"How to Reduce Congestion"

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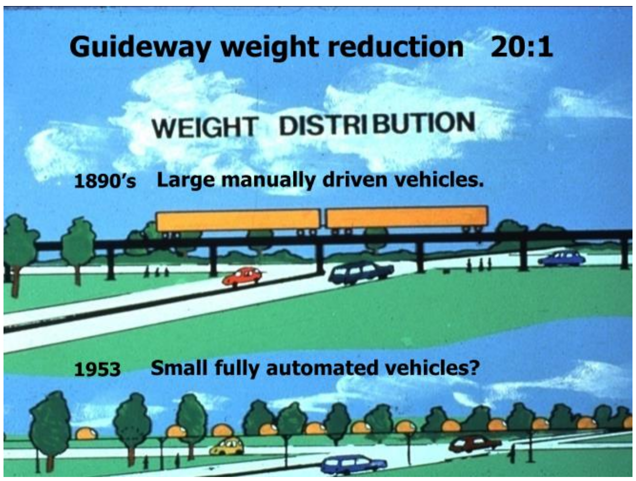
Virtually every week the newspapers contain articles about increasing congestion, often with suggested solutions – pathetically inadequate. More and more scenes like this exist and take hours to untangle.



Congestion is not new. In the 1890s, congestion got so bad in Boston, New York, Philadelphia, Cleveland, and Chicago that planners were directed to consider a new level – elevated or underground. As we know, they did both. Since underground is more expensive, they planned and built elevated rail systems, still at great expense, using the technology then available: Large, manually driven vehicles.

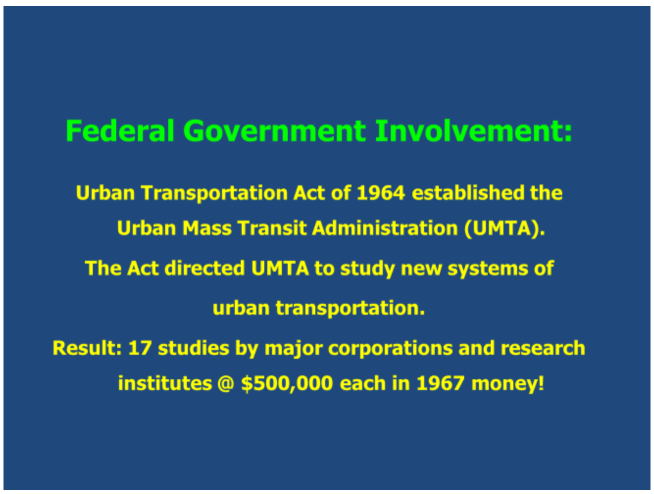
In 1953, two transportation engineers, Donn Fichter[1], working in Chicago, and Ed Haltom[2], working in a Dallas suburb, independently imagined that if the large vehicles would be replaced by many small, light-weight vehicles, the guideway size, weight and cost could be reduced by a factor upwards of 20:1. Automation had come out of World War II and they were convinced that it could control these vehicles. They understood that the vehicles could not be allowed to stop on line, but, to minimize trip time and maintain throughput, *stops would have to be off-line*, just like on a freeway! This combination of four ideas came to be called “Personal Transit” and later “Personal Rapid Transit” or “PRT.”[3]

[1] Donn Fichter, *Individualized Automatic Transit and the City,* Providence, 1964.

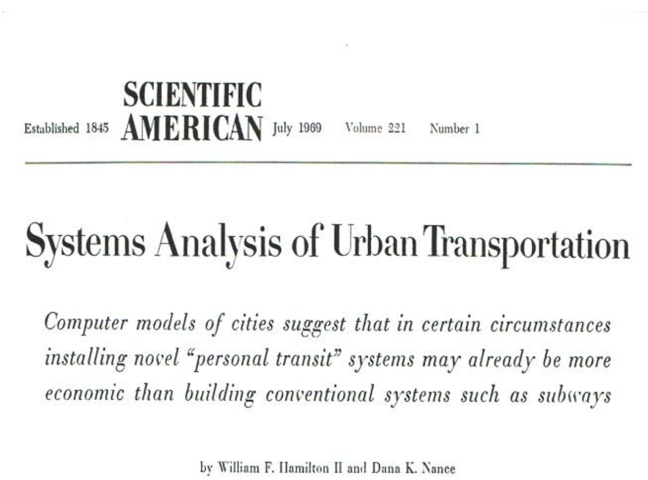
[2] Monocab, Incorporated, p. 86-7, *Personal Rapid Transit II*, University of Minnesota, December 1973.

[3] Today, planners call it an “Automated Transportation Network,” ATN.

Autonomous cars are much in the news. Some people argue that they will replace PRT, but will they? With the considerations given here, they will be complementary. In a mix of manually driven and autonomous cars, with the autonomous cars programmed to maintain a safe separation, a manually driven car will invariably slip in between, thus requiring the rear car to slow down and thus the cars behind to brake, thus increasing congestion. PRT is for congested roads where there is no room for a bus or a train, and where autonomous cars will get bogged down with the rest of the traffic.



In addition to Fichter and Haltom, during the late 1950s and early 1960s at least four other transportation thinkers independently invented, or is it better to say "discovered" the concept now called PRT?[4] Some of them talked to Congressmen, because of which, when the Urban Transportation Act was passed in 1964 funds were authorized to study the new ideas.



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Systems Analysis of Urban Transportation

Computer models of cities suggest that in certain circumstances installing novel "personal transit" systems may already be more economic than building conventional systems such as subways

by William F. Hamilton II and Dana K. Nance

In *Scientific American* for July 1969, the work of one of those companies, the General Research Corporation of Santa Barbara, California, was summarized. GRC, with experience in defense and space research, performed a comprehensive systems analysis of urban transportation problems and their solutions using mainframe computers and involving an interdisciplinary team of 18 professionals. As their basis, they laid out PRT guideways in Boston, Houston, Hartford and Tucson, and estimated ridership.

[4] and recently "Automated Transportation Network", ATN!

In general, the results of our analysis made clear that, even with the most optimistic view of what might be achieved through improvement of the existing methods of transportation, such improvement could not satisfy the real needs of our cities in terms of service.

I went to the *Scientific American* website and found that for $8 I could download the July 1969 issue. In the article entitled "Systems Analysis of Urban Transportation," I found this statement by the GRC team.

On the other hand, our tests of the new-technology approach, particularly the personal-transit type of system, showed that it could provide really dramatic improvements in service. The personal-transit system would offer city dwellers a degree of convenience that is not now available even to those who drive their own cars. The city and its suburbs could be linked together in a way that would bring new freedoms and amenities to urban living—for the ghetto dweller now trapped in the city's deteriorating core as well as for the automobile-enslaved suburban housewife.

Near the end of the article, I found this statement.

In 1968, UMTA summarized all 17 studies in a report called *Tomorrow's Transportation: New Systems for the Urban Future*, in which, among other systems, they described PRT and urged its development.

Why Off-Line Stations ?

They Permit:

- **At least freeway-lane Throughput with**
- **Small vehicles, and therefore**
- **Small, low-cost guideways.**

Result: Adequate Capacity and Minimum System Cost!

They Permit:

- **Nonstop trips and**
- **Minimum trip time.**

Result: High Ridership – Reduced Congestion!

But, won't the variable-friction problems of autonomous cars still occur?

Not with frictionless braking provided, we will see, by direct electromagnetic interaction between vehicle and guideway.

- Computers in PRT systems reroute empty vehicles from stations where they are in excess to stations needing them or in or out of storage stations, and the vehicles run only when there are demands for service; whereas in conventional transit, in which the stations are on line, the vehicles must run on a schedule regardless of the need to pick up or drop off passengers. *Off-line stations permit a very substantial decrease in operating cost and energy use.*

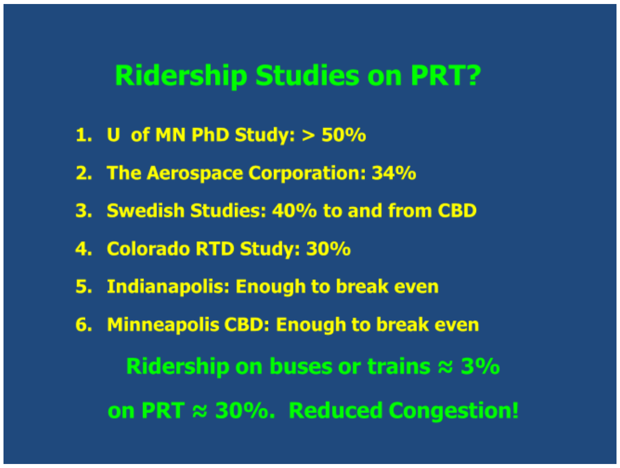
- Since computers reroute vehicles between stations 24/7, service is always available. In off-peak periods, there will always be at least one vehicle waiting in every station. In peak periods, computer simulations show that the average wait is about one minute. There is no need to shut down because vehicles do not move unless there is a demand for service.

- With off-line stations and small vehicles, the stations can be sized to demand. Some stations may need only two or three loading berths and others up to 15 to 20. With on-line stations, every station must be as long as the longest train because a person could wish to get on or off at any point. With off-line stations and small untrained vehicles, station cost is saved!

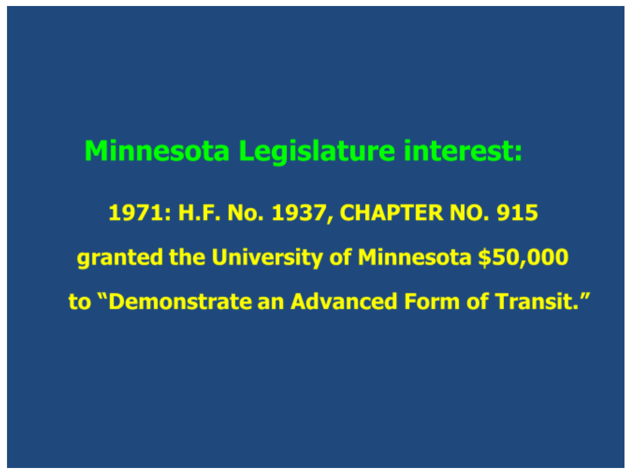
- In planning the light-rail line in St. Paul, Minnesota, the planners initially intended to place stations a mile apart to permit an average speed of about 27 mph. But, when announced, citizens demanded that the stations be placed every half mile, which reduces the average speed at most to about 19 mph, *which substantially reduces RIDERSHIP*. With conventional transit, speed must be sacrificed for access or access for speed. With off-line stations, the system has both speed and access.

- With nonstop trips, the wait time for a random passenger to join a passenger already in a vehicle increases as the square of the number of stations,[5] and after a few stations is too long to be of interest. Thus, if a person is alone, he or she rides alone, and otherwise with one's own travelling companions.

[5] J. E. Anderson, *Transit Systems Theory,* p. 89. www.advancedtransit.org/library/books.



These ridership studies show that in a developed PRT system roughly a third of the trips in an urban area will be taken by PRT. In the latter two studies, a mode-split calculation was not made, but the ridership was sufficient for these systems to break even. Except in rare situations, in conventional rail systems ridership is so low that fare revenue pays only about one third of the operating costs and none of the capital cost. The rest must be covered by taxes.[6] If the Federal Government did not contribute to these costs, these systems would not be built.



The University of Minnesota's Center for Urban and Regional Affairs was given the task of responding to the Legislature. I was given the task of coordinating the work of the Task Force. We visited all sites in the USA at which PRT systems were being developed, some with full-scale test tracks.

We found that by far the most promising PRT system was designed at The Aerospace Corporation[7] by a team of systems engineers working under the direction of genius Vice President Dr. Jack H. Irving.

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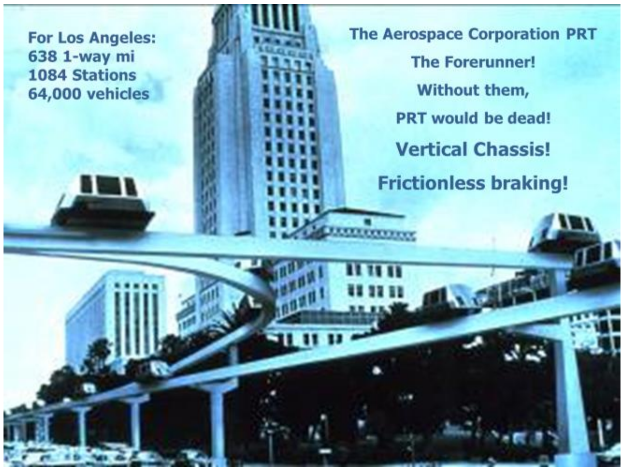
[6] J. E. Anderson, *Transit Systems Theory,* Chapter 6. www.advancedtransit.org/library/books.

[7] www.aerospace.org



Here is a photomontage of The Aerospace Corporation PRT system.[8] They laid out a large system for Los Angeles, with the properties given in the upper left corner of this picture. A unique feature of this system is that the guideway is narrower than the vehicles. This resulted from their finding that *the minimum weight, minimum cost guideway is narrower than the vehicles*.[9] This finding required the development of a **vertical chassis** and gives minimum visual impact. This system used linear pulsed D.C. motors, which provided consistent **frictionless braking.**

Minnesota Senate:
1973: Hearings & Field Trips.
1974: S. F. No. 2703, CHAPTER No. 57:
The Metropolitan Transit Commission (MTC),
an Operating Agency(No R&D), shall "plan an automated, small-vehicle, fixed-guideway system."
MTC had Lobbied against new Technology.
Two proposals: Aerospace & consultant.

The Minnesota Senate formed a Transit Subcommittee, which held hearings at which the Metropolitan Transit Commission (MTC), the Metropolitan Council, and the University Task Force were each asked to answer the same questions. Field trips followed, during which the Subcommittee visited several automated-transit development groups including The Aerospace Corporation at their headquarters in El Segundo, California. Subsequently, the Act defined here was developed and signed into Law by the Governor of Minnesota.

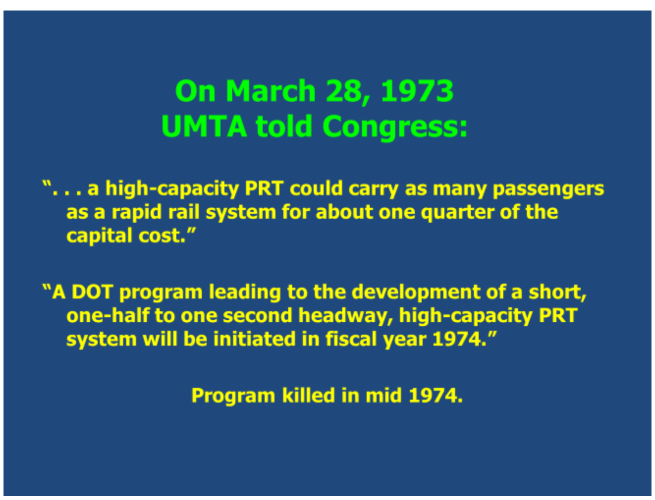
Now I must back up. In the late 1960's the Industrial Engineering Department of the University of West Virginia in Morgantown engaged a consultant, funded by UMTA, to investigate PRT as a means for moving students between campuses of the University of West Virginia. The small town of Morgantown is situated in a mountain valley with almost all the traffic of the city funneled along one U. S. highway. Thus, congestion is as bad as it is in much larger cities. The consultant recommended the Alden StaRRcar, which was being developed in Bedford, Massachusetts, as the PRT system they concluded should be deployed.

[8] Jack H. Irving, Harry Bernstein, C. L. Olson, Jon Buyan, *Fundamentals of Personal Rapid Transit,* 1978.

[9] J. E. Anderson, *Transit Systems Theory,* 1978, Section 10.2, "Optimum Cross Section Based on Bending Stress." Further analysis of the Aerospace guideway shows that once the depth is determined and with it the width required for motors, without increasing the width any further the guideway is sound in a 180-mph crosswind, far more than cities specify.

UMTA's report *Tomorrow's Transportation* stated: "A premature rush to demonstrate certain of the new systems and components in urban areas would be uneconomic and wasteful pending further research and development." *But that is exactly what they did*: The Secretary of Transportation determined to use Morgantown as the basis for a national demonstration of the PRT concept. UMTA staff visited Alden StaRRcar at their facility in Bedford and found that it was a group of only six people, much too small, they decided, to be the basis for a national demonstration. Therefore, UMTA engaged the Jet Propulsion Laboratory as the system contractor, Boeing the vehicle designer and builder, Bendix the control engineer, and F. R. Harris the fixed-facility designer and builder. The contracts were let in December 1970 and political UMTA determined that the system had to be in operation by October 1972 in time to help reelect President Nixon. None of these companies had any experience with PRT. JPL soon realized that they were being used only as a "money-pass-through" with no time or budget for the systems engineering in which they excelled. Thus, in August 1971 JPL resigned from the program and Boeing was given the job of project manager. The Alden StaRRcar was a six-passenger vehicle. The UMTA Administrator decided, based on no understanding of the PRT concept, that that was too small and ordered that the vehicles have room for 8 seated passengers and 13 standees, resulting in a substantial increase in vehicle weight and size. An F. R. Harris Vice President asked UMTA what vehicle weight they should assume as the guideway design load. He was told to assume the vehicles would weigh as much as rapid-rail vehicles, whereas the basic idea of PRT is to use vehicles small enough and light enough to minimize the weight of the guideway. This and other decisions increased system cost so much that Congress lost interest in PRT.[10]

Notwithstanding the substantial knowledge The Aerospace Corporation had developed in PRT and the very detailed proposal they submitted to the MTC, the MTC selected a consultant that had no experience with PRT. That consultant was aware of the Morgantown program, in which the system was called "PRT." They laid out guideways for the Twin Cities based on Morgantown "PRT," producing the obvious result that for Minnesota, "PRT" was declared too expensive and not worth considering.

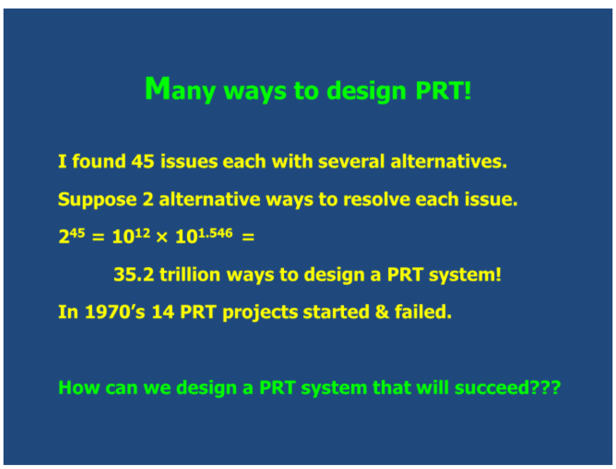


In 1971, the Office of Science and Technology in the Executive Office of the President got interested in PRT after hearing presentations by Dr. Jack Irving and me. The result was that in the January 1972 State of the Union Message, published on the front page of the January 21, 1972 issue of the *New York Times*, President Nixon announced a program of new technology initiatives, the lead of which was "*the development of a system of small vehicles running at close spacings in a network of guideways to carry people nonstop from origin to destination in cities.*" After much negotiation, and notwithstanding the Morgantown program, UMTA announced the program given in this slide. By mid-1974, heavy lobbying killed it. It was lobbied to death by two groups:

[10] Years later, an Alden StaRRcar Vice President told me that an UMTA engineer told him that they were going to design the Morgantown system in such a way that it would kill the idea of PRT once and for all – non-R&D people in this part of UMTA!

Transit operators and companies developing automated transit systems that would lose their market share if high-capacity PRT were to be developed.

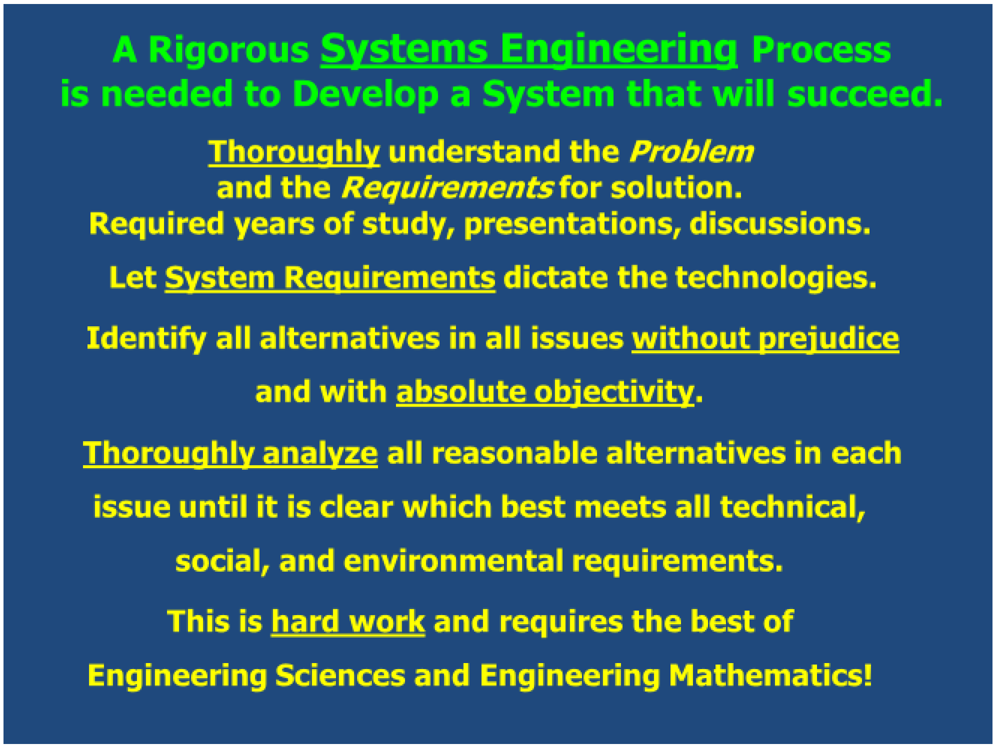
Conference Proceedings.[11]

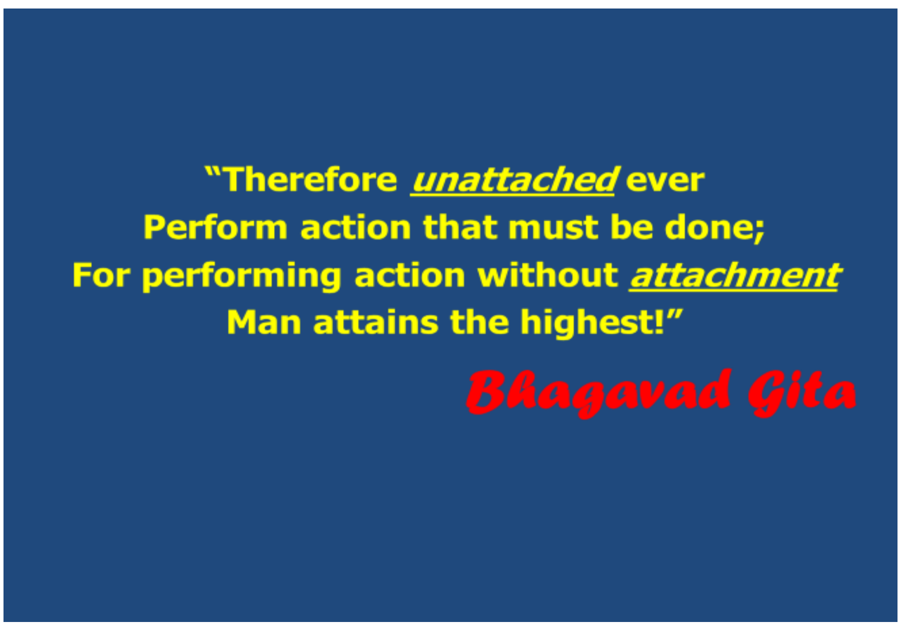


I initiated my PRT design project in 1981 in the only way I could – as a senior mechanical-engineering design project. Having by that time 13 years of experience in PRT, feedback from hundreds of presentations given in the US and abroad, under no serious time pressure, and aware of 14 PRT projects that no longer existed, I resolved to apply systems-engineering principles to the design of a PRT system that could win.[12] I followed rigorously the procedure shown on the next two slides.

[11] Conference Proceedings: *PRT, PRT II, PRT III*, Published at the University of Minnesota, 1972, 1974, 1976.

[12] The 45 issues are given in http://faculty.washington.edu/jbs/itrans/jea2.gif





I particularly like this statement from the Bhagavad Gita, written over 2500 years ago, because the word "unattached" sums the idea that in the design process we must follow the *requirements*[13] objectively and without prejudice, not pet ideas about how things should be done. Every PRT system that was designed to someone's pet ideas failed![14]

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[13] Requirements, CDPRT pages 126-130,

[14] Rules of Engineering Design, CDPRT pages 89-91.

The Design Advances

`82: $100,000 Patent-Development Grant.

`83: Company formed, Directors invest $120,000.

`84 – `85: Davy McKee Engineering Company invests $700,000 in services to refine the design, find suppliers, prepare proposals.

`86: I move to Boston University.

`87-`89: Engineers from Raytheon, U.S. DOT, General Electric assist on free time in advancing the design and working with potential applications.

Illinois Legislative Act of late 80's established the Regional Transportation Authority (RTA),

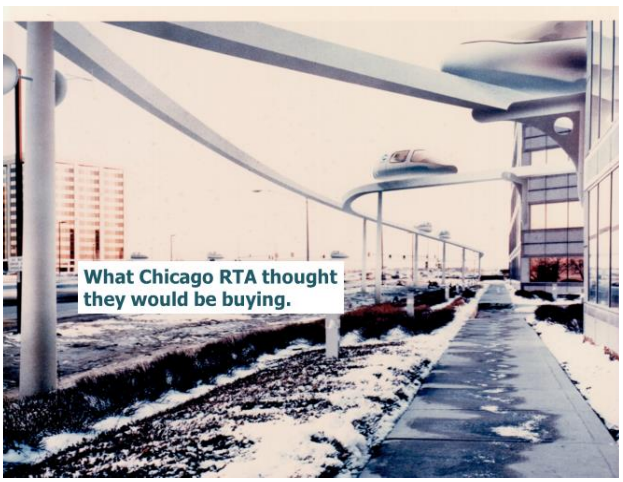
directed that the RTA shall "encourage experimentation in developing new public transportation technology."

`89: We met the RTA Chairman – he went to work!

`90: RTA Requests Proposals for 2 parallel PRT design studies @$1.5 M each to lead to a test program.

`91: Our system selected w/ Stone & Webster prime.

`93: Our system selected for test program, w/ Raytheon prime!

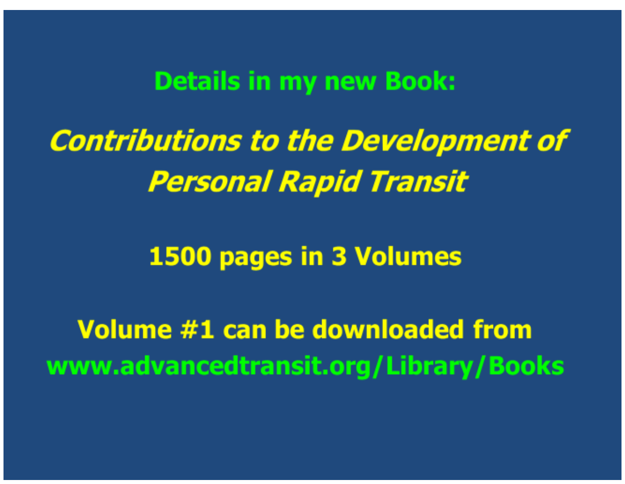


In 1991, our $1.5M PRT study for the RTA was initiated with Stone & Webster Engineering Company as prime contractor. The illustration shown here was developed by RTA staff and was shown in several of their publications. It clearly shows the narrow-guideway design that I had adopted from The Aerospace Corporation PRT work.

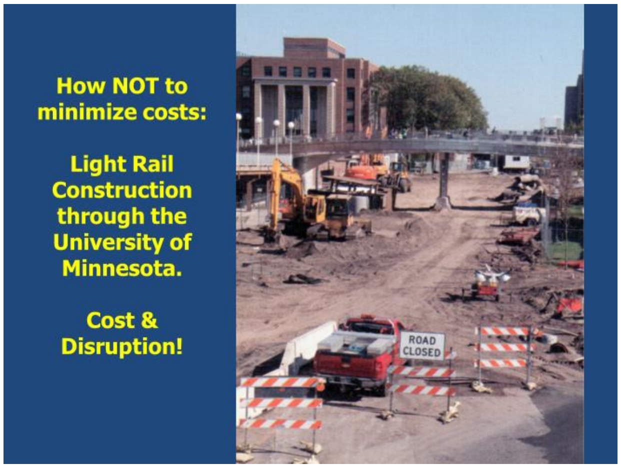
Stone & Webster could not supply the $20M needed to match the same amount from the RTA for the test-track program. Raytheon Company stepped in and agreed to match the funds provided by the RTA needed to design, construct, and operate a test system consisting of a third-mile guideway, one station and three vehicles. New management came in, locked all prior work in a file drawer, and decided that they could come up with a better design in a year using their radar engineers. In such a rush and with no prior experience in PRT they more than doubled the guideway width and depth, and quadrupled both the weight of the vehicle and the system cost developed under Stone & Webster. The result was that the RTA dropped the program and said no more about PRT. **A tragedy!** Publicity about the RTA program, however, caused other groups to initiate PRT planning and development work.

One of the new PRT design groups was Woo Bo Engineering Company of Seoul, Korea. I worked with them and they developed the video introduced here, which in the presentation is a movie of the operation of a PRT system visually like the system I had designed.

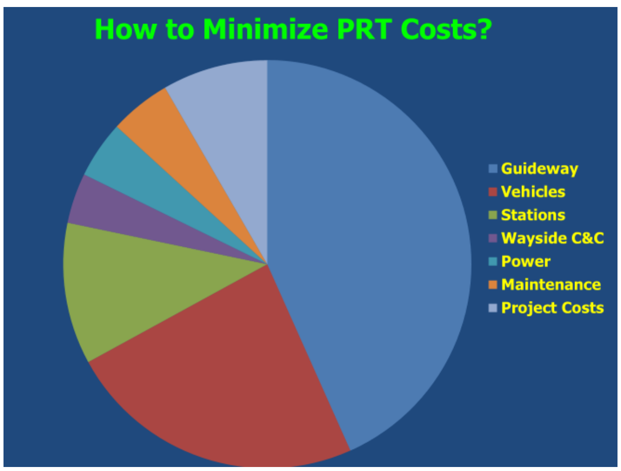
I have mentioned that I found 45 issues that needed to be considered, of which the 10 most important are shown here. Each of the issues has been subjected to a detailed tradeoff analysis, which has resulted in selection of the alternatives shown in white. The reasons for the selections made in these issues can be found in papers included in Volume 1 of my book, which is announced in the next slide.



In Volume 1 of my book (CDPRT), pp. 131-207, you can find analyses of the first 10 key issues in sufficient detail to justify the selections.



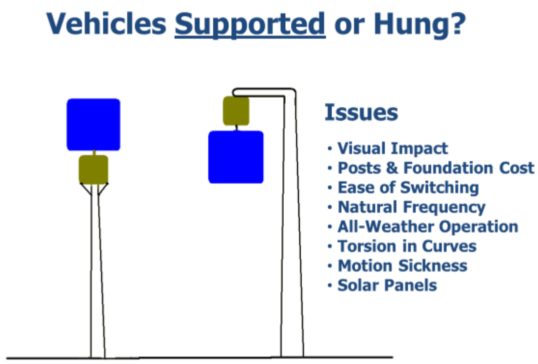
In contrast, I show here the University Avenue light-rail system under construction through the University of Minnesota. Such scenes could be witnessed along the entire 10-mile length of this system, where construction resulted in many businesses being forced out of business. This is exactly what we do **not** want to do.



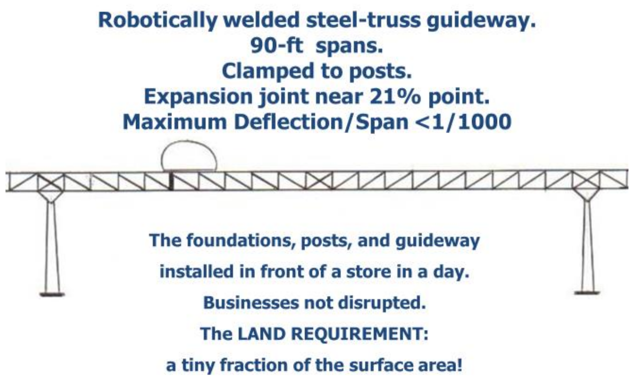
Here is the cost distribution of our system, showing with no surprise that the guideway, being the most expensive component, deserves primary attention.[15] Years before, I found in a surprising number of PRT development programs that the guideway design was usually taken as an afterthought.

We have already commented that the minimum weight, minimum cost guideway is narrower than the vehicle, thus requiring a unique vertical chassis, as first recommended by The Aerospace Corporation.[16]

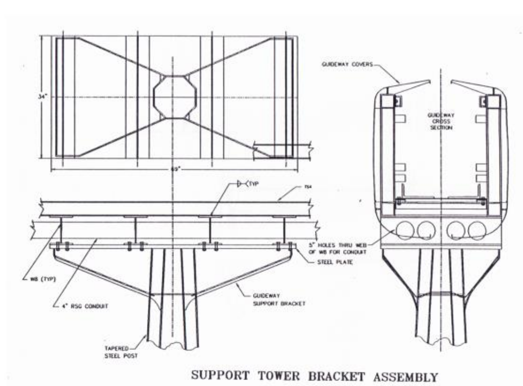
[15] Costs, CDPRT, pages 559-623.
[16] Guideway Design, CDPRT, Task 5, pages 848-1122.



Do we support the vehicles above the guideway or do we hang them below? All-weather operation is a key requirement. With the vertical chassis, we cover the guideway shown on page 16 for nine reasons, which include minimization of penetration of snow. In Volume I of my book, just mentioned, I provide analyses of each of the issues listed on this slide, and show why it is better to support rather than hang the vehicles.[17]



The most economical way to span a distance is with a truss. In a first course in structural analysis the student learns that if the supports of a beam are unconstrained, the maximum deflection under a uniform load is five times as much as if the supports are clamped. This idea was used in the Aerospace PRT design. As shown here and in the next slide, we therefore use a bracket to clamp the guideway to each post. This practice also substantially increases torsional stiffness. In a clamped beam under uniform load, the bending moment is zero near the 21% point. If the necessary expansion joint is placed there, it takes mostly shear and very little bending, which simplifies the design.

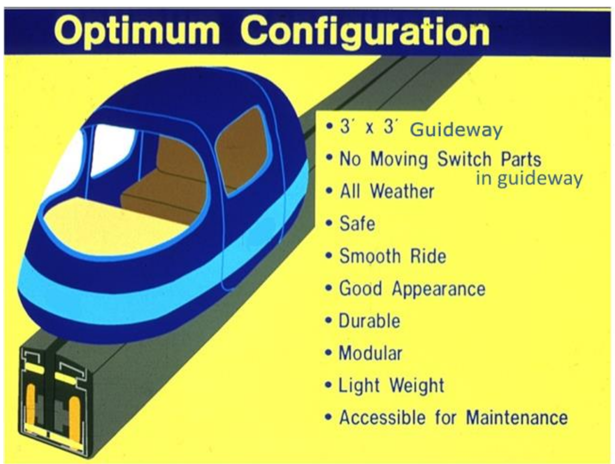


Here is the bracket that was designed during our PRT design study to connect the guideway to the post. It will be subject to detailed finite-element analysis before being released to production.

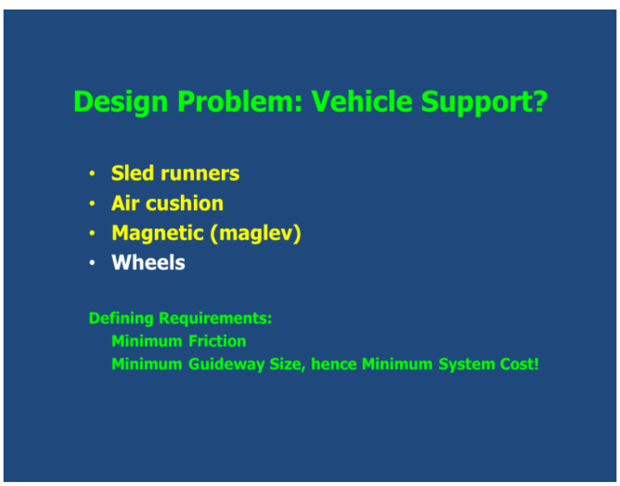
[17] Analyses of Alternatives, CDPRT, pages 131-207.

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

After the Stone & Webster work on our guideway, we developed a complete analytical analysis of the guideway in both straight and curved sections.[18]

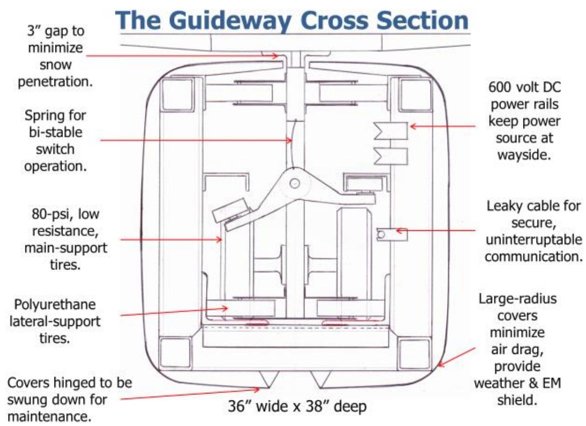


We show here what we found to be the optimum guideway-vehicle configuration with the ten most important requirements. The top requirement is guideway size, and we have shown how we minimize it.



The next design problem is vehicle suspension. Several PRT designers have supported their vehicles on air-cushions. This requires a wide and thus more expensive guideway with greater visual impact. Several companies have used maglev support, mostly because of the attraction of doing something futuristic. But for urban speeds these programs rarely got out of R&D and ended with a guideway wider and more expensive than needed. Wheel support allows the most concentrated loads and thus the narrowest, least expensive guideway.

[18] J. E. Anderson, Structural Properties of the Guideway. CDPRT pages 936-962.
J. E. Anderson, The Polar Moment of Inertia of the Guideway. CDPRT pages 1043-1053.
J. E. Anderson, Deflection of a Curved Guideway. CDPRT pages 1025-1042.



Here is our guideway cross section. Note the narrow vertical chassis. It need be only 2 inches wide and will be fabricated from high-strength steel.[19] The main-support wheels use low-friction, high-pressure tires and run on smooth steel angles with no chuckholes or curbs to run over. Polyurethane-tired wheels provide lateral support. The switch is an arm with a polyurethane-tired wheel on each end, one of which grabs a rail mounted in the merge and diverge sections of the guideway. The guideway cover is made of a thin composite material with aluminum sprayed on the inside to provide electromagnetic shielding. By using a curve radius at the top and bottom of the cover at least one sixth the height of the cover, the drag coefficient to lateral wind loading is only a little more than 0.5, whereas without the covers the drag coefficient goes to 2.[20] Thus the covers reduce the lateral wind loading by a factor of almost four.[21]

Here is an artist's conception of the system without the necessary guideway-post brackets. The covers satisfy nine requirements:

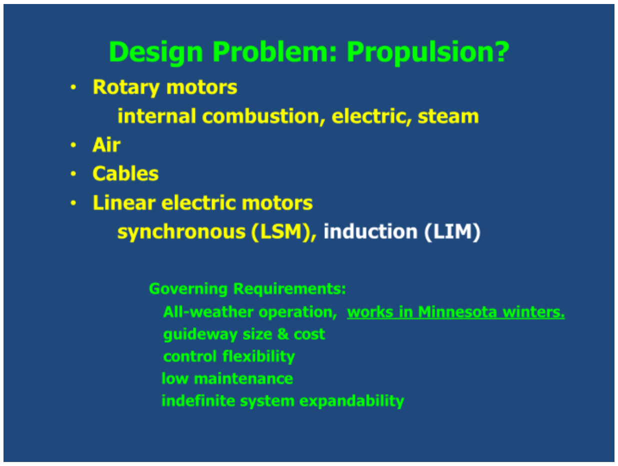
1. They shield the tires from the sun.
2. They provide EM shielding.
3. Without covers, frost would form on the guideway interior on clear winter nights.
4. Very little snow and ice can enter the 3 in gap at the top, and the bottom is opened 6 in.
5. Air drag has been mentioned.
6. A sound-deadening material can be sprayed on the inside of the cover.
7. Without the covers, sun shining on one side will heat the steel guideway more than the other side, thus producing differential stresses that the covers eliminate.
8. If necessary, though rarely, the covers can be swung down for maintenance.
9. The covers can be textured and colored to suit the community.

A Chicago sculptor referred to our system with the statement given at the bottom of the slide.

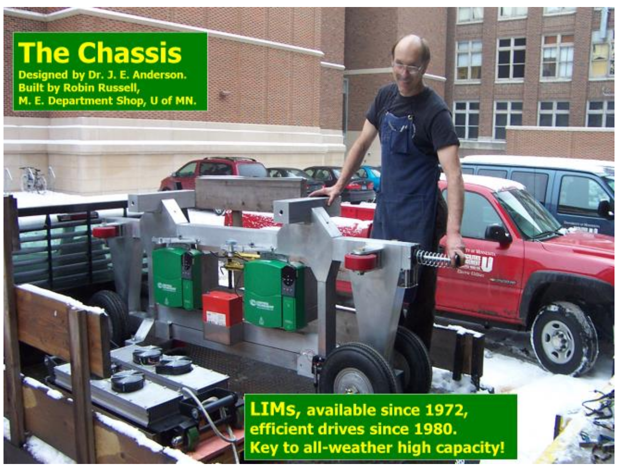
[19] Steel has a fatigue limit while aluminum does not. J. E. Shigley and C. R. Mischke, *Mechanical Engineering Design,* p. 275.

[20] Scraton, C. and Rogers, E. W. E. 1971. Steady and Unsteady Wind Loading. *Phil. Trans. Roy. Soc.* London a. 269:353-379.

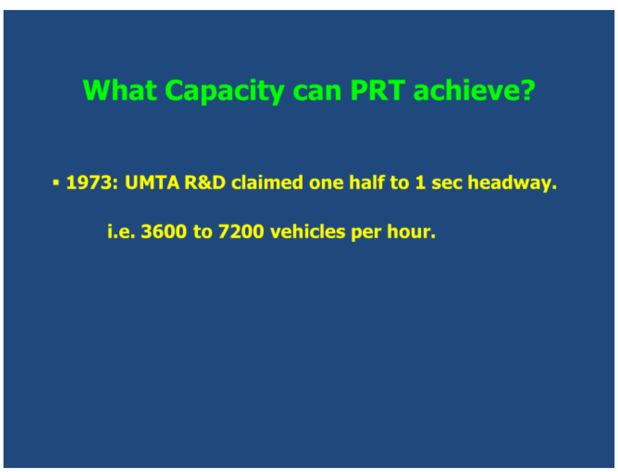
[21] Guideway Covers, CDPRT, Task 6, pages 1224-1229.



There are many ways to propel PRT vehicles. Most PRT designers selected rotary electric motors with acceleration and braking forces dependent on friction. Two PRT designers used air propulsion, which is very noisy. Cables are practical when the vehicles go only forward and backward on a single section of guideway. Linear synchronous motors are used on very high speed systems and simply don't work at the short headways we need. LIMs provide frictionless operation. They are well developed and provide consistent acceleration and braking in any weather, which is essential for short-headway operation.[22]

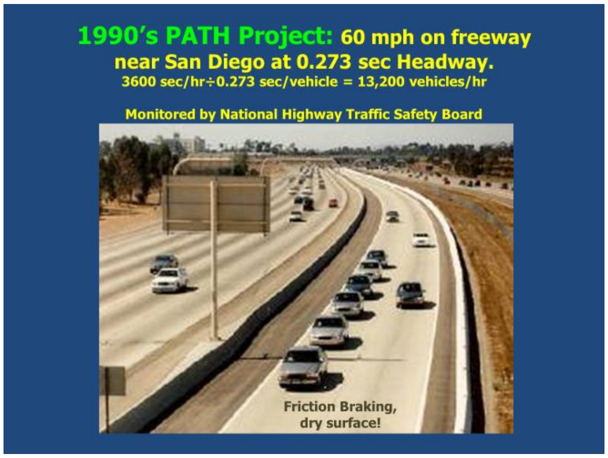


Here is the vertical chassis[23] I designed with the man who built it. It supported the vehicle's cabin 12 hours a day for the 12 days of the Minnesota State Fair with no failures. The LIMs are in the lower left corner not yet installed. Each green box is a variable-frequency drive that drives one of the two motors.[24] To maximize efficiency of LIMs, variable frequency is essential.[25] Note the vertical shear plates that support the bracket attachments to the vehicle's cabin. These brackets have passed careful finite-element analysis. The red box is a battery that provides power for on-board functions.



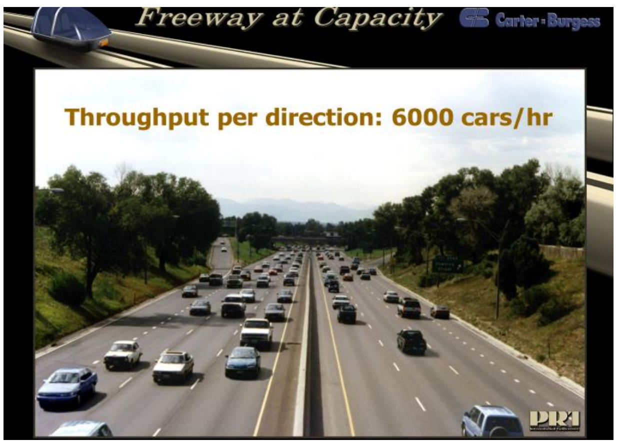
As mentioned on page 8, over 40 years ago UMTA engineers advised their Administrator that they could operate vehicles safely at half-second headways, which implies at most 7200 vehicles per hour.[26] This conclusion assumed use of linear electromagnetic motors. Using propulsion and braking through wheels, operating headway is limited to 6 sec[27] or 1800 vehicles per hour.

[22] Propulsion, CDPRT, Task 8, pages 1455-1482.
[23] Chassis, CDPRT, Task 4, pages 720-847.
[24] www.emerson.com. Variable-frequency drives were not available until about 1980 – too late for Aerospace PRT.
[25] Properties of a Linear Induction Motor, CDPRT, Vol. 3, pages 1473-1482.
[26] Capacity, CDPRT pages 489-517.
[27] Automated Transit Network Feasibility Evaluation for San Josè Mineta International Airport, San Josè, CA. Aerospace Corporation Report No. ATR-2012(5629)-1, October 19, 2012, Page 76.



The PATH Project was funded by the U. S. Congress.[28] A series of 17-foot-long Buick LeSabres were operated at a nose-to-tail spacing of 7 ft at 60 mph, corresponding to a headway of 0.273 seconds, a headway believed to be safe in dry conditions. With our 9-foot-long vehicles and the same nose-to-tail spacing, we would achieve a headway of 0.182 sec or 19,800 vehicles per hour, and using LIMs <u>we can do it in winter conditions</u>. Since a freeway lane achieves about 2000 vehicles per hour, this corresponds to almost 10 freeway lanes of travel – far more than required in any but the most extreme situations.

6000 vehicles per hour is adequate for a wide variety of applications.



This sequence shows first a three-lane freeway (the 4th lane is an acceleration lane) operating at close to capacity. The second illustration shows the people in the cars, the third shows them moved to the center, and the 4th shows them in PRT vehicles. With LIM propulsion, our system easily handles that flow in the presence of snow and ice, and reduces the land requirement by a factor of 20:1!

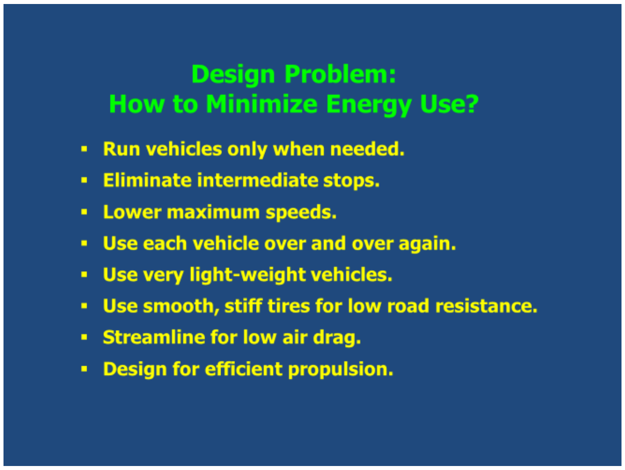
[28] PATH video, available upon request.

This illustration shows a major advantage of an elevated PRT system using a narrow guideway. The guideway can barely be seen from the air, yet using LIMs it can move many times the flow on the arterial streets below.

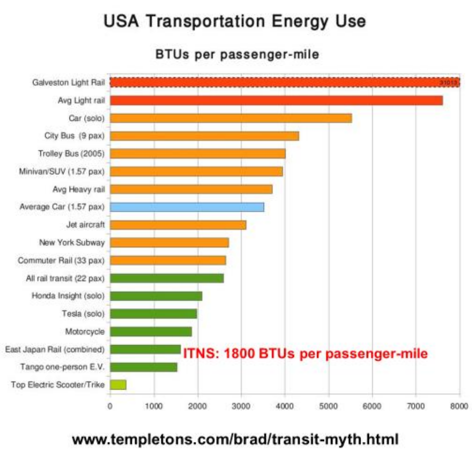
The land requirement for our elevated PRT system is tiny, whereas the automobile system requires a large fraction of the surface area of a city. This huge land use is the reason the automobile system produces **CONGESTION**.

ITNS,[29]

[29] CDPRT, pages 260-288.



Using off-line stations, our system agrees immediately with the first four of these recommendations. By proper design of the remaining four, one has a system that is as energy efficient as possible. [30]



Brad Templeton wondered how much energy various means of travel use per passenger-mile. He mined federal data to find out, and summarized his results on this chart. To his surprise light rail topped the list. Why? 1) Because of inherently low occupancy averaged over a day.[31] 2) Because, to maximize average speed and thus ridership, planners of surface-level rail systems like to place the stations at least a mile apart and accelerate the trains up to 60 mph between stations. A three-car train weighs empty about 330,000 lb. The peak kinetic energy of such a train, without passengers, is about 15 kW-hr and, because of finite efficiency, the input energy is several times as high. This amount of energy is added and then turned into heat every mile, i.e. approximately every 2 minutes. Assuming an efficiency of 30%, typical of power plants, this is 1500 kW-hr[32] for every operating hour.[33] Some of that energy can be recovered through regenerative braking, but because of finite efficiencies not much! With stations every half mile, the energy use per passenger-mile is even greater. With nonstop trips, attainable with off-line stations, it is not necessary to go to such a high maximum speed. On the same line, 35 mph will achieve a higher average speed. Moreover, every quantity that increases with speed increases as the square of speed and $(60/35)^2 = 2.94$.

[30] J. E. Anderson, Transit Energy Use, CDPRT pages 530-552.

[31] The Director of Transit Development for the MTC in the late 1970's told several of us that the daily average occupancy of their 60-passenger buses was only 2.5 people per vehicle – shockingly low! This is a load factor of only 2.5/60 = 4.2%

[32] The average U. S. household uses about 31 kW-hr per day.

[33] See the Appendix.

Design Problem:
How to Achieve High Reliability & Safety?

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

The features shown here are designed into ITNS. Checked Dual Duplex computers and fault-tolerant design are explained with the next slide.[34]

The Key to Safety

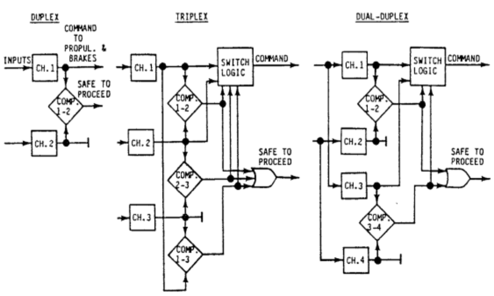


FIGURE 3: MICROPROCESSOR REDUNDANCY CONFIGURATIONS

This diagram was taken from a Boeing report on a study of automated transit for UMTA. On the left is a pair of identical microprocessor control systems, each capable of operating a vehicle. A safe-to-proceed signal is obtained when the two microprocessors agree on a schedule of between about 100 and 200 milliseconds. During that interval, a command to apply the brakes is given, which must be canceled by the safe-to-proceed signal. (This procedure is an example of fault-tolerance, and is used wherever possible.) If the two microprocessor control systems do not agree, the vehicle is commanded to stop. Not liking this result, both Boeing and Honeywell engineers considered triplex and dual-duplex configurations. In a Boeing paper, the selection of dual-duplex is explained.[35]

ITNS Mean Time Between Unsafe Failures

Source: "Failure Analysis in ITNS."

Type of Failure	MTBUF, years
On-Board Computer System	4(10)^20
Communications System	137,000
On-Board Encoder System	214,000
On-Board Propulsion System	700,000
Vehicle Incapable of moving	75,000
Pushing incidents w/ 1000 vehicles	75
Zone Controller	30(10)^18
Vehicle-to-vehicle Collision	10^12
Merge Collision	10^13
Lifetime of Universe	14(10)^9
Auto/ITNS Potential Accident Rate	20(10)^12

Based on the method of calculation given in Boeing reports, in the paper "Failure Analysis in ITNS"[36] I calculated the Mean Times Between Unsafe Failures shown here based on a microprocessor MTBF of 10,000 hours, which was achieved in the early 1980s. People often ask how often it might be necessary to push a vehicle. This analysis found that in a fleet of 1000 vehicles a pushing incident may occur in about once in a lifetime. In the bottom line, the auto accident rate taken from a federal report is divided by the reciprocal of the system MTBUF. We found a ratio of 20 trillion to one!

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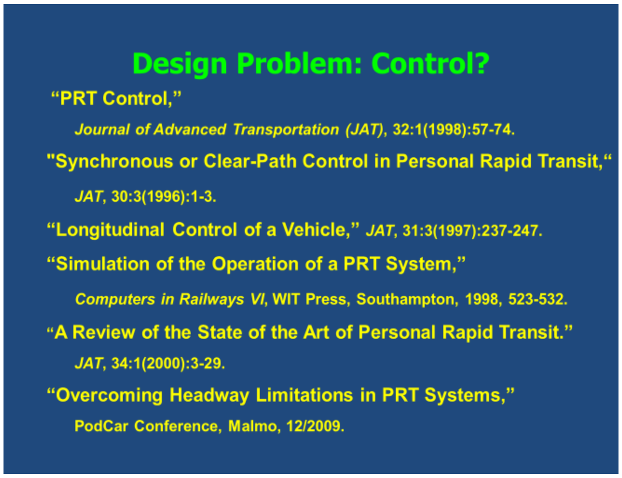
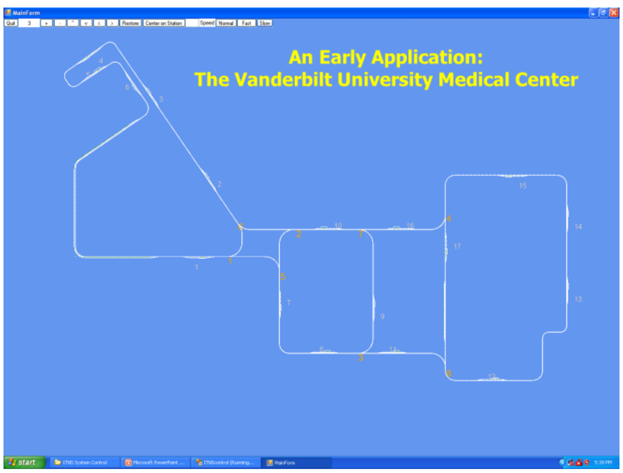
[34] Safety & Reliability, CDPRT, pages 624-681.

[35] R. C. Milnor & R. S. Washington, 1984. "Effects of System Architecture on Safety and Reliability of Multiple Microprocessor Control Systems," IEEE Conference Paper. Today, we do much better than in 1984.

[36] CDPRT, Vol. 2, pages 642-668.

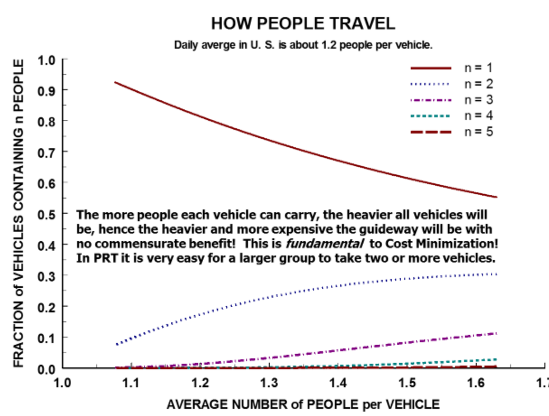


The ITNS control system is based on the papers shown here.[37] Control analysis has been performed by more analysts in more places than any other feature of ATN.[38] Four basic strategies for control have been studied: Synchronous, quasi-synchronous, asynchronous, and trans-synchronous. Asynchronous control has been analyzed with car following, whereas Aerospace Corporation developed quasi-synchronous with point following. Point following means that each vehicle follows a trajectory calculated in the vehicle computer. After extensive simulation work, I found that the best approach is asynchronous point following.



For many years, I have worked with transportation planners at the Vanderbilt Medical Center in Nashville, Tennessee. The area around the ITNS guideway layout shown here is the site of many medical facilities on streets too narrow for large regional buses. These planners would like to have the buses that pickup patients from many sites in Tennessee dropped off in a park in the upper left corner of this diagram, and from there take ITNS to the desired medical facility. They laid out this network and I have used it as a basis for refining the control system.

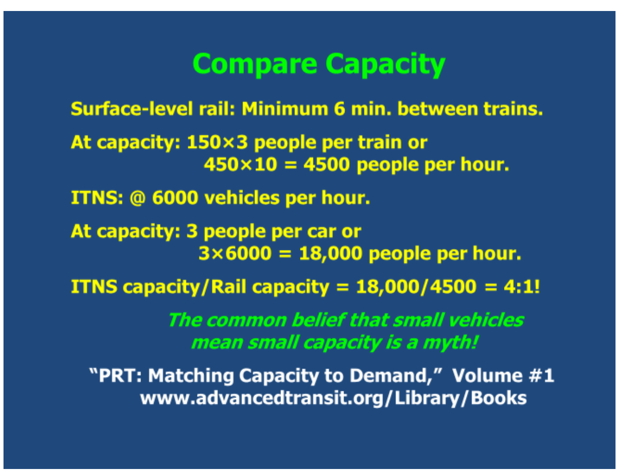
Cabin Design.[39]



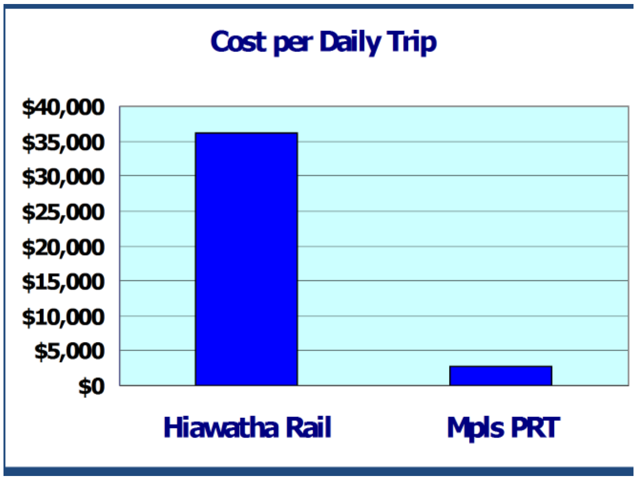
[37] Control, CDPRT, Task #7, pages 1230-1454.

[38] J. E. Anderson, "The Future of High-Capacity PRT," References, CDPRT, pages 231-233.

[39] Cabin Design, CDPRT, Task # 3, pages 682-719.



Metro Transit said that the Hiawatha Rail Line cost about $720,000,000 and carries about 20,000 riders a day, giving about $36,000 per daily trip. We laid out an 8-mile ATN system to serve Downtown Minneapolis and estimated its cost to be about $100,000,000. Since it has not been built yet, assume its cost is



$200,000,000. An independent consulting firm estimated ridership to be about 74,000 rides a day. Dividing 200,000 by 74 gives $2700 per daily trip, lower than the rail line by a factor of more than 13.

Revenue on ITNS can be from
Passenger movement +
Freight movement +
Focused Advertising.
Costs include Cost of Land.

Conventional Transit:
Revenue covers
30% of Operating Costs,
0% of Capital Costs.
ITNS:
In many applications,
Revenue will cover all Costs.

Verification of the costs and revenue of ITNS requires a detailed analysis of a specific system based on a layout like the one given above for the Vanderbilt Medical Center. Such an analysis can be based on our papers on PRT Network Economics.[40]

Results of Systems Engineering

	Conventional Surface Rail	ITNS	ITNS/Rail
Ridership	3%	30%	10/1
People/Hour	4500	18,000	4/1
Cost, $/Pass-mi	$2.05	$0.19	0.09/1
Energy Use, BTU/Pass-mi	7600	1800	0.24/1
Land Use, sq-ft/mile	60,720	2140	0.035/1

[40] CDPRT, Vol. 2, pages 559-607.

Summarizing our findings, we get the results shown on this slide.

We have studied all the types of applications shown here. For example, the Manager of Parks Operations Research at Disney World near Orlando, Florida, visited me when I was teaching at Boston University. He had heard a presentation of my work in Orlando, based on which he mentioned numerous applications of my system at Disney World. He had a long list of questions, the last of which was “Who will build it?” We did not have an answer at that time. They are still waiting.

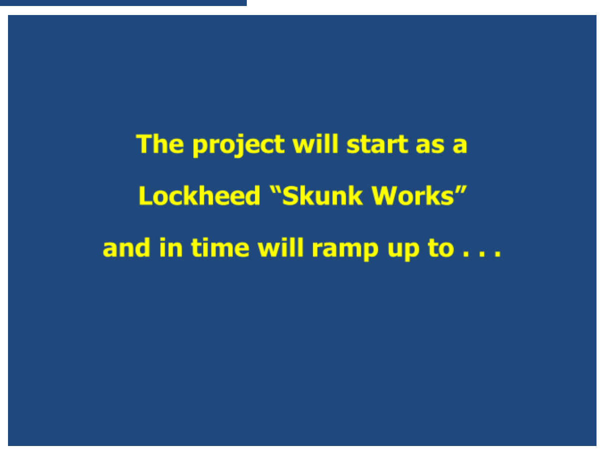
For an application to be profitable, it must be laid out carefully in an area of sufficient population density, and there must be enough riders, which must be estimated by a detailed ridership analysis.[41]

NEXT STEP:

[41] Planning, CDPRT pages 1510-1535.

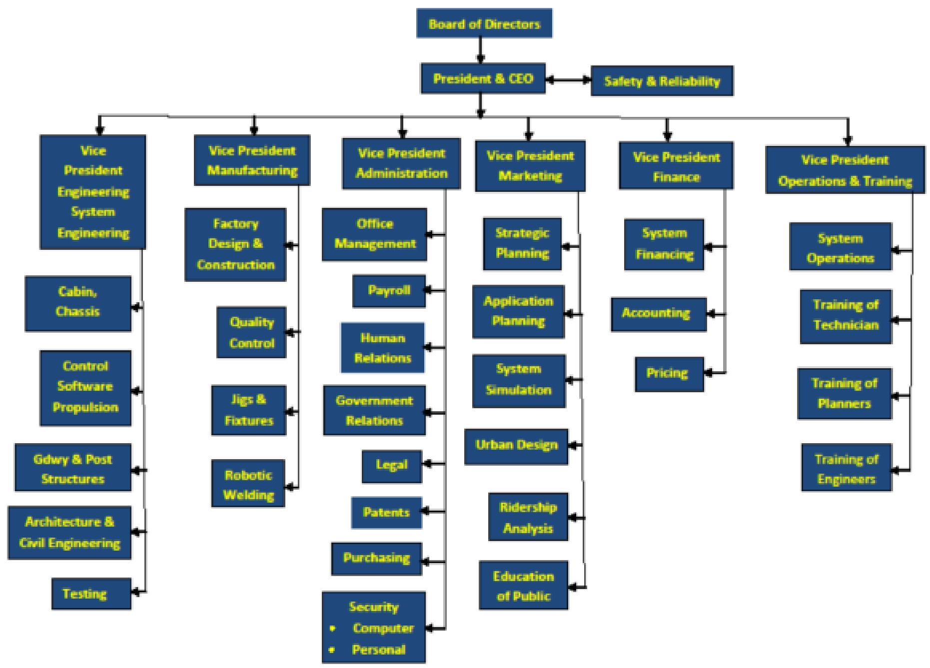
Test Program.[42]

Detailed information needed to define and direct each of these tasks can be found in our Business Plan, which is included in Volume 1 of *Contributions to the Development of Personal Rapid Transit.*[43]



[42] Test Program, CDPRT pages 1495-1509.

[43] CDPRT pages 333-417.



Market:

Requirement: No Controversy!

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

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

The Vision . . .

Hundreds of Applications like these:


Thanks to Chiphol Forward,
Amsterdam!

Appendix

Light-Rail Energy Use

W_t = 3-car Train Empty Weight, lb = 330,000 lb

W_p = Average person weight, lb = 140 lb

p_t = Average number of people in each train = 21.4[44]

C_{train} = Train capacity, people = 180(3) = 540 people

Load Factor = $\frac{p_t}{C_{train}} = \frac{21.4}{540} = 4.0\%$

V_{max} = Maximum speed of train, mph = 60 mph = 88 ft/sec

V_{ave} = Average speed of train, mph

g $= 32.2\ ft/sec^2$

A_{max} = Maximum acceleration of train, ft/sec^2 = $\frac{1}{8}g$

T_{tt} = Station-to-Station time, sec

T_{dwell} = Dwell time, sec = 20 sec

L_{sta} = Distance between stations, 1 mi = 5280 ft

L_{trip} = Trip distance, assume 4 mi

ϵ = Propulsion efficiency = 0.3

KE_{max} = Maximum kinetic energy of the train

1 kW-hr = 2.655(10)^6 ft-lb = 3412 Btu

$$KE_{max} = \frac{1}{2}\left(\frac{W}{g}\right)V^2$$

For this example, assume 3-car train:

$$W = W_t + p_t W_p = 330{,}000 + 21.4\times 140 = 333{,}000\ lb$$

$$V_{max} = 88 ft/sec$$

Then

$$KE_{max} = \frac{333{,}000}{64.4}(88)^2 = 40.04(10)^6\ ftlb \times \frac{1\ kWhr}{2.655\ (10)^6 ftlb} = \ 15.08\ kWhr$$

---

[44] To result in about 8000 Btu per passenger-mile.

$$L_{sta} = V_{max}\left(T_{tt} - T_{dwell} - \frac{V_{max}}{A_{max}}\right)$$

$$T_{tt} = \frac{L_{sta}}{V_{max}} + \frac{V_{max}}{A_{max}} + T_{dwell}$$

For this example, assume

$$T_{tt} = \frac{5280\,ft}{88\,ft/sec} + \frac{88\,ft/sec}{0.125g} + 20\,sec = 101.86\,sec = 1.698\,min$$

$$Stops\ per\ hour = \frac{60\,min/hr}{1.698\,min/stop} = 35.34$$

$$Energy\ Input\ per\ hour\ per\ train = \frac{KE_{max}}{\epsilon} \times Stops\ per\ hour = \frac{15.08\,kWhr}{0.3}\times 32.34$$
$$= 1626\,kWhr/hr$$

$$Average\ speed\ of\ train = V_{ave} = \frac{L_{sta}}{T_{tt}} = \frac{1\,mi}{1.698\,min}\times\frac{60\,min}{1hr} = 35.34\,mph$$

$$Trip\ Time = \frac{L_{trip}}{V_{ave}} = \frac{4mi}{32.34\,mph}\times 60\frac{min}{hr} = 7.421\,min$$

$$Energy\ input\ per\ trip\ per\ train = \frac{1626\,kWhr}{hr}\times\frac{7.421}{60} = 201\,kWhr$$

$$Energy\ per\ passenger - mi = \frac{201\,kWhr}{(p_t\ passengers)(4\,mi)} = \frac{201}{21.4\times 4} = 2.348\,kWhr\times 3412\frac{Btu}{kWhr}$$
$$= 8012\frac{Btu}{PassMi}$$

Note that with 21.4 people per train, or a load factor of only 21.4/540 = 4.0%, the energy use per passenger-mile is about the same as the energy use of 8000 Btu per passenger-mile given by Brad Templeton for the Galveston LRT system. This load factor is slightly lower than given by Reference 31 for the Twin City bus system. In any case, these numbers reflect the huge inefficiency of transit operations with on-line stations. With off-line stations, the average load factor is about 20% − five times higher! Why is it so difficult to switch to off-line stations, minimum-sized vehicles, minimum-sized elevated guideways, and automated control? These technologies are easily available, and extremely reliable. Tradition has dominated, even at great expense!