Simulation and Analysis of a Demand Responsive, Automated Transit System

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This paper describes a computer simulation of a 12-station personal rapid transit system with offline stations and headways of 10 sec. The simulation has a vehicle assignment algorithm which permits one diversion of vehicles in service to pick up passengers at stations enroute who request the vehicle's programed destination. Results show the diversion strategy provides improved service over a nonstop PRT, for load factors below 30%. At higher demand levels, the additional delay involved in diverting the vehicle outweighs the savings in waiting time.

Introduction

ONE of the results of the current effort to make public mass transit more attractive has been the introduction of personal rapid transit (PRT) systems. These systems attempt to meet the challenge of shifting people from their private automobiles to mass transit by offering riders small, semiprivate, computed controlled vehicles running on fixed guideway systems with offline stations.[1] Patrons utilizing the system are offered nonstop origin-destination service, with vehicles running on a demand basis.

At this time, a number of PRT-type hardware concepts have been built and demonstrated, along with still more numerous paper studies. However, there is a distinct discrepancy between the concept of PRT which emerges from the paper studies and the hardware systems which have actually been built. While the paper studies emphasize small vehicles offering a true personal service and operating at headways of no more than 1 or 2 sec, the hardware systems have demonstrated larger vehicles operating at headways of 10 sec or more and carrying upwards of 20 passengers. This discrepancy is indicative of the difference between our reach and our grasp in the field of automated vehicle operation. An unfortunate result is that much of the performance data on PRT available to transportation planners bears no relationship to the capabilities of the available PRT hardware.

It was with this problem in mind that we determined at Howard University to develop a PRT simulation geared to the relatively large headways and passenger capacities typical of current hardware systems. We wanted a tool to determine what level of service these systems actually could deliver in a realistic operating environment. We realized that, whereas paper studies have often assumed large-scale grid patterns covering an entire metropolitan area, the systems actually built were invariably far more modest, consisting of loops, shuttles, or simple networks with perhaps two or three nodes. We designed our program to permit the synthesis of such simple networks in a modular fashion, out of a combination of simple loops. This served not only the primary object of flexibility, but also permitted program validation using some excellent theoretical insights into loop behavior, developed by Anderson and Sher of Minneapolis Honeywell.[2]

A final feature which we feel is essential for adequately simulating the performance of large vehicle PRT systems is the ability to offer shared ride service. This service strategy compromises the pure origin-destination character of the PRT by permitting limited stops enroute to collect other passengers with the same final destination.

At the present time we have completed development of the basic loop simulation software which has been exercised on 12 and 18 offline station configurations, with both shared ride and nonstop operating strategies. The results have been validated against the Anderson-Sher loop theory and offer some interesting insights into the advantages and limitations of the shared ride concept.

Basic Loop Module

Figure 1 shows the basic loop module. It may consist of any number of offline stations, spaced at arbitrary locations along a closed loop of any desired length. A limited number of empty vehicles may be stored at each station.

Vehicle movement on the mainline of the loop assumes perfect vehicle velocity control at a fixed speed. This is equivalent in performance to a synchronous-type headway control concept where vehicle position is correlated with the location of a slot moving around a fictitious guideway in the central computer. Vehicle velocity and headway may be arbitrarily specified. The basic loop simulation performs the following

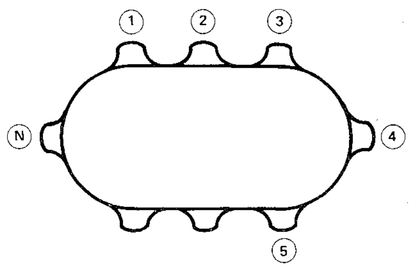

Fig. 1 The basic N station loop module.

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functions: a) passenger generation: b) vehicle assignment; c) vehicle insertion; d) vehicle movement; and e) vehicle removal. These will be briefly described.

Passenger Generation

Passenger arrivals at each station are Poisson distributed with a separate, independently variable mean for each origin-destination pair. The Poisson random variate is generated using a method suggested by H. Kahn of the Rand Corp., by means of the inequality[3]

$$\prod_{i=0}^{N} u_i < e^{-\lambda}$$

N uniform random numbers are generated and multiplied successively until the inequality is satisfied. The Poisson random variate, NX, with mean λ, would be equal to $N-1$. If the inequality is satisfied with the generation of the first uniform random number, the variate NX would be equal to zero.

Vehicle Assignment

The vehicle assignment routine is the most important section of the basic loop module. It is in this section that vehicle operating policy is carried out. Also, through changes in the vehicle assignment routine, it is possible to convert the program to offering either shared ride service or nonstop passenger service.

The vehicle assignment section includes an equation for computing the average waiting time for groups of passengers going between the different origin-destination pairs in the system. Calculation of the average waiting time begins when the first patron (or group of patrons) requesting a vehicle arrives at the station, and ends when the vehicle occupied by that patron, as well as any other patrons arriving after him, and going to the same destination, is inserted onto the main guideway. Included in this period are time spent waiting to board the vehicle, and time spent in the vehicle waiting for clearance to merge onto the main guideway.

The value of the average waiting time is updated with each increment of the simulation clock, for all origin-destination pairs with patrons waiting for a vehicle or waiting to be inserted onto the mainline.

When a trip is inserted onto the main guideway, the average waiting time for the origin-destination pair involves is transferred into the simulation data record, while trip identification information and passenger counts are transferred into the guideway block being used. The average waiting time for the origin-destination pair involved is then reset to zero. Calculations for that pair are resumed with the arrival of the next patron with that original-destination assignment.

Vehicle trip assignment is performed at the time the first patron for an origin-destination pair arrives at the station. Patrons for an origin-destination pair arriving after a vehicle has been assigned for the pair also use the same vehicle.

Assignment of vehicles under the nonstop ride operating policy is rather straightforward. In an effort to keep from depleting storage too quickly, a search is made to see if there is a vehicle upstream with the searching station as its destination. If there is such a vehicle, a check is made to see if it has already been tagged for use upon entering the station. If not, the vehicle is assigned to the trip. This check and search procedure is made for all blocks within an arbitrarily selected arrival time of the station. The time constraint is imposed to avoid having the patrons wait too long. Upon finding and assigning a vehicle for the trip, a board time is assigned to the trip, based upon the expected vehicle arrival time. When the system clock reaches this arrival time, the passengers are permitted to board.

If no vehicles are available on the main guideway, within the arrival time constraint, a vehicle is then requested from the station's vehicle storage, and also to reduce the number of one passenger vehicle trips, the patron first requesting the vehicle is required to wait an arbitrary time interval before being allowed to board the vehicle. If there are no vehicles in the station's vehicle storage area, patrons requesting a vehicle must wait and repeat the assignment routine each increment of the simulation clock, until they succeed in obtaining a vehicle.

Under the shared ride operating policy, on additional step is included in the assignment routine. Upon searching down the line and finding no unassigned vehicles scheduled to arrive at the station, a check is then made of those same blocks to see if there is a vehicle with the same destination as the patron requesting a vehicle. If there is such a vehicle, and it has room for additional passengers, it is then rerouted to the station looking for a vehicle. (However, a vehicle is only allowed to be pulled off the mainline once for a shared ride.) Once again, a board time based on the estimated vehicle arrival time is assigned to patrons requesting the vehicle. Should this search fail to find an available vehicle on the mainline, recourse is made to the station's vehicle storage in the same way as for the nonstop ride operating policy. Conversion of the simulation program from shared ride to nonstop ride status is accomplished by making all vehicles on the mainline appear to be unavailable for use for a possible shared ride.

Vehicle Insertion

Vehicle insertion onto the mainline is accomplished through the use of a merge ramp priority routine, plus a second routine which is responsible for checking for empty blocks on the mainline adjacent to a station. Vehicle insertion onto the mainline is regulated by the second routine which determines whether there will be a conflict with mainline traffice. If the merge block is found to be vacant, all information concerning the trip at the head of the insertion queue is simply transferred into that block.

The vehicle priority routine inserts vehicles onto the mainline on a first-come first-served basis (corresponding to their positions on the merge ramp). Position on the merge ramp is determined by using two counters. The first counter gives trips a position in the insertion queue as soon as passengers are on board. The second counter keeps track of which vehicle in the merge queue is at the front of the line.

Vehicle Movement

As stated earlier, vehicle movement on the mainline is assumed to be under synchronous control. Under this concept, vehicle movement is regulated to correspond with the progress of a moving cell identified with the vehicle in the central computer.[4,5]

This method of operation is achieved in the simulation by dividing the main guideway into a series of numbered slots or blocks. Movement of a vehicle about the main guideway is accomplished by transferring trip information in one block to the block ahead of it at each increment of the simulation clock.

Vehicle Removal

At each increment of the simulation clock, a check is made of the status of designated vehicle egress blocks located throughout the system. For each station, a check is made to determine whether its designated egress block is occupied. If so, another check determines if the vehicle occupying the block has that station as its secondary or final destination—in which case the vehicle or trip is removed from the main guideway.

Removal is accomplished by transferring all trip information into the simulation's permanent data record, along with data acquired from other finished trips. At the same time, vehicle storage in the station is increased by one, signifying the arrival of the now empty vehicle into storage. Data from shared trips is kept separate from data for nonstop trips made during the same run.

Program Validation

The basic loop module has been exercised using both 12- and 18-station configurations with station demand levels from 40 to 1000 passengers per hr. Vehicle storage was limited to 15 vehicles per station, headway was set at 10 sec, and vehicle speed at 30 fps.

Poisson passenger arrivals were used with equal mean arrival rates assumed between all origin-destination pairs. Distance between stations was arbitrarily chosen as 3000 ft.

To eliminate transient effects, the simulation was allowed to run for 30 min of simulation time (about 1/2-3/4 min of CPU time), and then the output data record was reset to zero. The simulation was then allowed to run an additional hour of simulation time, during which actual data were recorded.

To validate the simulation, the results were compared with analytic data based upon equations developed by Anderson and Sher. Their work (see p. 23 of Ref. 2) indicates that the waiting time for a loop system with more than one passenger per vehicle will be limited by

$$(n-1)h/2 \leq WT \leq n(n-1)h/4 \tag{1}$$

where n = number of stations; h = headway, sec; WT = waiting time, sec. The maximum station flow (see p. 21 of Ref. 2) which can be accommodated by assigning only one passenger to each vehicle is given by

$$F = 7200/nh \tag{2}$$

where F = station flow, passengers per hr. Equation (2) defines the lower flow bound at which the limits of Eq. (1) should be expected to apply.

Figure 2 plots these theoretical values, along with simulation results for 12- and 18-station shared ride systems and a 12-station nonstop system. The nonstop system, as expected, becomes asymptotic to the Anderson and Sher upper bound on waiting time at high flow levels. Using shared rides, waiting times are reduced below the maximum value predicted by Anderson and Sher, but remain within their overall envelope. Since shared rides provide more frequent vehicle arrivals at stations, this result is as would be expected. In all cases simulation waiting times for flows above the limit set by Eq. (2) are bounded by the limits of Eq. (1).

Figure 3 shows the average vehcile occupancy for 12- and 18-station systems with shared rides and a 12-station system with nonstop rides. As would be expected, the larger waiting time for the 18-station system produces a higher load factor. Shared rides also produce higher load factors than a nonstop policy.

In addition, Fig. 3 plots the two theoretical relationships determining vehicle occupancy for a nonstop, 12-station system. These are that the vehicles should always carry at least one passenger and that vehicle flow rate is limited by the minimum headway. The latter may be represented by the equation

$$N = Fhn/7200 \tag{3}$$

F = station flow, passengers per hr, and N = average vehicle occupancy. For one passenger per vehicle, Eq. (3) reduces to Eq. (2).

A strategy of attempting to dispatch passengers after no more than an 80-sec delay was followed in the simulation runs. This strategy serves to minimize waiting time by increasing the number of vehicles dispatched. Thus, the simulation would be expected to track the theoretical value for average occupancy unless the waiting time is less than 80 sec, or the theory would produce occupancies of less than one. (In which case vehicle flow would be reduced.) Figure 3 shows the expected correlation between theoretical and simulation load factors for the 12-station nonstop case.

Impact of Shared Rides on Level of Service

Results of the loop simulation provide useful insight into the benefits and disadvantages of the shared ride concept. From Fig. 2, it is clear that significant reductions in waiting time are possible. Figure 4 shows the percent reduction in waiting time as a function of station demand level. It will be seen that a demand level of 120 passengers per hr produces the maximum reduction in waiting time. Such demand would be typical of a lightly used rail transit station during nonpeak hours. At very low levels of station demand there is insufficient traffic on the mainline to create significant opportunities for shared rides. On the other hand, at high flow

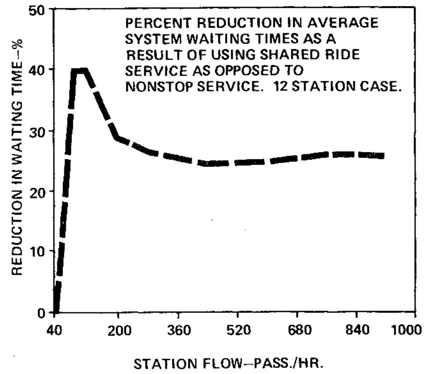

Fig. 2 Average waiting time results.

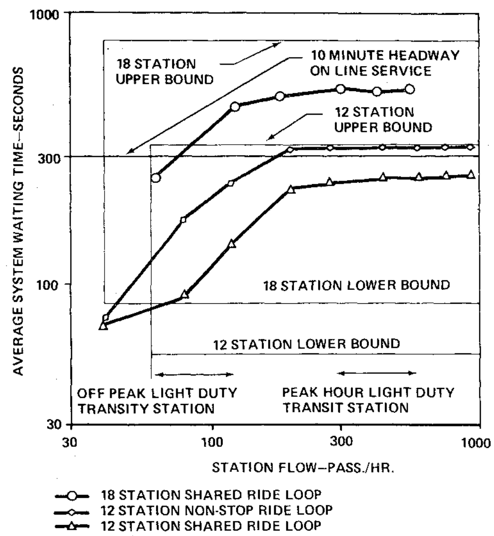

Fig. 3 Vehicle occupancy levels.

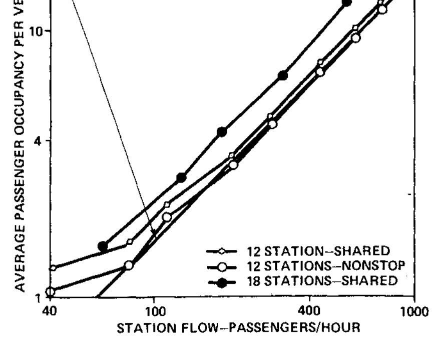

Fig. 4 Average waiting time reductions.

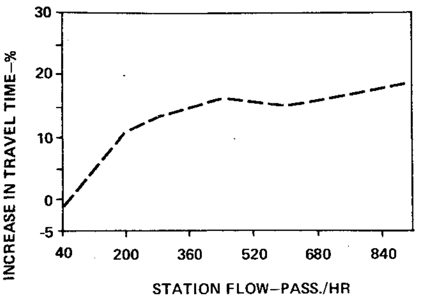

Fig. 5 Average system travel time.

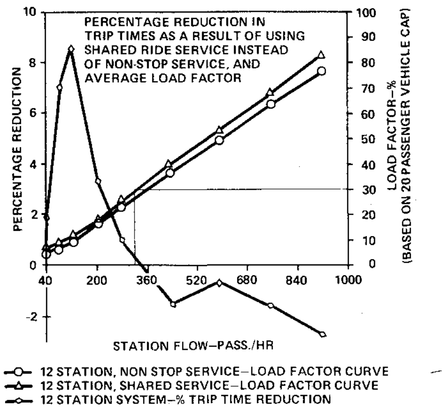

Fig. 6 Percentage reduction in trip times and average load factor curves.

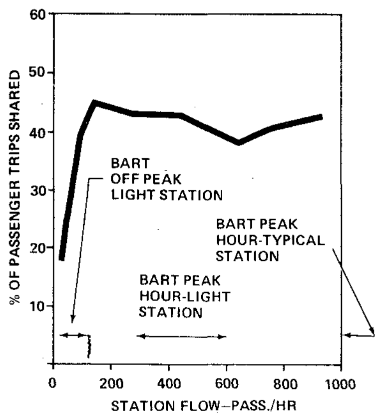

Fig. 7 Shared ride algorithm results.

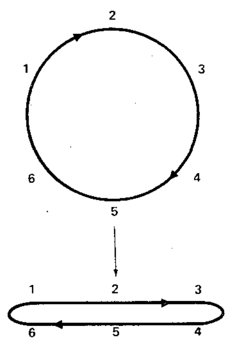

Fig. 8 Generation of a two-way track from a simple loop system.

rates the insertion delay required to insert vehicles onto the mainline from the station becomes appreciable.

Since both shared and unshared rides must be inserted into the main flow, the use of shared rides increases the insertion queue length. This reduces the savings in waiting time when the flow is congested.

Although Fig. 4 shows significant waiting time advantages for shared ride service, these must be weighed against the increased travel time. Passengers on board the diverted vehicle have their travel time increased by the need to stop in the station to pick up the shared riders and then wait to remerge onto the mainline. Fig. 5 shows the increase in travel time as a function of demand level. At low demand levels, mainline traffice is light and the extra insertion time does not impact heavily upon the diverted passengers travel time. Under congested conditions, the travel time penalty approaches 20%. This is sufficient to cancel out the savings in waiting time from the shared ride policy.

The proper parameter to optimize is savings in trip time, where trip time includes both waiting time and time traveling onboard the vehicle. Figure 6 plots trip time savings using the shared ride concept. For high flow rates, it is clear that the simple nonstop service is preferable. However, at station flows below 360 passengers per hr, there is an advantage to the shared ride concept. At these demand levels, a 20-passenger PRT vehicle would be operating at a 30% load factor. This might be typical of off-peak hour service during the afternoon period. Trip time savings using the shared ride concept reach a maximum of about 9%.

It is interesting to notice that a great many shared rides are obtained using the shared ride algorithms in this simulation. Figure 7 shows that typically some 40% of the vehicles pick up a shared ride. Figure 7 also confirms the difficulty in obtaining shared rides when the mainline traffice is very sparse (at the low demand levels).

Network Synthesis Using the Basic Loop Module

The basic loop module may be readily used to synthesize simple networks by incorporating so-called "dummy stations." Vehicles on one loop whose destination lies on another loop are ordered to exit at a dummy station. The existing vehicles are then moved to an insertion lane for a corresponding dummy station on the othe loop. The effect is to generate a quasi-synchronous network. The intersection is under local control. The primary loop always has the right of way, with vehicles transferring between loops by the software equivalent of a full stop sign,

Two-way shuttle tracks may be generated either independently or as a part of a network by collapsing a loop, as suggested by Anderson and Sher (see pp. 25-28 of Ref.2). Origin-destination demand levels are set to zero for loop combinations which are not compatible with the two-track model. Thus, in Fig. 8, all collapsed track flows except 1 to 2 or 3, 2 to 3, 4 to 5 or 6, and 5 to 6 would be set equal to zero.

Conclusions

The basic loop module has been demonstrated to simulate automated vehicle flows accurately. Investigation of the use of shared rides shows this concept has potential for off peak hours—such as during the afternoon. It is not useful for extremely light demands—such as the "owl period," because of insufficient opportunities to share rides. It also cannot be used to improve service during the all important rush hour. It must be emphasized that these conclusions are based upon a 12-station simulation using a specific set of system management rules and may not be borne out by further investigations. By use of dummy stations, the basic loop module can be used to synthesize most of the simple networks currently under serious consideration for PRT operations.

References

[1] MacKinnon, D., "High Capacity Personal Rapid Transit Developments," Office of Research and Development, Urban Mass Transportation Administration, Washington, D.C., 1973, p. 1.

[2] Anderson, P.A. and Sher, N.C., "Analysis and Simulation of Small Vehicle, Offline Station, Demand Responsive Transit Systems," Rept. 7203-3001, Honeywell Inc., Minneapolis, 1973.

[3] Martin, F. F., *Computer Modeling and Simulation*, Wiley, New York, 1968, p. 83.

[4] Sirbu, M. A., "Feasibility of Automated Guideway Control," Vol. II of Systems Analysis of Urban Transportation, Report to the U.S. Dept. of Housing and Urban Development, Washington, D. C., Jan. 1968, National Technical Information Service, New York, 1968, p. 205.

[5] Roseler, W.J., Williams, M.B., Fond, B.M., and Waddell, M.C., "Comparisons of Synchronous and Asynchronous PRT Vehicle Management and Some Alternative Algorithms," Johns Hopkins University, Silver Spring, Md., 1972, p. 2.