The SkyWeb Express personal rapid transit system

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Abstract

Numerous investigators, observing that conventional transit systems are no match for the automobile on a modern road, have sought a means for movement of people that would attract many more riders while reducing costs. Understanding the benefits of automation, this activity led to the consideration of systems consisting of very small, automatically controlled vehicles running on a network of small, low-cost elevated guideways. To obtain adequate capacity and to decrease trip time, the stations would be placed off-line. In this way the system would have the attractiveness of a freeway, which permits private travel at minimum trip time, but would require a great deal less space. In the late 1960s this concept became called Personal Rapid Transit (PRT) and governments began investing in it. Unfortunately, there are a great many ways to design a PRT system and at that early stage there was no serious theoretical work to determine how best to accomplish such a design. As a Professor of Mechanical Engineering at the University of Minnesota, the author became interested in this problem in 1968 and during the 1970s was able to study all of the PRT work underway around the world, and thereby develop a comprehensive set of criteria to guide him to an optimized version of PRT. That version is now called SkyWeb Express. The paper briefly discusses the advantages of use of off-line stations and the design of the necessary guideway, vehicle, station, operations, and control system. Means for obtaining the necessary safety and reliability are then discussed, followed by a brief discussion of system costs and cost effectiveness. Finally, a list is given of benefits for the community and the patrons.
Keywords: personal rapid transit, automated guideway transit, automated people movers, automated highways, optimization, cost-effective design, automatic control, urban transportation, people movement, system design.

1 Introduction

SkyWeb Express is an optimized [1] version of Personal Rapid Transit (PRT), which is a system of transit distinguished by the use of small, light-weight vehicles running under fully automatic control non-stop between any pair of off-line stations in a network of minimum-sized guideways usually elevated so that they will not interfere with surface traffic. There are many benefits to such a system, the leading of which are that the travel time in a city will be shorter and more reliable than possible in other travel modes and that the land required for transportation is a tiny fraction of that required for the automobile system.

After many years in the wilderness, the concept of PRT is coming of age. There is now serious interest at Heathrow and SeaTac International Airports, Dubai, South Korea, the New Jersey and Minnesota State Legislatures, Minneapolis, Sweden, Norway, and likely elsewhere.

SkyWeb Express was developed by the author with the able assistance of many engineers. He began his design in 1982 at the University of Minnesota following 13 years of activity in the field of PRT, which included research, teaching, planning, lecturing, running conferences, work in industry, and founding of the Advanced Transit Association [2]. For readers interested in the design process, the author regards that the main reason for continued interest in his design is that he followed rigorously a set of rules for design [3] that he developed through practice, teaching and research into the design process. More detail about the background of and all aspects of the author's design can be found in Anderson [4].

2 The off-line station: key to PRT

The feature that separates PRT from conventional transit is the off-line station, which is illustrated in Figure 1. The advantages of off-line stations combine to produce a major breakthrough in urban transportation.

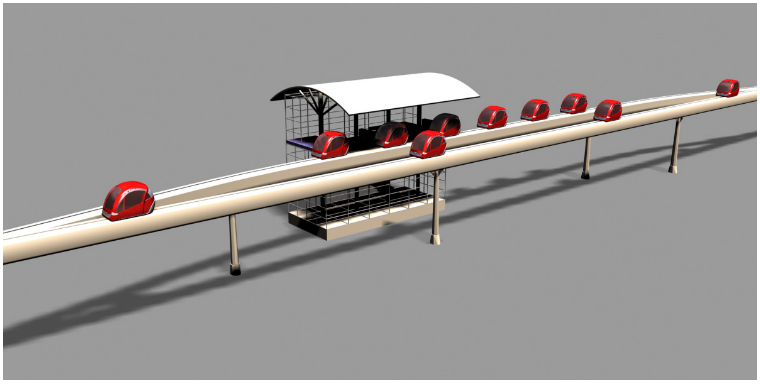

Figure 1: An off-line station in a SkyWeb Express system.

Off-line stations permit small vehicles to run on the main line at time spacings measured in seconds or fractions of a second rather than in minutes, as is the case with conventional transit, thus providing high capacity [5].

Off-line stations permit non-stop travel so that the travel time is less in a city than possible by other modes, thus attracting many more people to transit.

Off-line stations permit vehicles to wait for people rather than people for vehicles.

Off-line stations enable vehicles to run only when there are demands for service, thus markedly reducing operating costs.

Off-line stations enable people to travel economically any time of day or night.

Off-line stations can be placed closer together than practical with conventional rail systems because close station spacing does not reduce travel speed. Closer station spacing provides greater access to the community. Analysis [1] has shown that once a guideway is built, only a modest increase in the system ridership will cause a decrease in the system total cost per passenger-km when a station is added.

Off-line stations permit high throughput with small, light weight vehicles, the use of which permits the design of minimum weight, minimum cost guideways, which permits much more guideway to be built economically, which provides much greater access to the various areas of a city.

3 Guideway

Almost all of the automated guideway transit programs of the 1970s are no longer active mainly because of inadequate consideration of the criteria for guideway design. In studying all of these systems, the author accumulated 25 criteria for guideway design, and found it necessary to spend more time perfecting the guideway design [6] than any part of the system other than the control system. Of all the guideway systems the author examined, he found that the compact U-shaped configuration using top-mounted vehicles that had been developed by The Aerospace Corporation [7] was by a wide margin superior to others, but we accepted this basic configuration only after examining every other reasonable alternative and within each means for minimizing cost. Our design process led us to the steel-truss design shown without its covers in Figure 2. It has been subject to a great deal of computer analysis and is configured to ease the problem of obtaining adequate tolerances on the wheel-support running surfaces.

The guideway is shown covered in Figure 3. It has a slot 102 mm wide at the top to permit the 76-mm-wide chassis to pass through, and a slot 152 mm wide at the bottom to let any snow, ice, or debris fall through. The covers keep out the vast majority of ice and snow while permitting access for maintenance; they provide electromagnetic shielding, noise shielding, and ultraviolet shielding for the tires; they shield the power rails from frost formation; they markedly diminish differential thermal expansion in the truss structure; they reduce air drag from winds by use of curved surfaces at the upper and lower edges; and they permit the community to match the physical appearance of the guideway to the surroundings. Some of the vehicles will be required to run during a snow or ice storm to keep the running surfaces clear.

Figure 2: The SkyWeb Express guideway.

Figure 3: The SkyWeb Express vehicle.

4 The vehicle

The SkyWeb Express vehicle is shown in Figure 3. It has a single seat 1372 mm wide similar to the back seat of a taxicab and permits a maximum passenger load of 295 kg counting baggage. This interior width permits a wheelchair to enter and rotate forward with two of the three seats folded up, and to be accompanied by an attendant. A pair of fold-down backward facing seats at the front of the cabin enable the cabin to accommodate five persons. Making the vehicle larger than this increases vehicle weight, hence guideway weight and increases station length and cost, all without a commensurate increase in ridership.

The vehicle is sized for the 97.5 percentile male, which requires 1422 mm interior height. By use of an inverted U-shaped door that slides over the entire top, entry and exit by elderly and disabled persons is easy – a person can walk straight in and then sit down. The exterior height of the vehicle's passenger cabin is 1600 mm and the exterior length is 2590 mm, giving a length to height ratio corresponding to the Golden Section or Fibonacci ratio. The vehicle has a projected weight of 522 kg, and has a pleasing aerodynamic shape.

Within the cabin there is a two-way communication system to inform the passengers of any unusual event and to permit the occupant to announce to the system operator any emergency medical problem such as a heart attack, in which case the central operator can change the vehicle's destination to that of the nearest hospital. There will also be a "Next Stop" button that will permit a passenger to disembark at the next station for any reason, and a "Go" button to initiate the trip faster than would occur with a timer.

The cabin is mounted on a simple vertical chassis that resides inside the guideway and to which are attached pneumatic main-support tires and polyurethane-tired wheels to provide lateral support. The vehicle is propelled and braked by a pair of linear induction motors (LIMs), which are mounted at the bottom of the chassis to keep the center of gravity as low as possible. Use of LIM propulsion permits the tires and the running surface to be smooth so that the main-support wheels need not steer, thus simplifying and minimizing the cost of the design. A parking brake is mounted on the chassis that consists of a pair of high-friction surfaces that press down on the running surface.

A pair of switch arms mounted in the chassis and rotated about a longitudinal axis permit switching with no moving track parts. The stiffnesses of all of the tires and the position of the switch arm have been determined by detailed dynamic simulations of the motion of the vehicle, particularly through merge and diverge sections of the guideway. All of the components of the vehicle are either commercially available or easily designed.

Since April 10, 2003 we have had one vehicle operating under automatic control on an 18.3 m segment of guideway. Since then we have given well over 4000 rides both in our facility in a suburb of Minneapolis and at the Minnesota State Fair. There have been no failures of the control and propulsion system. The only failure occurred when a cable that operated the automatic door jumped off its pulley. Obtaining adequate reliability of the door mechanism is the most difficult problem in the design of the vehicle.

5 The stations

There is nothing particularly novel about the design of the stations. Elevated stations will be equipped with at least one elevator and a stairway. Security in stations will be assured by open design, lighting, television monitoring, motion detectors, a two-way communications system, and short to zero waiting time. Once the operation of PRT is understood, there need be no operators in the stations. There will, however, be a monitoring station for every 10 to 20 stations where human operators can watch the activity at stations via television monitors, which would be activated either by the station communication system or in off-peak hours when more than one person arrives in the station or when a person loiters. Each station will be equipped with fare collection equipment, which is described next.

6 Operations

Once the basic layout of a PRT system is understood, it is seen that there is nothing novel about its operation. In each station, there will be a system for fare collection, destination selection, and access to a vehicle. Since each vehicle is occupied by a group travelling together by choice and headed to the same destination and the fare is charged per vehicle rather than per person, entry to the vehicle is obtained by means of a valid fare card. There need, therefore, be no turnstiles. With today's smart-card technology advancing each year, a process designed today will likely be obsolete in a few years, so care must be taken to design so that technological advances can be accommodated.

7 Control

The most demanding task in the design of a PRT system has been control. In an earlier position at Honeywell, Inc. the author was engaged in design of control and navigation of aircraft and spacecraft. With this background, he was able to follow closely all of the significant work on PRT control research and application during the 1970s and 1980s and he used this background to develop the architecture for control of SkyWeb Express [8], [9]. An important feature of the control system is that for the sake of safety and dependability all of its computers – in vehicles, at wayside, and central – are dual redundant, which means that two pairs of computers make up each "computer." The outputs of each pair are matched every 10 to 20 seconds and then the combined outputs of each pair must match for all to be well. Lack of a match causes the vehicle computer system to command a trip to the maintenance shop after completing the current trip. Detailed work on failure modes and effects shows that in such systems, a patron will very rarely be aware of a failure.

The SkyWeb Express control system is hierarchal. The vehicle control system does as much as it can do. It follows a speed command and generates and follows commands to manoeuvre within ride-comfort specifications. These manoeuvre commands carry a vehicle from the station to line speed, from the main line to a stop at a station berth, from one speed to another, or from one position in the main line to one farther back relative to the other vehicles. The latter manoeuvre permits safe merging. The vehicle measures its speed and position by means of redundant sensors and transmits it to a wayside computer called a "zone controller," and it receives the correct line speed from a zone controller. The vehicle computer is configured so that if it does not receive the speed signal from the zone controller a second time it commands itself to creep speed while warning others of its action.

The entire guideway is divided into zones – station zones, merge zones, diverge zones, and line zones. The computer system at each of these zones provides the correct line speed for its zone at least 10 times a second, commands manoeuvres of specific vehicles, and monitors the motion of each vehicle so that in case of an anomaly it can remove the speed signal, which causes each vehicle to command itself to creep speed. The central computer optimizes the redistribution of empty vehicles to minimize wait times and collects data on the performance of the system.

8 Safety and reliability

The topic of safety in design and operation of PRT system has been developed [10] in terms of operations and minimum headway requirements. Key features are the use of fault-tolerant design in hardware and software wherever possible, use of a minimum number of moving parts, use of a switching system that has no moving parts, and use of dual redundant computers. Moreover, in a $1,500,000 design study of PRT performed for the Northeastern Illinois Regional Transportation Authority, extensive work has been done on failure modes and effects analysis in conjunction with a comprehensive method for calculating on-time performance [11], hazard analysis, and fault-tree analysis.

9 Costs and cost effectiveness

Capital and operating costs have been developed for SkyWeb Express with the assistance of four large engineering firms in five rounds of analysis and have been updated to the present time with price indices obtained from the *Engineering News Record*, taking into account that the costs of computer and communications components have decreased. In calculating the costs, it was assumed that there will be an elevator in each station, and each vehicle will be equipped with a heater and a small automobile air conditioner. The result of the cost analysis is that it has been confirmed that in many but not all applications SkyWeb Express can be built and operated without public subsidy, assuming fare levels consistent with current transit fares.

As a PRT system grows it becomes increasingly cost-effective. System cost is roughly proportional to length of guideway and number of stations. However, ridership increases roughly proportional to the number of places connected. For example, a five-station system provides for twenty unique trips, five stations each serving four others. If a sixth station is added, for one-sixth more cost, the system will provide for thirty unique trips, a fifty percent increase. Generally, system cost grows linearly while ridership grows exponentially.

10 Benefits

10.1 Community benefits

An optimized PRT system can begin usefully as a small application and can grow almost indefinitely according to need, with line speeds in various parts of a network of guideways selected appropriately. By starting in the inner city and expanding according to a plan, PRT may *reduce urban sprawl* by making the inner city a much more desirable place to live. Its benefits for the community are the following:

- It minimizes cost per passenger-km, thus requiring little or no subsidy.
- It increases economic vitality by reducing transit subsidies.
- It attracts a significant fraction of present auto trips.
- It provides mobility for the elderly, young, and disabled.
- It has sufficient capacity to handle a wide variety of applications.
- It increases ridership on either bus or rail by providing greater access.
- It is safe not only for the passengers, but for nearby pedestrians and motorists.
- It operates safely in all but the most extreme weather conditions.
- It becomes safe and inexpensive for employees who need to work late shifts.
- It is much more energy efficient than the current automobile system.
- Its required electrical power can come from renewable sources.
- It reduces dependence on oil.
- It reduces unsightly and unhealthy air pollution.
- Its operation is very quiet.
- It uses less than 0.1% of the land ─ the auto system uses 30% to 70%.
- It enables much more urban land to be put to higher use.
- It causes very little surface-level disruption during installation.
- It stimulates commerce by easing the connection of buildings.
- It makes higher density housing more liveable.
- It enables more people to work and learn wherever they live.
- It makes the 24-hour city a reality.

10.2 Benefits to patrons

The remarkable result of a long search for the most cost-effective solution to the transit problem ─ optimized PRT [1] ─ is a *humanizing technology* with the following benefits for the riding public.

- A short walk to a station.
- A simple fare-payment procedure.
- Reasonable trip cost.
- Minimum or no wait.

- A seat for everyone.
- A short, predictable trip time.
- No vehicle-to-vehicle transfers.
- 24-hour, on-demand service.
- Easy for everyone to use.
- No driver's license needed.
- Privacy.
- No crowding.
- Space for luggage, a wheelchair or a bicycle.
- Comfortable jerk-free motion.
- Quiet.
- Minimum anxiety.
- Maximum safety.

References

[1] Anderson, J. E., Optimization of Transit-System Characteristics. *Journal of Advanced Transportation*, 18(1), pp. 77-111, 1984.

[2] Anderson, J. E., Some Lessons from the History of Personal Rapid Transit, http://www.skywebexpress.com/pdf_files/150k_additional.

[3] Anderson, J. E., Rules for Engineering Design, http://www.skywebexpress.com/pdf_files/150k_additional.

[4] Anderson, J. E., A Review of the State of the Art of Personal Rapid Transit. *Journal of Advanced Transportation*, 34(1), pp. 3-29, 2000.

[5] Anderson, J. E., Personal Rapid Transit: Matching Capacity to Demand. http://www.skywebexpress.com/pdf_files/150k_additional.

[6] Anderson, J. E., The Design of Guideways for PRT Systems. http://www.skywebexpress.com/pdf_files/150k_additional.

[7] Irving, J. H., Bernstein, H., Olson, C. L., and Buyan, J. *Fundamentals of Personal Rapid Transit,* Lexington Books, D. C. Heath and Company, Lexington, MA, 1978.

[8] Anderson, J. E. Longitudinal Control of a Vehicle. *Journal of Advanced Transportation*, 31(3), pp. 237-247, 1997.

[9] Anderson, J. E. Control of Personal Rapid Transit Systems. *Journal of Advanced Transportation*, 32(1), pp. 57-74, 1998.

[10] Anderson, J. E. Safe Design of Personal Rapid Transit Systems, *Journal of Advanced Transportation*, 28(1), pp. 1-15, 1994.

[11] Anderson, J. E. Dependability as a Measure of On-Time Performance of Personal Rapid Transit Systems. *Journal of Advanced Transportation*, 26(3), pp. 101-212, 1992.