Application of a Large-Scale Dual-Mode Simulation to Milwaukee County

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Monte Carlo simulation, a technique for evaluating cost versus service trade-offs in the design of a dual-mode transportation system, is applied to a large-scale system for Milwaukee County. Model formulation, experimental design, analysis of alternative design configurations, and possible refinements of both the model and the methodology are considered. Experimental results show that, although there is an apparent interaction between system design and operations, within a reasonable range system performance is relatively insensitive to changes in operating conditions. Operating differences resulting from the size of the dual-mode network are noted. A reduction in dual-mode station capacity produced little effect except increased station congestion. Although problems associated with computer resource requirements did exist, it is concluded that methodological improvements would help make this type of simulation useful.

In recent years there has been an increasing interest in new and innovative concepts in mass transit, such as dial-a-ride (1, 2), personal rapid transit (PRT) (3), and dual mode (4). The development of these systems has created a need for new tools and techniques that will help transportation planners to compare alternative system designs. This paper presents an application of one such technique, Monte Carlo simulation, to a dual-mode transportation system.

A dual-mode system consists of vehicles that can be manually operated for collection and distribution of passengers on the city streets and can also be operated as line-haul vehicles on high-speed and automated guideways. Work has been done on the physical design of such systems (5). Software to support the planning of dual-mode facilities in specific urban areas is relatively scarce. One study performed in Milwaukee County (6) applied conventional traffic simulation techniques to a dual-mode network but did not fully consider the dynamics of a more sophisticated demand-responsive system. It has been suggested that Monte Carlo simulation could be used to monitor the activity of dual-mode buses (7). This paper presents the results of applying a similar model to traffic data in Milwaukee County.

The previous Monte Carlo simulation model assumed that the automated guideway operated in a single loop and that no transferring of passengers was allowed at dual-mode stations. The simulation model used in this study differs in the following major ways:

1. Any general type of guideway network configuration can be handled.
2. Once a bus is loaded onto the guideway, one intermediate stop is permitted to service passengers waiting at a station.
3. Buses collecting passengers in an off-guideway service area may pick up passengers who have different destinations and deposit them in passenger queues at the station.
4. Buses do not leave the guideway at the central business district (CBD) station location.
5. Station queuing disciplines allow limited parallel processing of buses.
6. Bus and operator requirements are no longer inputted constraints but are computed by simulation.

In addition to discussing the results of applying the dual-mode simulation to real data, this paper also discusses (a) the assumptions of the dual-mode transit system being simulated, (b) the methodology and the model used in the simulation, and (c) refinements in both the simulation model and the procedure used in applying it. The main objective of the study was to evaluate the practical aspects of applying the methodology to a large-scale system, but an attempt is also made to draw some conclusions from the simulated results.

DUAL-MODE TRANSIT SYSTEM

The dual-mode configurations used in this study were completely demand responsive. The Milwaukee metropolitan area was divided into a number of local service areas, each of which was serviced by a single guideway station. It was assumed that trip demands within the service area would be generated randomly and that small 20-passenger buses would be dispatched from the guideway station, on a call basis, in one of two passenger pickup modes: (a) a general pickup mode in which passengers waiting the longest time would be serviced regardless of final destination and (b) a dedicated pickup mode in which only passengers with a common destination would be assigned to a bus. Once passengers from the local service area arrived at the station, they might have to wait at the station for a bus to be dispatched to their final destination or they could continue directly onto the guideway by using the same bus. For a bus to be loaded onto the automated guideway, it would have to be assigned another local service area as its final destination. This bus, however, could also be assigned, either at time of dispatch or en route, one intermediate stop for the purpose of handling passengers waiting at the station. Each station in the network would serve as a holding area for both buses and operators; the operators, of course, would only be used to drive the local, off-guideway buses.

All stations in the dual-mode network except the CBD station would be operated in the same way. Local stations, however, could vary in the number of buses they could handle at one time. Within the CBD, buses were not allowed to leave the guideway but proceeded in a loop, stopping at each of a number of passenger drop-off and pickup points. Travel time through the CBD was fixed up to a certain limit. Once a capacity point was reached, headways for CBD buses were reduced by an amount proportional to the excess volume. In the simulation, the average travel time for off-guideway buses in service areas outside the CBD is a function of the number of passengers riding in a particular bus and the service area itself. Random variations around this average travel time are allowed.

SIMULATION MODEL

Design

The simulation model was developed by representing the status of the dual-mode system on the computer, by

identifying events that cause changes in this status, and then by having the computer deal with these events. For the model described here eight events, given in the table below, were used. The possible effect of each event on the status of a bus is also given.

Event	Bus Status Before	Bus Status After
Trip demand	–	–
Release of new service area bus	–	In general pickup mode In dedicated pickup mode
Release of new guideway bus	–	Loading onto guideway
Arrival of bus at station	On guideway link	On new guideway link Unloading off guideway
Arrival of general pickup bus	In general pickup mode	Loaded onto guideway Removed from system
Arrival of dedicated pickup bus	In dedicated pickup mode	Loaded onto guideway
Bus loaded onto guideway	Loading onto guideway	On guideway link
Bus ready at station	Unloading from guideway	In general pickup mode In dedicated pickup mode Loading onto guideway

The status of the dual-mode system was represented in the computer by counts of passengers who had specific origins and destinations and were waiting in each service area and in each station. Counts were also maintained of buses at various locations in the dual-mode network.

The following example illustrates how the simulation handles various events. A general pickup bus arrives at a station designated i. The count of general pickup buses servicing area i is decreased by one and, if passenger demand is sufficient to warrant continuing the bus onto the guideway, the count of buses waiting in station i is increased by one. At the same time passenger queues at the station that represent people waiting for destinations other than those assigned to the continuing bus may be increased. On the other hand, passenger queues for the destination that will be serviced by the bus are decreased to zero or by as much as the capacity of the bus allows. Also at this point in the simulation, the time at which the continuing bus will be loaded onto the guideway is computed, and statistics are updated. A similar process occurs for the other events.

A number of assumptions are made in determining the timing and sequencing of these events. The times between successive demands are assumed to be generated from an exponential probability distribution, where the demand rate of each area equals the reciprocal of the total number of trips originating in that particular area. The destination for each trip is computed from a discrete probability distribution in which the probabilities are determined by dividing each element in a row of the trip table by the row sum. The on-the-road travel time for each bus is estimated separately for each service area and inputted into the simulation by specifying minimum and maximum travel times. These figures are then assumed to represent the three standard deviation limits of a normal probability distribution and are thus used to compute mean and variance. The mean of this distribution is then adjusted upward during the simulation by 15 s for each passenger being picked up and 9 s for each passenger being dropped off. Service-area buses are allowed to operate in the general pickup mode, in which a bus may be assigned a number of final destinations, and in the dedicated pickup mode, in which a bus collects only passengers having a single destination station. Trips that both begin and end in a single service area were not handled by this simulation.

When a bus from the service area arrives in a non-CBD station, when a new bus is released directly to the guideway, or when a bus stopping for an intermediate stop is ready to load passengers, the time at which this bus will enter a particular guideway link is computed. It is assumed that the bus will approach a loading ramp that has a capacity to process a limited number of buses in parallel. If the ramp is not congested, a fixed time is allowed for the bus to process passengers and accelerate onto the guideway. Otherwise, delays caused by congestion are assessed. In the simulation a bus can bypass the loading area if there is no need for that bus to pick up or drop off passengers. At this point the guideway-bound bus is also assigned a final destination and possibly an intermediate stop by means of a set of operating rules that will be discussed later. An intermediate stop may be preassigned when conditions permit, or an option may be enforced that allows a bus to decide, depending on demand, whether or not to stop as it approaches an intermediate station on the guideway.

Once a bus is on a guideway link, the time at which the bus arrives at the next station is computed from link distances and a speed factor inputted at the beginning of the simulation. The actual link to which the bus is assigned is determined from a table that provides the next link on the path from any station to any other station. These paths may be, but do not necessarily have to be, minimum travel-time paths.

When a bus arrives at a station, a check is made to see if that bus should stop or continue. If it continues, the next link and travel time are determined as described above. If it stops at either the final destination or an intermediate station, a delay time is determined in a manner similar to that used to describe buses leaving a station. If a destination station is in the CBD, this process is slightly modified in that the model assumes that the bus circles around a loop and stops at each of a series of equally spaced platforms.

In monitoring bus activity the simulation program computes total time and average number for buses in each of the following locations in the dual-mode system:

1. Buses traveling within the local service area,
2. Buses leaving the service area that stop at the station for passenger pickup or drop-off,
3. Buses leaving the service area that bypass the station and are loaded directly onto the guideway,
4. Buses entering the service area that stop at the station for passenger pickup or drop-off,
5. Buses entering the service area that bypass the station,
6. Buses on non-CBD guideway links, and
7. Buses on the CBD loop.

These computations are also made for buses that are in the process of making an intermediate stop; that process would overlap with items 2 and 4 above.

Average time and number were computed for passengers waiting both at a station and within the service area, and data were maintained for average bus loading, which is expressed as a fraction of the total utilized capacity for all the active buses in the system. The simulation also monitored the maximum number of operators and buses used during the collection period. In addition, a number of counters were incremented each time a certain type of activity occurred. This information is useful in checking the face validity of the simulation and in identifying potential problems in the operation of the dual-mode network.

These data were collected on an aggregated, system-wide basis. A routine that could collect similar information for each station could easily be written, but such detailed data collection would be costly in terms of computer time and storage. The best strategy would be to

use the more aggregated program for experimentation purposes and then use the more detailed program on a one-shot basis.

Control of Simulated Operations

A number of operating decisions are made during the course of the simulation, including decisions on when and where to dispatch buses and on whether or not to allow intermediate stops. Such actions are controlled within the model by a set of simple decision rules of the following form: If x is at or exceeds level y, then do z. The major concern in determining parameter values was to set them at levels that would provide an efficient operation for each alternative design. This requires some experimentation with the operating parameters before other types of comparisons are made. The main purpose of the experimentation, or model tuning, is to avoid comparing a poorly operated configuration with a well-operated one. It should also be possible to make limited conclusions about what the important operating factors are (e.g., bus loadings, dispatching delays, intermediate stops, or station delays).

Table 1 gives a list of eight parameters used as a basis for making operating decisions. The parameters control the event sequence at three different points in the simulation. First, a decision must be made concerning when and in what pickup mode buses should be dispatched into the service area. This decision depends on either the number of passengers waiting for a particular destination or the passenger wait times. When a bus at the station is ready to distribute passengers within the service area, it checks the queues of service-area passengers waiting to be transported to various destinations. If the number of the largest queue is greater than or equal to the value represented by the parameter SAN, then that bus will, while dropping off current passengers, pick up passengers only in the largest queue, thus operating in a dedicated pickup mode. Otherwise, that bus will operate in a general pickup mode, collecting passengers from as many queues as capacity allows. The wait-time value SAT is used when there are no active buses available to serve a particular queue. Wait times are checked every 30 s. If a passenger has been waiting for pickup for a period longer than SAT, an empty bus is dispatched to handle passengers in that queue. If the total number of passengers waiting to be transported to the same destination reaches the bus capacity, an empty bus is immediately dispatched in the dedicated pickup mode.

A second set of decisions must be made when a bus arrives at a station from the service area. If a bus is operating in the dedicated pickup mode, the station queue containing passengers waiting to be transported to the assigned destination is checked and, if it is empty, the bus bypasses the station. In either case, if the total number of passengers in the bus is greater than the parameter STN1, the bus is not allowed any intermediate stops.

A general pickup bus will always stop at the station to discharge passengers and check the station queues. If the largest queue (including passengers delivered by the bus that just arrived) is less than the value of STN2, the bus is removed from the system. Otherwise, the bus continues onto the guideway having been assigned the same destination as that of the longest queue. Another check is made against STN1 to determine whether an intermediate stop should be allowed; then a second check is made of all queues having destinations along the path the bus will follow. If the number of passengers waiting for transport to intermediate stations is greater than or equal to the value of STN3, an intermediate stop is preassigned. If a sufficient number of station passengers are not available, the bus is assigned a single destination and is released to the guideway; an intermediate stop may be assigned in transit. The wait-time check against STT may trigger the release of an empty bus, which may then be assigned an intermediate stop as described above. When a station queue reaches the level of bus capacity, an empty bus is immediately dispatched to the guideway.

Finally, a decision must be made as to whether a bus approaching an intermediate station should stop. This decision, when allowed, is based on the number or wait time of waiting passengers who have the same destination as the bus. For an intermediate stop to be assigned in transit the number of waiting passengers must exceed the parameter GWN or the wait time must exceed GWT.

Varying the eight parameters given above would have some obvious general effects. For example, because the major trade-off in any transportation system is that between service, as measured by wait and travel times, and transit-system design efficiencies, as measured by bus and operator utilization and the size of transit facilities, lowering wait-time values may improve service measures but may also substantially increase bus and operator requirements.

APPLICATION

The simulation discussed above was applied to actual 1990 peak morning demand projections for Milwaukee County. Sketches of three alternative networks used in the project, as well as a more detailed discussion of procedures and data inputs, are available elsewhere (10). Station locations in the first configuration closely approximated those of the Allis Chalmers study (6). The two other configurations used a subset of the original 41 stations.

Data comparing the three configurations are given in Table 2. A few trips between station pairs, in which passengers would have to go considerably out of their way if they used the dual-mode system, were eliminated. The total number of trips eliminated for this reason was small compared to the total transit demand (Table 2). A total of 400 traffic zones were assigned to stations by examining a map and assigning zones in the general area of a station to that station. An estimate was then made of the minimum and maximum on-the-road travel times for buses within a station service area by examining the area interzonal and intrazonal travel times. This is the input into the simulation that most needs refinement. In this project, such estimates required considerable subjective judgment, but there are techniques available for dial-a-ride simulation (8, 9) that could provide a more objective and precise means of developing these data.

It was decided in this application to analyze the simulation under 1990 peak-load, steady-state conditions. This required first running the simulation until the dual-mode network was loaded with buses. The relative effects of varying a number of factors could thus be evaluated apart from time-dependent influences. In addition, because data could be collected over relatively short time intervals, computer time could be saved. The following approach was used.

1. Values for all the controllable factors were arbitrarily set (factor set refers to a specific group of experimental factor levels).
2. An initialization run was made in which statistics such as total times, average numbers, and average bus loadings were reinitialized and examined at 10-min intervals to see if they were relatively unchanged over two successive intervals.
3. After these steady-state criteria were met, data were collected for four additional 10-min intervals, the last two of which were used as the experimental observa-

tion and a replication of the experimental observation for the first factor set.

4. For different factor sets, the simulation was restarted at the point at which it was terminated in step 2. As in step 3, these subsequent factor sets were also run for four 10-min intervals, the first two of which were discarded because time had to be allowed for the effect of the experimental treatment to be realized. As discussed above, the next two data-collection intervals represented an observation with one replication.

The use of data derived from steady-state conditions should tend to produce results that are worse than one would expect in a real-life situation. During regular operation of dual-mode systems, demand would usually build to a peak and then taper off. Under these circumstances, the steady state simulated here would probably never be realized. However, since the objective of simulation is to compare alternative designs, these steady-state values should provide measures of the relative effect of various design and operating factors on overall system performance.

In determining specific values for each factor in a factor set, values first had to be established for the eight operating parameters discussed previously. Because using the same parameter values across all three networks might bias the results in favor of a certain type of configuration, and because the relation between system design and operation is of interest in itself, experiments were conducted that had the effect of "tuning" the operations of a system to a particular configuration.

The wait-time parameters SAT, STT, and GWT were arbitrarily set at 5 min. It was felt that, because of the traffic volumes involved in the simulation, there would in most instances be sufficient demand to trigger bus activity before obtaining a 5-min wait; these parameters would thus have little effect on the results. After the initial tuning procedure was completed, these maximum wait times were reset to 7.5 and 10 min to verify this assumption.

The other five operating parameters—SAN, STN1, STN2, STN3, and GWN—were simultaneously varied by using a quarter-fraction factorial design procedure that allowed measurement of all five first-order effects and the interaction effects between STN1 and STN2 and between STN3 and STN2. [For detailed discussion of this experimental procedure the reader is referred to Davies (11) and Myers (12).] After the initial experiment is completed, a series of new values can be determined for the operating parameters by fitting a regression plane to some measure of operating "goodness"; the new values should lie along a line that yields the maximum increase in this goodness measure. By conducting further experiments along this line (the path of steepest ascent), a series of improved simulation results should be realized until operating conditions that are at least closer to the best possible result are found. Further experimentation may or may not be desired depending on the new results.

The numerical values of the five parameters used in each initial experiment are given in Table 3. By using the numbers given in Table 3 rather than identical factor levels for each network, we were able to include in the experiments some preliminary runs.

There is probably no single statistic that can be used that is indicative of the goodness of a particular run. Instead, a somewhat arbitrary weighting of service statistics (measured by total times) and design statistics (cost) was used. Basically, for the service-related data, simple assumptions such as the following were made: (a) Waiting within the service area is more desirable than a wait in the station and (b) traveling on the automated guideway is more desirable than traveling in the service area or being processed through a station. An attempt was made to use some economic base for the design weight. A report prepared by Rohr Industries (5) was used to estimate annual vehicle and station cost. A trade-off factor that specified the relative weight given service and cost factors was arbitrarily set at a level that would balance these two criteria so that neither service nor cost would dominate the tuning procedure. Details on the formulation of these statistics—a procedure called the design effectiveness measure (DEF)—and results of a sensitivity analysis performed on these weights are given elsewhere (10).

When a set of satisfactory operating parameters is obtained, valid comparisons of the three networks can be made. Because the tuning procedures were conducted under conditions of excess capacity, an attempt was also made to observe the effect on the dual-mode system of reducing station size. Further experimental runs were made for different non-CBD station capacities. Additional runs could also be made for different guideway speeds, bus sizes, CBD capacities, and station delays.

SIMULATION RESULTS

All three simulations reached a steady state in 120 min. Therefore, time intervals ending at 130 and 140 min were used for initialization of the factor set, and data were collected in the two 10-min intervals ending at 150 and 160 min. Table 4 gives the results of the initial tuning experiments in Table 3 and summarizes a regression against the DEF measure. The fact that significant results were obtained in only two cases indicates either that the sensitivity of operating parameters was low in overall performance or that the statistical tests were not powerful enough to distinguish the differences. After detailed examination of the data, it was felt that results were stable enough statistically to discern some relationship but that more than a single replication was needed to obtain statistical significance. Because of computer time limitations, however, further runs could not be made.

This discussion attempts to relate the results given in Table 4 to selected items from the detailed output of the simulation. A more complete presentation of these data is available elsewhere (10).

The large negative coefficients for STN1 and STN2 in configuration 1 corresponded to a greater average number of passengers on a bus at the higher levels of STN1 and STN2, which allowed more intermediate stops (Table 1). In this case, system efficiency was improved by allowing intermediate stops, but the price paid was increased wait times. The net result, however, was a desirable lowering of the DEF. Similarly, the lower STN3 coefficients in the smaller configuration indicated that network operations should allow fewer preassigned intermediate stops. Negative coefficients for SAN and STN2 seemed to suggest that passengers could be allowed to wait longer at home or at the station in the two larger networks but that these wait times become more critical in the third, smaller network.

A path of steepest ascent was computed for all configurations and further observations were made. Because of low sensitivity in the DEF to variations in these parameters, the effort made here was not extensive. The final values of the operating parameters that were used in further experiments are given in Table 5. In every case, the DEF was only slightly lowered. However, this lack of sensitivity was not always observed. In a preliminary run, parameters STN1 and STN2 were set at the same level. This produced a situation in which very few intermediate stops were allowed and total bus requirements grew to such a point that the simulation had to be aborted.

As mentioned earlier, the delay-time parameters SAT, STT, and GWT were also increased from 5 to 10. For configurations 2 and 3 the DEF showed a slight increase, but for configuration 1 it decreased from 2.282 to 2.171. The assumption that the five activity-triggered parameters would dominate the delay-time parameters seemed to hold for the smaller networks but not for configuration 1. Results are thus reported for configuration 1 for conditions of 5 and 10-min maximum delay.

A comparison of bus activity across the three configurations is given in Table 6. Examining activity in service areas and stations reveals an expected pattern. Lower bus loadings from the larger networks result in a greater number of buses being dispatched to both the service area and the guideway. A lower percentage of buses are assigned dedicated pickup and a larger percentage are not allowed intermediate stops within the smaller network. The percentage of buses dispatched to the guideway that do make intermediate stops is drastically reduced.

In examining guideway link volumes, the capability of a single guideway lane to handle a specified number of buses is of interest. By dividing link volumes by link distances, the minimum spacing between the buses is varied (under 5-min maximum delays) from roughly one bus every 50.3 m (165 ft) for configuration 1 to one every 114 m (374 ft) in configuration 3.

Another means of comparing these networks was to develop a scenario for the typical trip within each configuration. This required the use of average time data, which, although collected by the simulation, were not reliable because of the short data-collection period. Estimates were therefore calculated by dividing average numbers by the corresponding activity counts (Table 7). As one would expect, service-area guideway travel times and service-area wait times decreased with increasing network size. The increased intermediate stops and the additional number of stations tended to produce higher station delays in the larger network. Because all passengers would not be stopping at the station or participating in intermediate stops, these two items were appropriately reduced in computing total trip time. Increased network size shortened typical waits by 3 to 4 min and travel times by 5 to 11 min.

All experimentation was done under conditions of ex-

Table 1. Operating parameters.

Parameter	Statistic	Decision Made When Statistic ≥ Parameter Value
SAN	Number of service-area passengers	Assign bus to dedicated pickup
SAT	Wait time of service-area passengers	Release new service area bus
STN1	Number of station passengers having certain destination	Assign bus to single destination only
STN2	Number of station passengers having certain destination	Continue local bus onto guideway
STN3	Number of station passengers having intermediate destination	Assign bus to intermediate stop
STT	Wait time of station passengers	Release new guideway bus
GWN	Number of station passengers having certain destination	Assign intermediate stop to bus on guideway
GWT	Wait time of station passengers having certain destination	Assign intermediate stop to bus on guideway

Table 2. Comparison of three dual-mode network configurations.

Statistic	Configuration 1	2	3
Service area			
Number of traffic zone assignments			
Average	9.3	17.8	31.1
Maximum	23	36	50
Minimum	4	6	19
Trip origins (non-CBD)			
Average	2660	4825	8114
Maximum	6258	10 934	15 592
Minimum	703	2293	4224
On-road trip time, min			
Average, all areas	15.8	18.7	24.0
Standard deviation, all areas	3.7	4.6	6.3
Maximum	36	40	50
Minimum	2	2	2
Guideway network			
Number of non-CBD stations	40	21	12
Number of links	122	74	42
Total link distance[a], one way, km	325	297	251
Average link distance, km	5.3	8	12
Total trips assigned to guideway[b]	107 884	102 825	98 876
Interstation routes not included	21	8	2
Interstation trips not included	1846	2817	625

Note: 1 km = 0.62 mile.

[a]Total link distance may include two or more links that occupy, in part, the same physical guideway.

[b]Total transit trips number 119 102. Interstation trips on excluded routes and trips within a single service area make up the difference.

Table 3. Experimental values of operating parameters.

Configuration	Parameter	Factor Set 1	2	3	4	5	6	7	8
1	SAN	18	16	16[a]	18	16	18	18	16
	STN1	12	14	12	14	12	14	12	14
	STN2	2	2	5	5	2	2	5	5
	STN3	5	5	5	5	8	8	8	8
	GWN	8	11	8	11	11	8	11	8
2	SAN	16[a]	14	14	16	14	16	16	14
	STN1	12	14	12	14	12	14	12	14
	STN2	5	5	8	8	5	5	8	8
	STN3	5	5	5	5	8	8	8	8
	GWN	8	11	8	11	11	8	11	8
3	SAN	18[a]	16	16	18	16	18	18	16
	STN1	13	15	13	15	13	15	13	15
	STN2	6	6	8	8	6	6	8	8
	STN3	3	3	3	3	5	5	5	5
	GWN	9	11	9	11	11	9	11	9

[a]Initial factor set.

Table 4. Regression analysis of initial tuning experiments.

Parameter	Configuration	Mean Factor Level	Distance Between Levels	Regression Coefficient ($\times 10^3$)	F-Ratio
SAN	1	17	2	-0.12	0.02
	2	15	2	-1.89	1.34
	3	17	2	1.77	1.49
STN1	1	13	2	-1.70	3.46
	2	13	2	-9.03	30.77[a]
	3	14	2	-2.34	2.64
STN2	1	3.5	3	-1.15	1.60
	2	6.5	3	-3.30	4.10
	3	7	2	0.51	0.13
STN3	1	6.5	3	-2.65	8.41[b]
	2	6.5	3	-1.49	0.83
	3	4	2	1.98	1.88
GWN	1	9.3	3	0.86	0.88
	2	9.5	3	-0.87	0.28
	3	10	2	0.74	0.27

[a]Significant at 0.01 level. [b]Significant at 0.05 level.

Table 5. Final values of operating parameters.

Configuration	Parameter SAN	STN1	STN2	STN3	GWN	DEF ($\times 10^6$) Initial[a]	Final
1	17	15	4	8	9	2.295	2.282
2	16	17	7	7	10	2.242	2.196
3	15	18	6	2	9	2.600	2.579

[a]Parameter values for initial factor set are given in Table 3.

Table 6. Comparison of bus activity for three configurations.

Item	Configuration 1		Configuration 2	Configuration 3
	5-Min Delay	10-Min Delay		
Service Area				
Trip demand	19 197	20 476	18 308	16 987
Buses dispatched	1383	1222	1057	977
General pickup, %	18	6.4	26	40.8
Dedicated pickup, %	78.4	88.4	72	57
Station				
Buses to guideway	1383	1059	955	825
No stop allowed, %	18.1	32.1	60.9	80.6
Preassigned stop, %	58.4	51.5	30.3	16.5
Intermediate stops				
Number	942	651	340	152
Percent	68	61.5	35.6	18.4
Buses to CBD	228	232	223	204
Guideway				
Buses on highest volume link	64	60	86	74
Buses on next highest volume link	63	58	55	60

Table 7. Trip times for three configurations.

Item	Configuration 1		Configuration 2	Configuration 3
	5-Min Delay	10-Min Delay		
Travel time, min				
Service area	18.8	18.9	22.9	29.5
Station outbound-inbound	1.2	1.2	0.9	0.8
Guideway	12	12	10.8	13.1
CBD	7.9	7.9	7.9	7.9
Intermediate stops[a]	1	0.9	0.9	0.8
Wait time, min				
Service area	10.1	10.5	12.0	15.1
Station[b]	1.6	2.2	1.4	0.9
Total time, min				
Wait time	11.3	12	12.7	15.4
CBD travel	27	26.9	27.1	32.5
CBD total	38.3	38.9	39.8	47.9
Non-CBD travel	32.8	32.7	34.9	43.6
Non-CBD total	44.1	44.7	47.6	59

[a] Reduced by fraction of total trips making intermediate stop. [b] Reduced by fraction of total trips stopping at station.

Table 8. Effects of station capacity restrictions.

Item	Station Capacity Factor				
	1000	2500	3500	4500	5500
Total ramps	255	132	92	67	55
DEF ($\times 10^8$)	2.196	2.207	2.206	2.216	2.229
Average number of buses stopping at stations					
Outbound	74.6	83.2	94.7	110.6	130.2
Inbound	23.7	26.4	28.5	32.0	34.4
Average times, min					
Outbound[a]	0.63	0.70	0.77	0.80	1.01
Inbound[b]	0.33	0.36	0.37	0.41	0.42
Intermediate stop	0.88	0.98	1.10	1.32	1.50
Average bus loadings	0.793	0.792	0.793	0.797	0.796
Bus requirements	3618	3641	3637	3652	3694
Operator requirements	2456	2465	2450	2454	2446

[a] Includes only buses at final destination station.
[b] Includes only buses at origin station.

cess capacity in station and CBD areas. Station capacity can always be manipulated by changing the number of ramps or the capability to process buses in parallel. To allow simultaneous changes at all stations, a capacity factor was used that simply states that there is at least one ramp for every X trip origins or destinations at a station. In the initial runs this factor was set at 1000 trips/ramp; it was then increased for configuration 2 from 1000 to 5000, in increments of 500. The effect on station capacity should be minimal until a certain point is reached. That point is difficult to estimate precisely, as can be seen from the selected data in Table 8; definitely poorer results were realized sometime after overall system capacity was reduced to between 92 and 55 ramps. In Table 8, the increased bus requirements appear to be roughly in agreement with the increased number of buses waiting in the station queue. In fact, capacity restriction appears only to affect station-related activity. The tabulated results show that both bus loadings and operator requirements remain virtually unchanged, outside of statistical variations.

SUMMARY AND CONCLUSIONS

Simulation Results

The main objective of this project was to demonstrate the applicability of the simulation methodology to a large-scale system. There was no attempt to make as thorough a study of the dual-mode networks as would probably be made if a specific design were to be recommended for implementation. But it is possible to draw some conclusions about dual-mode operations in Milwaukee.

The major items examined in this report were the interaction between operating policies and system design, the effects of network size, and the effect of restricting station capacity. The results were largely predictable. All the networks within a reasonable range appeared to be relatively insensitive to changes in operating conditions. Parameters affecting the number of intermediate stops seemed to be most critical. More intermediate stops and lower bus loadings were realized in the larger networks. No clear superiority was found between the 41-station and the 22-station networks, but the 13-station network (configuration 3) was definitely inferior. Effects of restricted station capacity were interesting in that, although the number of buses within stations increased by 40 percent, there appeared to be little or no effect elsewhere in the system.

Bus and operator requirements are important outputs of such a simulation but, because of steady-state conditions, the results reported here would be higher than expected in a real-world dual-mode system. The simu-

lation did provide upper bounds for these data and did show that configuration 2 required fewer buses and operators than the other networks to service nearly the same demand levels.

Methodology

In designing large-scale, service-oriented transportation systems it is important to examine alternative system operations, to isolate critical factors and bottlenecks, and to identify the cost versus service trade-offs that may exist. The methodology described here is, for the most part, capable of meeting these objectives. The major drawbacks of the simulation procedures are the time required to prepare input data and the extremely high computer costs. There are, however, methodological refinements that can help to overcome some of these problems.

Substantial computer time savings can be realized through more efficient data-collection procedures. It would undoubtedly have been useful in this case to experiment with the time period for data collection. A shorter interval in data collection would tend to increase the statistical variance of the results but at the same time allow for more replications and thus result in better estimates. The 10-min intervals used in this simulation were probably longer than necessary.

One means of reducing total experimentation and thus computer time would be to integrate into the simulation procedure some analytical models—perhaps queueing models to generate station-related inputs. An iterative procedure has already been suggested (10) that would tie queueing into the simulation. Similarly, service-area travel-time inputs can be better estimated by integrating dial-a-ride simulations into this model. Further consideration might also be given to developing better ways of dispatching buses and how these could be incorporated into the simulation.

There was no attempt in this project to examine the non-steady-state behavior of the dual-mode system. Data on a whole day's operation would definitely be of interest and could be easily generated. In analysis of non-steady-state conditions, data collection must span an entire day or at least an entire a.m. or p.m. peak demand period. It would take much longer to obtain a sample result under these conditions; most of the initial experimentation would thus have to be done under steady-state conditions.

The work described here represents an exercise whose main purposes were to see what type of results were obtainable from a large-scale simulation and to examine the practicality of the methodology. It is important to note that, in applying such a methodology to the real design of a dual-mode system, the objectives must be much more specific and the simulation program must be able to meet those objectives. The scope of such a project must be precisely stated and the project plans carefully formulated.

ACKNOWLEDGMENTS

This report was prepared as part of a program of research and training in urban transportation at Marquette University sponsored by the Urban Mass Transportation Administration, U.S. Department of Transportation. The conclusions are not necessarily those of the sponsoring agency.

REFERENCES

1. Demand-Responsive Transportation Systems. TRB, Special Rept. 136, 1973.
2. Demand-Responsive Transportation. TRB, Special Rept. 147, 1974.
3. A. J. Sobey and J. W. Cone. The Case for Personal Rapid Transit. HRB, Highway Research Record 367, 1971, pp. 70-90.
4. L. M. Cole, ed. Tomorrow's Transportation—New System for the Urban Future. U.S. Department of Housing and Urban Development, 1968.
5. Dual Mode Transit Systems. Rohr Industries, Inc.; Urban Mass Transportation Administration, U.S. Department of Transportation, Sept. 1974.
6. Milwaukee County Dual Mode Systems Study: Socio-Economic Evaluation. Urban Mass Transportation Administration, U.S. Department of Transportation, Vol. 3, Dec. 1971.
7. T. J. Heintz and A. Chatterjee. A Simulation Model for Planning Dual Mode Bus Systems. High Speed Ground Transportation, Vol. 10, No. 1, Spring 1976, pp. 31-46.
8. K. W. Heathington, J. Miller, R. R. Knox, G. C. Hoff, and J. Bruggeman. Computer Simulation of a Demand-Scheduled Bus System Offering Door-to-Door Service. HRB, Highway Research Record 251, 1968, pp. 26-40.
9. L. L. Howson and K. W. Heathington. Algorithms for Routing and Scheduling in Demand-Responsive Transportation Systems. HRB, Highway Research Record 318, 1970, pp. 40-49.
10. T. J. Heintz. An Application of a Large Scale Dual Mode Simulation Model to Milwaukee County. Marquette Univ., 1976.
11. R. H. Myers. Response Surface Methodology. Allyn and Bacon, Boston, 1971.
12. O. L. Davies. Design and Analysis of Industrial Experiments. Hafner, New York, 1956.

Publication of this paper sponsored by Committee on New Transportation Systems and Technology.