HOW to DESIGN a PRT GUIDEWAY

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Abstract

The guideway is the most expensive item in a PRT system. Yet in all but a few cases the design of the guideway was more or less an afterthought – something that did not require a great deal of attention. This is a major reason many PRT systems have not survived. Primary attention had to be placed on the development and design of the control system because it was the single technological advance that made consideration of PRT possible. With limited resources, control downgraded the importance of everything else about a PRT system. During the long history of PRT development and design, guideways have been designed for Veyar, Monocab, TTI, StaRRcar, Uniflo, Dashaveyor, Morgantown, The Aerospace Corporation PRT System, Cabintaxi, CVS, Aramis, ELAN-SIG, VEC, Swede Track, Mitchell, SkyCab, Taxi 2000, PRT 2000, Microrail, Skytran, MonicPRT, ULTra, Vectus, and others. This plethora of designs likely has had much to do with the reluctance of city planners to recommend PRT. No two of these guideway designs are very close to each other. Now that the control problem is well understood, it is time to turn more attention to the guideway. The purpose of this paper is to stress the importance of adequate consideration of guideway design requirements and criteria as the basis for the design of guideways that have the potential of becoming standardized and widely deployed.

Introduction

As an engineering professor working on PRT for 13 years with no commitment to any particular system, I was privileged to visit the inventors and developers of Veyar, Monocab, TTI, StaRRcar, Uniflo, Dashaveyor, Morgantown, The Aerospace Corporation PRT System, Cabintaxi, CVS, Aramis, ELAN-SIG, VEC, Swede Track, Mitchell as well as other AGT systems then under development including Westinghouse Skybus, Jetrail, Airtrans, Ford-ACT, UTDC, Universal Mobility, H-Bahn, Krauss-Maffei, VAL, and AGRT. Later I developed Taxi 2000 and watched in dismay as it degraded into PRT 2000, mainly because guideway design was not taken seriously. Later I learned of Austran, Cybertran, SkyCab, Microrail, Skytran, MonicPRT, ULTra, and Vectus. Now there are many more offerings than I can name. Some of these systems were on paper only, some were built as test tracks, and some were built as applications, but they all provided opportunities to become aware of the variety of guideway designs.

At the University of Minnesota early in my work on PRT I coordinated a Task Force on New Concepts in Urban Transportation. We conducted planning studies of PRT for Minneapolis, St. Paul, and Duluth and soon saw that such studies were mandatory to real understanding of the problems of designing and installing a PRT system, including its guideway. We discussed our work with many public officials, planners, and interested citizens not only in Minnesota, but in many locations around the United States, Canada, Europe, and Asia. We reviewed the work of the many government-funded studies related to AGT design. The most helpful for guideway design were [Snyder, 1975], [Stevens, 1979], and [Murtoh, 1984]. Out of this experience, I was able to write down a hopefully comprehensive set of requirements and criteria for the design of a PRT guideway, and subsequently found a design configuration that met them all. The discussion in this paper applies to elevated guideway structures for the simple reason that after trading off underground, surface-level, and elevated systems planners almost always opt for elevated systems.

As overall guidance for guideway design I find it difficult to improve on the following statement [Pushkarev, 1982] by Louis J. Gambaccini, New Jersey Transportation Commissioner and creator of the nation's first statewide public transit agency.

> "Fixed guideway transit is not a universal solution nor should it be applied in all urban areas. Fixed guideway is a potential strategy, as is the bus, the ferry boat, the car pool or the van pool. In many possible applications, fixed guideway is a superior strategy. But whatever strategy is finally selected, each should be evaluated not in the narrow context of transportation alone, nor solely in the framework of accounting. It should be measured in the broader context of its contribution to the overall long-term aspirations of the urban society it is supposed to serve."

Our challenge today is to design and build PRT systems even more able to "contribute to the overall long-term aspirations of the urban society" than Mr. Gambaccini could imagine thirty years ago.

Definitions

From the Oxford American Dictionary:

A Need: A circumstance in which a thing or a course of action is required.
A Criterion: A standard of judgment.
An Attribute: A quality that is characteristic of a person or thing.

From Wikipedia:

A Requirement: A necessary attribute, capability, characteristic, or quality of a system in order for it to have value and utility to a user.

Design Process

After decades of experience in the practice and teaching of engineering design I realized that the first step in a design process is to study deeply and follow rigorously a comprehensive set of rules of engineering design. I make no claim that my set [Anderson, 2007a] of such rules is complete, and I welcome collaboration with other experienced engineering designers to develop a more comprehensive set. But I have observed that the less successful PRT guideway designs have resulted primarily from violating one or more of these rules. What is now commonly called "risk management" consists mainly in following rigorously such a set of rules. My contribution was inspired by reading, as a young design engineer, the Rules of Engineering of W. J. King

[King, 1944]. Beginning with these rules, the design processes I used to arrive at my conclusions about the design of a PRT system are summarized in a DVD [Anderson, 2008d].

The next step is to write down a simple statement answering this question: What does a PRT guideway really need to do if it is to win competitions? Here is my short answer:

> A PRT guideway must carry vehicles containing people safely, reliably, and comfortably in all reasonable environmental conditions for up to 50 years over curves, hills, and straight sections at an acceptable range of speeds, acceptable cost, and acceptable visual impact.

But, we need to be more specific. Only by long experience in the design of whole PRT systems can one unearth all of the requirements and criteria for guideway design. Designing a PRT guideway cannot be done successfully without a great detail of development work on the whole system because the guideway design depends on other system features and other system features depend on guideway specifics [Anderson, 2000, 2008a]. In the following section, in no particular order, I give my list of guideway design requirements. All are important. To be successful, none can be ignored. For clarity and ease of reading, I list the requirements for the design of an elevated guideway without comment and without quantification. I then discuss alternative system issues and tradeoffs that in some cases affect guideway design and in others are influenced by the guideway-design requirements. Next, I list three guideway-design tradeoffs. Then, I suggest design criteria. Finally I state how, by using this process, I arrived at my guideway design. My bottom line goal for decades has been to design a system of urban transportation that can recover all of its costs from revenue – to turn urban transportation into a profitable enterprise.

PRT Guideway Design Requirements

1. The guideway must assure an acceptably high level of safety for the passengers that ride in the vehicles mounted on it in all reasonable circumstances.

2. Consistent with other requirements, the guideway must have minimum size, weight and capital cost.

3. The appearance of the guideway must be acceptable and variable to suit the community.

4. The switching concept for merge and diverge sections of the guideway must be straightforward, easily explained, and one of the first items to clarify while developing the configuration.

5. Accommodation of hills, valleys, and horizontal curves must be straightforward.

6. The design must permit straightforward manufacturability and installation.

7. Ride comfort must be acceptable.

8. The design must be compatible with the Americans with Disabilities Act.

9. The guideway must be designed to minimize operating cost.

10. The minimum span length must be determined from careful city planning.
11. The guideway must be designed for long life under the variable vertical, lateral, and longitudinal loads that can reasonably be expected.
12. The guideway must be designed to withstand reasonable earthquake loads.
13. There can be no passenger injury due to collisions of street vehicles with support posts, falling trees, etc. if such events may be possible.
14. The system must be designed to operate in the presence of wind, rain, snow, ice, lightning, dust, salt and other airborne corrosive substances, nesting birds and insects, i.e. in a general outdoor environment.
15. The guideway must be designed so that under winter conditions, guideway heating will not be necessary, except for systems not intended to operate under winter conditions.
16. The guideway must be easy to erect, change, expand, or remove.
17. The guideway design must permit access for maintenance.
18. The guideway must be designed for relief of thermal stresses.
19. The guideway must be designed for competitive operating speeds.
20. The guideway design must permit the system to expand indefinitely.
21. If power rails are used, the guideway must be designed so that frost will not form on them.
22. It must be very difficult if not impossible for anyone to be electrocuted by the system.
23. The guideway must be designed with adequate torsional stiffness.
24. It must be very difficult if not impossible to walk on the guideway.
25. The guideway design must liberalize the required post-settling tolerance.
26. The guideway design must eliminate slope discontinuities.
27. There must be space in the guideway for the communication means.
28. The design must minimize electromagnetic interference.
29. The design must minimize acoustical noise.
30. The design must minimize the potential for vandalism or sabotage

31. Provision must be made in the guideway design to prevent corrosion.

32. There must be no place in the guideway for water accumulation.

33. The design must provide for vibration damping.

Issues and Tradeoffs in PRT System Design

Early in my career at the University of Minnesota, I was privileged to hear a lecture by California Institute of Technology Professor Fritz Zwicky, in which he stressed "the morphological approach which attempts to view all problems in their totality and without prejudice." During World War II, he was deeply engaged in the design of jet engines, in which process, before any detailed design was begun, he and his colleagues wrote down in chart form every way they could conceive that a jet engine could be designed. The process described in his book [Zwicky, 1962] is general. It is a useful guide to the design of anything, and it strongly influenced the way I taught engineering design and in the methodology I practiced in the design of my PRT system. Zwicky's influence is present in the preceding and following discussion. One makes progress by "standing on the shoulders of giants." Zwicky was one of the giants. Here are some of the results of morphological thinking:

1. Safety issues. These issues are mentioned because they need to be treated as part of the overall PRT system design process. Neglecting any one of them can result in rejection. Discussion of the details is, however, beyond the scope of this paper. [Irving, 1978; Anderson, 1978a; Anderson, 1994]
    a. How can the control system be designed for maximum practical safety?
    b. How can the vehicles be designed for maximum practical safety?
    c. What should be the minimum operational headway?
    d. Should seat belts, air bags, or neither be required?
    e. Should shock-absorbing bumpers be designed into the vehicles?
    f. How should potential collisions with street vehicles or other objects be handled?
    g. How can people be prevented from walking on the guideway?
    h. How can the possibility of electrocution be prevented?
    i. How should fire safety issues be handled? NFPA 130.
    j. How should evacuation and rescue be handled?

2. Is the system predominately elevated, at grade, or underground? The issues are
    a. Congestion relief
    b. Safety
    c. Land requirements
    d. Costs

3. Is a walkway along the guideway necessary?
   This issue has been debated for a long time [NFPA 150, Anderson, 1978b]. If one or more vehicles are stranded on the guideway, how should passengers be rescued? The requirement of a walkway will make the guideway larger and more expensive, for which reason the gui-

deway designer would like not to be required to include walkways. There are two essential subsidiary considerations that must be understood:

a. Can all kinds of people including the elderly and the disabled in all reasonable kinds of weather use a walkway? Could a walkway be acceptable in rainy, snowy, or windy conditions? A little reflection shows that a walkway would be usable for the more able bodied people in a warm and dry climate, and thus, if PRT is to be acceptable for all people, it must be possible to design the system in such a way that the mean time between incidents in which a walkway would be desirable is long enough to be acceptable [Anderson, 2006], and in the remote situation in which someone might need to be rescued a means other than a walkway is acceptable.

b. Can the system be designed in such a way that the mean time between circumstances in which a walkway would be useful is so rare that other rescue means become acceptable?

These questions were studied in sufficient detail in the Chicago PRT Design Study[1] that it was concluded that walkways would not be required except in circumstances such as river crossings. When there is ground underneath the guideway, the preferred alternative rescue means would be a fire truck or a cherry picker. Even when crossing rivers, detailed work on analysis of hazards and potential failures and their effects [Stone & Webster, 1991] resulted in the conclusion that rescue could best be accomplished by means other than a walkway. The study team concluded that PRT systems can be designed to be sufficiently simple and reliable that walkways will not be needed.

4. Should the system be dual mode or single mode, i.e., with vehicles captive to the guideway? This question has been studied [Irving, 1978; Anderson, 2007b] in sufficient detail to convince us that we should concentrate on single-mode PRT systems. We considered many issues including
   a. The effect on community development patterns.
   b. The effect on system cost and ridership.
   c. The effect on capacity.
   d. The effect on those who cannot, should not, or prefer not to drive.

5. Should the vehicles be supported above the guideway or should they hang below? This is a complex tradeoff that I have examined in increasing detail [Anderson, 2008b]. The issues are:
   a. Visual impact
   b. System cost
   c. Natural frequency
   d. Ease of switching
   e. Rider security
   f. All-weather operation
   g. Torsion in curves

[1] Formally, the Northeastern Illinois Regional Transportation Authority PRT Design Study of 1990.

6. How should the vehicles be suspended? [Anderson, 2008c]
    a. Wheels
    b. Air cushions
    c. Magnetic fields

7. How should the vehicles be propelled? [Anderson, 1994; 2008d]
    a. Rotary motors
    b. Linear motors
        i. Induction
        ii. Synchronous
        iii. Air
        iv. Rope

8. What should be the people-carrying capacity of the vehicles? [Anderson, 1986]
    a. Understand the size of groups in which people travel.
    b. Understand the ease of taking two or more vehicles.
    c. Understand the effect of vehicle size on system cost.
    d. Need to accommodate wheelchair + attendant, bicycle, baby stroller, <u>or</u> luggage.

9. Assuming electric motors, should they be rotary or linear? [Anderson, 1994]

10. Should the motors be on board the vehicles or at wayside? [Anderson, 2008d]

11. If the motors are on board, should they draw power from batteries or power rails? [Anderson, 2008d]

All of these tradeoffs and more will affect the cost and performance of the system and should be studied very carefully before detailed design is initiated.

Tradeoffs in PRT Guideway Design

1. Cross sectional dimensions: The minimum-weight cross section should be used. [Anderson, 1978, Chapter 10; 1997; 2007c]
2. Material: Steel, concrete, composite?
3. Truss or plate or pipe?

PRT Guideway Design Criteria

1. <u>Vertical and Lateral Design Loads</u>. This is the only set of criteria considered by Moutoh, 1984. One must consider dynamic loading due to vehicles moving at speed, wind loads, earthquake loads, longitudinal loads due to braking vehicles, and loads due to street vehicles crashing into the support posts, if that is to be permitted. The best study I have seen on dynamic loads is one done in the M. I. T. Mechanical Engineering Department by Snyder, Wormley, and Richardson [Snyder, 1975]. In their computer studies, they simulated vehicles of various weights operating at various speeds and various headways, and running over guideways of various span lengths. By placing their results in dimensionless form, the

usefulness was extended considerably. I studied their results [Anderson, 1978a] and noted that the shorter the minimum headway the smaller was the difference between dynamic and static deflection, and in the theoretical limit of zero spacing between vehicles the dynamic and static deflection are the same, i.e., the guideway cannot tell the difference. Assuming PRT vehicles operating at a minimum headway of half a second, I found that the maximum dynamic guideway deflection and stress with vehicles operating at line speed was less than the maximum deflection and stress with vehicles nose-to-tail on the guideway. Therefore the maximum possible vertical load becomes a uniform load and it is easiest to calculate. The loading criteria used in the Chicago PRT design study were

1) Fully loaded vehicles nose to tail on span + 30 m/s (70 mph) crosswind.
2) No vehicles + 54 m/s (120 mph) crosswind. [I now assume 80 m/s (180 mph)]

The maximum wind load on a guideway can be substantially reduced by reducing its drag coefficient based on known wind-tunnel data [Hoerner, 1965], [Scraton, 1971].

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

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

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

5. <u>Maximum allowable deflection</u>. The AASHTO bridge standard is span/800.

6. <u>Minimum allowable span</u>. The Chicago PRT design study conclusion: 28 m (90 ft)

7. <u>Ride Comfort</u>
    a. Observe the ISO standards for acceleration vs. frequency
    b. Observe the ISO standard acceptable constant acceleration and jerk for normal and emergency operation, which are also given in the ASCE APM Standards.

8. System Life. The Chicago RTA specified 50 years.

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

10. The minimum line headway needs to be specified at the beginning of the design program based on detailed site-specific planning studies. When it is not, as has usually been the case, the system may be destined for a limited range of applications. Based on many independent studies we have designed for a minimum headway of half a second. [Anderson, 1994]

11. Design for the expected environment
    a. Rain, ice, snow of a given rate of accumulation.
    b. Ambient temperature range, typically -40^{o}C to +50^{o}C.
    c. Lightning protection.
    d. Sun.
    e. Dust, sand, salt.
    f. Nesting bees, birds, squirrels, etc.
    g. Earthquakes – Design to maximum expected horizontal acceleration at the site.
    h. Fire. [NFPA 130]
    i. Vehicles crashing into posts. [Anderson, 2006, Appendix A]
    j. Interference from other elements of the urban scene.
    k. Ice build up on power rails due to clear winter night sky.

12. Speed range. Select the cruising speed to minimize cost per passenger per unit of distance. Consider that turn radii, stopping distance, kinetic energy, and the energy needed to overcome air drag all increase as the square of speed; and that energy use depends on streamlining, low road resistance, and propulsion efficiency. Consider that the maximum operational speed for acceptable ride comfort is proportional to the guideway natural frequency, which depends on guideway stiffness and the type of support. [Anderson, 1997]

13. Costs. The design team should aim for costs sufficiently low to be recoverable in fares, i.e., the system should be designed to be a profitable private enterprise. Such a conclusion clearly cannot be reached without a great deal of development work, but by striving for this goal the design team will insure its future.

14. Require a small amount of vibration damping in the guideway.

15. Acoustical noise should be less than the noise of automobiles on streets.

16. Electromagnetic noise generated cannot interfere with existing devices.

17. Communication means must be accommodated.

18. Expansion. Design so that the system can be expanded indefinitely.

19. Design to minimize the effects of vandalism and sabotage.
    a. Assign young engineers to study ways to vandalize the system and how to prevent it.
    b. The spread-out nature of a PRT system provides no inviting target.

My Conclusions [Anderson, 2007c, 2008a, 2008d]

1. Resolving the basic tradeoffs related to the guideway, I reached the following conclusions:
    a. The guideway will be mostly elevated.
    b. Single mode.
    c. Supported vehicles.
    d. Wheeled suspension.
    e. Linear-induction-motor propulsion.
    f. Motors on board, powered via power rails.

2. Before designing the guideway, determine the vehicle maximum weight with careful weight-minimization design.

3. Use the optimum guideway cross section for minimum weight and cross sectional area.
    a. The optimum guideway is narrower than it is deep.
    b. A vertical chassis is required.
    c. Careful attention must be given to the attachment of the cabin to the chassis. Detailed finite-element analysis gives a practical solution.

4. The minimum-weight, minimum-size guideway is a steel truss.
    a. Robotic welding is required for acceptable cost.
    b. Corrosion protection is required.
    c. The guideway should be clamped to the posts for maximum stiffness.
    d. Expansion joints should be placed at the point of zero bending moment in uniformly loaded spans.

5. Cover the truss with composite covers, opened 10 cm (4 in) at top, 20 cm (8 in) at bottom, with curve radii at top and bottom 1/6th guideway height, hinged at bottom and latched at top, with a thin aluminum layer and sound-deadening material on the inside [Anderson, 2008a]. The benefits are:
    a. The interior of guideway is protected from all but very minimum snow and ice.
    b. The interior is protected from effects of the sun on the tires and other equipment.
    c. Differential thermal expansion is eliminated.
    d. The exterior environment is shielded from electromagnetic and acoustic noise.
    e. The power rails (if used) are protected from the winter night sky, which prevents ice accumulation.
    f. Wind drag is 40 % of that on an opened truss. [Scraton, 1971]
    g. The interior of the guideway can be accessed for maintenance.
    h. The appearance of the guideway can be selected to suit the community.

General Conclusions

I studied the field of PRT pro and con for several years before becoming sufficiently convinced that within this technology, properly optimized, would someday be a means of realizing urban environments of a quality far superior to that possible using only conventional technology, and thus serious involvement would be a worthy use of my time. A very important finding of the UMTA studies of 1968 was that if only conventional transit would be deployed, congestion would continually increase, but if the new personal transit systems would be deployed, congestion could be contained. [Hamilton, 1969]

I envisioned more and more clearly as the years of my involvement progressed that when PRT in some form becomes accepted by the transportation-planning community *it will be open technology, studied in regular engineering classes in universities.* There will have to be sufficient commonality in these systems so that planners will be convinced that they can be expanded and supported with assurance that multiple suppliers will be available decades hence. Ideally, the preferred designs will be determined by the market place. *The details of the designs will be found in the open literature*. Vehicles will be supplied by various companies, will be selected by competent engineering companies in consultation with the client, and will operate on standard guideways. Control systems including their software will be studied in universities and trade schools, and a number of companies will supply them. This is exactly the way all civil works are designed, bid and built. Good engineers and engineering companies will do well in PRT based on competence, as is true of those who specialize in other public works. *The all-too-common thought of inventing a unique system that will make one fabulously rich is not only a fallacy but may be a major deterrent to full commercialization of this technology. This is a problem for those who look for a huge return. Those of us interested in realizing this technology need to work together for the betterment of society.*

Quoting the Engineers' Creed [NSPE, 1954]: *"The engineer places service before profit, the honor and standing of the profession before personal advantage, and the public welfare above all other considerations."* Roads are funded by governments. The rights of way for PRT guideways will have to be provided by governments and their designs will have to be approved by governments if the potential of PRT is to be realized. Paraphrasing Gambaccini: *"PRT should be measured in the broader context of its contribution to the overall long-term aspirations of the urban society it is supposed to serve."*

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