Courses of Study for Engineers preparing to work on PRT Design

- **Systems Engineering applied to PRT Systems**
- **The Simulation and Control of PRT Systems**
- **The Design of a PRT System**
- **Instructor bio**

Instructor

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Systems Engineering applied to PRT Systems[1]

The Future of High-Capacity PRT

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

After deriving the HCPRT concept, work is reviewed on the important factors that the design engineer needs to consider in contributing to the advancement of HCPRT, so that after shaking out the good from the not so good features of the basic concept cities, airports, universities, medical centers, retirement communities, etc. can comfortably consider deploying HCPRT systems. Once PRT systems are in operation we can expect that universities will teach courses on HCPRT design and planning and that a number of competent firms will be involved in manufacturing HCPRT systems. HCPRT is close to moving to mainstream and can bring about a brighter future for mankind.

A Review of the State of the Art of Personal Rapid Transit

A review of the rational for development of personal rapid transit, the reasons it has taken so long to develop, and the process needed to develop it. The author summarizes arguments that show how the PRT concept can be derived from a system-significant equation for life-cycle cost per passenger-mile as the system that minimizes this quantity. In the bulk of the paper the author discusses the state-of-the-art of a series of technical issues that had to be resolved during the development of an optimum PRT design. These include capacity, switching, the issue of hanging vs. supported vehicles, guideways, vehicles, control, station operations, system operations, reliability, availability, dependability, safety, calculation of curved guideways, operational simulation, power and energy. The paper concludes with a listing of the implications for a city that deploys an optimized PRT system.

Optimization of Transit-System Characteristics

A system-significant equation for the cost per passenger-mile is developed and from it, using available data, it is shown that the system that minimizes cost per passenger-mile has all the characteristics of the

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[1] Most of the papers abstracted here can be found on www.prtnz.com

true PRT concept.

Automated Transit Vehicle Size Considerations

Nine considerations are developed that will assist an analyst desiring to determine the optimum size of an automated transit vehicle. These considerations are travel behavior, network operations, personal security, treatment of disabled riders, social considerations, safety, dependability, capacity, and cost.

The Structural Properties of a PRT Guideway

Calculation of the structural properties of a U-shaped truss guideway in both bending and torsion. Determination of the guideway natural frequency and the critical speed.

Safe Design of Personal Rapid Transit Systems

The safety of PRT systems involves careful attention to all features of the design such as the use of a hierarchy of fault-tolerant redundant control system, bi-stable fail-safe switching, back-up power supplies, vehicle and passenger protection, and attention to the interaction of people with the system. Safety, together with reliability and adequate capacity, must be achieved while making the system economically attractive; hence techniques to achieve these goals at minimum life-cycle cost are primary in PRT design. The paper describes the relevant features in a new transit system and the principles of safe design required to develop it.

Control of Personal Rapid Transit Systems

The problem of precise longitudinal control of vehicles so that they follow predetermined time-varying speeds and positions has been solved. To control vehicles to the required close headway of at least 0.5 sec, the control philosophy is different from but no less rigorous than that of railroad practice. The preferred control strategy is one that could be called an "asynchronous point follower." Such a strategy requires no clock synchronization, is flexible in all unusual conditions, permits the maximum possible throughput, requires a minimum of maneuvering and uses a minimum of software. Since wayside zone controllers have in their memory exactly the same maneuver equations as the on-board computers, accurate safety monitoring is practical. The paper discusses the functions of vehicle control; the control of station, merge, and diverge zones; and central control.

Synchronous or Clear-Path Control in Personal Rapid Transit

An equation is derived for the ratio of the maximum possible station flow to average line flow in a PRT or dual-mode system using fully synchronous control. It is shown that such a system is impractical except in very small networks.

Dependability as a Measure of On-Time Performance of Personal Rapid Transit Systems

Dependability is defined in this paper as the percentage of person-hours of operation of a PRT system completed with a delay less than a prescribed value.   Such a definition, while desired in conventional transit, cannot be measured without asking every patron the destination of his or her trip, which is impractical. This definition is practical in a PRT system. The paper shows both how to calculate Dependability in advance of deployment of a PRT system and how to measure it while the system is in operation. The method provides the basis for precise contract language by which to measure on-time performance.

Life-Cycle Costs and Reliability Allocation in Automated Transit

In any system composed of many subsystems and components there is a performance requirement that must be met and it is desirable to meet it at minimum life cycle cost. It is generally possible to manufacture each component to fail less frequently but at higher cost. Thus the acquisition cost of the component increases as the mean time to failure (MTBF) increases but the support cost decreases as the MTBF increases, so the life-cycle cost is a bathtub curve as a function of MTBF with a single minimum point. If all of the components were selected at their minimum points, the system life cycle cost would be minimum, but generally the performance would be less than required. To minimize the life-cycle cost at a higher level of performance the MTBF of each component must be select at a longer time than the value that minimizes the life-cycle cost for that component. This is a constrained minimization problem, i.e., the problem of finding the values of the MTBF of each component that meets the performance requirement at minimum life cycle cost. This problem is solved and results in an equation for optimum MTBF of each component in terms of the normal and emergency operation of the system and the life-cycle-cost characteristics of each component. The method is a useful tool to guide the development of any system.

Calculation of Performance and Fleet Size in Transit Systems

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

The Capacity of Personal Rapid Transit System

A comprehensive discussion of the question of both required and obtainable capacity in PRT system based on both observation of the behavior of people and on theory. It is shown that once a network of PRT guideways is laid down rather than the few widely spaced lines of conventional rail system the required capacity of both lines and stations is remarkably modest. As a result a modern PRT system will exceed the maximum practical throughput of most conventional rail systems.

Energy Use in Transit Systems

The energy use of heavy rail, light rail, trolley bus, motor bus, van pool, dial-a-bus, auto, and PRT are compared. The energy required to overcome air drag, rolling resistance, and inertia; the energy require for heating, ventilating, air conditioning; and construction energy are calculated. The factors used for the conventional transit systems are averages given in federal data report “National Urban Mass Transportation Statistics.”

High-Capacity Personal Rapid Transit

1. Introduction
2. The problems to be addressed
3. Rethinking transit from fundamentals
4. Derivation of the new system
5. Off-line stations are the key breakthrough
6. The attributes of high-capacity PRT
7. The optimum configuration
8. Is high capacity possible with small vehicles?
9. System features needed to achieve maximum throughput reliably and safely
10. How does a person use a PRT system?
11. Will PRT attract riders?

12. Status
13. Economics of PRT
14. Land savings
15. Energy savings
16. Benefits for the riding public
17. Benefits for the community
18. Reconsidering the problems
19. Significant PRT activity
20. Development strategy

The Simulation and Control of PRT Systems

Control of Personal Rapid Transit Systems

The problem of precise longitudinal control of vehicles so that they follow predetermined time-varying speeds and positions has been solved. To control vehicles to the required close headway of at least 0.5 sec, the control philosophy is different from but no less rigorous than that of railroad practice. The preferred control strategy is one that could be called an "asynchronous point follower." Such a strategy requires no clock synchronization, is flexible in all unusual conditions, permits the maximum possible throughput, requires a minimum of maneuvering and uses a minimum of software. Since wayside zone controllers have in their memory exactly the same maneuver equations as the on-board computers, accurate safety monitoring is practical. The paper discusses the functions of vehicle control; the control of station, merge, and diverge zones; and central control.

Simulation of the Operation of Personal Rapid Transit Systems

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

Longitudinal Control of a Vehicle

Generally applicable formulae for the gain constants in a proportional plus integral controller required for stable control of the speed of any vehicle in terms of natural frequency, damping ratio, vehicle mass, and thruster time constant. An example, based on a simulation of the controller and vehicle, is given. The theory shows that only speed and position feedback are needed. Acceleration feedback is unnecessary.

Failure Modes and Effects

A wide range of failure modes in PRT systems are treated with estimates the mean time to failure of each and the degree of redundancy needed to meet requirements of performance and safety. In developing the results, many details of the control system required are explained.

The Geometry of a Vehicle Moving in 3-D Space

The Reference Frames and the Velocity Vector. Components of Acceleration. Maximum Speed based on Comfort Acceleration. The components of Jerk. The Differential Equations of the Spiral Transitions. Plane Transition Curves at Constant Speed. The Transition Curve with no Region of Constant Curvature. The Transition Curve with a Region of Constant Curvature. The Roll-Rate Limit. Nonlinear Effects. Yaw-Pitch Coupling. Large Yaw Angles. Superelevation.

Equations needed to compute a direction change in a horizontal or vertical plane

The Governing Differential Equations. Calculation of the Slope of the Curve. Calculation of the Coordinates of the Curve in the Region of Positive Jerk. The Limit Condition for a Section of Constant Curvature. Calculation of the Coordinates of the Curve in the Region of Constant Curvature. Calculation of the Coordinates of the Curve in the Region of Negative Jerk. A Program for Calculating the Curve in Local Coordinates

The Transition to an Off-Line Station

Generally applicable differential equation for the transition curve. Solution with constant speed. Equations for constant-speed transition. The transition to an off-line station. Limits. Quarter and half point values. Transition with variable speed. The Curvature. The Slope of the Transition Curve. The Transition Curve. The Length of the Transition. The Station Speed. The Maximum Slope of the Transition Curve. Solution for large lateral displacement. Collection of the Equations for the Transition. Calculation of the Speed into a Station. How does the Station Throughput change with Station Speed? A Program to Compute the Transition. Numerical Solution for the Transition for Arbitrary Speed Profile.

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

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

Layout of a PRT Network

Quantitative layout of a PRT network including properties needed for vehicles and passengers. List of constant values for the system. Programs to calculate and plot the system.

Setup of Control Zones in a PRT Network

Design criteria. Hardware required for control. Equation for minimum distance between branch points. Control Strategy. Explanation of Control Zones.

Kinematics of motion of PRT vehicles

The equations needed to calculate speed and position vs. time for acceleration to line speed, stop in given distance, slip given amount, speed change, and emergency stop. The results are needed both in the code of a real system and in a simulation program.

Description and code for a PRT Vehicle Controller

A vehicle controller designed to follow speed/and distance vs. time profiles.

Positioning of Vehicles and their Movement

Required number of vehicles. Initial vehicle placement. Vehicle movement. When can a vehicle leave a station? Resolving a merge conflict. A diverge point. Entering and moving through a station.

Additional Code needed to Operate a PRT Simulation

The demand matrix. Generation and Processing of Passengers.

Equations for Command Point Positions

Switch, Deceleration, Diverge, and Merge Command Points

Structure of a Simulated PRT Control System

Functions of vehicle, zone, and central computers. Description of the physical system to be simulated.

Stopping Distance vs. Transition Length

Derivation of the relationship between stopping distance and the transition length to an off-line station.

The Program of Calculations Required to provide data to Operate the PRT Network Simulation Program

Universal constants. Apex data. Station data. Demand matrix. Branch data. Compute azimuth, direction change, curve properties, straight sections, start coordinates, station data, guideway coordinates, jump points, main arc lengths at jump points, branch-point apexes, distance of branch-command points from the branch points, station Command-Point distances from the branch-point ahead. Load vehicles. Compute station-to-station distances and the number of the station upstream of each branch point. Definitions of the arrays used in the simulation program.

The PRT Network Simulation Program

Generating, loading, and disembarking passengers.
The Command Points and Actions
  Command Line Speed, Reset On Station Exit, Diverge Control, Merge Control, Switch At Station Switch Point, Decelerate to Berth, Advance In Station, Call Empty Vehicles, Speed Change, Emergency Stop.
Additional Routines needed in the Simulation
  Calculate Maneuvers, Up-Date Times, Power and Energy

The Design of a PRT System

The Future of High-Capacity PRT

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The Structural Properties of a PRT Guideway

Calculation of the structural properties of a U-shaped truss guideway in both bending and torsion. Determination of the guideway natural frequency and the critical speed.

Dynamic simulation of a vehicle passing through a merge or diverge section of guideway

The purpose of this dynamic simulation is to determine maximum loads on the wheels and the tire stiffness required to insure passenger comfort.

The Tradeoff between Linear and Rotary Propulsion in PRT Systems\

Analysis of a Bi-Stable Switch

The Optimum Switch Position

Conditions for a Vehicle to Tip

Coasting Tests

LIM Clearance in Vertical Curves

Stopping Distance vs. Transition Length

Policy Issues that will guide the design of the system.

Safety and Security issues, handicapped access, passenger comfort and convenience, operational convenience, ticketing, weather, loading, performance, and standards.

Systems Engineering and Safety

A great deal of systems engineering work has been done to arrive at the current configuration of the a PRT system. The team needs to be sure that the hardware and protocols selected for system control take advantage of the current state of the art. A major part of any automated guideway transit engineering program is to insure that the system will be safe. The safety engineering shall

Review prior work on hazards analysis, fault-tree analysis, and failure-modes-and-effects analysis.
Tabulate data on component reliability from data sources such as the AF Reliability Center.
Estimate system dependability and hence safety using an available model.
Estimate the optimum component mean times to failure that will permit the system dependability criterion to be met at minimum life-cycle cost.
Review the ASCE Automated People Mover Standards to be sure that they are complied with.
Examine in detail the safety implications of the component and subsystem design, and recommend changes when necessary.
Become conversant in safety technology, for example through the System Safety Society.

A series of documents written as Requests for Proposals for the final design and construction of the components of a full-scale test loop with its vehicles, station and maintenance shop will be studied. Each of these RFPs has been written in sufficient detail to enable companies to bid on the work required.

Guideway and Posts – structural engineering

Guideway Covers – mechanical engineering

Chassis – mechanical engineering

Cabin – industrial design and mechanical engineering

Control software and hardware – electronics and software engineering

Propulsion System – power electrical engineering

Wayside Power and Guideway Electrification – power electrical engineering

Civil Works – civil engineering

The Station, Maintenance Shop, Control and Demonstration Room.
Foundations and Landscaping.

Program of Testing – test engineering in cooperation with all others

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Following his undergraduate work he developed methods of structural analysis of supersonic-aircraft wings at the Structures Research Division of NACA (now NASA), and contributed to the design of the F-103 wing. He then moved to the Honeywell Aeronautical Division where he designed aircraft instruments including the first transistorized amplifier used in a military aircraft and performed computer analysis of autopilots for military and space applications. While there he invented and led the development of a new type of inertial navigator now used widely on military and commercial aircraft, and also led the advanced development of a solar-probe spacecraft.

In 1963 he joined the Mechanical Engineering Department at the University of Minnesota and later directed its Industrial Engineering Division. He chaired a Symposium on the Role of Science and Technology in Society; initiated, managed and lectured in a large interdisciplinary course "Ecology, Technology, and Society;" coordinated a 15-professor Task Force on New Concepts in Urban Transportation; and chaired three International Conferences on Personal Rapid Transit (PRT) following which he was elected first president of the Advanced Transit Association.

During the 1970s, Dr. Anderson consulted on PRT planning, ridership analysis, and design for the Colorado Regional Transportation District, Raytheon Company, the German joint venture DEMAG+MBB, and the State of Indiana. For several years he was Distinguished Lecturer for the American Institute of Aeronautics and Astronautics. He lectured widely on new transit concepts and was sponsored on several lecture tours abroad by the United States Information Agency and the United States State Department. In 1982 he was presented with the George Williams Fellowship Award sponsored by the YMCA and presented for public service, and the MPIRG Public Citizen Award.

In 1978 he published the textbook *Transit Systems Theory* (D. C. Heath, Lexington Books), which he has used in his course "Transit Systems Analysis and Design." In addition to engineering students, enrollment in this course has included professional transportation engineers from across United States as well as from Sweden and Korea. In 1981 he initiated and led the development of a High-Capacity PRT system through five stages of planning, design and costing. He developed computer programs for vehicle control, station operation, operation of multiple vehicles in networks, calculation of guideways curved in three dimensions to ride-comfort standards, study of the dynamics of transit vehicles, economic analysis of transit systems, and calculation of transit ridership.

In 1986 he was attracted to the Department of Aerospace and Mechanical Engineering at Boston University where he taught engineering design and transit systems analysis and design; and where he organized, coordinated and lectured in an interdisciplinary course "Technology and Society." On his own time, he organized a team of a half-dozen engineers and managers from major Boston-Area firms to further develop High-Capacity PRT. In May 1989, the Northeastern Illinois Regional Transportation Authority (RTA) learned of his work together with Raytheon Company and, as a result, initiated a program to fully develop PRT. This led to a $1.5M PRT design study led by Stone & Webster Engineering Corporation, followed by a $40M joint development program funded by Raytheon Company and the RTA. While at Boston University, he developed the Maglev Performance Simulator used by the National Maglev Initiative Office, U. S. Department of Transportation, to study the performance of high-speed maglev vehicles traveling within ride-comfort standards over the curves and hills of an interstate expressway.

Following the RTA program, Dr. Anderson gave courses on transit systems analysis and design to transportation professionals in the U. S. and Europe, and he engaged in PRT planning studies including several simulations of PRT and automated baggage-handling systems. In 1992 his PRT system was selected unanimously by a 17-person steering committee over bus and rail systems for deployment at the Seattle-Tacoma International Airport. In 1996 he chaired an international conference on PRT and related technologies in Minneapolis. In 1998 his work led to acceptance of his PRT system as the preferred technology promoted for the Greater Cincinnati Area by a committee of Forward Quest, a Northern Kentucky business organization. In the period 2000-2002 he designed and supervised the construction of a full-scale vehicle that operated automatically on a short segment of guideway for thousands of error-free rides. In 2005 he founded PRT International, LLC through which, with the assistance of several colleagues, he has developed from basic principles a new and improved version of PRT. He continues the challenging task of determining how to fully commercialize a superior PRT system.

For his patents on PRT, the Intellectual Property Owners Foundation named Dr. Anderson an Outstanding American Inventor of 1989. In 1994 he was Distinguished Alumni Lecturer at North Park University in Chicago. In 2001 he was elected Fellow of the American Association for the Advancement of Science for his work on PRT. He registered as a professional engineer in Minnesota and Illinois, authored over 100 technical papers and three books, and is listed in 36 biographical reference works including *Who's Who in America* and *Who's Who in the World.*