DESIGN ANALYSIS OF STATIONS AND INTERSECTIONS OF
A HIGH-CAPACITY PERSONAL RAPID TRANSIT NETWORK

K. Thangavelu, D. S. Berry, and B. M. Shaefer, Northwestern University

This paper describes an effort to develop geometric designs for high-capacity personal rapid transit links, stations, and intersections and to predict and evaluate their performance under quasi-synchronous control at different design and operating conditions. The system assumed 1-way routes and vehicle accelerations and decelerations only on the off-lines. The geometric design of off-lines at stations and intersections considers recommended normal and centripetal acceleration and jerk rates, allowable radius of curvature, required maneuver zone length, and required capacity of the off-line and the line spacing chosen. Typical conditions for a large urban area are considered. In the PRT system, vehicle queues are formed on the upstream and downstream sides of station platforms and intersection turns. The modeling, analysis, and simulation of these queues are described. The excess capacities and the sizes of queuing zones needed can be obtained from simulation results for stations and intersections of different capacities. The resulting average waiting time, the probability of vehicle rejection on the upstream side, the probability of forced switching to prevent the stopping of vehicles on the downstream side, and the achievable guideway density are given as functions of design and operating parameters. The possible trade-offs among design capacity, traffic density, length of queuing zone, and user costs involved at stations and intersections are discussed.

THE CONCEPTS of people movers, personal rapid transit systems, and dual-mode vehicle systems originated in the last decade as solutions to urban transportation problems. The personal rapid transit (PRT) system is proposed as an alternative to automobile use on urban arterial streets. These systems use automobile-sized vehicles on grade-separated guideways and are operated by electronic controls and computers. Complete network traffic control enables efficient routing, scheduling, empty-car dispatching, and balanced loading of the network.

During the past few years various strategies for network traffic control have been proposed: synchronous cycle concept, synchronous slot concept, quasi-synchronous concept, and multizone zone-synchronous concept. The selected network control philosophy affects the system performance—station and intersection use, waiting times and delays in the system, average speed of travel, average trip length, possible guideway density—and also the control, communication, and computer requirements for the vehicle and the network subsystems.

The ongoing research work at Northwestern University consists of designing a hypothetical PRT network for possible application in a large metropolitan area and simulating its operation under various network control strategies to study the effect of control strategy on system performance. This paper deals with the design of stations and intersections for a PRT network under quasi-synchronous control.

ASSUMPTIONS

1. Vehicles operate at uniform speeds over 1-way guideways. The speed selected results in an average speed of travel higher than that possible with automobiles.
2. The stations and intersections are located on off-line guideways, which are designed with consideration to system effectiveness and geometric limitations.
3. The vehicles accelerate and decelerate only in the off-lines.
4. The network spacing and station distribution permit easy accessibility of the system in the CBD and inner-city areas and accessibility from the developed portion of land in the outer rings.
5. The vehicles are automobile-sized and can carry 4 to 6 persons. The average occupancy is 1.5 persons.
6. The vehicle spacing and control systems provide for acceptable levels of safety.
7. The network meets the personal travel demand for automobiles and bus transit expected within a typical large metropolis in 1990.

**ABBREVIATIONS AND NOTATION**

The abbreviations and notation used in this paper are given below.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>am</td>
<td>maximum centripetal acceleration;</td>
</tr>
<tr>
<td>C</td>
<td>guideway capacity, in vehicles/hour;</td>
</tr>
<tr>
<td>Cₕ</td>
<td>station capacity, in vehicles/hour;</td>
</tr>
<tr>
<td>Cᵥ</td>
<td>capacity ratio between main line and HIS;</td>
</tr>
<tr>
<td>Cᵥₚ</td>
<td>C/Cᵥ, theoretical capacity of HIS;</td>
</tr>
<tr>
<td>Cᵥᵣ</td>
<td>velocity ratio between main line and HIS;</td>
</tr>
<tr>
<td>f</td>
<td>tire friction factor;</td>
</tr>
<tr>
<td>H₀</td>
<td>vehicle interarrival time or headway, in s-cycles;</td>
</tr>
<tr>
<td>HIS</td>
<td>high impedance section;</td>
</tr>
<tr>
<td>J</td>
<td>smallest integer such that (when Cᵥ involves a fraction) JCᵥᵣ is an integer;</td>
</tr>
<tr>
<td>K</td>
<td>spacing factor;</td>
</tr>
<tr>
<td>Lᵥₜ</td>
<td>trigger zone length, in feet;</td>
</tr>
<tr>
<td>LCC</td>
<td>local control computer;</td>
</tr>
<tr>
<td>Lₛ</td>
<td>station spacing, in miles;</td>
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<tr>
<td>LVS</td>
<td>local vehicle sensors;</td>
</tr>
<tr>
<td>m</td>
<td>m = Tᵥ/[((Cᵥ - 1)Jₖ), maximum number of vehicles accommodated in the upstream and downstream queues after Markovian renewal process;</td>
</tr>
<tr>
<td>nₖ</td>
<td>average number of vehicles block circling;</td>
</tr>
<tr>
<td>Nₑc</td>
<td>time to communicate, compute, and command vehicle switching, in s-cycles;</td>
</tr>
<tr>
<td>Nᵥₑₚ</td>
<td>travel time from switch to merge node on main line, in s-cycles;</td>
</tr>
<tr>
<td>Nᵥₑᵣ</td>
<td>minimum travel time on downstream side from HIS exit to merge node, in s-cycles;</td>
</tr>
<tr>
<td>Nᵥₑᵣₘ</td>
<td>maximum number of slots from switch to slot sensor;</td>
</tr>
<tr>
<td>Nₛ</td>
<td>number of stations/square mile;</td>
</tr>
<tr>
<td>Nₛₜ</td>
<td>number of slots to be checked to ensure forced switching with given probability;</td>
</tr>
<tr>
<td>pₒ</td>
<td>probability of vehicle being observed block circling;</td>
</tr>
<tr>
<td>pᵣ</td>
<td>probability of forced switching;</td>
</tr>
<tr>
<td>pᵣᵣ</td>
<td>probability of vehicle rejection at switch;</td>
</tr>
<tr>
<td>pₒₚ</td>
<td>(1 - Uᵣ) + pₒ, probability of an empty slot being observed on the main line;</td>
</tr>
<tr>
<td>pᵣᵣᵣ</td>
<td>probability of vehicle being observed seeking switching from main line to HIS or merging from HIS to main line during an s-cycle;</td>
</tr>
<tr>
<td>qᵣᵣ</td>
<td>(1 - Pᵣᵣ), probability of a vehicle being switched at the switch;</td>
</tr>
<tr>
<td>R</td>
<td>allowable radius of curvature;</td>
</tr>
<tr>
<td>Rᵥᵣ</td>
<td>Rᵥᵣ = pᵣᵣ/qᵣᵣ, average number of block-circling rounds;</td>
</tr>
<tr>
<td>S</td>
<td>spacing between vehicles;</td>
</tr>
<tr>
<td>Sᵥᵣ</td>
<td>Sᵥᵣ = S + Lᵥᵣ, length of slot, in feet;</td>
</tr>
<tr>
<td>Sᵥ/V</td>
<td>s-cycle, the time for slot to cross any point on main line;</td>
</tr>
<tr>
<td>Sᵥᵣ</td>
<td>slot ratio, the reciprocal of pₒ;</td>
</tr>
<tr>
<td>Sᵥᵣᵣ</td>
<td>slot time, in seconds;</td>
</tr>
<tr>
<td>tₒᵣ</td>
<td>average interarrival time between vehicles on HIS;</td>
</tr>
<tr>
<td>tᵣᵣ</td>
<td>average block-circling time;</td>
</tr>
<tr>
<td>tᵣᵣᵣ</td>
<td>average waiting time in queue;</td>
</tr>
<tr>
<td>tᵣᵣᵣᵣ</td>
<td>average total waiting time;</td>
</tr>
<tr>
<td>Tᵥᵣ</td>
<td>trigger advance;</td>
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</tbody>
</table>
TH = maximum number of triggers provided;
THN = maximum number of triggers required to allow waiting vehicle to occupy
slot vacated by forced switching;
TM = maximum allowable number of triggers on the downstream side;
TR = trigger used by the vehicle—vehicle waiting time in s-cycles;
TN = trigger used by the vehicle—vehicle waiting time in s-cycles;
U = guideway density;
Urs = guideway density downstream of switch;
Urx = guideway density upstream of switch and on line off which smaller number
of vehicles turn;
V = main-line velocity;
HIS velocity;
\( p_o = p_v/p_s \), density for downstream queue; and
HIS density.

HYPOTHEtical PRT NETWORK DESIGN

Main Lines

The hypothetical PRT network was designed to meet the traffic demand for the
Chicago metropolitan area in 1990 as forecast by the Chicago Area Transportation
Study (CATS) for the finger plan of the Northwestern Illinois Planning Commission (1).
The CATS area in the 1956 study consisted of 8 rings. Each ring was treated as a
uniform area and the internal trips, external trips, and through trips made in each
ring by automobiles and bus transit were obtained. Based on trip lengths, peak-hour
factors, and vehicle occupancy, the loaded vehicle flow rates per mile width of corri­
dor per direction were obtained.

The maximum possible flow is less than the theoretical capacity of the main guide­
way because of the gaps left between vehicles to enable other vehicles to enter from
stations and intersections. Hence, the main-line traffic density or the volume-
capacity ratio is 0.6 to 0.85 at peak times. Several of the vehicles on the guideway
will be empty, proceeding to stations to pick up passengers or returning from stations
after dropping passengers. Thus, the effective use of the guideway is 0.6 or less at
peak times.

The first PRT system should have a theoretical guideway capacity of 3 to 4 times
the capacity of a freeway lane to justify the efforts, time, and funds required for re­
search and development. This requires vehicle headways of about 0.5 sec and results
in an actual loaded-vehicle flow rate of about twice the freeway lane volume. With
this capacity, line spacings of \( \frac{1}{4} \) mile in the CBD, \( \frac{1}{3} \) mile in the inner city, and 1 mile
in outer rings meet the traffic demands in the Chicago area. Speeds of 20, 40, and
60 mph respectively may be considered for the above areas, based on average speeds
of travel desired and the off-line lengths needed at stations and intersections.

Stations

If 1 station is placed on each link, 100 percent of the area in the CBD and inner-city
areas and 39 percent of the area in the outer rings will be within \( \frac{1}{3} \)-mile walking dis­
tance from stations. If 2 stations are placed on each link, the accessible area can be
increased to 64 percent, but the guideway speed will have to be decreased to 40 to 50
mph in the outer rings.

The peak-hour passenger load per station can be estimated from the traffic demand
data. Excess empty vehicles must be provided to stations to serve stochastic passenger
arrivals. Stations must be designed with excess vehicle-handling capacity to accom­
modate stochastic vehicle arrivals. Thus, effective use depends on station and vehicle
use and is of the order of 0.6 or less. The station theoretical capacity is based on
proper vehicle occupancy and effective use.

The ratio of theoretical guideway capacity to the station capacity affects queue char­
acteristics and station performance. This ratio varies in the range of 8 to 18 for the
CATS area PRT network. Table 1 gives the guideway and station capacities and the capacity ratio for CATS area rings (2).

GEOMETRIC DESIGN OF STATIONS AND INTERSECTIONS

The geometry of the off-lines at stations and intersections has been considered by Dais (3, 4). These consist of a switch, a maneuver zone, a high-impedance section (HIS), a rear maneuver zone, and a merge (Figs. 1 and 2).

Switch and Merge

Vehicles exit the main line through the switch and enter the main line through the merge. These consist of 2 Euler spiral pairs. A lateral displacement of 12 ft between center lines of the main line and the off-line is reasonable for a vehicle width of 7 ft. The lateral displacement produced depends on allowable maximum centripetal acceleration and jerk rates. Since superelevation would be difficult to provide for the switch and the merge, all of the lateral acceleration must be balanced by the tire friction and will be experienced by passengers. For a maximum centripetal jerk of 0.125 g/sec, as observed by the Japanese National Railway (5), the $a_x$ will be 0.14 g. The switches and the merges are designed with $a_x$ varying from 0.14 g at 20 to 40 mph to 0.11 g at 60 mph, as recommended by Moyer and Berry (6). At higher speeds, 2 small circular arc segments are used in between the wind-unwind segments of the Euler spirals to obtain the necessary lateral displacement.

Maneuver Zone

The maneuver zones consist of 3 overlapping regions: trigger zone, speed-change zone, and queuing zone.

Speed-Change Zone—The speed-change zones (ramps) provide for vehicle deceleration from $V$ to $V_s$ on the upstream side of the HIS and vehicle acceleration from $V_s$ to $V$ on the downstream side of the HIS. These use trapezoidal deceleration and acceleration profiles. Normal acceleration and jerk rates of 0.25 g and 0.25 g/sec respectively are used for the ramps.

Queuing Zone—The capacity of the HIS off-line is much less than that of the main line. The stochastic vehicle arrival results in queue formation in front of the HIS. The station and turn performances can be measured in terms of probability of vehicle rejection at the switch, the average waiting time in queue, the number of vehicles block circling from a given station, and the total delays on the upstream side. All these depend on $C_r$, $\rho_s$ for the queuing process, and the queue size provided.

Vehicles move at the speed of the HIS on the queuing zone. On the downstream side, the queuing zone is provided immediately after the HIS. The larger the relative velocity is between the main line and the HIS, the smaller the queuing zone length will be.

Trigger Zone—The trigger zone is provided at the switch end of the maneuver zone on the upstream side and the HIS end of the maneuver zone on the downstream side. Triggers, typically electrical loops, are provided at equal spacings on the trigger zone. The trigger spacing depends on the velocity ratio between the main line and the HIS and the length of slot on the main line. Triggers actuate vehicle deceleration circuits and initiate deceleration at proper points on the upstream side and acceleration at proper points on the downstream side. The triggers are operated by the local control computer, which receives communication from local vehicle sensors located on the main line (Fig. 1).

HIS

A platform is the HIS at stations, and the turn is the HIS at intersections. The platforms are linear and use moving belts. People use the belt to deboard and board the vehicle as it moves slowly along the platform. Belt speed is synchronized with that of the vehicles at the platform. Belt stations result in high capacity with small platform size and queue-zone length.
Table 1. PRT system guideway and station design factors.

| Rng | Peak-Hour Person Trips/Direction/Mile Lines/Mile Width of Corridor Width of Speed Ring (persons/hour) | Speed (mph) S_L S_K N_L L_3 C_3 C_L |
|-----|-------------------------------------------------|----------|----------|----------|----------|----------|----------|
| CBD | 13,350                                           | 2        | 20       | 15       | 7,200    | 0.116    | 32       | 720      | 10       |
| 1   | 9,200                                            | 1        | 40       | 25       | 8,640    | 0.106    | 8        | 960      | 9        |
| 2   | 9,270                                            | 1        | 40       | 25       | 8,640    | 0.106    | 8        | 864      | 10       |
| 3   | 9,690                                            | 1        | 40       | 25       | 8,640    | 0.106    | 8        | 720      | 12       |
| 4   | 9,435                                            | 1        | 40       | 25       | 8,640    | 0.106    | 8        | 720      | 12       |
| 5   | 5,040                                            | 1        | 40       | 30       | 7,200    | 0.141    | 4        | 480      | 15       |
| 6   | 3,300                                            | 1/4      | 40       | 30       | 7,200    | 0.141    | 4        | 480      | 15       |
| 7   | 2,580                                            | 1/4      | 60       | 45       | 7,200    | 0.118    | 2 to 4   | 1 to 1/4 | 480      | 15       |

Figure 1. PRT off-line station.

Figure 2. Plan view of PRT intersection.

Figure 3. Triggering on upstream and downstream sides.

Figure 4. Numbering triggers on upstream and downstream sides.
Given the proper spacing between vehicles on the platform, the required vehicle and belt velocity can be obtained for the given station capacity. The platform length is chosen so that it provides for a platform time of 15 to 25 sec and is an integral multiple of slot length at the platform.

The turn consists of an arc with Euler spiral transitions at either end. In high-capacity PRT systems, the turns cannot be designed with the same capacity as that of the main line, for this requires a high turn velocity and hence a large radius of curvature and superelevation, which is unacceptable to the urban situation. The allowable radius of curvature in the urban areas is less than 40 ft for the turns. A tire friction factor of 0.2 g was considered realistic to allow for wet guideway conditions and rubber-tired wheels. If \( R = 35 \text{ ft} \) and \( f = 0.2 \text{ g} \), the allowable maximum turn velocity is 15 ft/sec, which results in a theoretical turn capacity of 4,500 vehicles/hour and slot lengths of 12 ft at the turn. This capacity is considered sufficient in all rings, for only a fraction of main-line vehicles seek to turn at any intersection.

Lower speeds of turning can be used with lower turn capacities and will result in decreased acceleration and jerk during turns. \( \text{Cr} \) is the ratio of theoretical main-line capacity to the theoretical turn capacity, in vehicles/hour. For CATS area intersections, capacity ratios of 1.6, 2, and 3 were considered.

### QUEUING PROCESS ON UPSTREAM SIDE OF HIS

#### Vehicle Arrival on Main Line

In PRT systems using synchronous and quasi-synchronous control, the vehicles move in discrete slots of length \( S_t = S + L_v \). The time taken for a slot to cross any point on the main line is \( S / V \) and is called an s-cycle.

Vehicle observation by the LVS is a Bernoulli process. The probability of a vehicle being observed at LVS seeking switching from the main line to HIS is \( p_v = p_v / \text{Cr} \). The number of vehicles seeking switching during \( n \) s-cycles is given by a binomial distribution of parameters \( n \) and \( p_v \). \( \text{C}_r \) is a measure of the service rate, while \( \text{Cr} \) is a measure of service time in s-cycles.

For the Bernoulli vehicle arrival process, the vehicle interarrival time \( n \) has a geometric distribution. The probability of \( n \), \( p(n) = p_v q_v^{n-1} \), where \( q_v = (1 - p_v) \).

#### Vehicle Maneuver on Upstream Side

A vehicle switched to the off-line moves at main-line speed on the switch. If it need not wait in queue, it traverses the trigger zone at the same speed and decelerates from A to HIS gate G1, as shown in Figure 3.

Suppose another vehicle on the main line with vehicle 1 is switched. If \( H_2 \) is less than \( \text{Cr} \), the vehicle has to wait in queue. If vehicle 2 starts deceleration at the same point as vehicle 1, it will collide with vehicle 1 before reaching G1. If vehicle 2 starts deceleration at the same instant as vehicle 1, it will reach G1, \( H_2 \) s-cycles after vehicle 1. This will result in low use of the HIS capacity, for the HIS can admit 1 vehicle every \( \text{Cr} \) s-cycles. By properly choosing the point where vehicle 2 starts deceleration, one can make the vehicles enter the HIS at intervals of \( \text{Cr} \) s-cycles without collision.

The distance of the point of initiation of deceleration from A is given by

\[
y = \frac{S_t}{(\text{Cr} - 1)} (\text{Cr} - H_2)
\]

\( \text{Cr} \) may be integer or noninteger. Choose a small integer \( J \) such that \( J\text{Cr} \) is an integer. The triggers are located at spacings of \( S_t / [(\text{Cr} - 1)J] \). The value of \( y \) can then be given in terms of number of triggers counted.

The trigger spacing and the time taken to traverse a trigger spacing at normal speed before triggering are both called a trigger. Therefore,

\[
1 \text{ trigger} = \frac{S_t}{(\text{Cr} - 1)J} \text{ ft} = \frac{S_t}{(\text{Cr} - 1)J} \text{ sec}
\]
The triggers are numbered as shown in Figure 4. The lowest trigger is called the base trigger. When the vehicle advance, \( C_r - H_0 \), is positive, triggering has to be advanced:

\[
T_n = (C_r - H_0)J
\]

Given the trigger used by the \( N \)th vehicle, that used by the \((N + 1)\) vehicle is given by

\[
T_{n+1} = T_n + T_A = T_n + J(C_r - H_0) \quad \text{if } T_n \neq 0
\]

\[
T_{n+1} = T_n + T_A = 0 \quad \text{if } T_n = 0
\]

if \( JH_0 > (T_n + JC_r) \)

When \( JH_0 \) is greater than \((T_n + JC_r)\), the vehicle interarrival time on HIS is greater than \( C_r \) s-cycles. \( T_n \), the maximum number of triggers provided, is finite because of the cost of triggers and the trigger zone. If the trigger required by the vehicle is greater than \( T_n \), the vehicle will be rejected at the switch.

Queuing Process on Upstream Side and Its Simulation

In Eq. 3, \( C_r \) is the service time and \( H_0 \) is the vehicle interarrival time in s-cycles. Hence, \( T_n \) and \( T_{n+1} \) are the vehicle waiting time in terms of \( 1/J \) s-cycles for the queuing process involved. \( 1/J \) s-cycle may be called a cycle. A cycle may be used as a unit of time for the off-lines. The queue can be represented by the model \( M/D/1-F \), FIFO, for the vehicle arrival is a Markovian process (the vehicle arrival is an independent process, being a Bernoulli process), the service time is constant, and the queue size is finite.

The main HIS characteristics of interest are \( p_r \) and \( t_{wt} \), both of which should be minimized. The vehicle is rejected when the required waiting time exceeds \( T_n \) or when the queue is full. If \( M \) is the maximum line length provided for, then \( p_r = P_m \), the probability that there are \( M \) vehicles in the line. At stations the rejected vehicles go around the block, increasing the travel time and the trip length and unnecessarily loading the guideway.

The probability of rejection and the average waiting time in queue depend on \( C_r \), \( \rho_s \) for the queuing process, and \( T_n \). The maximum length of queue increases linearly with \( T_n \). Vehicles having a minimum headway of 1 s-cycle require \((C_r - 1)J\) triggers. Hence, \( T_n \) may be provided as integral multiples of \( J(C_r - 1) \) so that an integral number of successive vehicles may be accommodated in the queue after the renewal process.

The queuing process was simulated to determine the probability of vehicle rejection, the average waiting time in queue, and the vehicle interarrival time on the HIS. Experiments were conducted with \( C_r \) values of 8, 12, and 15 for stations and 1.6, 2, and 3 for intersections. \( \rho_s \) for the queuing process was varied from 0.6 to 0.9, and the value of \( m \) was selected in the range of 2 to 8.

Figure 5 shows the flow diagram for the simulation model used. The program is written in FORTRAN IV for execution on the CDC 6400 computer. Each experiment was repeated for 10 independent runs. As a fixed number of 600 vehicles were switched to the off-line, the total number of vehicles received, the total number of vehicles rejected, the trigger used by each vehicle (and hence vehicle waiting time), the vehicle interarrival time at HIS gate \( G_1 \), and the number of rounds made by the vehicle before switching were noted. Also the number of vehicles block circling was noted at regular intervals of 60 s-cycles at stations. Hence, \( p_r, t_{wt}, t_s, \) and \( n_b \) were all calculated for each run. From the 10 independent observations made during the 10 runs, the mean values of \( p_r, t_{wt}, t_s, \) and \( n_b \) were obtained for each experiment. The total waiting time at stations was the sum of waiting time in queue and average block-circling time. The probability and cumulative probability distributions were also obtained.

Characteristics of Queuing Process

Probability of Rejection—Figure 6 shows the variation of \( p_r \) with \( m, C_r \), and \( \rho_s \) at the station upstream side. \( p_r \) decreases at a decreasing rate as \( m \) and, hence, queuing zone lengths are increased. The law of decreasing return applies here. As \( \rho_s \) decreases,
Figure 5. Upstream operation simulation.

Figure 6. Variation of $p_1$ at station on upstream side.

Figure 7. Variation of $p_1$ at intersection.
the average queue length and waiting time in queue decrease, and, hence, \( p \) decreases. At stations, \( p \) decreases as \( C_r \) decreases at \( \rho_s = 0.9 \) because of the increased service rate. At \( \rho_s = 0.8 \), \( p \) first increases and then decreases as \( C_r \) decreases.

The relations given by Saaty (7) were used to calculate \( p \) values for different values of \( m \) and \( \rho_s \). These \( p \) values do not depend on \( C_r \). The calculated \( p \) values lie within the range of \( p \) values observed at different capacity ratios during simulation.

A probability of rejection of 1 to 2 percent is acceptable at stations at peak time. A \( p \) value of 2 percent is obtained for \( \rho_s = 0.8 \) at \( m = 6 \) and for \( \rho_s = 0.9 \) at \( m = 12 \). Thus, higher values of \( \rho_s \) require large trigger zone lengths. A \( \rho_s \) value of 0.8 is feasible for station operation at peak time. During the peak hour, the average \( \rho_s \) will be only 0.64 and, hence, \( p \) will be about 0.2 percent. \( m = 6 \) at \( \rho_s = 0.8 \) results in 6 vehicles being rejected during the peak 20 min in a busy high-capacity station. If \( m = 4 \) were used, \( p = 0.055 \) at \( \rho_s = 0.8 \), resulting in 14 vehicles being rejected during the peak 20 min at the busy station. The \( m \) values of 4 to 6 are reasonable for the stations. Higher values of \( m \) are not recommended because of decreasing benefits.

Figure 7 shows the variation of \( p \) at intersections. Use of noninteger capacity ratios results in increased probability of rejection. A \( p \) value of 1/40 is reasonable for intersections. This is achieved with \( m = 3 \) at \( \rho_s = 0.9 \) and \( m = 5 \) at \( \rho_s = 0.8 \). Since the intersection downstream requires more triggers, a \( \rho_s \) value of 0.8 and \( m = 5 \) are recommended for all intersections. The selected value of \( p \) results in a rejection of 20 vehicles during the peak 20 min in the inner city with \( C_r = 3.0 \). During the other 40 min of the peak hour, \( \rho_s \) is less than \( p \), is of the order of 0.006 to 0.008.

Number of Vehicles Block Circling From Station and Average Number of Rounds Made—At stations, the rejected vehicles block circle and return to the station. The observation of block-circling vehicles on the main line is a Bernoulli process. The number of vehicles block circling has a binomial distribution of parameters \( n \) and \( \rho_b \), where \( n \) is the number of slots around the block and \( \rho_b = p/[(1 - p)] \).

A \( \rho_b \) value of 0.5 percent is allowable; i.e., the average number of vehicles block circling from a station may be 1/200 of the number of slots available around the block. Figures 8 and 9 show the variation of \( \rho_b \) with \( m \), \( C_r \), and \( \rho_s \). At \( \rho_s = 0.8 \), \( \rho_b = 0.35 \) to 0.5 percent at \( m = 4 \) and \( \rho_b = 0.1 \) to 0.2 percent at \( m = 6 \). Thus, \( m = 4 \) to 6 is acceptable at stations. \( \rho_b \) values were both measured and computed from \( p \); they vary with \( m \), \( C_r \), and \( \rho_s \) exactly as \( p \). Average block-circling times were calculated from the \( \rho_b \) values measured. These are given in Table 2 for \( m = 4 \) to 6 and \( \rho_s = 0.8 \).

Average Waiting Time in Queue and Total Waiting Time—The variation of \( t_{q} \) is shown in Figure 10. The queuing time increases as \( C_r \), \( m \), and \( \rho_s \), increase. It increases at a decreasing rate as \( m \) increases. The average queuing time is maximum for the infinite queue and is given by

\[
W_q^* = (\rho_s/2)[C_r/(1 - \rho_s)]
\]

At stations, \( t_{q} \) is the sum of average block-circling time and average queuing time. The variation of upstream total waiting time at stations is shown in Figure 11 for \( \rho_s = 0.8 \). The decreasing utility of additional triggers is evident above \( m = 6 \). At stations, \( m = 4 \) results in total waiting time of 20 to 23 sec in the CBD and inner city and 30 sec in the outer rings. Assuming that acceptable \( t_{q} \) is less than or equal to 30 sec, \( m = 4 \) is acceptable. At \( m = 6 \) and \( \rho_s = 0.8 \), \( t_{q} \) is 13 to 17 sec in the CBD and inner city and 20 sec in the outer rings. Thus, \( m = 6 \) is sufficient for \( \rho_s = 0.8 \).

At intersections, \( m = 5 \) and \( \rho_s = 0.8 \) result in average queuing time of 0.87 s-cycles at \( C_r = 1.6 \), 1.46 s-cycles at \( C_r = 2.0 \), and 2.9 s-cycles at \( C_r = 3 \).

Possible Trade-Offs in Design of HIS

Stations and intersections can be designed with less excess capacity (higher capacity ratio) and a higher number of triggers or more excess capacity and a smaller number of triggers and hence smaller queue size. A third dimension is added by user costs, such as the average total waiting time and the inconvenience caused by the vehicle rejection at a switch. Thus, a trade-off is possible among HIS design and operating costs, trigger costs, and user costs involved.
Figure 8. Variation of $p_B$ with $m$.

Figure 9. Variation of $p_B$ with $C_r$.

Table 2. Block-circling time on PRT network in CATS area.

<table>
<thead>
<tr>
<th>Ring</th>
<th>Average Turn Time (s-cycles)</th>
<th>Main-Line Link Time (s-cycles)</th>
<th>Total Block-Circling Time (s-cycles)</th>
<th>$t_w$ (sec)</th>
<th>$t_{w_l}$ (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBD</td>
<td>56</td>
<td>54</td>
<td>440</td>
<td>0.062</td>
<td>0.025</td>
</tr>
<tr>
<td>1</td>
<td>75</td>
<td>72</td>
<td>588</td>
<td>0.059</td>
<td>0.024</td>
</tr>
<tr>
<td>2</td>
<td>75</td>
<td>72</td>
<td>588</td>
<td>0.062</td>
<td>0.025</td>
</tr>
<tr>
<td>3, 4</td>
<td>75</td>
<td>72</td>
<td>588</td>
<td>0.065</td>
<td>0.023</td>
</tr>
<tr>
<td>5</td>
<td>75</td>
<td>72</td>
<td>588</td>
<td>0.055</td>
<td>0.0225</td>
</tr>
<tr>
<td>6, 7</td>
<td>73</td>
<td>100</td>
<td>692</td>
<td>0.061</td>
<td>0.0225</td>
</tr>
</tbody>
</table>

Note: $p_s = 0.9$ at $m = 7$ has almost the same block-circling time as $p_s = 0.8$ at $m = 4$.

Figure 10. Variation of $t_{wq}$ with $C_r$, $m$, and $p_s$.

Figure 11. Variation of $t_{w_l}$ at station on upstream side.
Figures 12, 13, and 14 show for the stations typical probability and cumulative probability distributions of the number of vehicles block circling, the waiting time in queue, and the vehicle interarrival time at the HIS. Similar curves were obtained for intersections. A fraction of the vehicles have constant interarrival time at the HIS, but others have geometrically distributed interarrival time with a minimum of \((JC_r + 1)\) cycles.

### QUEUING PROCESS ON DOWNSTREAM SIDE OF HIS

The vehicles in queue on the downstream side of the HIS are waiting for empty slots on the main line. The queuing is accomplished by the relative velocity between the main line and the off-line. The vehicle waiting and merging are exactly similar to vehicle merging on freeways.

Triggers are provided to initiate vehicle acceleration at different points on the queuing zone so that the vehicle catches its assigned slot on the main line. The triggers are numbered as shown in Figures 3 and 4.

Suppose a vehicle is triggered by the base trigger at HIS gate G2. If the next vehicle arrives after \(H_{os}\) s-cycles at the HIS exit and the available empty slot has a headway of \(H_0\) s-cycles on the main line with the slot used by the previous vehicle, then the position \(y\) of the point for initiation of vehicle acceleration from G2 is given by

\[
y = \frac{S_h}{(C_r - 1)} (H_0 - H_{os})
\]

(5)

If triggers are placed at spacings of \(S_h/[(C_r - 1)J]\) ft, \(y\) is given in terms of number of triggers counted, as on the upstream side. If \(T_N\) is the trigger used for the \(N\)th vehicle, then

\[
T_{N+1} = T_N + J(H_0 - H_{os}) \quad \text{if} \ T_N \neq 0
\]

\[
T_{N+1} = J(H_0 - H_{os}) \quad \text{if} \ T_N = 0
\]

\[
T_{N+1} = 0 \quad \text{if} \ JH_{os} > (T_N + JH_0)
\]

(6)

Equation 6 is the recursive equation for waiting time in queue for the queuing process involved. The trigger used by the vehicle gives its waiting time in cycles. The queue has a general distribution for vehicle interarrival times. The slot arrival on the main line is a Markovian process (Bernoulli process). The queue size is finite. Hence, the queue can be represented by the Model G/M/1-F, FIFO.

### Vehicle Merging From Downstream Side

At intersections, let \(p_v\) be the probability of vehicle arrival at the exit of a high-density turn. The ratio between a smaller number of vehicles turning off a line and a larger number of vehicles turning off the cross line is the turn ratio. The probability of slots being observed for merging the larger number of vehicles is

\[
p_{sl} = (1 - U_{rx}) + p_v \cdot TR
\]

(7)

Hence, the traffic density \(\rho_o\) for the downstream queue is given by \(p_v/p_{sl}\).

Because of the stochastic nature of vehicle and slot arrival, excess empty slots should be provided on the main line to enable easy vehicle merging. Hence, the \(\rho_o\) to be used is less than 1.0 at stations and intersections.

At intersections, \(C_r\) is small and a large number of vehicles seek to merge. \(TR\) will often be less than 1, and \(p_{sl}\) will be less on the line from which the smaller number of vehicles turn off. \(p_{sl}\) and \(s_r\) can be varied by varying \(U_{rx}\). Thus, merging requirements at intersections determine the feasible guideway density.

The number of triggers provided on the downstream side is finite. Hence, the allowable vehicle waiting time is limited. If a vehicle does not get a slot within this time, it will have to be stopped on the downstream side. This may adversely affect
Figure 12. Probability of number of vehicles block circling.

Figure 13. Probability of queuing time.

Figure 14. Probability of interarrival time in HIS.
the HIS operation and result in undesirable vehicle rejection on the upstream side. A low-priority vehicle on the main line can be forced to switch to the off-line and its slot used to merge a vehicle stopped on the downstream side. If the LVS is located several slots before the switch, the LCC can be provided with information regarding the status of vehicles on several slots so that an empty vehicle may be selected for forced switching without any cost to the users.

Simulation of Downstream Queuing Process

Since the queuing process involved on the downstream side is difficult for analytical study, the required excess slots on the main line, the number of triggers to be provided on the downstream side, the probability of forced switching, and the feasible guideway traffic density were all determined by the simulation method. Experiments were conducted at different vehicle arrival rates by varying $C_r$ and keeping $p_o$ constant at 0.8. The vehicle interarrival times at HIS gate $G_1$ measured during upstream simulation were used to create vehicle arrival. Different numbers of triggers were chosen for the downstream side.

At intersections, $p_o$ was varied from 0.7 to 0.9. The slot arrival was created, and the resulting $p_r$ was measured during the merging process. Hence the acceptable combination of $T_m$ and $p_o$ for the downstream side was obtained. At intersections, choosing $p_o$ determines the $p_{SL}$ required. If $TR$ is known, the required $U_{tr}$ can be obtained. A $p_r$ value of 1/80 is considered acceptable at intersections. This results in forced switching of about 10 vehicles during peak time at a busy intersection with a capacity ratio of 3.0.

At stations, the number of vehicles seeking to merge is small. However, the vehicle interarrival time is large, and hence, for the same values of $p_o$ as used at intersections, the service time is large. This results in a long waiting time and hence a large number of triggers. Thus, stations require smaller values of $p_o$ and larger slot ratios. The experiments were conducted by varying $U_r$ on the upstream side of the station switch from 0.7 to 0.9. For different capacity ratios and constant $p_o$ of 0.8, the resulting $p_{SL}$ and $p_o$ were measured as well as the $p_r$ and average queuing time at different values of number of triggers provided. Based on an acceptable $p_r$ value of 1/200 at stations, the required $T_m$ was selected.

When forced switching is adopted, the downstream side should have a certain minimum number of triggers provided to allow time for the vehicle waiting to catch the slot emptied by forced switching. The minimum number of triggers is given by

$$T_{MN} = N_{CMS} + (N \Delta - 1) - N_{cr} \quad (8)$$

The number of triggers used and the location of the slot sensor are also related. The maximum allowable number of triggers is given by

$$T_{MX} = N_{CMS} + N_{CSH} - N_{cc} - N_{cr} \quad (9)$$

At stations and intersections, for different numbers of triggers, $T_m$ for the upstream and downstream sides, $N_{CMS}$, $N_{cr}$, and $T_{MN}$ were calculated for all rings in the CATS area. The maximum available sensing space before stations and intersections was determined, and $T_{MX}$ was obtained. These values are given in Table 3 for stations. The selected values of $T_m$ lie in the range of $T_{MN}$ to $T_{MX}$.

Let $N_{CSL1}$ be the position of the slot from the merge node when vehicle 1 reaches the HIS exit. Therefore,

$$T_1 = N_{CSL1} - N_{cr} \quad (10)$$

If $H_{05}$ is the headway between vehicles at HIS and $H_0$ is the headway of the next available slot, then

$$N_{CSL2} = N_{CSL1} - H_{05} + H_0$$

$$T_2 = N_{CSL2} - N_{cr} \quad (11)$$
Table 3. Values of $N_{cr}$, $N_{CMS}$, $T_{MN}$, and $T_{MX}$ at station.

<table>
<thead>
<tr>
<th>Region</th>
<th>Speed (mph)</th>
<th>$N_{cr}$</th>
<th>Value</th>
<th>$N_{CMS}$</th>
<th>$m_1$</th>
<th>$m_2$</th>
<th>Value</th>
<th>$T_{MN}$</th>
<th>$m_1$</th>
<th>$m_2$</th>
<th>Value</th>
<th>$T_{MX}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CBD</td>
<td>20.0</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>36</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>39</td>
<td>6</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>21</td>
<td>4</td>
<td>3</td>
<td>37</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>39</td>
<td>6</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>22</td>
<td>3</td>
<td>3</td>
<td>37</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>39</td>
<td>6</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>23</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inner city</td>
<td>35.8</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>46</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>48</td>
<td>6</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>31</td>
<td>4</td>
<td>3</td>
<td>47</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>48</td>
<td>6</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>31</td>
<td>6</td>
<td>3</td>
<td>48</td>
<td>6</td>
<td>3</td>
<td>2</td>
<td>48</td>
<td>6</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>32</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outer rings</td>
<td>50.0</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>42</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>43</td>
<td>6</td>
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<td>2</td>
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<td>3</td>
<td>31</td>
<td>4</td>
<td>3</td>
<td>43</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>43</td>
<td>6</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>31</td>
<td>6</td>
<td>3</td>
<td>43</td>
<td>6</td>
<td>3</td>
<td>2</td>
<td>43</td>
<td>6</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>32</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 15. Variation of $p_j$ at stations.

Figure 16. Variation of $t_{eq}$ at stations on downstream side.

Figure 17. Number of vehicles forced to switch at intersections.

Figure 18. Average queuing time at intersections on downstream side.
When \( T_2 > T_0 \), forced switching is adopted. The position of the first vehicle to be checked is given by

\[
N_{\text{cslf}} = \max(\text{max}(N_{\text{cslf}} - H_D + 1, N_{\text{cslf}} + 1) + 1)
\]  
(12)

Successive vehicles are checked to select a vehicle for forced switching.

Results of Simulation on Downstream Side

Figures 15 and 16 show the simulation results for the station downstream side. At stations, \( T_{\text{sh}} \) is 18 and \( T_{\text{sy}} \) is 24 when LVS is placed on the first slot on the intersection merge. A value of 20 to 24 triggers with \( U_T = 0.85 \) results in \( p_\text{f} \) of 0.004. Hence, at peak time only, 1 vehicle in 250 will require forced switching. About 2 to 3 vehicles will be accommodated in the downstream queue. The average vehicle waiting time is less than 2.0 sec.

At stations, values of \( m = 4 \) for upstream and \( m = 2 \) to 3 for downstream resulting in total trigger zone length of 70 to 80 ft are acceptable; \( m = 6 \) for upstream resulting in total trigger zone length of 104 ft is sufficient. On the upstream side, the length of the trigger zone is constant at all values of \( C_r \), but the number of triggers varies. On the downstream side, the number of triggers increases slightly with \( C_r \), but the trigger zone length decreases with an increase of \( C_r \).

At intersections, \( T_{\text{sh}} \) varies from 17 to 25 and \( T_{\text{sy}} \) varies from 29 to 42. However, if the vehicles are allotted slots while they are on the turn, \( T_{\text{sh}} \) and \( T_{\text{sy}} \) can be decreased. \( T_s \) can then be low to decrease the downstream trigger zone length.

Experiments were conducted in which \( T_s \) was varied from 10 to 28 at different values of \( C_r \) and \( p_o \). Figures 17 and 18 show the simulation results for the intersection downstream side.

\( p_r \) increases at an increasing rate as \( p_o \) is increased at all values of \( C_r \) and \( T_s \). \( p_r \) is large at higher values of \( C_r \), because of higher interarrival time of vehicles and hence higher service time at the same \( p_o \). \( p_r \) decreases as \( T_s \) is increased. A \( p_r \) value of 1/80 was selected as acceptable. The same value of \( p_r \) is obtained at higher values of \( p_o \) when the \( T_s \) used is large at a given \( C_r \). At lower values of \( C_r \), lower \( T_s \) and yet higher values of \( p_o \) can be used.

Table 4 gives the \( p_o \) values feasible and, hence, \( U_{T_s} \) and \( U_{T_r} \) values feasible at different values of \( T_s \) and \( C_r \) for \( p_r \) of 1/80. Higher values of \( p_o \) require more triggers and trigger zone length. A trade-off is possible between a higher value of \( T_s \) and a smaller value of \( U_{T_s} \).

\( U_{T_s} \) values of 0.85 at \( TR = 0.75 \) and about 0.75 at \( TR = 0.5 \) were considered acceptable from guideway and intersection operation considerations. This requires a \( T_s \) value of 18 at all values of \( C_r \). The resulting trigger zone length varies from 80 ft in the outer rings to 100 ft in the CBD at \( C_r = 3.0 \). At lower values of \( C_r \), because of smaller relative velocity and velocity ratio, \( L_{tr} \) is higher. At \( C_r = 1.6 \), \( L_{tr} \) is 270 ft in the outer rings and 168 ft in the CBD.

Thus, use of larger capacity ratios and hence smaller capacities are preferred wherever possible. Also the variation of \( U_{T_s} \) with \( TR \) is small at larger capacity ratios; hence, \( U_{T_s} \) can be kept in the range of 0.70 to 0.85 for most intersections.

\( t_w \) increases with \( p_o \), almost linearly, and increases with \( T_s \) and \( C_r \), as is expected. At the selected value of \( T_s \), \( t_w \) varies from 4.6 s-cycles at \( C_r = 3.0 \) to 5.5 s-cycles at \( C_r = 1.6 \). \( t_s \) at an intersection varies from 7.7 s-cycles at \( C_r = 3.0 \) to 6.4 s-cycles at \( C_r = 1.6 \). At higher values of \( C_r \), the time spent at the intersection off-line is slightly more. However, because of lower \( L_{tr} \) and hence the resulting higher feasible speeds of the main line, the travel time will be less at \( C_r = 3.0 \) than at \( C_r = 1.6 \).

Figure 19 shows the operating chart for intersections and stations. Suppose \( p_o \) for an intersection leg is given. It is shown as point A in Figure 19. \( p_o \) can be selected based on allowable \( p_r \), available \( T_s \) on the downstream side, and \( C_r \). Point B gives the required \( p_{ili} \) and CD gives \( U_{T_s} \). If \( TR \) is known, \( U_{T_s} \) can be obtained. If \( U_{T_s} \) is given, the required \( TR \) and \( p_r \) for the cross leg can be obtained. If higher values of \( TR \) are used, \( U_{T_s} \) can be large, as Figure 19 shows.
Table 4. Operating values at intersections for $p_1 = 1/80$.

<table>
<thead>
<tr>
<th>$C_r$</th>
<th>$T_a$</th>
<th>$p_0$</th>
<th>$U_{Tr}$</th>
<th>$L_{Tr}$</th>
<th>$t_{si}$</th>
<th>CBD</th>
<th>Outer Rings</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>16</td>
<td>0.7475</td>
<td>0.7766</td>
<td>0.8433</td>
<td>0.9099</td>
<td>4.20</td>
<td>87.2</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>0.785</td>
<td>0.7979</td>
<td>0.8646</td>
<td>0.9312</td>
<td>6.10</td>
<td>119.9</td>
</tr>
<tr>
<td>2.0</td>
<td>16</td>
<td>0.670</td>
<td>0.7402</td>
<td>0.8402</td>
<td>0.9402</td>
<td>4.70</td>
<td>213</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>0.921</td>
<td>0.7657</td>
<td>0.8657</td>
<td>0.9657</td>
<td>6.60</td>
<td>293</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>0.980</td>
<td>0.7919</td>
<td>0.8919</td>
<td>0.9919</td>
<td>9.30</td>
<td>373</td>
</tr>
<tr>
<td>1.6</td>
<td>16</td>
<td>0.945</td>
<td>0.7209</td>
<td>0.8459</td>
<td>0.9701</td>
<td>5.40</td>
<td>240</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>1.00</td>
<td>0.7500</td>
<td>0.875</td>
<td>1.000</td>
<td>5.80</td>
<td>330</td>
</tr>
</tbody>
</table>

CONCLUSIONS

A PRT network has been designed to carry all internal automobile trips occurring in 1990 in a high-density large metropolis. The theoretical guideway capacities required are about 4 times those of freeway lanes. With line spacings of $1/4$, $1/5$, and 1 mile in the CBD, inner city, and outer rings respectively for the network of 1-way routes, respective speeds of 20, 40, and 40 to 50 mph are feasible.

Stations using moving belts are recommended for high-capacity PRT systems having station capacities of 480 to 960 vehicles/hour. Such belt stations result in shorter platform lengths and smaller vehicle queues at stations. The geometric design of stations and intersections has assumed acceptable and conservative normal and centripetal acceleration and jerk rates.

The stations should be designed with 25 percent excess capacity, for only 80 percent use is possible. The stations should provide for accommodating a maximum of 4 to 6 vehicles on the upstream queuing zone and 2 to 3 vehicles on the downstream queuing zone. The average waiting time will be 20 to 30 sec on the upstream side and
less than 2.0 sec on the downstream side, and probability of rejection on the upstream side at peak time is 2 percent. At a guideway density of 0.85, the probability of forced switching at stations will be 1/250 at peak time.

For intersections, capacity ratios of 1.6, 2.0, and 3.0 were considered. The turns in a high-capacity PRT network cannot be designed for the same capacity as the guideways, for this will result in unacceptably large radii of curvature and superelevation. The intersection should accommodate a maximum of 5 vehicles on the upstream side of the turn and provide for a maximum waiting time of 18 s-cycles on the downstream side. A probability of rejection of 1/40 and probability of forced switching of 1/80 are feasible at peak time. To keep the feasible guideway density at 0.75 to 0.85, the turn ratio should be larger than 0.5 and as high as 0.75. The average waiting time at an intersection is less than 2.0 sec on the upstream side and 3.0 sec on the downstream side.

The trigger theory can also be used for vehicle merging with synchronous control strategy and will result in less maneuver zone length, less power required, and less inconvenience to passengers.

At present a 60-station PRT network operating under quasi-synchronous control is being modeled for simulation to determine possible average guideway density, average speed of travel, vehicle use, total waiting times and delays, and other operating data. The proposed simulation of the 60-station network will provide an opportunity to test various new ideas introduced in this project.

**COMPARISON WITH PREVIOUS WORK**

York (8) simulated a PRT network under quasi-synchronous control. The guideway capacity was 3,600 vehicles/hour. In the present paper theoretical guideway capacities of 7,000 to 8,000 vehicles/hour were considered realistic for the PRT to be an efficient alternative to the automobile.

Dais (4) used large centripetal acceleration and jerk rates, superelevation for switches, and small separation between the main line and the off-line in the geometric design of off-lines at stations and intersections. These are unacceptable to some transportation engineers. Lower rates are used in this paper.

A high-capacity PRT system requires station capacities of 480 to 960 vehicles/hour. Since use of taxi stations results in large vehicle queues, belt stations are preferred. Munson (9) simulated belt stations by using gates on the upstream and downstream sides. However, the relations between main-line and off-line capacities and velocities and gate spacing were not given. Munson did not treat the station problem as a queuing process, and the trade-offs possible among service rate, traffic density, queue zone length, and user costs were not considered.

In contrast with the approach used by Munson, the approach in this project involved detailed mathematical analysis and queues modeled as M/D/1-FIFO and G/M/1-FIFO. The influence of HIS capacity, traffic density, and number of triggers on excess capacity and queue zone length required, average block-circling time, and total waiting time has been considered, and the possible trade-offs have been analyzed. The probability and cumulative probability distributions of waiting time in queue and inter-arrival time on HIS have also been obtained.

Brill (10) modeled vehicle motion ahead of a bottleneck as a queuing model and obtained the distribution of slow-down points for a freeway system.

Munson (9) simulated an intersection with off-line capacity and speed the same as those for the main line, as used in a low-capacity, low-speed PRT system, and slot shifting that used repeated combined acceleration-deceleration maneuvers on the main line to reduce the probability of rejection. Such maneuvers require large excess power and result in much brake wear and passenger inconvenience. Dais (4) simulated intersections of the same capacity as the main line and assumed vehicle stopping on the off-line.

For the high-capacity PRT network in this project, intersection capacity is less than main-line capacity and slot slipping maneuvers are only on the off-lines. To prevent rejection of high-priority vehicles at the switch, forced switching is adopted at stations
and intersections. It constrains the number of downstream triggers, depending on sensing space available and the length of main line between switch and merge.

REFERENCES