tern, which will provide walking accessibility to more
of the CBD. Had the guideway length been held constant,
and the spacings and number of stations varied, the ef-
fect of station spacing on trip diversions would have ap-
peared to be reversed.

The same problem of choosing which parameters to
hold constant is the source of the intuitively unappealing
trend of increasing diversions with increased station
spacings shown in Figure 5. A reader could easily con-
clude from that figure that the best way to increase DPM
ridership is to locate stations as far apart as possible,
since the increasing ridership trend on that figure is the
strongest of any presented in the paper. This, of course,
disregards travelers' willingness to walk and walk-
refusal distances. Would it not be less potentially mis-
luding to present that figure with guideway length as
the independent variable, or to replot the results for
constant guideway length, with station spacings and
number of stations varying?

There is a very real need for the development of
planning tools that can be used to design DPM systems.
The demand-related aspect of the work reported in the
paper appears to be a worthy contribution toward filling
this need, but the supply modeling seems to have suffered
from some overly generalized geometric assumptions.
Combination of the demand analysis reported here with
a more geometrically specific supply analysis such as
I suggested in another article (3) would produce a
significantly more powerful DPM design tool. The re-
sults derived by use of such a DPM design tool need to
be presented so that the significance of the respective
independent and dependent variables is made unmistak-
ably clear to avoid possible misinterpretations.

REFERENCE

3. S. E. Shladover. Activity Center Circulation: The
Competition Between Automated Guideway Transit
and Pedestrianization. Transportation Research,
Vol. 11, No. 4, Aug. 1977, pp. 265-278.

Authors' Closure

The discussion is useful on two grounds: It ventilates
some of the problems associated with the complexity of
DPM system design and it provides the opportunity for
us to clarify the possible misconceptions arising from
the paper and omissions therein.

Let us handle the omissions and misconceptions first.
Our analysis assumes that (a) the station coverage areas
are diamond-shaped, not annular, which is indeed a
necessary assumption for a grid street pattern; (b) sta-
tions are spaced equally, far to do otherwise would be
unnecessarily complex and unmanageable; (c) guideways
are aligned either as a loop or a shuttle; (d) stations are
located to maximize coverage, which could, nevertheless,
lead to overlap, particularly if there are a large number
of stations, spaced close together; and (e) service is
provided without skip stops, alternate routes, or other
sophisticated arrangements, a reasonable assumption
for the first wave of DPMs.

The explanation for the very different patterns of DPM
diversions among walking trips and line-haul transit
trips with respect to station spacing, number of stations,
and coverage, lies in the fact that the walking trips di-
verted to the DPM involve two new walk links, access and
egress, but the transit trips diverted involve only one.
This occurs because the transit station and DPM station
are located at the same point.

The discussant is quite right that the use of the sys-
tem length as a variable in the graphics would add an-
other valuable dimension to the paper. Indeed, longer
system length would provide added DPM accessibility
for walk trips, albeit with the danger of diminishing ef-
fectiveness. Unfortunately, in the interest of brevity,
only a sampling of the derived relationships are shown.

The full report, which this paper summarizes, pro-
vides an estimate of DPM demand for 504 explicit com-
binations of DPM and CBD characteristics, including
system length, for each of five categories of demand.
From these, serious evaluation of alternative DPM con-
figurations can take place. In addition, six DPM service
alternatives, two line-haul transit arrangements, and a
spectrum of highway configurations are treated in the
analysis. We hope that a reading of the full report will
remove any unintended misinterpretations that emanated
from the necessarily telescoped version presented here.

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Development of Efficient Central
Management Strategies for Advanced
Group Rapid Transit Systems

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SRI International, Menlo Park, California
Norman R. Nielsen, Information Science Laboratory, SRI International, Menlo Park,
California

This paper presents a summary of a computer-aided method for develop-
ing efficient central management system strategies for advanced group
rapid transit systems by use of medium-sized, automatically controlled
vehicles that travel on dedicated guideways. Some efficient central man-
agement strategies for group rapid transit systems are presented.
agement system strategies developed for a test network that uses the
method are presented and discussed in detail. The method consists of an
iterative process in which experienced transit system operators make com-
plex, judgmental decisions and a computer performs extensive and repeti-
tive computations. This computer-aided method allows transit system
operators to compare the consequences of various central management
system strategies in terms of such measures as passenger wait times, num-
ber of passenger intermediate stops, vehicle fleet size, vehicle load factor,
and vehicle flows in various guideway sections and at various passenger
stations. After studying such measures, operators can develop a set of
efficient and realistic central management system strategies. The
computer-aided method and the associated computer simulation pro-
gram are general in nature and can be used to develop central manage-
ment system strategies for a variety of network configurations and trip
demand data.

As part of a feasibility study of an advanced group rapid
transit (AGRT) system in an urban environment, which
was undertaken for the Urban Mass Transportation
Administration (UMTA) (1, 2), we developed a powerful
simulation program to test various central management
system (CMS) strategies for the AGRT system proposed
by Rohr Industries. The AGRT system uses medium-
sized, automatically controlled vehicles that have a
typical capacity of 12 passenger vehicles. Rohr's
CMS is based on the nonsynchronous mode of vehicle
control. Typical headways are 4-6 s; the minimum
allowable headway is 3.1 s.

AGRT systems typically will be used in urban en-
vvironments where the network to be served has a grid
pattern. Furthermore, for AGRT systems that use
relatively small vehicles to provide personalized ser-
vice, demand-responsive service is more desirable
than fixed-schedule service, particularly during off-
peak periods. Even during peak periods, fixed-
schedule strategies do not necessarily provide efficient
service and a high vehicle-load factor. When a route
network is even moderately complex and vehicle size
is small, numerous routing and scheduling strategies be-
tween various origin-destination (O/D) pairs become
possible. Therefore, a sufficiently detailed CMS
simulation program was developed to test several
strategies for a variety of networks and trip demand
data.

This paper presents the basic functional details for
the CMS simulation program and the results of the ap-
lication of the program to a test network. The
methodology and the simulation program developed are
essentially independent of the design details of the
AGRT system.

THE PROBLEM

Central management of an AGRT system requires the
development of an efficient strategy of operations to
serve a specified demand given (a) a guideway network
in terms of the O/D nodes (passenger stations) and
connecting links (guideway tracks), (b) the O/D demand
data of passengers, and (c) the capacity of AGRT ve-
hicles. Unfortunately, no single criterion of efficiency
can be defined realistically. However, the following performance measures can be used to compare various
alternatives:

1. Wait and trip times of passengers,
2. Number of intermediate stops between various
O/D pairs,
3. Deviations from shortest distance routes between
O/D pairs,
4. Vehicle fleet size required,
5. Vehicle flows on links and in stations,
6. Delays under failure conditions, and
7. Capital and operating costs.

The study of such measures will enable experienced
transit system planners and operators to develop ef-
ficient CMS strategies after a few iterations.

METHOD OF APPROACH

The central management of an AGRT system has the
following major functional requirements:

1. Vehicle assignment in response to a trip request,
2. Route designation of vehicles,
3. Empty vehicle management, and
4. Suitable contingency plans for failure conditions.

The alternatives available to the designer of a CMS
essentially consist of two types of design variables:

1. Planning variables—variables that must be de-
dined early in the design process (e.g., station sizes,
turnarounds, bypasses, storage and maintenance areas,
and fleet size), and
2. Operating variables—variables that can be ad-
justed dynamically once the AGRT system has been put
in place (e.g., stopping policies, vehicle assignment
policies, vehicle routing policies, and operating fleet
size).

These design variables can be combined in a number
of ways, and their combination requires considerable
human judgment; however, the manual calculation of
various performance measures for various combina-
tions of design variables is a difficult and laborious
process. In view of these considerations, the study
team developed a method whereby complex judgmental
decisions (such as the definition of alternative stopping
policies) could be made by experienced transit system
operators, and the extensive and repetitive computa-
tions needed to calculate various performance measures
could be performed by a computer. A simulation
program was developed to test various combinations of
design variables, study their consequences in terms of
relevant performance measures, and eventually de-
velop a set of efficient CMS strategies. Figure 1 shows
the overall human/machine iterative process by which
suitable CMS strategies can be developed.

Figure 1. Man-machine iterative process associated with the
development of CMS strategies.
Table 1. Overview of the principal functional models of the CMS simulation program.

<table>
<thead>
<tr>
<th>Functional Model</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger-station interface</td>
<td>To generate random numbers of trip requests of varying party sizes and with varying O/D basis.</td>
</tr>
<tr>
<td>Gate operations</td>
<td>To calculate the dwell time a vehicle spends in a station on the basis of boarding and deboarding.</td>
</tr>
<tr>
<td>Vehicle-station interface</td>
<td>To calculate the time a vehicle spends in a station in addition to dwell time, as a function of station configuration.</td>
</tr>
<tr>
<td>Station capacity</td>
<td>To determine whether vehicles can enter a station based on a prespecified capacity.</td>
</tr>
<tr>
<td>Trip assignment</td>
<td>To locate a vehicle within a prespecified vicinity of trip requesting station, test its acceptability, and assign it to the request.</td>
</tr>
<tr>
<td>Routing</td>
<td>To route the vehicle on a switch-by-switch basis based on prespecified switching tables.</td>
</tr>
<tr>
<td>Empty vehicle distribution</td>
<td>To route empty vehicles based on prespecified algorithms. The algorithm will be developed offline.</td>
</tr>
<tr>
<td>Training vehicles</td>
<td>To study the possibilities and consequences of entraining the vehicles.</td>
</tr>
<tr>
<td>Scheduled vehicles</td>
<td>To model the operations of scheduled vehicles.</td>
</tr>
<tr>
<td>Zone management</td>
<td>To model the effects of zone congestion and the strategy for relieving this congestion.</td>
</tr>
<tr>
<td>Central scan</td>
<td>To model the central scan functions of the CMS.</td>
</tr>
<tr>
<td>Longitudinal/headway control</td>
<td>To measure, in a simplified manner, that headway between vehicles is sufficient on the guideway based on average vehicle velocity and allowable number of vehicles.</td>
</tr>
<tr>
<td>Merge/demerge switch control</td>
<td>To calculate switch delay and sequence for a vehicle approaching a merge switch.</td>
</tr>
<tr>
<td>Vehicle position and velocity control</td>
<td>To describe the link position and link transit time of vehicles.</td>
</tr>
<tr>
<td>Network configuration</td>
<td>To describe and specify a network with links and switch points.</td>
</tr>
<tr>
<td>Link congestion</td>
<td>To model the effects of link congestion and the strategy for dealing with congestion.</td>
</tr>
<tr>
<td>Network status</td>
<td>To provide a report on link, zone, and station loading for purposes of vehicle management.</td>
</tr>
<tr>
<td>Alarm</td>
<td>To generate the time, type, and location of an emergency (i.e., failure conditions) based on a prespecified algorithm.</td>
</tr>
<tr>
<td>Failure management</td>
<td>To model failure management procedures for failures of a vehicle, link, station, and zone.</td>
</tr>
<tr>
<td>Performance measures and</td>
<td>To generate the specified performance measures in the specified formats.</td>
</tr>
<tr>
<td>statistics generation</td>
<td></td>
</tr>
</tbody>
</table>

SUMMARY OF THE CMS SIMULATION PROGRAM

A dominant consideration in the development of the CMS simulation program was to provide an efficient, cost-effective tool for testing CMS implementation concepts. Thus, a program was designed whose running time and costs per run were not excessive. This was accomplished by using sufficiently detailed models of the following basic CMS functions:

1. Trip assignment,
2. Empty vehicle management,
3. Failure management (e.g., vehicle, link, zone, and station), and
4. Performance measures and statistics.

Models associated with functions not directly related to central management (e.g., longitudinal-headway control) were relatively simple to model. Table 1 presents an overview of the functional models associated with the CMS simulation program.

SUMMARY OF PROGRAM INPUTS AND OUTPUTS

The input data for the CMS simulation program can be grouped according to

1. Network geometry,
2. Demand,
3. Parameters associated with certain models,
4. CMS strategies, and
5. Simulation run options.

Data related to network geometry typically consist of various link numbers, their lengths, connectivity, the location of stations and storages, and their relation to main-line links.

Data related to demand are generated by use of a random trip generation program based on the given or assumed average hourly O/D matrices for various hours of the day and certain specified parameters. The designer can select any period of a day (e.g., 6:00-9:00 a.m.) or an entire 24-h period to test various CMS strategies for that period.

The CMS simulation program contains certain models, such as vehicle movement in links and dwell time of vehicles at berths, that require specification of some parameters. For example, the velocity-headway curve is used to model vehicle movement in the links. The velocity-headway curve was modeled as a second-order equation of the form:

\[ H = K_1/v + K_2 + K_3v \]  

where \( H \) = the headway in seconds and \( v \) = the velocity in miles per second. The program user has to specify the values of the coefficients \( K_1, K_2, \) and \( K_3 \).

Input data that specify the major elements of a CMS strategy under normal conditions consist of

1. Vehicle search regions associated with each station,
2. Vehicle type search priority,
3. Allowable on route stations between various O/D pairs,
4. Allowable number of stops between various O/D pairs, and
5. Route specification between various O/D pairs.

Vehicle search regions for various stations are specified in terms of links, other stations, and the storage and maintenance areas. The CMS simulation program is designed to search for vehicles sequentially in links, stations, and storages, in the order specified. Other elements of the strategy have to be specified in a similar way.

The program user can specify certain data associated with simulation run options. These data include the times at which the outputs are to be printed or the times at which network statistics are to be set to zero (e.g., at 8:00 a.m., 9:00 a.m., or 10:00 a.m.). A complete list of data related to simulation run options is included in the technical specifications for the AGRT-CMS simulation program (5, 4).

The CMS-simulation program was used to develop various efficient CMS strategies for a test network provided by UMTA. The basic geometric configuration of the test network is shown in Figure 2. Basic data about the network are given below (note 1 km = 0.6 mile).
The CMS-simulation program provides a capsule report, for quick analysis, as well as detailed information associated with various performance measures, for detailed analysis. Typical output data from an actual run are presented in Figures 3-5. (The models were designed for U.S. customary units only; therefore, values in Figures 3-5 are not given in SI units.)

**EXAMPLES OF CMS STRATEGIES FOR A TEST NETWORK**

To demonstrate the effectiveness and performance of the CMS-simulation program, UMTA provided the study team with a test network and O/D demand data. The basic geometric configuration of the test network is shown in Figure 2. An initial detailed network layout was prepared by the study team based on the basic test network. The detailed network includes certain turn-arounds to allow for one-sided stations and to provide an alternative path in case of failures of certain links. The network also includes six storage areas for vehicles that can be called on either a demand-responsive or fixed-schedule basis.
Figure 5. Sample of O/D data.

**ORIGIN-DESTINATION DATA FOR DEMAND TRIPS**

**FOR PASSENGERS TRAVELING FROM ORIGIN STATION 1**

<table>
<thead>
<tr>
<th>Destination Station</th>
<th>Number of Passengers</th>
<th>Avg. Net Travel Speed (mph)</th>
<th>Maximum Waiting Time (Minutes)</th>
<th>Average Trip Time (Minutes)</th>
<th>Mean Wait Time as Percent of Mean Trip Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3</td>
<td>29.43</td>
<td>4.77</td>
<td>3.48</td>
<td>1.22</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>24.63</td>
<td>5.03</td>
<td>3.36</td>
<td>1.63</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
<td>28.18</td>
<td>5.03</td>
<td>4.22</td>
<td>1.49</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>29.82</td>
<td>4.42</td>
<td>4.36</td>
<td>1.04</td>
</tr>
<tr>
<td>7</td>
<td>11</td>
<td>30.93</td>
<td>5.72</td>
<td>3.65</td>
<td>1.84</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>29.62</td>
<td>5.64</td>
<td>4.04</td>
<td>2.10</td>
</tr>
<tr>
<td>10</td>
<td>7</td>
<td>25.28</td>
<td>5.65</td>
<td>3.71</td>
<td>1.58</td>
</tr>
<tr>
<td>TOTALS FOR ORIGIN</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| 1                   | 42                   | 28.13                      | 5.72                           | 3.83                        | 1.53                                       | **Table 2. O/D demand data for the morning peak period.**

<table>
<thead>
<tr>
<th>Origin Station Number</th>
<th>Destination Station Number</th>
<th>1 2 3 4 5 6 7 8 9 10 11 12</th>
<th>BSUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>3</td>
<td>11</td>
<td>11</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>7</td>
<td>12</td>
</tr>
<tr>
<td>5</td>
<td>133</td>
<td>118</td>
<td>121</td>
</tr>
<tr>
<td>6</td>
<td>48</td>
<td>35</td>
<td>51</td>
</tr>
<tr>
<td>7</td>
<td>100</td>
<td>120</td>
<td>82</td>
</tr>
<tr>
<td>8</td>
<td>153</td>
<td>186</td>
<td>56</td>
</tr>
<tr>
<td>9</td>
<td>103</td>
<td>98</td>
<td>41</td>
</tr>
<tr>
<td>10</td>
<td>39</td>
<td>33</td>
<td>30</td>
</tr>
<tr>
<td>11</td>
<td>124</td>
<td>110</td>
<td>156</td>
</tr>
<tr>
<td>12</td>
<td>36</td>
<td>52</td>
<td>27</td>
</tr>
<tr>
<td>CSUM</td>
<td>752</td>
<td>773</td>
<td>563</td>
</tr>
</tbody>
</table>

**Note:** The numbers given are baseline numbers of trips. To calculate the passenger demand during morning peak hour (8:00-9:00 a.m.) numbers should be multiplied first by a factor of 2 to reflect the peak effect and then by a factor of 1.175 to reflect average party size. These factors were specified by UMTA.

Basic O/D demand data for the morning peak demand period are shown in Table 2. Similar tables were provided for off-peak and evening-peak periods. By use of these basic hourly demand data and certain specifications, we generated a random trip demand file for the entire 24-h period, during which approximately 80 000 trips were requested.

**Experiments for Morning Peak Period**

The following five strategies were tested for the morning peak period:

1. All en route stations eligible for stops, and no limit on number of intermediate stops;
2. All O/D pairs served nonstop;
3. Same as for strategy 1, but only one intermediate stop allowed;
4. Nonstop service for high-demand O/D pairs, one intermediate stop allowed for medium-demand O/D pairs, and no limit on stops for low-demand O/D pairs; and
5. Same as for strategy 3, but 20 special service routes used for highest demand O/D pairs (e.g., station 5 to station 1, special service vehicles every 2 min; station 5 to station 2, special service vehicles every 2.5 min).

Comparative summaries of several performance measures for these five strategies are given in Table 3. Strategies 1 and 2 generate some unacceptable situations. For strategy 1, the average effective travel speed becomes very low, 40 km/h (25 mph); only 55 percent of the trips are served within a mean wait time of 5 min; the vehicle arrival rate at station 4 is excessive, and total station rejections are very high. For strategy 2, the needed vehicle fleet and link flows are quite high compared to other strategies. The philosophies of strategies 3, 4, and 5 appeared promising and were improved by use of later versions of the program, by modifications of the capture regions, and by improvements in selection of allowable stops.

**Experiments for Midday Period**

The following strategies were tested for the midday period (12:00 n.-1:00 p.m.):

1. All en route stations eligible for stops, and no limit on number of intermediate stops;
2. All O/D pairs served nonstop; and
3. Same as in strategy 1, but only one intermediate stop allowed at most.

None of the three strategies creates any unacceptable situations, and each one is a reasonably good candidate strategy. Strategy 1 requires the fewest number of vehicles, but only 32 percent of the trips are served nonstop; the other trips served have one or more intermediate stops. Strategy 2 is the best from the passengers' point of view, but it requires a larger fleet.
Table 3. Comparison of five CMS strategies for the morning peak period.

<table>
<thead>
<tr>
<th>Performance Measure</th>
<th>Strategy 1</th>
<th>Strategy 2</th>
<th>Strategy 3</th>
<th>Strategy 4</th>
<th>Strategy 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of passengers</td>
<td>10 213</td>
<td>10 276</td>
<td>10 383</td>
<td>10 319</td>
<td>10 369</td>
</tr>
<tr>
<td>Boarded</td>
<td>9 954</td>
<td>10 174</td>
<td>10 214</td>
<td>10 180</td>
<td>10 279</td>
</tr>
<tr>
<td>Mean wait time (min)</td>
<td>4.08</td>
<td>3.59</td>
<td>4.44</td>
<td>3.25</td>
<td>2.62</td>
</tr>
<tr>
<td>Maximum wait time (min)</td>
<td>22.92</td>
<td>15.17</td>
<td>13.87</td>
<td>10.95</td>
<td>16.25</td>
</tr>
<tr>
<td>Trips, &lt;10-min wait ($)</td>
<td>-89</td>
<td>-100</td>
<td>-99</td>
<td>-100</td>
<td>-100</td>
</tr>
<tr>
<td>Trips, nonstop</td>
<td>-34</td>
<td>100</td>
<td>-56</td>
<td>-91</td>
<td>-90</td>
</tr>
<tr>
<td>Trips, one stop</td>
<td>-36</td>
<td>-44</td>
<td>9</td>
<td>-10</td>
<td></td>
</tr>
<tr>
<td>Trips, two or three stops</td>
<td>-30</td>
<td>-54</td>
<td>-52</td>
<td>-56</td>
<td>-56</td>
</tr>
<tr>
<td>Average system travel speed (km/h)</td>
<td>-40</td>
<td>-54</td>
<td>-52</td>
<td>-56</td>
<td>-56</td>
</tr>
<tr>
<td>Time-weighted fleet</td>
<td>262</td>
<td>308</td>
<td>244</td>
<td>267</td>
<td>311</td>
</tr>
<tr>
<td>Vehicle arrival/departure (vehicle/h)</td>
<td>3 245</td>
<td>2 432</td>
<td>2 760</td>
<td>2 507</td>
<td>2 771</td>
</tr>
<tr>
<td>Maximum</td>
<td>405</td>
<td>254</td>
<td>343</td>
<td>271</td>
<td>323</td>
</tr>
<tr>
<td>Station number</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Passenger queue</td>
<td>62</td>
<td>51</td>
<td>63</td>
<td>46</td>
<td>37</td>
</tr>
<tr>
<td>System average</td>
<td>155</td>
<td>133</td>
<td>178</td>
<td>116</td>
<td>68</td>
</tr>
<tr>
<td>Highest average</td>
<td>11</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Maximum link flow (vehicle/h)</td>
<td>734</td>
<td>865</td>
<td>709</td>
<td>788</td>
<td>837</td>
</tr>
<tr>
<td>Link number</td>
<td>32</td>
<td>4</td>
<td>34</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Rejections</td>
<td>362</td>
<td>12</td>
<td>55</td>
<td>9</td>
<td>15</td>
</tr>
<tr>
<td>Total</td>
<td>362</td>
<td>12</td>
<td>55</td>
<td>9</td>
<td>15</td>
</tr>
<tr>
<td>Percent</td>
<td>11.5</td>
<td>0.5</td>
<td>2</td>
<td>0.4</td>
<td>0.55</td>
</tr>
<tr>
<td>Systemwide vehicle load factor</td>
<td>0.55</td>
<td>0.36</td>
<td>0.46</td>
<td>0.39</td>
<td>0.35</td>
</tr>
</tbody>
</table>

Note: 1 km/h = 0.6 mph.
*20 special routes.

size and generates higher link flows than either strategy 1 or 3. Strategy 3 offers a good combination of attractive user-related performance measures (54 percent of the trips are nonstop; 46 percent have only one intermediate stop) and a medium-sized fleet. Only a minor fraction of passengers waits the maximum of 10 min. This could be rectified easily by improvements to the search sequence of links in the vehicle search region.

During periods of low or medium demand it is possible to implement several policy variations with acceptable operations and user-related performance measures. Thus, one could use a large number of vehicles and provide nonstop service or use relatively fewer vehicles and provide service with at most one stop.

Experiments for Evening Peak Period

Results of the morning peak period simulation runs indicated that the two extreme strategies of allowing all en route stops (strategy 1) or serving all O/D pairs nonstop (strategy 2) create certain unacceptable situations. Since the traffic volumes in the evening peak period are the same as those in the morning peak period (reverse direction), we did not test the two extreme policies for the evening peak period. Strategy 4, tested for the morning peak period, appeared to be a good candidate for the first test experiment for the evening peak period. Thus strategy 4 was tested after appropriate adjustments in the directionality of high-demand O/D pairs and stations to be stopped at and some modifications in capture regions to account for the reverse flows. The results of this experiment are comparable to the results of the strategy 4 experiment for the morning peak. This strategy was refined later by use of the final version of the program.

Some Conclusions Related to Peak and Off-Peak Period Strategies

After we conducted experiments for the morning peak, midday, and evening peak periods and established that the two extreme strategies of allowing all en route stops (strategy 1) and no en route stops for all O/D pairs (strategy 2) produce certain unacceptable phenomena (e.g., high link flows and excessive station rejections), we concentrated on refining strategies that use a combination of nonstop, fixed route (both one-way and closed loop), and one intermediate stop strategies for various O/D pairs. Several combinations were tested. Based on the results of these tests we concluded that

1. For both the morning and evening peak periods, a demand-responsive strategy that provides nonstop service for high-demand O/D pairs and (at most) one intermediate stop service for medium- and low-demand O/D pairs gives the best overall combination of passenger- and operation-related performance measures. Other strategies result either in high link flows, excessive wait times, or excessive station arrival and departure rates.

2. For medium-demand periods (i.e., 11:00 a.m.-3:00 p.m.) a variety of strategies is possible. Even the two extreme strategies of serving all O/D pairs nonstop or allowing all en route stops between each O/D pair result in service that is acceptable and do not cause any excessive link flows or station arrival and departure rates.

3. For very low-demand periods, no significant operational advantage results, even if en route stops are allowed, unless very long wait times (greater than 10 min) are tolerated. Most passengers dislike long wait times or intermediate stops, particularly at night. Thus it was concluded that nonstop, demand-responsive service is most appropriate for very low-demand periods during nighttime (e.g., from 10:00 p.m. to 6:00 a.m.).
Experiments to Develop CMS Strategies for the 24-h Period

A final set of experiments was conducted to develop composite CMS strategies for various periods of the day. The overall pattern of the demand level at various periods of the day as specified by UMTA is shown in Figure 6. Between 10:00 p.m. and 6:00 a.m., the demand level is very low—approximately 300 passengers/h. On the other hand, the demand during the 8:00-9:00 a.m. and 4:00-8:00 p.m. periods is substantially high—approximately 10,000 passengers/h. During the midday period, the demand is medium—about 5000 passengers/h.

The general strategies used for various periods of the day are shown below.

### Table 4. Summary of hourly system performance during different periods of the day.

<table>
<thead>
<tr>
<th>Performance Measure</th>
<th>Time Period</th>
<th>1:00-2:00 a.m.</th>
<th>8:00-9:00 a.m.</th>
<th>1:00-2:00 p.m.</th>
<th>5:00-6:00 p.m.</th>
<th>9:00-10:00 p.m.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of passengers</td>
<td>Boarded</td>
<td>300</td>
<td>10,261</td>
<td>49,18</td>
<td>10,323</td>
<td>1,699</td>
</tr>
<tr>
<td></td>
<td>Disembarked</td>
<td>305</td>
<td>10,271</td>
<td>49,09</td>
<td>10,425</td>
<td>2,032</td>
</tr>
<tr>
<td>Mean wait time</td>
<td></td>
<td>4.10</td>
<td>3.07</td>
<td>3.12</td>
<td>3.55</td>
<td>3.24</td>
</tr>
<tr>
<td>(min)</td>
<td></td>
<td>7.01</td>
<td>6.64</td>
<td>9.78</td>
<td>11.33</td>
<td>7.60</td>
</tr>
<tr>
<td>Maximum wait time</td>
<td></td>
<td>4.10</td>
<td>3.07</td>
<td>3.12</td>
<td>3.55</td>
<td>3.24</td>
</tr>
<tr>
<td>(min)</td>
<td></td>
<td>7.01</td>
<td>6.64</td>
<td>9.78</td>
<td>11.33</td>
<td>7.60</td>
</tr>
<tr>
<td>Average system travel speed (km/h)</td>
<td>40.30</td>
<td>45.90</td>
<td>52.87</td>
<td>44.76</td>
<td>48.00</td>
<td></td>
</tr>
<tr>
<td>Number of passengers</td>
<td>Rejections</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Percent</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Vehicle search regions were also adjusted to suit the demand and empty vehicle availability patterns. A summary of hourly performance during various periods of the day is shown in Table 4. Variations of some important performance measures at various hours of the day are shown graphically in Figures 7 and 8.

**SUMMARY OF RESULTS**

During morning and evening peak periods, a demand-responsive strategy that serves high-demand O/D pairs nonstop and makes at most one intermediate stop between medium- and low-demand O/D pairs proved to be very effective. During off-peak periods, all O/D pairs can be served nonstop within a mean wait time of about 3 min if a demand-responsive strategy is used.

Demand-responsive strategies adapt easily to fluctuations in demand. An overall increase of up to 140 percent in the demand levels throughout the network can be handled without creating a serious problem in vehicle flow rates. The system appears to degrade gracefully under increasing demand levels.

The results of the failure experiments (wherein a vehicle, a link, and a station were failed separately for 15 min each), as measured by the extra wait times and the number of passengers that had to be diverted, appeared to be within tolerable limits and were as expected.

A maximum fleet of about 265 vehicles is needed to provide satisfactory service during morning and evening peak periods within a systemwide mean wait time of slightly more than 3 min. Under normal operating conditions, 80-90 percent of the passengers can be served within a 5-min mean wait time during morning and evening peak periods; 97 percent can be served within a 7-min mean wait time. Almost nobody has to wait more than 10 min.

Average systemwide speed is 45-48 km/h (28-30 mph). This takes into account the civil speed limits of 32 and 40 km/h (20 and 25 mph) imposed by right-of-way.
way constraints in certain portions of downtown areas and in turnaround links.

Systemwide load factors during morning and evening peak periods are about 51 and 49 percent, respectively. These values are in close agreement with those calculated theoretically. The load factor at night is about 9 percent. The demand at night is very low and passengers should not have to wait too long. The load factor during midday is about 28 percent if a nonstop strategy is used. This seems quite acceptable when the nonstop service and short wait times are considered. However, the load factor can be improved if stops and longer wait times are allowed. It is possible to trade off mean wait time with fleet size, particularly during off-peak periods.

Figure 7. Mean wait time and system average speed during various periods of the day.

Figure 8. Vehicle load factor and fleet size during various periods of the day.
CONCLUDING REMARKS

The computer-aided method and the CMS simulation program discussed in this paper can be used to develop

1. Efficient CMS strategies for urban transportation networks, including vehicle assignment (demand responsive, fixed schedule, and mixed), stopping and routing, empty vehicle management, and failure management for vehicle, station, and guideway link failures;
2. Network geometry details, such as station capacities, location of bypasses and turnarounds, and storage and maintenance areas; and
3. Optimum vehicle fleet size consistent with the desired level and quality of service.

Although the simulation program was developed with reference to an AGRT system that uses 12-passenger automated vehicles, it is highly modular. Those few modules that are unique to a particular system can be easily modified and used to evaluate alternative CMS strategies for other types of transportation systems, such as bus systems or other forms of automated guideway transit systems.

The simulation program was used to develop several CMS strategies for a test network and O/D data provided by UMTA. The test results indicate that CMS strategies are readily adjustable so that 80-90 percent of trips can be accomplished within a mean wait time of 5 min. The generally held notion that fixed-schedule service is superior to demand-responsive service during high-demand periods was found to be incorrect. Some demand-responsive strategies developed and tested for the test network for peak demand periods also gave extremely good results—that is, high vehicle load factors and very short mean wait times. In addition, the demand-responsive strategies were found to be more adaptive to failures and dynamic variations in demand than fixed-schedule strategies.

CMS strategies, particularly for transportation systems that use small vehicles on complex routes, require further research and experimentation so that basic guidelines can be established for the development and refinement of algorithm parameters for planners of future systems. The simulation program developed is a powerful tool with which to test various CMS strategies. It can be improved further, however, to expand its capabilities.

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REFERENCES


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Electric Cars for Urban Transportation

William Hamilton, General Research Corporation, Santa Barbara, California

Within 10 years rapid technological advances will make the production of electric cars by a major manufacturer a likely possibility. Widespread use of electric cars would drastically reduce the amount of petroleum consumed for urban transportation and also cut automotive air pollution and noise significantly. Under current conditions and trends, however, sales of electric cars are likely to be relatively modest, unless a larger role is deliberately planned for them in order to reap their potential benefits for conservation and environmental quality. This paper is a summary of an investigation of the effects of large-scale use of electric cars on energy, the environment, and the economy.

Electric cars offer major potential advantages for urban transportation: the convenience and mobility of the internal-combustion automobile without its dependence on petroleum or its major environmental problems. Recent electric cars have had very limited appeal, primarily due to the short range between recharges and high overall costs. New batteries that will substantially relieve both range and cost disadvantages are expected soon. With these batteries and more ef-