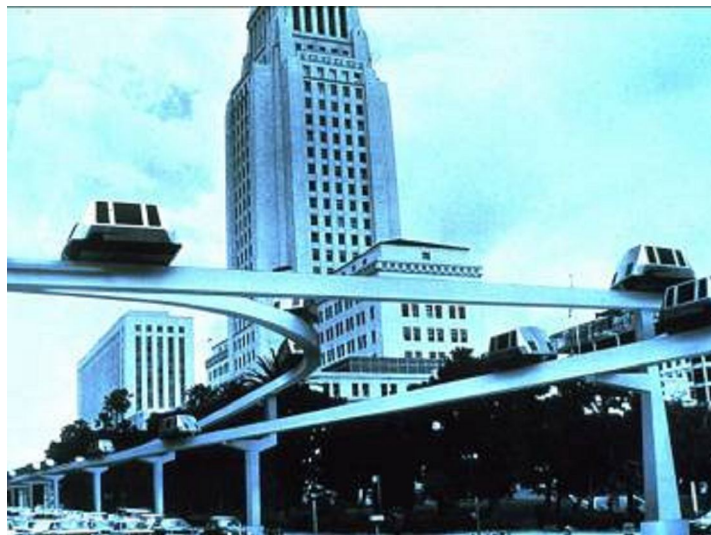


The Future of High-Capacity Personal Rapid Transit

J. Edward Anderson, Ph.D.



**PRT International, LLC
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The often-shown photomontage of The Aerospace Corporation High-Capacity PRT system is shown on the front page of this paper in tribute to their pioneering work on Hi-Cap PRT, without which this author would have long since turned to other pursuits.

The Future of High-Capacity Personal Rapid Transit

*J. Edward Anderson*¹

High-capacity personal rapid transit (Hi-Cap PRT) is a concept that has been evolving for over 50 years. Notwithstanding attempts to kill it, it has kept emerging because in optimum form it has the potential for contributing significantly to the solution of fundamental problems of modern society including congestion, global warming, dependence on a dwindling supply of cheap oil, and most recently terrorism. The future of Hi-Cap PRT depends on careful design starting with carefully thought-through criteria for the design of the new system and of its major elements. Many people have contributed importantly to the development of PRT and the author regards the work during the 1970s of The Aerospace Corporation to be by far the most important, without which this author is certain that he could not have maintained interest in the field.

After deriving the Hi-Cap PRT concept, the author reviews work on the important factors that the design engineer needs to consider in contributing to the advancement of Hi-Cap PRT, 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 Hi-Cap PRT systems. We look forward to the day when universities will regularly teach courses on Hi-Cap PRT design and planning and when a number of competent firms will be manufacturing Hi-Cap PRT systems. Hi-Cap PRT is close to moving to mainstream and can bring about a brighter future for mankind.

1. Introduction

This paper is written for the Advanced Automated Transit Systems Conference, Bologna, Italy, November 7-8, 2005. It represents a summary of my work in the field of Personal Rapid Transit over the past three and a half decades and can be considered a sequel to a paper I wrote for the *Journal of Advanced Transportation* Millennium Issue. [1]

It must be remembered in thinking about a new transportation system that transportation is a means to an end, not an end in itself. Many years ago, while at the University of Minnesota, I was invited to give an honors seminar for liberal-arts students on PRT. As the term progressed I asked each student to write a story about what life would be like in a city in which PRT was the major form of transportation. To get PRT into the story various students wrote about calling up the cars and waiting for them, neither of which would be necessary in a PRT system. We concluded that a feature of a city in which PRT was the dominant mode would be that transportation would simply not be a topic of discussion. You can read a story about life with PRT, written by Chip Tappan, Chairman of the Cincinnati Sky Loop Committee. It can be found on the web page www.skyloop.org/life-with-the-loop.htm.

¹ PRT International, LLC, 5164 Rainier Pass, Minneapolis, Minnesota, USA, 55421, jeanderson01@gmail.com

For reasons that will be apparent from Chip Tappan's story, Hi-Cap PRT is the "Holy Grail" sought by innovative transit developers since the 1950s. Hi-Cap PRT addresses a wide range of outstanding problems of our worldwide civilization that have become more and more severe as the decades have passed. These problems include

- Increasing congestion
- Declining downtown activity
- Dependence on oil while demand exceeds production
- Air pollution
- Deaths and injuries from auto accidents
- Costs of transportation
- Excessive sprawl
- Isolation of the poor and of those unable to drive or who prefer not to drive.
- Global warming
- Terrorism

Books can be and have been written on each of these problems, and assuming no new solution, Pucher and Lefèvre [2] concluded: "The future looks bleak both for urban transport and for our cities: more traffic jams, more pollution and reduced accessibility." The thought that a new type of transit system can address all of these problems is remarkable, but this paper and its references show that it can. The attitude needed to think positively in the face of overwhelming problems on a global scale is being developed by a growing number of thinkers, for example Philosophy Professor Glen Martin [3] and Barbara Marx Hubbard [4].

A series of studies sponsored in 1967-1968 by the United States Urban Mass Transit Administration showed that if only conventional forms of transit are deployed, congestion will continue to increase, and with it many of the problems listed above; but, if personal transit systems are deployed, congestion can be mitigated. The most easily obtained summary of this work was published in *Scientific American* [5]. Unfortunately, notwithstanding serious interest at the federal level in the United States for six years after the publication of those results, the new systems were considered too radical for the conventional transit community. They lobbied to kill a budding federal program to develop Hi-Cap PRT in favor of conventional rail systems that provide a few lines at very high cost while leaving huge portions of urban areas without effective transit service. The turning point was likely the following statement by Frank C. Herringer, Urban Mass Transportation Administrator on March 27, 1974 before the Transportation Subcommittee of the Committee on Appropriations of the U. S. House of Representatives: "This means that a high-capacity PRT could carry as many passengers as a rapid rail system for about one quarter the capital cost." This was too much for the conventional rail community. PRT was too radical for them.

Thanks largely to the work of members of the Advanced Transit Association, work on PRT continued in the United States at a low, poorly funded level until the Northeastern Illinois Regional Transportation Authority became interested in 1989. Their PRT program, announced in 1990, coming as it did from the second largest transit organization in the United States, caused a great deal of renewed interest in PRT. Serious organizations have in the past year issued requests for proposals for PRT systems. In the past month the British Airport Authority announced that they will build a PRT system at Heathrow International Airport using the technology called ULTra, developed at Bristol University in the United Kingdom. Congratulations to them!

Development of a transit system capable of addressing the real problems of urban civilization has required the inventor to start from a clean sheet of paper. The inventor must consider transit in an interdisciplinary way as a field of requirements and characteristics, setting aside known characteristics of existing transit systems that were introduced over a century ago. Developing criteria for a new urban transportation system involves much more than engineering. The system engineer may take the lead, but must work closely with architects, planners, geographers, economists, sociologists, psychologists, political scientists, public officials, and interested citizens. In the following paragraphs I will show how, with the support of many colleagues expert in many fields, I developed and recommend to a new generation of transit designers the kind of process I believe can result in success. To have made some progress I “stood on the shoulders of giants” and the new generation can now see much farther based on all of the work done in the past four decades. My first detailed attempt at the theory of PRT was published in 1978 [6]. During the 1970s I became acquainted with eight persons who could clearly show that they independently invented the concept we now call personal rapid transit. I am not one of them but I benefited greatly from meeting and conversing with them all. Their work collectively initiated serious interest in PRT.

2. Design Process

Developing a totally new transit system is a daunting task. Success requires a comprehensive and disciplined design process. During my career I rarely worked on anything that had been done before, which has been an advantage for me. As a design engineer, while a full-time employee at the Honeywell Aeronautical Division and later a consultant to both private and public organizations, I acquired some knowledge of the design process. Over several decades I led senior mechanical engineering students in design projects and studied the work of others who performed research into the design process. This experience led me to develop the following set of 15 rules of engineering design that if followed rigorously will lead to excellent results. I have sadly found, however, that all too few engineers follow such a rigorous set of procedures, and I have observed that designs of those who do not show the lack of discipline.

2.1. Consider the transit system as a field of requirements and characteristics. It is easy for an engineer, and all too common, to jump right into specific designs before thoroughly understanding all of the requirements that relate the subject system to its environment. To make genuine progress, it is absolutely necessary to take the time to study the problem for which an engineering solution is desired in as broad an interdisciplinary context as the problem requires. In the design of a new transit system, this means understanding and documenting all of the desired performance, environmental, social, and economic requirements. By the “field of characteristics” I mean all of the alternative system characteristics possible. For example, a vehicle could be suspended on wheels, air cushions, magnetic fields, or sled runners. Detailed study of the requirements must lead to a set of criteria that will guide the design.

2.2. Identify all trade-off issues. One trade-off issue in transit design is the means to be used for suspension, and four possibilities are given above. We found 45 trade-off issues (see Section 7), certainly not an exhaustive list, but one that must be considered, explicitly or implicitly, in designing a new transit system. By considering such issues explicitly with the criteria firmly in mind, the task of design is clarified and organized.

2.3. Develop all reasonable alternatives within each trade-off issue. Often, by rushing into

details too quickly, practical alternatives are overlooked; someone else finds them and develops a superior design. Perhaps more important is that the designer who has not examined alternatives carefully before committing to a design cannot defend the design rationally and then becomes emotionally “locked in” to one approach when others point out superior alternatives. All too often such a designer causes more harm than good in advancing a design.

2.4. Study each alternative until the choice is clear, rational and optimal. This is hard work, but if not done rationally the design may have fatal flaws. Such a process creates designs that are difficult or impossible to better, which is the objective of a good designer.

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

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

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

2.8. Recognize that while emotion is a fundamental driving force in human behavior, emotion must not select alternatives. Emotional commitment is vital for any human being to commit fully to a task, but it must be set aside when making design decisions. A good design engineer must be free of emotional “hang-ups” that inhibit making use of all information available, calmly sorting through the pros and cons of each approach before recommending a solution, and being willing to accept someone else’s idea when objective analysis shows that it is superior. Too few engineers have a deep understanding of the subconscious factors that motivate and direct thinking. Yet it is necessary for the engineer to put the ego in the background when making design decisions. The following verse from The Bhagavad Gita, written perhaps 4000 years ago, hits the nail on the head.

*“Therefore unattached ever
Perform action that must be done;
For performing action without attachment
Man attains the highest.”*

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

a prime phenomenon that destroys profitability of design offices. The motivating drives that produce it must be understood and controlled. The human emotion that says “we can do it better than you can” is okay if it is controlled, but when it prevents an engineering office from making good use of ideas developed elsewhere, as is all too often the case, it is destructive.

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

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

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

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

2.14. Design for function. Sounds obvious, but is too often overlooked. A Japanese engineer reduced the cost of a magnetron for an infrared oven from over \$500 as developed by an American engineering firm to under \$5 by asking himself what the magnetron is really supposed to do. I reduced the design of an instrument from 90 parts to 19 by asking: What was the real function of the device? The new design passed a much tougher vibration specification than the former.

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

3. General Criteria

Following is a list of general criteria that resulted from much discussion during the 1970s. It is needed to guide the design of a new type of transit, but is not necessarily listed in the order of importance. Specific criteria needed to design the various subsystems come later.

- The energy efficiency must be very high.
- The land requirement must be very small.
- The system must be genuinely attractive to auto users.
- The trip time must be competitive with auto trips.
- Capital and operating costs must be low, desirably low enough to be recovered by fares.
- The system must meet accepted ride-comfort standards.

- The design must meet the requirements of the Americans with Disabilities Act.
- The system must be available at all hours of the day to everyone.
- The system must be able to use renewable energy sources.
- The air and noise pollution must be very low.
- As little material as possible must be used.
- The new system must be at least two orders of magnitude safer than present systems.
- There must be less than about 1 hour of delay in every 10,000 hours of operation.
- The system must not be an attractive target for terrorists.
- The system must not compromise personal security and privacy.
- The system must be expandable without limit.

Meeting these criteria requires a great deal of optimization, a process that is too often ignored because it requires a good deal of engineering mathematics.

4. Derivation of the General Features of the System from the Criteria

The next task is to develop the general characteristics of the new system from the criteria. The first point is that if the system is to be able to attract auto users, it must be competitive in trip time between many points. Also it must be safe and reliable. For these reasons the new system cannot be one more system running on the surface – it must provide an exclusive guideway either elevated or underground. Underground systems are so expensive that it is clear that we had to attempt to devise a low-cost elevated system, the visual impact of which will be acceptable. Consequently, we concentrate on how to design an acceptable elevated system.

By studying the dynamics of vehicles or trains moving over elevated guideways [7] it became clear that if the people-carrying capacity of the vehicles can be distributed over the guideway in many small units in which adult passengers are all seated instead of a few large conventional vehicles of the same capacity, the weight per unit of length of the guideway can be reduced by a factor of at least 20.

This marked reduction is due to both static and dynamic factors. Statically, if the load is spread in small vehicles, the maximum load on any single span is far less than if large trains pass only every few minutes, and the vehicle weight per unit of length is much smaller if the vehicle is designed for seated passengers only. Dynamically, it was shown [7] that the ratio of dynamic to static deflection is much less with many vehicles moving at close spacing rather than a few vehicles or trains running at large spacing. Indeed, as the headway between small vehicles gets smaller and smaller, the ratio of dynamic to static deflection approaches unity. I found [6] that the governing vertical load on the guideway occurs with fully loaded vehicles standing still nose to tail – the governing load is the easiest to calculate. Moreover, I found that the International Standards Organization (ISO) ride-comfort standard for such a guideway is not exceeded until the vehicles are traveling at above about 45 m/s (100 mph), which covers a very wide range of applications.

The next logical question is this: Would not a system of small vehicles of a given total capacity cost more than a system of large vehicles of the same capacity? Isn't there an economy of scale favoring large vehicles? Many engineers have assumed so. After all, there are many more motors, wheels, etc. in the fleet of small vehicles. Examination of data on the cost and weight per unit of capacity of transit vehicles shows [8], surprisingly perhaps, that there is no

economy of scale – the large vehicles cost as much per unit of capacity as the small ones. A major factor in cost is production quantity. Large transit vehicles are assembled pretty much by hand, while higher-production techniques are practical with small vehicles. Moreover, with many small vehicles, the equipment needed to move them around and service them is much smaller, and the required facilities are much smaller. It is clear that if a system of such small vehicles is to work, the vehicles must be controlled automatically.

We have seen that the use of many small vehicles rather than a few large ones reduces the cost of the guideway substantially. The cost of a fleet of vehicles of a given capacity is the cost per unit of people-carrying capacity multiplied by the people-carrying capacity. We then observe that the people-carrying capacity required to move a given number of people is proportional to the trip time – the longer the trip time, the more vehicles there will be on the guideway at any one time. The shortest possible trip time is obtained if all of the trips are nonstop, and this becomes practical if **all of the stations are on bypass guideways off the main line** as illustrated in the following plan view. This is of course the principle of the expressway and why people prefer to travel on them rather than on arterial streets with all of their stop signs and lights.



An important consideration in developing the criteria for the new system is whether or not the vehicles should be able to run on normal streets as well as on guideways. A system that does this is called dual mode. [6, 10, 27] While its vehicles run on a network of guideways, a dual-mode system operates exactly like a PRT system. Dual mode may have stations similar to PRT stations, or vehicles may leave the guideway without any station platforms, thus saving their cost. Dual mode has the advantages for auto drivers 1) that the same vehicle may be taken from home to any destination, similar to driving an automobile; and 2) that congestion *on the guideway* may be avoided because of the shorter headway and the managed flow possible under automatic control. In many respects, dual mode is much like the system envisioned by advocates of IVHS (Intelligent Vehicle Highway Systems), except that special narrower guideways could be used. Dual mode does not come, however, without disadvantages, most of which are inherent and not subject to technical improvement.

The following are some of the disadvantages of dual mode, which lead me to conclude that it is best to concentrate on systems of small vehicles captive to the guideway. If the distance is too far to walk and oil is too expensive, small electric cars can be used to take people from home to station. Such cars, called “station cars” have already been put into use in the United States at least in California.

1. Dual-mode vehicles will have to be inspected carefully before entering the guideway, and the inspection time will reduce markedly the throughput at each entry point.
2. Maintenance of dual-mode vehicles would be done privately, just as it is with autos today, so the condition of vehicles entering the guideway would be much more difficult to determine than it would be in a PRT system in which the condition of the vehicles can be monitored and maintenance can be controlled.
3. Dual-mode vehicle must be designed for both the street and the guideway, making them heavier and more expensive than captive vehicles. Street vehicles must be designed for

- side collisions and rollovers, whereas PRT vehicles captive to a guideway do not.
4. The requirement for operation on the street limits flexibility in design of a minimum size, minimum cost guideway.
 5. Since dual-mode vehicles would be more expensive than regular automobiles, they would be purchased near the beginning of dual-mode operation by only the wealthy.
 6. A question then is how much guideway would have to be built before even a wealthy person would purchase a dual-mode vehicle?
 7. At least in early stages taxes would have to pay for installation of the guideway, a guideway that only the wealthy could afford to use. There has been much debate on this question related to requirement for payment for a fast lanes on freeways, and will be much more contentious when it comes to paying for a whole system of guideways for the rich.
 8. One must be able to drive a dual-mode vehicle on city streets, so the idea of dual mode will be of no use to those who can't or don't chose to drive. A characteristic of transit is that it is available to everyone.
 9. In downtown areas, dual-mode vehicles cannot always be permitted to enter the street system because congestion could then back up onto the guideway, so the downtown network would have to operate identically with PRT, but with bulkier guideways.
 10. Dual-mode vehicles would have to be stored like conventional autos, sitting unused all day, whereas captive PRT vehicles are ready for the next trip as soon as one is completed.
 11. The time required to retrieve a dual-mode vehicle at the end of the day downtown will be much longer than the time to wait for a PRT vehicle captive to the guideway.
 12. Dual-mode stations would be more complex, expensive, and land-consuming than PRT stations because they must provide PRT-type stations as well as on- and off-ramps for dual-mode vehicles and ramps for rejected vehicles.
 13. Dual-mode designers usually speak in terms of only a minimal guideway network being needed, which would render use of the system marginal for those who do not drive.
 14. Developing a dual-mode guideway that will meet all of the criteria listed in this paper has not been shown to be possible. Every dual-mode guideway designed thus far has serious problems.
 15. Dual-mode ridership has been shown [10] to be no more than PRT ridership.
 16. Dual mode suffers from the attempt to combine two different functions, and as a result fails to excel at either.

5. The System Attributes Obtained

By assuming a transit system using minimum sized vehicles operating automatically non-stop between offline stations, we observe that the following attributes are either directly apparent or can be readily achieved:

- Nonstop trips
- High throughput. Similar to automobiles on a freeway, the small transit cars can run seconds or fractions of a second apart rather than minutes apart, as is necessary with the on-line stopping required of buses, streetcars, and trains.
- Small, low-cost, low-visual-impact guideways.

- Around-the-clock availability because the cars can be automatically rerouted into the stations to keep a supply of cars in or coming to each station all the time.
- A short wait in the peak hours when all the cars are in use, and no wait off peak.
- Travel on demand – no schedules. This is very important. The vehicles now need to move only when there are demands for service, which markedly reduces operating costs.
- Close station spacing. With on-line stopping, the farther apart the stations are the higher can be the average speed, but larger spacing between stations reduces access to the system. With off-line stations we have our cake and eat it too – stations can be placed as close together as needed (within a geometric limit) to provide access while a high average speed is maintained. The economics of adding stations to existing lines is very favorable [8, Appendix B].
- Stations sized to demand. With train systems, every station must be as long as the longest train. With off-line stations, the stations can be sized to the expected demand at each station.
- All of these factors contribute to low cost and high ridership.

6. Ridership Potential

Estimation of ridership on a potential PRT system is as important as the engineering factors that need to be understood to design the system, and involves measurement of human judgment and social interaction. We can appreciate intuitively that a system that will be available anytime of day or night, with a private ride in seated comfort, will be attractive, but just how attractive? In the period 1974-75 I worked for Colorado's Regional Transportation District on the largest study of transit alternatives ever performed in the United States, and was assigned to follow, understand, and report on the ridership studies.

In so doing I learned that there was an Institute of Behavioral Science at the University of Colorado where the faculty was engaged in studies of social judgment. They were quite interested in using their skills to develop a model to determine ridership on transit systems with new characteristics. Analysis of ridership on conventional transit systems did not need any new techniques because they could do regression analysis on existing transit systems to calibrate their models. With a new system, such conventional models could not be applied accurately because there was no basis on which to calibrate the models. One way used to get around this problem was to develop a video of the new system, show it to people, and ask detailed questions about their preference to ride it. Unfortunately, when facing a real situation people don't always behave as they think they would in the abstract. The way this problem can be solved using the theory of social judgment involves breaking the trip up into detailed steps, devising experiments with a wide variety of people on how they would behave during each step, and then from the results build a model with appropriately weighted factors. There is a wide ranging literature in social judgment with many examples of quite remarkable success. Unfortunately, to my knowledge, such a method is yet to be developed for estimating ridership on true PRT systems. Yet many estimates of ridership on PRT have been and must be made. I mention three:

1. One of the best early PRT ridership studies of which I am aware was performed by Professor Frank Navin of the University of British Columbia [9]. Using a standard logit model he broke time up into walk time, wait time, ride time, and transfer time with different coeffi-

icients for each. He then performed regression analysis on transit ridership from several cities to determine the coefficients. He found the following results:

	Low	High
Riding in bus	1.00	1.00
Walking to/from bus	1.65	2.08
Waiting for first bus	4.15	6.34
Transferring	6.62	10.0

This table means, for example, that for every minute spent riding a bus, one minute of waiting seems like from 4.15 to 6.34 minutes. In most ridership studies involving trains and buses, the consultants usually assume the coefficients for walking, waiting, and transferring are each taken as 2, which clearly will bias the results to more bus riders than will actually occur, thus making it more likely that a governing board will expand the bus system. Navin applied his ideas to estimation of ridership on a PRT system and came up with estimates greater than 50% of the daily trips.

2. Work at The Aerospace Corporation [10], using a novel “Monte Carlo” model, led them to conclude that a mode split to PRT in the Los Angeles Area of 30% was reasonable. In the Monte Carlo model they would start the trip at a random point, pick at random an individual in a certain income range appropriate to that point, pick a destination at random, calculate the walk, wait and ride time by both auto and PRT, include a factor for perceived trip cost, and then assign the person to either auto or PRT. They repeated the calculation with new randomly selected passengers until the result converged. The value of 30 % they obtained must be compared with the bus modal split, which for most U. S. cities hovers around 3%.

3. Swedish PRT planning studies performed in the 1990s [11] showed that “PRT can attract 20-25 % of today’s automobile trips.” They did not describe the method they used in published reports I have seen.

7. Required Tradeoffs

A table (<http://faculty.washington.edu/jbs/itrans/jea2.gif>) listing 45 possible tradeoffs that must be made in designing a PRT system can be found on Professor Jerry Schneider’s web page. We calculated the number of possible combinations to be about 10^{16} . The only way to resolve so many combinations must come through the development of suitable theory and through the disciplined process described above.

8. Control Criteria and Tradeoffs

The new type of transit, Hi-Cap PRT, will, as concluded above, be fully automatically controlled. The Bibliography given in Section 25 includes more published work on the control of PRT systems than on any other aspect of the subject. Even though I worked as a control engineer in the Aero Research Department at Honeywell, I observed what was going on during the 1970s in PRT control and concluded that a better task for me was to determine what should be controlled, while following the control work of others. Building on the work of others, I saw that

a PRT control system should consist of a hierarchy of three levels of control: vehicle control, wayside control by zones, and central control [12, 13, 14] and definitely that it should not be synchronously controlled, i.e., controlled so that a vehicle can be commanded to leave a station only if there is a clear path with no merge conflicts to the destination [15]. The criteria used are the following:

1. Changing conditions. The system must be designed so that the speeds can be reduced when the wind increases above set levels, and that the normal speed can be restored when the wind dies down. Moreover, the system must be responsive to any possible type of failure – system, vandalism, sabotage, or terrorism.
2. Ride comfort. Accepted criteria on maximum jerk and acceleration rates must be met.
3. Fail safety. The system must be designed to fail soft if it is to fail in any way.
4. Modularity & Expandability. The hierarchical system described is modular and line-replaceable units must be used. By breaking up wayside control among zone controllers that serve stations, merge points or diverge points, with the same code in each, any network configuration can be handled.
5. Less than one person-hour of delay for every 10,000 person-hours of operation [16].
6. Maximum throughput. The system must be designed so that there is no safety issue in reducing the line headway to about 0.5 second. This headway will accommodate the needs of a very large network.
7. Interchange flexibility. There are two types of line-to-line interchanges: X and Y. In an X-interchange two lines enter and two lines leave, one set above the other, and the flow diverges before it later merges. Such an interchange requires no central control because all potential conflicts can be solved at the interchange. In a system containing Y-interchanges, the flow must merge before it diverges, creating potential bottlenecks. But the visual impact of the system at Y-interchanges is much less than at X-interchanges and the guideway can be all at one level. Thus in many cases Y-interchanges are preferred and the control system must be able to handle them. I have found that it can do so quite readily.
8. Dead-vehicle detection. The system must be able to know if a vehicle has ceased to function at any location on the guideway.

During the 1970s there was much debate over quasi-synchronous vs. asynchronous control. I started my development of a PRT network control system using quasi-synchronous control, but needing to simulate a system with rather long minimum headway, I found that I could not succeed unless I switched to asynchronous control. Having done so, I found that I needed fewer subroutines and that asynchronous control also worked better at short headway. Asynchronous control does not require clock synchronization, which is artificial. Having developed exact equations for all possible speed changes, as others had done before me, I found that it is preferable to require each vehicle to follow a command trajectory than to control its motion by following the vehicle ahead. Such control is completely stable and is not subject to string-stability problems that plagued car-follower control. Thus, while in the 1970s the debate was between quasi-synchronous control with point-following, i.e., following speed-change commands; and asynchronous control with car-following, I found that the best scheme is an asynchronous point follower.

9. Guideway Criteria

Most of the PRT systems of the 1970-era faded away because of inadequate attention to the criteria for guideway design. That was also true in the Raytheon program of the 1990s. During the 1970s, as a university professor and chairman of the three international PRT conferences I was able to visit all of the PRT developers in all of the industrialized countries where PRT work was underway, study their systems, read their reports, and obtain reactions of others. This experience led me by 1980 to be able to list the following criteria for PRT guideway design.

1. 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.
2. Minimum size, weight and cost. These factors have been argued as being fundamental to PRT design. What I found [6] was that the minimum weight cross section, taking into account maximum vertical loads and maximum lateral wind loads, would be a little narrower than deep. The Aerospace Corporation [10] first reached this conclusion and also observed that this structurally optimum design would give the least visual impact, i.e., the smallest shadow.
3. Span. The guideway should be designed for spans of up to 27 meters (90 ft). Longer spans needed to cross rivers or major highways will use cable-stayed suspension-bridge technology.
4. Three dimensional. The guideway and its manufacturability must be design to accommodate hills and valleys as well as horizontal curves.
5. Weather protection. The system will need to operate in rain, snow, ice, dust, and salt spray, i.e. in a general outdoor environment. Some designers concluded that this required that the vehicles hang from the guideway; however, I found a number of reasons to prefer placing the vehicles on top of the guideway (see Section 10).
6. Guideway heating. The guideway must be designed so that under winter conditions, guideway heating will not be necessary.
7. Resistance to maximum wind load. Codes vary from city to city, so thinking in terms of hurricane winds I designed for 240 km/hr (150 mph) cross winds. I did not design for tornado winds, which can go well over 320 km/hr (200 mph) because it would be cheaper to replace failed sections than to build the entire system to withstand such an improbable load.
8. Resistance to earthquake loads. If an earthquake causes the earth to shear horizontally, as has happened, no design will prevent failure. The most common earthquake load translates to a horizontal acceleration. In the 1994 Los Angeles earthquake, horizontal loads up to 1.6 g were detected. The lighter the guideway, the easier it will be to design the foundations to withstand such a horizontal acceleration.
9. The guideway must be easy to erect, change, expand or remove. The guideway sections must be designed so that the system can be expanded by taking out a straight section and substituting a switch section.
10. Access for maintenance. I visited the H-Bahn design in Düsseldorf in 1974. The cars hung from an inverted U-shaped steel-plate guideway. There were power rails and communication lines on the inside of the guideway but no way to reach them. One had to assume that they would never require maintenance, which is an unacceptable assumption.

11. Relief of thermal stresses. Except at noon, the sun will shine on one side of the guideway, with the other side in the shade, thus causing one side to expand more than the other. In some cases this has caused structural failure.
12. The power rails must be shielded from the winter-night sky. Some PRT systems operate their vehicles with on-board batteries, so for them this is not a problem. However, on-board batteries add weight and must contain enough energy for the worst conditions of wind, grade, and trip length, which increase as the system expands; so it is better to pick up way-side power via sliding contacts. On clear winter nights heat radiates to a very cold space and as a consequence frost often forms on metallic surfaces. In the Airtrans system, which was installed at the Dallas-Ft. Worth Airport in 1972, it was found that on clear winter nights enough frost formed on the power rails that they had to be sprayed with ethylene glycol as a temporary expedient before starting the system each morning. Later they installed heaters in the power rails. A similar problem was discovered in the elevated guideway system installed at the Minnesota Zoo. In systems such as Cabintaxi in which the power rails were covered, frost formation was never a problem.
13. The design must provide adequate torsional stiffness.
14. Design to liberalize the required post-settling tolerance.
15. High natural frequency to obtain maximum speed. This is not as important a consideration as I once thought it was, but all else being equal higher natural frequency is better.
16. Lightning protection. The guideway must be well grounded.
17. Electrocution. It must be very difficult if not impossible for anyone to be electrocuted by the system.
18. Provide space for communication wires. Wireless communication may be practical, but is more likely to be subject to interference. Moreover, the system would likely have to rent the frequencies it needs, which would be prohibitively expensive. Thus there must be space for installation of a leaky cable for communications between the vehicle and the guideway.
19. Minimize electromagnetic interference. The U. S. Federal Communications Commission requires that any new element in a community not interfere with existing electronic devices. The motors or drives on a PRT vehicle may emit electromagnetic noise and the communications system may be subject to electromagnetic noise, so there must be shielding between the inside and outside of the guideway.
20. Minimize potential for vandalism or sabotage.
21. There must be no producers of vibration or noise.
22. Provision must be made for corrosion resistance.
23. There must be no place for water to accumulate.
24. The design must permit the appearance to be varied to suit the community.
25. It must be difficult if not impossible to walk on the guideway unless walkways are provided.
26. Thought must be given to providing for damping.

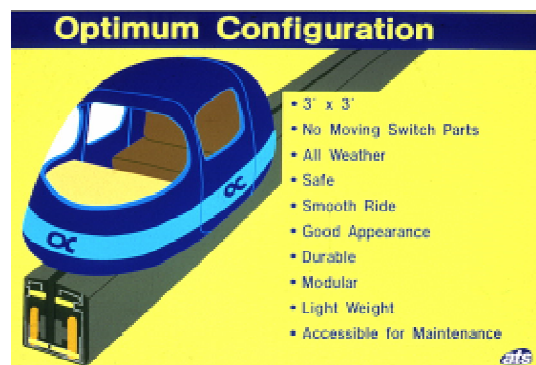


Figure 1.

27. Curved and branching sections. These are more difficult than straight sections; therefore it is prudent to think through first a design in which the many required curved, merge, and diverge sections will be easy to fabricate.
28. The guideway should be designed for 50-year life.

10. Suspension

Practical means of suspension include rubber tired or steel wheels, air cushions or magnetic levitation. Automated systems have been designed with vehicles suspended below a guideway, on the side of the guideway, and above the guideway. For reasons given in [1] I found that it is best to place the vehicles above the guideway. The need to keep the cross section of the guideway as small as possible and the status of development led me to conclude that wheeled suspension is best. Magnetic levitation requires the use of on-board magnets that will increase vehicle weight, and the surfaces against which they must run need to be wider than with wheeled suspension. Moreover, because of the need for high-speed switching, repulsive magnets must be used, which are more difficult to design than attractive magnets. Superconducting magnets have been used for this purpose in large vehicles but they are impractical in small vehicles. Air-cushion suspension requires a wider guideway than needed with wheeled suspension, resulting in higher costs and greater visual intrusion. In maglev and air-cushion suspension, power must be provided to keep the vehicle levitated. We thus chose wheeled suspension, yet we must keep an open mind and watch additional development to see if our conclusion remains correct.

To reduce noise and to provide some cushioning with wheeled suspension, we selected either pneumatic or the new airless tire recently announced by Michelin. For lateral suspension, solid polyurethane tires are adequate. Some engineers have expressed concern about the narrow guideway for reasons related to lateral suspension; but Mother Nature does not care if lateral suspension is provided on horizontal or vertical surfaces. The effective track width is the distance from the upper left lateral wheels down to the horizontal running surface, across to the right lateral running surface and up to the upper right lateral wheels. We met an important criterion – minimum cross section – by using vertical surfaces for lateral support.

11. Guideway Covers

Careful study of the guideway criteria led me to select a U-shaped steel-truss frame that would be clamped to the support posts with expansion joints at the point of zero bending moment in a uniformly loaded beam, i.e., at the 21% in the span where there will be very little bending as the vehicles cross the span [10]. It is illustrated in Figure 2. A steel truss frame is the lightest weight design possible, and, among other things will reduce the earthquake load on the posts and foundations. The lightest-weight guideway, a truss, will maximize the natural frequency of the guideway, and will minimize the cost of shipping. Computerized analysis has been performed on this guideway by six different engineering firms and a section has been fabricated. As shown in Figure 3, covers will be attached to the sides of the guideway. These covers have a

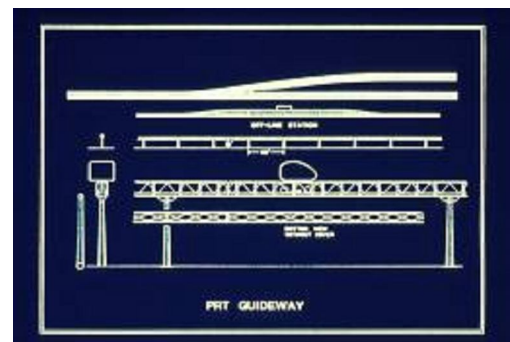


Figure 2.

narrow slot at the top to permit the chassis to pass through, and are opened at the bottom. They provide the following nine functions:

- They keep out almost all ice and snow, with the remainder easily disposed of.
- By applying a thin aluminum coating inside, they provide electromagnetic shielding.
- By applying a sound-dampening material to the inside surface they reduce noise to nearly inaudible level.
- They shield the tires from the Sun.
- They shield power rails from frost formation.
- They eliminate the problem of differential thermal expansion.
- By curving the covers at the top and bottom with a radius of about $1/6^{\text{th}}$ the depth of the guideway, the lateral air-drag coefficient is reduced from about 2 to about 0.6, with a proportionate reduction in the bending moments on the support-post foundations. Also, curving the covers at the corners will help debris or snow to fall off quickly.
- The covers can be removed or swung down to provide access for maintenance.
- The outside surface treatment of the covers can be varied to suit the community.

12. Capacity Potential

Consider a surface-level tram, streetcar, or light-rail system. A typical minimum schedule frequency or headway in these systems is 6 minutes or 360 seconds. In the United States, the modern light-rail vehicle has a design capacity of about 200 persons, and typically they run in two-car trains, thus moving a maximum of 400 people every 360 seconds. On the other hand, a great deal of evidence shows that Hi-Cap PRT vehicles can run about 0.5 second apart. Indeed in a program ran by the Automated Highway Consortium and monitored by the National Highway Safety Board four automobiles were demonstrated running about 0.25 seconds apart at 60 mph. So we can assume that a maximum of 720 Hi-Cap PRT cars can pass a point every 360 seconds. We recommend a 2.7-meter (9 ft) long vehicle with one bench seat that can be occupied by three adults, giving $720(3) = 2160$ persons in the same period in which 400 people would pass in light rail cars. In this case the capacity ratio is $2160/400 = 5.4$ to 1!

This is a line-haul comparison; however, Hi-Cap PRT will typically be deployed in networks, which by spreading out the load results in a much smaller requirement for line-haul as well as station capacity than conventional train systems. The problem of PRT capacity needs in lines and stations is addressed in detail in a paper sponsored by the Advanced Transit Association [17].

13. Vehicle Criteria

Up to this point, it has been concluded that the vehicle should be designed to be as small and as light in weight as practical and should ride above the guideway. Now it is necessary to be more specific [18]. Because of the nature of a PRT vehicle captive to a guideway, the considerations that led to a recommended vehicle configuration are different from those that enter into choosing the size of the family automobile. Again it is important to avoid snap judgments that have marginalized certain previous PRT systems. Following are nine factors that should be considered in selecting the vehicle size and configuration.

- Travel behavior. In the U. S. the daily average number of people per automobile is about 1.2 and in the rush period it is less than 1.1, indicating how people travel if they have a choice [19]. Think of the trips you take in one week. In what fraction of them do you ride alone, in what fraction with one other person, what fraction with two, etc.?
- Personal security. The way people travel if they have a choice, at least 90% of them take trips traveling alone. A small percentage of them travel in pairs, and an even smaller percentage in three's or four's, etc. People travel this way in taxis. Group riding by choice can be encouraged in PRT systems by charging a fare per vehicle rather than per person, as is commonly done with taxis. Expecting people to ride with unacquainted persons to fill the vehicles will discourage some people from riding at all. The smaller the vehicle, the higher will be the daily average load factor and the lower will be the overall cost per trip.
- Network operations. It was shown by detailed computer simulations conducted at Colorado's Regional Transportation District [20] that a system of vehicles operating between off-line stations and designed for random-group riding (GRT) runs into a problem that becomes more serious as a network grows, i.e., a vehicle coming into a station with people on board must have been committed to a given route. Thus a person wishing to board can't get into any vehicle, but must wait for a vehicle committed to the route the destination is on. As the system grows it turns out that the number of possible routes increases roughly as the square of the number of loops. Moreover, the system cannot know which of several loading berths the vehicle will stop at until it is switched to enter the station. So, in GRT there is too little time, particularly for slow moving people, to get to the desired vehicle. In short, simulations showed that the operation of such a station is impractical, and that the two practical systems are one that stops at all stations and one in which all people on board are traveling nonstop to their destination, i.e., a true Hi-Cap PRT system. Moreover, the odds of two unacquainted persons arriving at one station within a few minutes, let alone seconds, of each other intending to go to the same destination increases with the square of the number of station and becomes much too large to be practical when there are more than six or eight stations[6].



Figure 3. The covered guideway.

- Social considerations. One-person vehicles would minimize system costs, but are not socially acceptable. Two-person vehicles are too small for a wheelchair to enter and face forward. A vehicle with one bench seat, with sections that can fold up, designed for three adults seated side by side will accommodate a wheelchair and it was demonstrated that it will permit the wheelchair to rotate 90 degrees to face forward with room for an attendant. Moreover, to accommodate the wheelchair, there is room to place two fold-down seats in front of the cabin so that, when there is no wheelchair, the vehicle can accommodate three adults and two children. Also, a multi-purpose television screen can be positioned in the middle of the front of the cabin below the windshield. This configuration gives the shortest possible vehicle, which means the shortest possible stations.

- Throughput. The effect of vehicle length is a small factor, but the shorter the vehicle the greater is the practical throughput.
- ADA requirements - wheelchair access. The cabin described above accommodates a wheelchair with attendant, a passenger with a bicycle, a couple with a baby carriage, a couple with large suitcases, or even a Segway.
- Styling. The vehicle, in particular, must be designed very carefully to attract riders of all ages. The length/width ratio of the cabin should conform to the Fibonacci ratio – 1.618.
- Minimizing system cost corresponds to minimizing vehicle weight, size, and length.
- Finally, with a larger group it is very easy to use more than one vehicle. Portions of the group will leave seconds apart and arrive seconds apart, and on the way can be in touch by cellular telephone or by an intercom system that would be standard equipment for a variety of purposes.

14. Switching Criteria

In many of the PRT designs, switching has been considered an afterthought – something that can be considered later. This is usually a fatal mistake. With the need to switch into and out of off-line stations and from line to line, the ability to switch easily with minimum extra guideway weight is fundamental to the design of any PRT system. Here are the criteria I used. In so doing I found, upon searching through 36 switch patents, that the switch that met the criteria without exception had not been patented.

- No moving track parts. If a moving track part fails, an entire line of traffic is held up, but if a moving part on a vehicle fails, the worst that can happen is that one vehicle will be sent in the wrong direction. An alternative, recommended by The Aerospace Corporation [10], is to switch electromagnetically. If this can be done without excessive vehicle weight and if it can be 100% reliable, it is worth considering. In any case, it has been proposed that there must be a mechanical backup, and if so, the mechanical device may as well be, I concluded, the primary switch.
- Only two stable positions (bi-stability). There can be no chance of a hang-up in the middle.
- The two switch positions should be self-stable without a locking mechanism.
- There should be no possibility of hitting track parts under any circumstances. Thus the switch arm must rotate about a longitudinal axis.
- It must be possible to throw the switch manually from wayside or from the vehicle behind under failure conditions.
- Switch operation must be unaffected by centrifugal forces in turns.
- The switch must operate in all weather conditions.
- The switch must be operable from low-voltage battery power.
- The operation of the switch must be fail-safe.

How these criteria can be met is the subject of two expired patents in my name. These patents are now in the public domain. They can be found on the U. S. Patent Office web page.

15. Dynamics

To meet ride comfort criteria, particularly as the vehicle moves through either merge or diverge sections of the guideway, extensive dynamic-simulation analysis is needed. With today's computer programs, this work is straightforward and will determine certain geometric parameters in the guideway as well as acceptable unevenness or roughness in the running surfaces. With minimum-weight vehicles, the ride is mainly determined by the smoothness of the running surfaces, so how they are designed and how the dimensions are maintained is critical to the operation of the system.

16. Safe Design

Safe design of PRT systems has been the subject of many papers, many of which are included in the Bibliography, Section 25. Safe short-headway flow can be achieved by consideration of four factors [21]:

1. Braking and acceleration accuracy through wheels depends on the coefficient of friction at the running surface, changes in wet or icy weather, wind, and grade. This problem is solved by use of linear electric motors (LEM) for propulsion and primary braking because consistent braking can be achieved under all conditions. There are two types of LEMs, synchronous (LSM) and induction (LIM). LSMs require a winding in the running surface but are more efficient than LIMs. They may be the way to go, but I have yet to see the total tradeoff study, which will involve detailed design that will prove that the overall system cost per passenger-km will be less with LSMs than with LIMs. LIMs require a copper overlay on a steel plate, which is cheaper than a winding and which has been shown to be practical. There are many thousands of LIMs in operation in a wide variety of applications.
2. Reaction time. Human reaction time to emergency situations varies with the person and with the amount of drugs or alcohol consumed. The reaction time of LEMs is only a few milliseconds, hence automatic systems can operate safely at much closer headways than manually driven vehicles, which routinely operate at headways less than two seconds.
3. Braking time. Mechanical brakes can apply the full force, even if actuated automatically, in no less than about 0.5 second, whereas LEMs apply the full force in a few milliseconds.
4. Vehicle length. The vehicle I propose in Section 13 has a length of 2.7 meters (9 ft), whereas a common automobile has a length of at least 4.6 meters (15 ft). Vehicle length enters into the equation for minimum headway, so the shorter the vehicles the better.

The conclusion of many investigators for over thirty years has been that operation of PRT vehicles at half-second headway with the above features is safe, practical, and needed in large applications.

17. Reliable Design

In conventional transit systems, system reliability has been measured in terms of Availability, which is defined as the percentage of all revenue trips that are completed without interruption to a specified degree. This is a crude measure, but is the best that can be done because it is not practical in these systems to use a measure in terms of person-hours of operation and person-hours of delay. In PRT systems, we can record the expected and actual times of each trip, so we can develop a better measure. To distinguish it, I have called the new measure “Dependability” [16] and define it as the percentage of person-hours experienced by people entering and riding the transit cars with delays less than specified. The ratio of person-hours of failure to person-hours of operation can be called “Undependability” and is 1 minus Dependability. The dependability paper [16] shows both how to calculate Undependability and how to measure it continuously as a routine part of system operation. The calculated measure of Undependability depends on normal operations, emergency operations, and the failure characteristics of each component in the system. It is thus an important management tool in maintaining control of the design, and can be used in contract specifications as a specific measure of performance.

During the design process, the question frequently arises as to where to place design emphasis to achieve the Dependability goal at minimum life-cycle cost. This question came up in U. S. military programs when, thirty years ago the Joint Chiefs of Staff issued a memorandum directing that life cycle cost would be of equal importance to performance in future procurements. I was able to solve this problem [22] by considering the system life-cycle cost (LCC) to be a function of the mean times to failure (MTBF) of each subsystem, and within each subsystem each component. This is a constrained minimization problem, with dependability as the constraint, and was first solved by J. L. Lagrange (1736-1813). It has an elegant solution, and gives the MTBF of each component required to meet the specified system Dependability at minimum system LCC. The resulting equation is an important tool for managing the design program.

Study of reliable design requires detailed study of failure modes and effects [23], hazards analysis, and fault-tree analysis. This work was done for PRT during the Phase I PRT Design Study sponsored by the Northeastern Illinois Regional Transportation Authority, and is the subject of Chapter 6 of The Aerospace Corporation book [10]. See also my book [6].

18. The Appropriate Speed

The appropriate line speed of a PRT system has been much debated. The Aerospace Corporation [10], thinking in terms of PRT systems that would serve Los Angeles, assumed line speeds of 20 to 60 mph (8.9 to 26.8 m/s) depending on where the line was located, and they designed a PRT system that could achieve those speeds. DEMAG+MBB, in the design of Cabin-taxi [24], chose a line speed of 10 m/s as appropriate for German cities. Indeed such a speed with nonstop travel will give average speeds well above that achievable by automobiles in the inner city because of all of the stops they must make there. Higher line speed can be achieved at higher cost and with higher energy use. In the equation for cost per passenger-km, the factor that improves with average speed to a point is ridership. So theoretically it will be possible, when enough data is available, to find the line speed that will minimize cost per passenger-km. In rough attempts I have made at such a calculation I find optimum line speeds lower than I would have guessed. In a large metropolitan area, one can envision PRT lines along freeways, and in these cases line speeds of perhaps 18 to 20 m/s (40 mph) may be appropriate. There is always

pressure to increase line speed because slower speeds seem too tedious. In the 1990 Chicago studies a line speed of 30 mph (13.4 m/s) was specified.

19. Energy Use

The operational energy use of a PRT system can be reduced by the well-known means of minimizing vehicle weight, careful attention to aerodynamic-drag reduction, minimization of road resistance, minimization of speed, and propulsion efficiency. The demand-responsive characteristic of PRT, whereby vehicles move only if necessary, will substantially reduce energy use over that required in conventional transit systems with their on-line stopping. I have compared the energy use per passenger-km in a PRT system with a variety of conventional systems [25]. It should be possible for a PRT system to achieve energy efficiencies, including construction energy, equivalent to an automobile system achieving in the range of 30 to 40 km/liter (70 to 90 mpg) of gasoline. By contrast, using U. S. government data, I found that light rail systems in the U. S. achieve in the range of 4 to 6 km/liter (9 to 14 mpg) of gasoline on a per rider basis. The low value for light rail is due to a combination of factors, mainly inherently low daily average load factor, wasted kinetic energy, and construction energy.

20. Land Use Implications

In the United States, the automobile system requires about 30% of the land in residential areas and roughly 50% to 70% of the land in Central Business Districts. An elevated PRT system requires land only for the posts and stations, which amounts to only one unit of land in 5000 for a system with lines spaced on a square grid 0.8 km (0.5 mi) apart with stations every 0.8 km, which gives a maximum walking distance of 0.4 km. The land under a PRT guideway can be used for walking or bicycle trails, and the system does not impede the flow of surface traffic.



Figure 4. Illustrating tiny land use of PRT.

This enormous reduction in land required for transportation will permit Hi-Cap PRT to substantially reduce the congestion and air pollution produced by automobile traffic and will reduce the requirement for parking automobiles. As mentioned, because of the service concept inherent in PRT, a PRT system will attract a substantial fraction of the total number of vehicle trips, which means that PRT stations will be attractive sites for development, which means that it is likely that the system can attract enough revenue in reasonable taxes to pay for itself. Not nearly enough work has been done on this means for paying for a PRT system and indeed not enough work has been done on the implications of the very positive impacts a PRT system will have on the urban environment.

In new developments, such as new universities, retirement communities, etc., PRT can bring about the dream of an auto-free facility. For example, about 15 years ago the University of California was looking for a site for a tenth campus and specified that it be auto free. I gave a brief presentation to the site-selection committee of presidents and chancellors of the various UC

campuses and found that the effect was electrifying. Unfortunately that site was rejected because it had been inadvertently placed over an Indian burial ground, but the concept, once PRT is proven in daily practice, of an auto-free facility will be extremely attractive to developers.

21. A Bit of History

System	Year first run	Guideway Width, m	Guideway Depth, m	Gross Vehicle Mass, kg
Morgantown GRT	1972	3	1.8	5350
Raytheon PRT 2000	1995	2	2	3000
Taxi 2000 HI-Cap PRT	2003	0.89	0.99	815

Consider the progression in design of the above three automated guideway systems. The earliest is the Morgantown system, which is called “PRT” but uses 20-passenger vehicles. The program that developed it was 100% funded by the U. S. federal government. The guideway is a wide trough that, for winter operation, requires snow melting, which is expensive. It is so large and heavy that no other city has chosen to duplicate it. The design contracts were let in December 1970 with the stipulation that the system be operational 20 months later, in time to influence the 1972 presidential election. The team of companies that designed it had never been engaged in a PRT project, had no theoretical background on how to design a PRT system, and had much too little time to perfect a design. Nevertheless, the system is still running every day and is the only system that demonstrates automatically controlled vehicles operating day in and day out between off-line stations.



Figure 5. The Morgantown system.

Next is Raytheon PRT 2000. It used four-passenger vehicles that ran on a test track in Marlborough, Massachusetts. Raytheon and the Northeastern Illinois Regional Transportation Authority (RTA) jointly funded the design and test program. Raytheon abandoned the program after the RTA dropped the system from consideration. This was fundamentally due to two factors: First, the Raytheon division that managed the program was accustomed to taking contracts from government agencies that developed the required specifications. Thus, they had not developed their own independent capability for doing the market surveys and specification development needed to guide their engineers independent of government agencies. Second, the state of the art in PRT was such that the RTA was not able to find a technical-support contractor with any depth of understanding of PRT. This combination sunk the program. Compared with the Phase I PRT Design program, which was based on the Taxi 2000 design, the guideway width and depth doubled, the vehicle weight increased by a factor of four, and the over all cost tripled. This was too much for the RTA.



Figure 6. The Raytheon system.

The third system, shown in Figure 3, is Taxi 2000. I led the design process throughout the program and designed the vehicle, guideway, and control system based on the principles presented in this paper. The vehicle ran automatically on an 18.3-meter-long (60-ft) guideway and over 4000 rides were given with no failures. The system is ready for final design and construction of a test loop that will permit continuous testing of at least three vehicles operating at speeds up to 16 m/s (35 mph). Such a test system is the next logical step before building a real people-moving demonstration.

Estimates of the system costs of the above three systems show that they reduce in proportion to the gross weight of the vehicle – everything scales with vehicle weight.

22. Benefits of High-Capacity PRT

22.1 For the rider

- The system is available for use at all hours. It does not have to be shut down at night.
- The system can be used by everyone without exception.
- The vehicles wait for people, not people for vehicles.
- The trip is short, predictable, nonstop, comfortable and private.
- The trip cost will be reasonable – typically no more than a bus fare.
- The rush period wait time will typically be less than one minute, with no waiting in non-rush periods.
- Everyone will have a seat.
- The vehicles will be heated and air conditioned.
- There will be no crowding.
- There will be no transfers.
- Because the vehicles run on rubber tires and because the motors have no moving parts, very little noise will be generated.
- The probability of accidents will be very low.
- Because the stations will be well lit and monitored, personal security will be excellent.
- The ride will be smooth and comfortable.
- There will be space in each vehicle for luggage, a wheelchair, a bicycle, or a baby carriage.



Figure 7. A comfortable ride.

22.2 For the community in which the system is installed

- The land savings will be huge.
- The system will attract many auto users and if deployed widely will reduce auto congestion.
- The frequency of accidents will be well under one in 10^9 of that experienced with the auto system [23].
- The energy use will be relatively low.
- The system can use renewable energy, thus contributing to a reduction in the need for oil.

- The levels of air and noise pollution will be very low, thus deployed widely the system will contribute to reduction in global warming.
- The system can serve the vast areas of single-family housing found in every city.
- There will be no significant targets for terrorists, so the system should be of interest to Homeland Security.
- The use of the vehicles is much more efficient than in the auto system because as soon as one trip is finished the vehicle is available for another, thus keeping each vehicle in operation about 10 hours a day – 6 to 10 times as much as with an automobile.
- The system will provide faster inside-to-inside transportation.
- There will be easier access to stores, clinics, offices and schools.
- Movement of mail and goods on the system will be swift and easy.
- The land under the system can be used for walking, jogging or bicycle trails.
- More people-attracting parks and gardens will be possible.
- More livable high-density communities will be possible.
- The system will be profitable in many applications.

23. A Summary of Advantages of High-Capacity PRT

- It will create healthy urban environments of unparalleled efficiency.
- Deployed widespread it will reduce the problems of congestion and global warming.
- Deployed widespread it will be a major means of reducing dependence on oil.
- It is not an attractive target for terrorists.
- It is an essential technology for a sustainable world.
- The technology to build it is at hand and is well understood.
- All that remains is final design, construction, test, and deployment.

24. Strategy for High-Capacity PRT Development

The knowledge needed to build public works such as bridges, roads, rail systems, sewers, water systems, dams, buildings, sports arenas, theme parks, vacation resorts, shopping malls, etc. is widespread and is taught widely. There are many private consulting firms ready, able, and willing to design and build these facilities – provided they are financed. Entities whether public or private with the means to finance such facilities develop specifications and then release them in Requests for Proposals. With few exceptions, PRT systems do not yet enjoy this status, as a consequence of which the large majority of entities avoid them even when shown, if they are carefully designed, their superior characteristics.

The engineering science needed to build cost-effective PRT systems has been developed over the past forty or more years. Yet, with only a few exceptions, consultant firms have spent too little time studying the PRT alternative, and when they have the objective has too often been to reject it so that they can get on with what they know how to do. PRT departs fundamentally from conventional transit. It requires a whole new way of thinking about transit and what it can do for a community. This has created controversy. Moreover, each PRT design group has developed and promoted its own configuration in the design of the guideway, vehicle, switch, suspension, propulsion, control, station, power system, operating speed and a host of other factors,

unfortunately too often with inadequate planning and system engineering, which resulted in non-viable systems that discouraged the market. In the 1970s, one important result of this plethora of possibilities was to reject them all. It will be the market ultimately, not the designer, that will determine which if any of the proposed systems or combinations of systems will survive. The system engineer interested in developing a new viable version needs first to become immersed in planning studies of real systems in an interdisciplinary setting in order to appreciate fully the criteria needed for success, or otherwise learn in detail from those who have gone before.

The engineering science needed to design PRT systems can be found in the public domain either through books, reports, published papers, expired patents, web pages, and courses given; but this information is scattered, as a result of which many new people entering the field spend unnecessary time reinventing what is already known somewhere. A bibliography of papers is included in Section 25.

PRT network simulation programs and means of calculation performance [26] are needed for detailed study of the layout and performance of any PRT system. Such programs were written in the 1970s at The Aerospace Corporation, IBM, Princeton University, Johns Hopkins Applied Physics Laboratory, the University of Minnesota, MBB in Germany, and elsewhere. Because the U. S. federal government stopped supporting work on High Capacity PRT in 1974, almost all of the early work stopped before the end of the 1970s. However, today computer speed and memory are enormously greater and cheaper, and software techniques have improved markedly. Superior network simulation programs are being developed and can be developed without need for reference to the past work, although knowledge of the past public-domain work will make the task much easier.

The objective of those of us who have worked to commercialize PRT is to see these systems widely built and used. What is needed could be very much like the National Advisory Committee for Aeronautics (now NASA), which was established by the U. S. Congress in 1916 to advance the science and technology of flight. NACA performed a huge amount of theoretical and experimental work on aeronautics and made the results freely available in a steady stream of reports. American aviation benefited enormously from that work.

For ground transportation there has been no similar initiative, and people everywhere suffer by experiencing increasing congestion, air pollution, accidents, and all of the other well-known problems of conventional transportation. Those of us who understand PRT know that it can, if carefully designed, produce enormous benefits for society everywhere. The requirements for PRT development today are money and expertise. With funds to hire the necessary talent and with the knowledge that exists, PRT can be reduced quite readily to common practice. With demand pull, which has begun through release of several requests for proposals and the decision of BAA to acquire a PRT system, competent firms can be expected to begin to design and manufacture PRT systems, operating systems will begin to appear, and engineering schools will begin offering courses on all aspects of PRT.

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Figure 8.