRT Systems

High-Capacity Personal Rapid Transit

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.

Calculation of Performance and Fleet Size in Transit Systems

A consistent, analytic approach to the calculation of the parameters needed to analyze the performance and cost of transit systems of all types including network systems. The method developed is a

The Capacity of Personal Rapid Transit System

Energy Use in Transit Systems

Simulation of the Operation of Personal Rapid Transit Systems

A computer simulation program developed by the author to study the operation of personal rapid transit (PRT) systems of any size and configuration is described. The control scheme is asynchronous with maneuvers commanded by wayside zone controllers. The simulation runs on a PC, is accurate in every detail, and can be used to run an operational system, which would use dual-redundant computers on the vehicles, at wayside to manage specific zones, and in a central location to manage the flow of empty vehicles and to perform other system-wide functions. Some results are given.

Equations needed to compute the properties of curved guideways

The Governing Differential Equations. Calculation of the Slope of the Curve. Calculation of the Coordinates of the Curve in the Region of Positive Jerk, in the Region of Constant Curvature, and in the Region of Negative Jerk. The Limit Condition for a Section of Constant Curvature.

The Transition to an Off-Line Station

Generally applicable differential equation for the transition curve. Solution with constant speed. 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. The Maximum Slope of the Transition Curve. 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 Arbitrary Speed Profile.

A process for developing a program that will simulate the operation of PRT vehicles in a network of any configuration.

The step-by-step process required to develop the programs needed to set up and simulate the operation of any PRT network.

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

Control of Personal Rapid Transit Systems

Simulation of the Operation of Personal Rapid Transit 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.

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 Off-Line Stations

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

IV. The Design of a PRT System

The Future of High-Capacity PRT

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

Station, Maintenance Shop, Control and Demonstration Room.

Foundations and Landscaping.

Test Program