Some History of PRT Simulation Programs

J. Edward Anderson, Ph.D. P.E.

Abstract

This paper documents 32 vehicle simulation programs that have been developed since 1969 to simulate the operation of automated vehicles operating in networks of guideway under a variety of strategies.

Introduction

Every group intent on designing a marketable Personal Rapid Transit system has needed to have close at hand a simulation program that permits detailed study of the system's performance characteristics both for design and planning purposes. Since all or any assumptions made in developing the simulation must be thoroughly understood; each group, practically speaking, must develop its own simulation program. Many engineers have understood this necessity and in time I expect that the details will be taught in engineering courses to the benefit of not only PRT designers, but the consulting firms and planners who need to know the details. Over the 40 years in which I have been involved in PRT research, development and design I have become aware of 32 automated vehicle simulation programs of varying degrees of completeness, and it is my purpose in writing this paper to call attention to and discuss them, with the hope thereby that the best ideas will come into common use as the field of PRT matures. The simulation tool is the slide rule of PRT development. If there are additional similar simulation programs, I regret not including them, but I simply am not aware of them.

1970s Era PRT Network Simulation Programs

During the 1970s, at least the following organizations or individuals developed PRT simulation programs:

1. Royal Aircraft Establishment, Ministry of Defence, Farnborough, UK
2. The Aerospace Corporation, El Segundo, CA
3. Morgantown PRT Program
4. Morse Wade, IBM Corporation, Poughkeepsie, NY
5. Applied Physics Laboratory, Johns Hopkins University
6. Prof. Harold York, University of Minnesota
7. Marvin A. Sirbu, Massachusetts Institute of Technology
8. IBM Corporation, Gaithersburg, MD
9. Kandasamy Thangavelu, Colorado Regional Transportation District
10. Johnson, Walter & Wilde, Colorado Regional Transportation District
11. S & A Systems, Dallas, Texas
12. Dr. Sakasita, Colorado Regional Transportation District
13. Professor Alain Kornhauser, Princeton University
14. Messerschmitt-Bölkow-Blohm, Munich

15. University of Karlsruhe, West Germany
16. Raytheon Missile Systems Division

Royal Aircraft Establishment

D. I. Paddison, "Cabtrack Studies: Estimation of Capacity of Cabstops," RAE Technical Report 71132, June 1971. 49 pages and 10 figures.

J. C. H. Longrigg, "Cabtrack Studies: Data Sheets for Track Layouts," RAE Technical Report 71024, February 1971. 32 pages and 7 figures.

The Summary of Paddison's report contains the statement: "Results are presented of a digital computer simulation of the operation of six small and medium-sized Cab-stops." We now refer to "Cab-stops" as "Stations." Section 1.2 of Paddison's report contains the sentence: "Study of the control of a complete network will require a simulation of a network in operation." None of the RAE reports I have seen discuss a complete network simulation, but I have not seen all of the reports the study produced. However, Longrigg provides the formulae needed for calculating all of the curves and off-line transitions used in a complete PRT network.

The Aerospace Corporation

A. V. Munson, Jr., H. Bernstein, J. R. Buyan, K. J. Liopiros, and T. E. Travis of The Aerospace Corporation, "Quasi-Synchronous Control of High-Capacity PRT Networks," *PRT*[1], pp. 325-350. On page 349 the following paragraphs can be found:

> "The PRT network simulation was implemented to assist in establishing system performance parameters such as trip times, waiting times, empty car trip lengths, and guideway and stations loadings as a function of system configuration and operating strategies. A secondary but quite important objective was to provide a test bed for development and demonstration of routing and empty car handling algorithms.
>
> The simulation is implemented in SIMSCRIPT and is currently operational on The Aerospace Corporation CDC 6000 series computers. The configuration of a network with all of its components is specified parametrically and great flexibility is available. In the current version, PRT cars are simulated explicitly so that detailed records may be kept on individual simulated trips. This level of simulation has many uses but because of computer memory requirements is somewhat limited as to the network size that can be accommodated. Another version of the simulator, which uses much of the basic structure already developed, is being designed in which cars are modeled implicitly. This simulation will not provide the detail on individual trips, but will allow simulation of much larger networks for study of global questions such as guideway and station loadings."

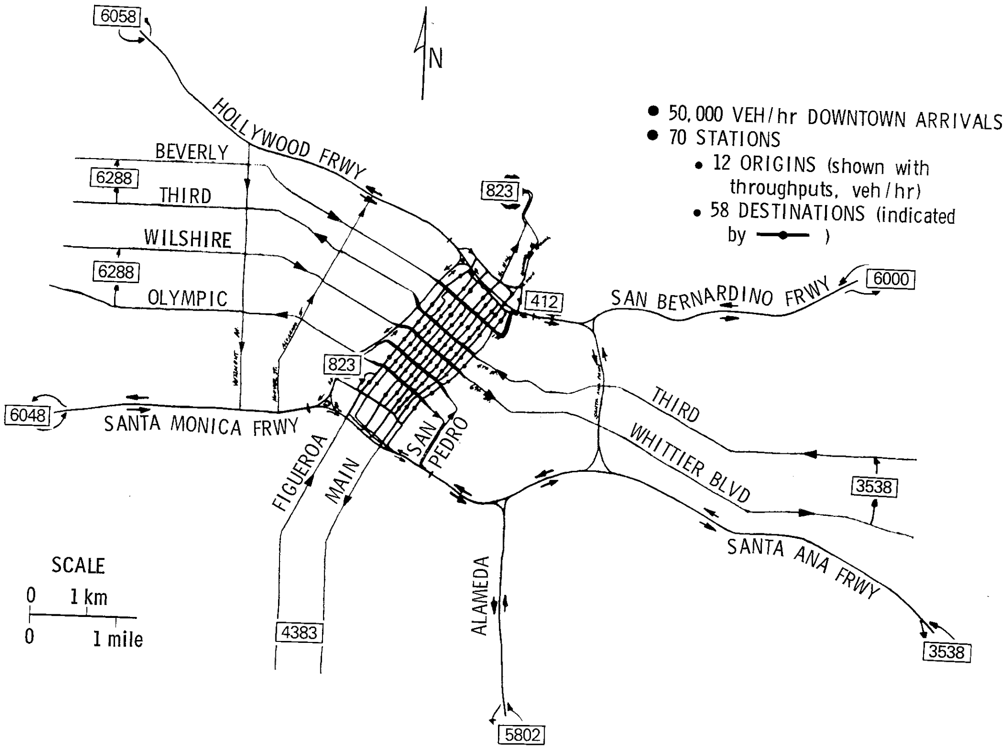
J. H. Irving, H. Bernstein, J. Katz, P. Dergarabedian, and T. H. Silva, The Aerospace Corporation, "Vehicle Management on Large PRT Networks," *PRT III*[2], pp. 345-368.

C. L. Olson, The Aerospace Corporation, *Independent Study of Personal Rapid Transit*, Report

[1] J. E. Anderson, J. L. Dais, W. L. Garrard, A. L. Kornhauser, *Personal Rapid Transit*, Institute of Technology, University of Minnesota, April 1972.
[2] D. A. Gary, W. L. Garrard and A. L. Kornhauser, *Personal Rapid Transit III*, University of Minnesota, June 1976.

No. UMTA-CA-06-0090-77-1, 16 December 1977.

Jack H. Irving, Harry Bernstein, C. L. Olson, and Jon Buyan, *Fundamentals of Personal Rapid Transit*, Lexington Books, D. C. Heath and Company, Lexington, Massachusetts, 1978, 332 pages.



The analysis of a PRT system requires the following steps:

1. Develop and calculate via computer the coordinates of the lines and stations of the network, which must assume certain types of stations and intersections, the discussion of which is given in the above-mentioned documents. As background for this work, equations for calculating all of the curves, transitions to off-line stations, and maneuvers had to be developed; and the throughput of stations and intersections had to be understood. For the Aerospace work, the curve and maneuver calculations are given in Appendix A of Irving et al. The earliest paper I have found on the details of the Aerospace work on station design and throughput is found in *PRT II*[3] on pages 449-460 in the paper "PRT Station Operational Strategies and Capacities," by K. J. Liopiros. Discussion of an intersection simulator is given in the above-mentioned *PRT* paper by A. V. Munson, et al.

2. Develop a switch table, i.e., for each line-to-line diverge point a Left or Right switch command gives the optimum path to every station in the system. The Aerospace papers describe in general terms their method for calculating such a table, which they call a Routing Table.

[3] J. E. Anderson, Ed. *Personal Rapid Transit II,* University of Minnesota, 1974.

3. Estimate ridership. The Aerospace papers describe a novel Monte Carlo mode split model that performs this task more accurately than methods generally used in estimation of ridership on conventional transit systems.

4. Estimate of the line and station loadings, the number of vehicles – occupied and empty – needed, the trip lengths, and for given line speeds the trip times. The results of such calculations are given and discussed in the Aerospace reports.

   NOTE: From my own analysis of a PRT network for Indianapolis in 1980, I developed a method for calculating these quantities. Subsequently one of my students at Boston University, Richard Komerska, developed a convenient method to perform the calculations on a PC. These works are referenced and discussed below under 1980 era programs.

5. Finally, detailed simulations are run in which the arrival, loading and unloading times of each passenger group are randomized. Such a simulation handles merge conflicts and all vehicle movements exactly as they would be handled in a real system. Thus this tool not only gives accurate information on wait times, ride times, and wave-offs; but it provides the tool needed to verify the operational software. Munson et all reported in the above-mentioned *PRT* paper that this work was done, apparently for small networks, but the network on which it was done is not identified in the papers I have referenced.

Morgantown PRT Program

R. H. Bryan, S. E. G. Elias, and R. E. Ward, "Simulation of West Virginia University's Personal Rapid Transit System," Summer Computer Simulation Conference, San Diego, CA, June 14-16, 1972. I have no detail on this work, but because this system, the Morgantown system, has been in operation since 1972 and was well funded, the simulation work would have to be complete.

Morse Wade, IBM Corporation, Poughkeepsie, NY

R. Morse Wade, Staff Engineer, IBM Corporation, "THE MANHATTAN PROJECT: A Cost-Oriented Control System for a Large Personal Rapid Transit Network," *PRT II*, pp. 417-423.

A preliminary analysis of a 500-mile synchronously controlled PRT network for Manhattan is presented; however, few details are given that would help one understand how it was done. It does not appear from the text that Wade carried his simulation to the level of following individual vehicles through the network.

Applied Physics Laboratory, Johns Hopkins University

The APL work to which I have access includes the following papers:

E. J. Hinman & G. L. Pitts, "Practical Safety Considerations for Short-Headway Automated Transit Systems," *PRT II*, pp. 375-380.

S. J. Brown, Jr., "Design Considerations for Vehicle State Control by the Point-Follower Method," *PRT II*, pp. 381-389.

W. J. Roesler, M. B. Williams, B. M. Ford and M. C. Waddell, "Comparisons of Synchronous and Quasi-Synchronous PRT Vehicle Management and Some Alternative Routing Algorithms," *PRT II*, pp. 425-438.

M. B. Williams, B. M. Ford, and M. C. Waddell, "Analysis of Multiple Party Vehicle Occupancy in an Automated, Guideway System, APL/JHU, CP 042/TPR 032, March 1976, 96 pages.

The first two of these papers are preparatory for simulating the operation of vehicles in a network of guideways. The third paper bases its results on a simulation of vehicles operating in a simple network of two-way guideways containing six stations, but interconnected in such a way that there are four paths from any station to any other. Asynchronous, quasi-synchronous, and fully synchronous operation were modeled. It appears that at least 360 vehicles were followed in the simulation. The operation of merges is described for the quasi-synchronous strategy. In the synchronous strategy, all merge conflicts are resolved before a vehicle is permitted to leave the origin station.

The fourth paper describes, as the title suggests, the operation of an automated guideway system using multi-party vehicles. From our interest in documenting simulation programs, this paper is important because it includes the code of its simulation program. Most of the results presented relate to a single two-way loop containing 12 off-line stations, but a more complex system containing three two-way branches meeting at a center point is mentioned. Data curves are shown corresponding to runs with up to about 650 vehicles. This statement is made: "Many aspects of system operation such as details of vehicle movement, i. e. speed variations and merging at station exits, and considerations of station design and capacity, were ignored." They were felt to have only secondary effects on the desired results, which were the relationship between fleet size, vehicle capacity, vehicle occupancy, passenger delays, and the number of intermediate stops required. How accurate that assumption may be can only be determined from a more detailed simulation model.

Prof. Harold York, University of Minnesota

H. L. York, "The Simulation of a PRT System Operating under Quasi-Synchronous Control," *PRT II*, pp. 439-447.

Professor York tested his PRT simulation program on the network shown on the next page, which consists of 23 stations, four multi-level interchanges, and four each of simple merges and diverges. He assumed one-second headway and with his demand he assumed 1100 vehicles. His program produced line flows in vehicles per hour and average waiting times, which he analyzed in some detail. He mentions accumulating data on aborts (which I now call wave-offs as a politically neutral equivalent) but shows no data. In his simulation he divided his guideway into fixed intervals of equal time, taking the set headway as the time interval, and in each interval he placed the destination number of the vehicle that occupies it, with zero for no vehicle. Presumably these time intervals correspond to shorter distances as the vehicles maneuver into and out of the stations. In this way the size of the network is a function of line speed, but need not be and is not stated. His program was written in FORTRAN and ran on a CDC 6400 mainframe computer.

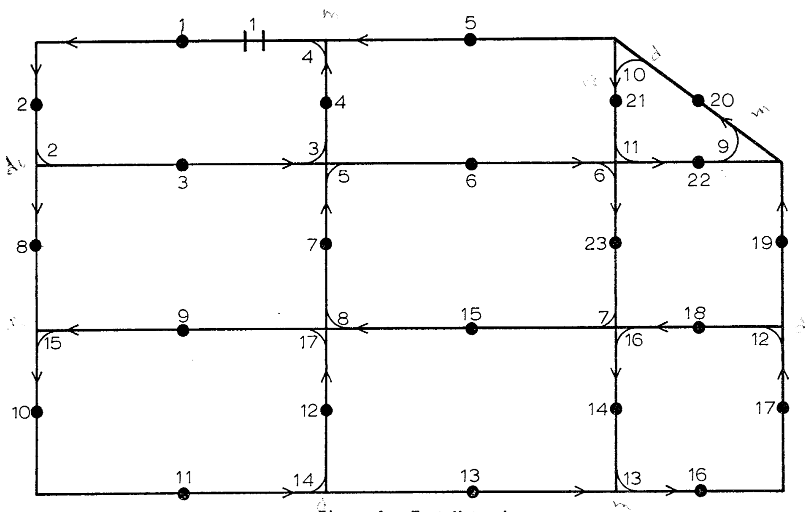
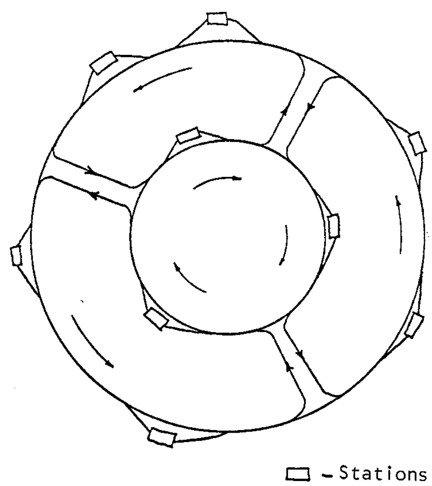


Figure 1. Test Network

Marvin A. Sirbu, Massachusetts Institute of Technology

Marvin A. Sirbu, Jr., "Station Configuration, Network Operating Strategy and Station Performance," *PRT II*, pp. 461-478.

In Dr. Siribu's work, he was mainly interested in understanding the performance and throughput of PRT stations of two types: parallel-loading and linear. To accomplish his purpose, he developed a simulation program in the Simcript 11.5 programming language that ran on an IBM 370/165 mainframe computer, and made runs of 1.5 to 6 hours of simulated time. His guideway, shown at the right, consisted of an outer and an inner concentric ring interconnected in three places with pairs of radial lines, thus giving 6 line-to-line diverges and 6 line-to-line merges. The flow in the outer ring was counterclockwise and in the inner ring clockwise. There were two stations on the outer ring between each pair of radial lines and one station on the inner ring between each pair of radial lines, making a total of nine stations. He operated vehicles in a modified synchronous scheme at 3 seconds headway. The modification was to permit vehicles to slip a slot to resolve merge conflicts, mainly as a result of occasional station rejections or wave-offs that could occur when a station was too full to receive a vehicle. He determined station capacity as a function of a tolerable frequency of station rejections. At each time headway he updated the positions of the vehicles on the links, merges and diverges. Station operations were event oriented in terms of random arrivals of customers, random loading



times, random unloading times, and as a result of these random processes variable vehicle dispatching times. His reports give customer statistics, vehicle statistics, and station statistics. He concluded that his linear stations provided better performance than his parallel-bay stations.

<u>IBM Corporation, Gaithersburg, MD</u>

Martin S. Ross and Alan D. Melgaard, "Systems Management Analysis of Large PRT Networks," *PRT III*, pp. 369-376.

On the network shown below, Ross and Melgaard simulated the operation of automated vehicles of various sizes assuming seven service polities ranging from pure PRT operation (demand responsive single party) to fully scheduled operation. The network has 22.8 miles of guideway, 22 off-line stations with 6 loading and unloading berths each, 36 merges and 36 diverges. They ran the simulations on an IBM 370/155 mainframe computer. Their simulation produced 25 measures of effectiveness that related to resource utilization, performance, and level of service in terms of wait times. The pure PRT runs used a minimum headway of 1 second with a fleet of 1193 vehicles. For the larger-vehicle systems the headways ranged from 2 to 15 seconds and the fleet consisted of 423 to 178 vehicles, with the smaller fleets used for the longer headway scheduled service. Their results showed a high level of sensitivity to vehicle capacity, service policy, and trip demand. For example, the average wait time for pure PRT was only 42 seconds, but for the larger-vehicle, multi-party services the average wait time was longer by a factor of 5 to 13.

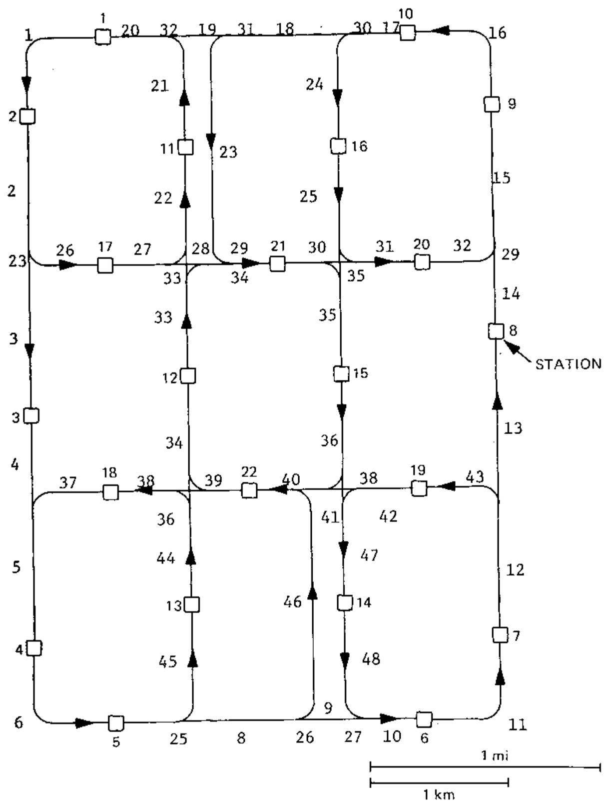


Figure 4. CBD Network

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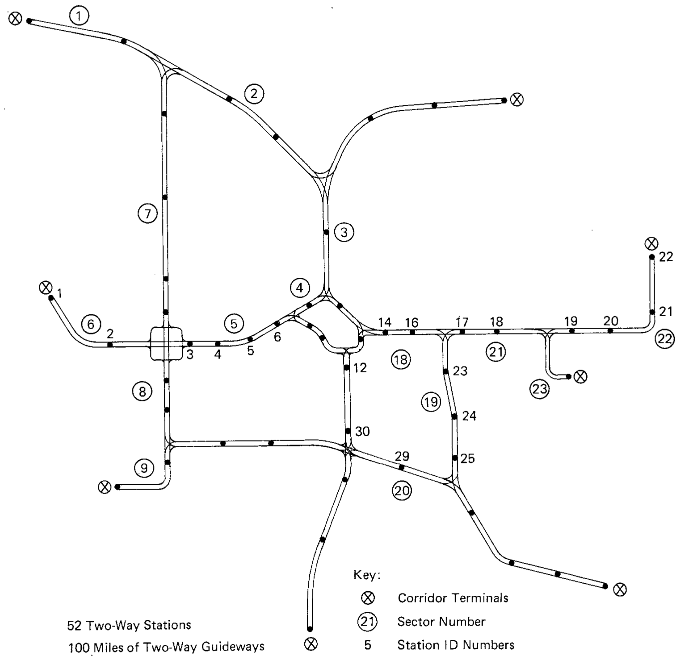
Thangavelu, Colorado Regional Transportation District

K. Thangavelu, "Development and Evaluation of Service Policies for Medium-Headway Automated Rapid Transit Systems," *PRT III*, pp. 329-344.

Thangavelu simulated the operation of medium capacity vehicles operating at a wide range of headways on the city-wide automated rapid transit network (Colorado RTD's 1973 plan) shown below. He assigned passengers to the stations from city-wide demand data that had been obtained in previous studies and determined the minimum-time routes based on a standard linear programming model. He tested dynamically scheduled and what he called "advanced scheduled service" policies. His program output some 23 parameters including every imaginable variable produced in operating such a system. Typical results show average waiting time, average number of stops, average vehicle occupancy, and empty-vehicle statistics.



Johnson, Walter & Wild, Colorado Regional Transportation District

R. E. Johnson, H. T. Walter, and W. A. Wilde, "Analysis and Simulation of Automated Vehicle Stations," *PRT III,* pp. 269-281.

Appendix A of this paper describes a simulation program that models the flow of vehicles through an off-line station. It is a discrete event simulator consisting of 16 routines, is written in FORTRAN IV, and ran on any CDC 6000 series computer.

Appendix B of this paper describes a second simulation program that includes a detailed representation of control-system operation. It is a Monte-Carlo, discrete event simulator also written in FORTRAN. "Extensive input options and input parameters were designed to allow the definition and input of diverse control systems concepts and operating philosophies." The program models passenger and vehicle movement through the station in detail in 0.1 sec steps. The authors say they were working on extending this program to simulation of an entire network.

S & A Systems, Dallas, Texas

J. G. Srygley, S. M. Stokes, and T. N. Coomer, "Transportation System Simulation – Case Studies". This paper was presented at the 46th National Meeting of ORSA (San Juan, Puerto Rico, October 16-18, 1974). It included detailed simulation modeling of GRT Off-Line Stations for Colorado RTD's Alternatives Analysis.

Dr. Sakasita, Colorado Regional Transportation District

Masami Sakasita, "An Analysis of Merge Control for the Automated Scheduled Transit (AST) System," RTD, January 1975, 87 pages.

This very detailed program was written to study through computer simulation the operation of merges. It is another excellent example of the use of computer simulation to study transit problems. The report contains a copy of the program used.

Professor Alain Kornhauser, Princeton University

Alain L. Kornhauser, Steven Strong, and Paul Mottola. "Computer-Aided Design and Analysis of PRT Systems," *PRT III*, pp. 377-384.

The PRT simulation program developed at Princeton University was applied as a 29 station, 21 interchange network for Trenton, New Jersey. The simulation operated in the quasi-synchronous mode and was designed to accurately model a hilly city. It used real demand data and resolved line-to-line merges and flows in and around the stations. A method of simulating the flow of empty vehicles is included in the paper. The outputs are wait times, passenger and vehicle miles traveled, fleet size, etc. Shared riding was investigated.

Messerschmitt-Bölkow-Blohm, Munich

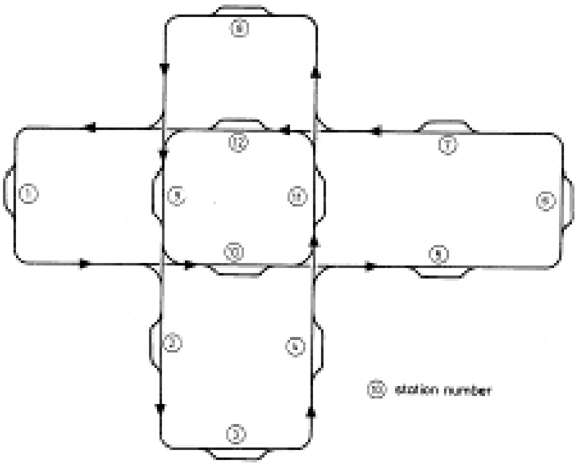
Richard Hesse, "Normal and Emergency Control of Automated Vehicles at Short Headways, with Special Emphasis on the Development, Testing, and Dynamic Simulation of the Cabintaxi System," *PRT III*, pp. 283-288.

Hesse describes a detailed simulation program MBB used to study the Cabintaxi PRT system in specific applications in German cities. The simulation is an asynchronous car follower and addresses all aspects of the movement of vehicles and passengers, passenger destinations, optimum vehicle paths, movement of empty vehicles and outputs the results on a color TV screen as well as in print format, which includes wait time statistics, passenger-miles traveled, energy use, etc. The program was written in assembler language and permitted a network size up to about 30 km, 63 stations, and 1000 vehicles to be studied. It could be expanded by a factor of 10 by enlarging the core memory. The program was used to develop and test network control systems and the optimization of network layouts with respect to topology, track positioning, stations and number of vehicles.

University of Karlsruhe, West Germany

Gerd Bahm, "The Influence of Fleet Size and Vehicle Capacity on the Performance and Service Quality of Group Rapid Transit Systems," *PRT III*, pp. 289-298.

Bahm developed a simulation model, written in the SIMULA 67 programming language, which simulated vehicles of any size or any number of seats operating under automatic control in a network of guideways. The vehicles operated quasi-synchronously in slot lengths that permit complete stoppage, i.e., the brick-wall stop distance. The model was a mixture of an event-oriented simulation and a discrete time-step simulation. It advanced in steps equal to the minimum headway. Passenger arrivals were randomized. The most important output variables were the waiting time, average speed, distance travelled, and headways between vehicles. The paper reported results of application of the model to the network shown here. The author concluded with the statement that he was investigating large networks.



Raytheon Missile Systems Division

D. Girard, "AGTT Car Follower Autopilot – Design and Simulation." Missile Systems Division, Raytheon Company, Memo No. SDD-76-836, 18 March 1976, 97 pages.

This report was prepared as a part of a program to prepare to bid on a federal RFP on control of PRT systems. To test the autopilot, which operated as a car follower, two simulation programs were developed: one of them, called String, employed six vehicles and was used for testing line maneuvers such as responding to line-speed changes, overtaking a slow vehicle, and emergency stopping. The other, called Merge, used forty vehicles to evaluate the merging process, test ride quality and determine the length requirement of the parallel data region. The larger number of vehicles was needed to reach steady state. The detailed dynamics of each vehicle was followed during these simulations.

1980s Era PRT Network Simulation Programs

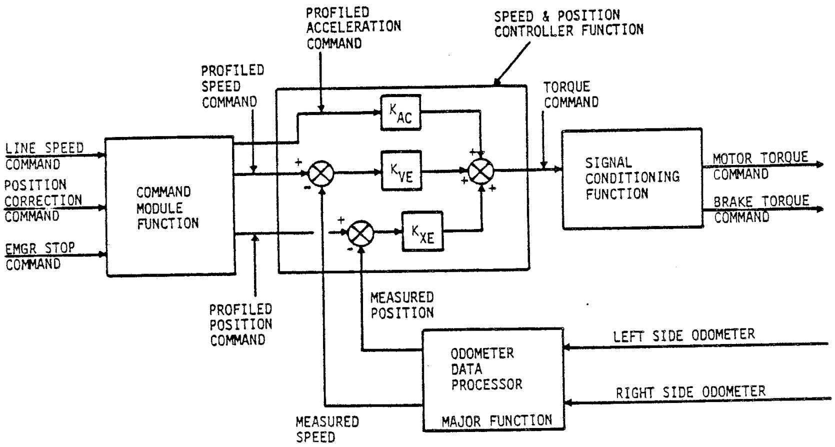
At the beginning of the 1980s, any serious work on a PRT simulation program required the use of computers far too expensive for an ordinary individual to afford, but by the end of this decade such a program could be developed on an easily affordable laptop PC. During the 1980s, PRT simulation programs were developed by at least the following organizations or individuals:

17. Boeing Company
18. Otis Elevator Company
19. The author.

Boeing AGRT Simulation Work

William E. Greve, Donald E. Haberman, and Robert P. Lang, "Advanced Group Rapid Transit Vehicle Control Unit Design Summary, Boeing Aerospace Company, UMTA-WA-06-0011-84-3, May 1985, 249 pages.

Don D. Lyttle, Dave B. Frietag, and Doug H. Christenson, Boeing Aerospace Company, "Advanced Group Rapid Transit Phase IIB, Executive Summary & Final Report," UMTA-WA-06-0011-86-1, March 1986, 205 pages.



The Boeing work in the AGRT program mainly involved developing a vehicle longitudinal control system (VLCS) that would control each of a system of vehicles operating in a network at a minimum of 3 seconds headway. Their controller was a "point follower" in that, as given in the above control block diagram, which is taken from page 18 of the above-cited Greve, Haberman and Lang report, each vehicle follows profiled acceleration, speed and position commands. Feedback of position and speed was taken from the odometers shown in the above diagram, which were digital encoders that directly provided distance information, and speed by differentiating the distance pulses. Proof of their control system involved extensive simulation work in which real components were an increasing portion of the simulation.

Otis AGRT Simulation Work

W. Womack, "Vehicle Longitudinal Control and Reliability Project Summary," Otis Elevator Company, Report No. UMTA-IT-06-0148-79-10, June 1979, 134 pages.

"Zone management and Control Conceptual Design," Otis Elevator Company, Transportation Technology Division, Denver, Colorado, August 1981, 124 pages.

These are reports of the second of the two federally funded AGRT studies aimed at development of an appropriate VLCS that would permit operation of vehicles in networks of guideways as close as 3 seconds apart. These reports describe a point-follower system in which each vehicle followed a calculated maneuver profile to accomplish slot slipping during merging, deceleration into a station berth, acceleration to line speed, and speed changes. During their development program Otis used simulations to verify in detail the operation of their control concept during all maneuvers.

J. E. Anderson simulation program

J. E. Anderson, "Calculation of Performance and Fleet Size in Transit Systems," *Journal of Advanced Transportation*, 16:3(1982)231-252.

Richard J. Komerska, *Development of a Modeling Tool for the Preliminary Design of Personal Rapid Transit Networks*, a Master of Science Thesis in Civil Engineering, University of California, Irvine, 1995 163 pages.

With reference to item #4 on page 4, the above paper derives equations from which to calculate the quantities indicated. Komrska programmed a model that provides a convenient way to make these calculations on a PC.

In August 1986, I initiated the development of a PRT simulation program at a time when I was teaching engineering at Boston University and at the same time organizing and working with a team of engineers to ready the specifications for an operational PRT system. Notwithstanding these other commitments, I had a working program ready by 1990 in time to be included in a proposal for a Phase I PRT Design Study for the Northeastern Illinois Regional Transportation Authority, which was completed in 1992. The program was subsequently used to analyze a 3-mile, 8-station network for Rosemont, Illinois.

With no budget for use of a mainframe computer or a DEC Workstation, both computer hardware and software were then quite limited for me. During my first year at BU I had access only to the first Compaq so-called "portable" PC, which had a 9-inch screen, only 64K internal memory and no hard drive. To see what my simulation was doing, the first version of which I had running within a month of a standing start, I had to refer to print output. A year later I was able to purchase a 286 machine, but it was too slow until it could be upgraded with the 287 coprocessor. A year or so later I upgraded to a 386 then 387. At the time, after experimenting with C, Pascal and various versions of BASIC, I programmed in BASIC because it took less time to program. But it was not terribly satisfactory until Microsoft came out with Quick BASIC 4.0, which a year or so later upgraded to Professional Basic 7.1, which I used for many years as my major computing device. Considering the other commitments I had and my limitations on hardware and software, I estimate that the development of a usable PRT simulation program with today's tools would take me working full time no more than about 4 man-months of effort or about 1000 hours at 60 hours per week.

1990s and 2000s Era PRT Network Simulation Programs

During the 1990s, as a result of the Chicago project, PRT development became quite active again. In Dr. Jerry Schneider's web page http://faculty.washington.edu/jbs/itrans/ in the index under Simulations reference to the following PRT simulation programs can be found. Because of the details given by Dr. Schneider, I see no need to comment further on these programs, except for my own.

20. Hermes PRT Network Simulator by Chris Xithalis (Greece)
21. PRT International (USA) www.prtnz.com
    J. E. Anderson, *Transit Systems Theory,* Lexington Books, D. C. Heath and Company, Lexington, MA 1978, 340 pages, available on www.advancedtransit.org for calculation of curves and maneuvers.
    J. E. Anderson, "Longitudinal Control of a Vehicle," *Journal of Advanced Transportation*, 31:3:237-247, 1997 for the gains of a vehicle controller.
    J. E. Anderson, "Control of Personal Rapid Transit Systems," *Journal of Advanced Transportation*, 32:1:pp. 57-74, 1998 for explanation for the asynchronous point-follower system.
    M. Joborn, "Empty freight car distribution at Swedish State Railways," *Computers in Railways VI*, WIT Press, Boston, Southampton, 361-370, 1998 for an effective means of moving empty vehicles.
    J. E. Anderson, "Simulation of the Operation of Personal Rapid Transit Systems." *Computers in Railways VI*, WIT Press, Boston, Southampton, pp. 523-532, 1998 for a description of the author's PRT simulator.
    J. E. Anderson, "A Review of the State of the Art of Personal Rapid Transit." *Journal of Advanced Transportation*, 34:1, 2000 for how the author applied Joborn's empty-vehicle movement concept.
22. Logistic Centrum's PRTsim software (Sweden)
23. RUF International (Denmark)
24. The Innovative Transportation Simulator (Italy)
25. TrakEdit: PRT Simulator from Taxi 2000 (USA)
26. Raytheon's NETSIM PRT Simulation Program (USA)
27. Calver Marketing (UK)
28. JKH Mobility Services' Simulation Program (USA)
29. Princeton's PRT Simulation Program (USA)
30. BASim (Australia)
31. Simulation and Analysis Tools for Urban Automated Rapid Transit Networks (S.A.T.U.R.N.) (Canada)
32. PRT Microsimulation (UK)

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