TRANSIT SYSTEM CIRCULATION SIMULATOR: A PRACTICAL DESIGN TOOL

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This paper presents a transit circulation simulation model to be used heuristically for evaluating and choosing from alternative designs. The simulator measures changes in the performance of a trial transit system that result from variations in the design parameters. These include location of transit nodes, demand flows, vehicle capacity and speed, location of routes, and number of vehicles per route. The model output includes system, route, and vehicle performance characteristics, number of passengers served, and their average in-system travel and wait times. A monitoring capacity provides information, at any time interval, for the number and location of passengers waiting for service, delivered, or en route. The time interval scanning technique is also used to trace the movement of vehicles through the transit system and to provide insight for the next trial scheme. The simulator is demonstrated through the analysis of a new transit system for a university activity center.

•THE contemporary transit system planner faces unprecedented concerns when formulating new or improved public transportation services. In spite of significant advances in transportation planning theory and the computing capability to process large, comprehensive data sets, the growing awareness of social and environmental impacts of transportation systems has made the problem more complex and challenging. The advent of interdisciplinary planning groups, including lay representation, is increasing the need for multiple alternative investigations and a more open style of decision making. A means to quickly trace the effects of a particular change in transit routing, vehicular selection, or other expenditure-related elements is desirable. Test plans that accommodate certain interests or social objectives can be examined in terms of resource allocation and, when compared with other schemes, an equivalent cost for granting these benefits can be illustrated. The analysis components include a model, the electronic means of mapping the physical trial plan and of processing the data, and the planning group that provides the data. What is apparently lacking is a practical algorithm to test the various proposed transit systems. This is sometimes referred to as the black box, which is an unfortunate description when the confidence of a multidiscipline group is sought. Regardless of name or method, however, it seems desirable to work with a means that is simple, direct in principle, and capable of being understood by most users.

Currently, major transit routes are established through the use of techniques originally developed for planning urban highway systems (1). The methodology consists of a sequence of models, commonly referred to as the model system of the transportation planning process, which has recently been modified by the Urban Mass Transportation Administration to include a minimum-path transit algorithm. A number of more specialized transit models have also been developed, but their application has been

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limited. A review of these transit-oriented models is helpful to establish the requirements of a generalized transit planning tool sensitive to operational policy. These models can be classified as the theoretical flow models (2, 3, 4), the socioeconomic model (5), the problem-oriented linear cost-based methods (6, 7, 8), and the route cost relative to level-of-service methods (1, 9). The major limitations of the theoretical models are their many qualifying constraints and assumptions that often require that the actual problem be modified to fit the analytical format. The solutions are correspondingly questionable. The problem-oriented models are directed toward specific situations, and their general use is limited because of narrow goals and the inadequate attention given to factors that directly affect use. These latter considerations include individual waiting time, total time spent in the system, and accessibility of the transit system. In addition, most problem-oriented methods of transit analysis are concerned with the performance of the total system and do not indicate individual travel time or the performance of system components such as specific routes and vehicles.

The available transit planning procedures are also incapable of incorporating and testing the full range of operational policy strategies relative to how they affect alternatives within a major transit plan. Thus a means for evaluating the effects of short-term improvements in existing systems, such as route structures, schedules, and vehicle allocation, is needed along with a means for planning new systems based on the complete range of available technological and operational procedures. Such a tool may be applied subsequent to the modal-choice phase of the urban transportation planning process so that the performance of the transit system can be simulated in a more detailed fashion than a conventional transit assignment currently gives.

MODEL SCOPE

The proposed transit system circulation simulator (TSCS) is designed as an analytical tool to be used in a heuristic approach to area-scale transit planning problems. It is intended to be a practical means of examining, through an iterative process, the governing parameters of various vehicular designs, route configurations, and operating policies for a given travel demand in a service area. The basic objective of its use can be to (a) minimize the required system's physical components, (b) minimize average individual travel time, or (c) establish an acceptable trade-off between the travel time and required system components.

A simulator model is not an optimum-seeking technique in itself, and an exact solution algorithm capable of dealing with large-scale dynamic transportation problems is beyond the present state of the art. However, the heuristic procedure used must be rigorous and exhaustive if it is to provide a probable and practical optimal solution. The model must be flexible in its ability to cope with the large number of constraints present in some situations; on the other hand, it must be capable of incorporating a considerable number of design variables. Ideally, it should be as free of built-in bias as possible, and it should rely on information supplied by each user.

Inputs

TSCS requires two types of input information: demand variables and system variables. These variables are then processed to establish measures of the system, route, and vehicle effectiveness. A basic flow diagram of TSCS is shown in Figure 1. The number and location of the system nodes (trip origin and destination points) are initially specified by dividing the service area into geographical points, each having a demand function (trips per unit time) and a distance component [miles (kilometers)] to all other nodes. These demand variables are given for all modal pairs and can be entered as either a uniform or a random distribution. When the latter approach is more realistic, it can be accomplished with Monte Carlo techniques.

The system variables characterize the transit service in terms of vehicle parameters and network factors. Those system measures associated with the vehicle describe its technology in terms of capacity and speed and specify the number of vehicles on each route or in the entire system. The network parameters are associated with the selection of the nodes that specify the location and number of routes in the network. Finally, loading and off-loading rules are established to select which passengers access or egress a vehicle at each node relative to the direction of travel.

Outputs

TSCS output consists of measures of performance of the entire system, each route, and every vehicle. Figures 1 and 2 show and Table 1 gives some of the performance characteristics that the model provides. During time interval t, the number of passengers waiting for service and the number of passengers who have reached their final destination are designated. The location of every vehicle, its future travel pattern (nodes and arrival times), the number of passengers on the vehicle, and the origins and final destinations are also specified. These summary performance characteristics are used to evaluate the system design relative to designated policy objectives. For example, the operator may desire that the system deliver a maximum number of passengers within a specified time period or that the time the average passenger spends in the transit system be less than some predetermined standard.

TRANSIT SIMULATOR

TSCS uses the time interval method for controlling the scanning process. At the end of each scanning period, time measures that describe all passengers in the system, those waiting for service and those aboard vehicles, are updated. Operationally, TSCS translates the given demand and system variables into performance characteristics and consists of three primary stages:

1. The information synthesizer collects and stores the demand and system variables, computes the transit system schedule, and gives the transit demand for each scanning interval;
2. The load and off-load procedure uses the system schedule, loading and off-loading instructions, and nodal demand to simulate the accessing and egressing of passengers as transit vehicles travel through the network; and
3. The performance characteristics collector calculates and catalogs the various measures of effectiveness for the transit system, routes, and vehicles.

Information Synthesizer

The information synthesizer, shown in Figure 3, integrates the system variables with the demand variables to produce the temporal distribution of demand, the node-to-node traveling and walking times, and the transit system schedule. The locations of the transit nodes determine the distance between all nodes in the transit network. Given this distance, the average system speed, walking times, and system travel times are determined for all nodal pairs. These nodal-pair walking times are later compared to the average system times to determine the true mode (transit or walking) for that nodal demand. The walking time is measured along the straight-line distance between nodal pairs, and the system time is measured along the transit links between nodes and includes the time at each node spent loading and off-loading passengers. When the transit routes and the number of vehicles per route are specified and the node-to-node travel times are produced, the transit system schedule is developed. A typical portion of this transit system schedule is given in Table 2 in matrix form. The rows represent the time interval t, and the columns represent the vehicles m. If the vehicle is at a transit node, element P(t, m) will be equal to that node's number. If the vehicle is not at a node, a zero will fill element P(t, m). For example, if vehicle 10 is at node 6 at

Figure 1. Flow diagram of transit system circulation simulator.

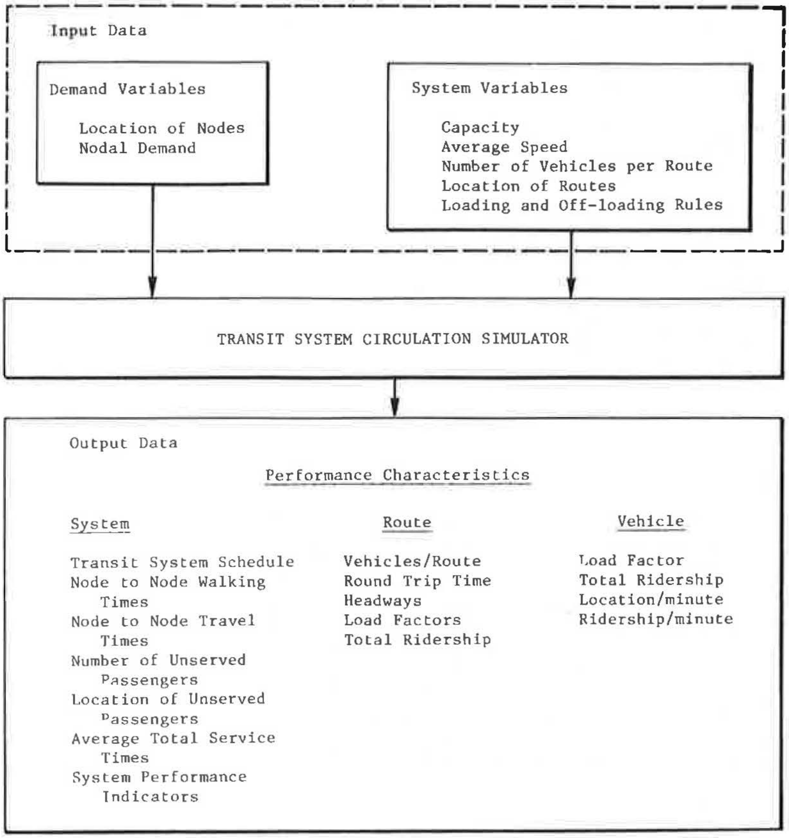

Figure 2. Transit system at time t.

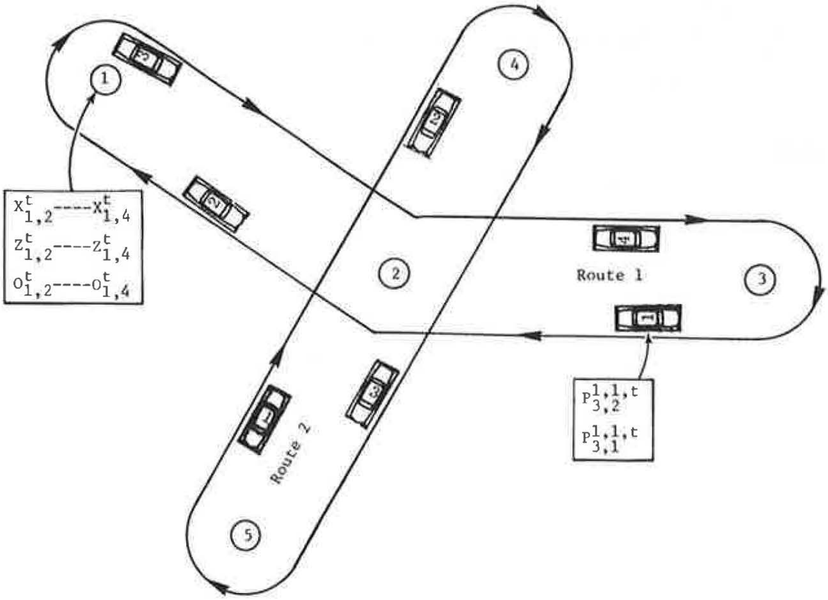

Table 1. System performance characteristics.

Characteristic	Description	Notation[a]
Passengers-in-system matrix	Number of passengers waiting at nodes i whose final destination is j	$X^{t}_{i,j}$
Delivery matrix	Number of passengers delivered at node j that enter system at node i	$Z^{t}_{i,j}$
Overflow matrix	Number of passengers at node i going to node j that could not board vehicle because their numbers exceeded capacity of vehicle	$O^{t}_{i,j}$
System time matrix	Average time spent by passengers (waiting and traveling) from node i to node j	
Average system time	Sum of travel time per passenger in minutes divided by total number of passengers	
Passenger en-route matrix	Number of passengers on vehicle p, on route q with origin i and destination j	$P^{p,q,t}_{i,j}$
Performance matrix	Total number of passengers waiting, delivered, and en route and time values for waiting and delivered passengers	$\Sigma X^{t}_{i,j} + \Sigma Z^{t}_{i,j} + \Sigma P^{p,q,t}_{i,j}$

[a] For any system of nodes, vehicles, and routes and any scanning period.

Figure 3. Information synthesizer.

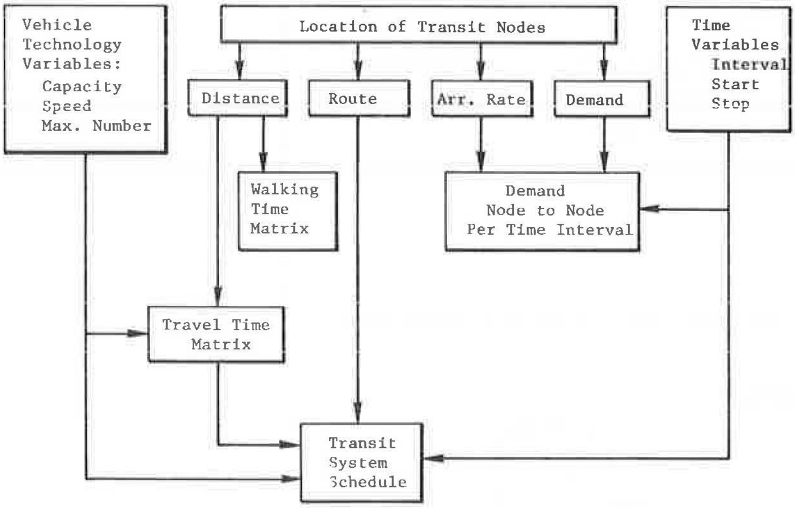

Table 2. Transit system schedule.

Time Interval	Vehicle Number 1	2	3	4	5	6	7	8	9	10
100	2	0	0	0	0	0	9	0	0	7
101	0	0	0	0	0	0	0	2	0	0
102	0	0	7	3	1	7	0	0	3	0
103	0	9	0	0	0	0	8	0	0	6
104	1	0	0	0	0	0	0	9	0	0
105	0	0	8	6	2	6	0	0	2	0
106	0	2	0	0	0	0	7	0	0	3
107	2	0	0	0	0	0	0	8	0	0
108	0	0	0	7	3	3	0	0	9	0
109	0	0	9	0	0	0	6	0	0	2
110	3	1	0	0	0	0	0	7	0	0

t = 103, then P(103, 10) = 6 as given in Table 2. If vehicle 9 is traveling between nodes at t = 100, then P(100, 9) = 0. Thus the transit system schedule represents the position of each vehicle for every time interval in the study period.

Load and Off-Load Procedures

The load and off-load procedures, shown in Figure 4, use a time-interval scanning procedure to update the demand for transit and to access and egress passengers on the vehicles that circulate on the routes. During each time interval, the position of each vehicle is monitored to determine if the vehicle is at a transit node, i.e., $P(t, m) > 0$, and if this is so, passengers are off-loaded and loaded.

There are two possible off-loading procedures: final delivery and transfer of passengers. The number of passengers who have reached their final destination and their corresponding travel times (passenger minutes) are added to the delivery matrix. If the passengers are to be transferred, the sums of all transfer passengers and their passenger minutes are added to the temporal demand matrix. After the off-load procedure is completed, the load subroutine is activated. The load subroutine is designed to load passengers from the temporal demand matrix to the vehicle matrices.

There are two types of loading conditions: (a) All passengers that are waiting for transit can board the vehicle without exceeding the vehicle's capacity or (b) the number of passengers waiting would exceed the maximum capacity of the vehicle. In the first case, the loading instructions are used to load the passengers and their time values into the vehicle matrix. In the second case, when the total number of passengers waiting for transit is greater than the number the vehicle can accommodate, a loading assumption governs. This assumption states that passengers are selected to board the vehicle in the same proportion as the individual nodal demand is to the total nodal demand. For example, if the maximum number of passengers to be loaded at node A, without exceeding the capacity of the vehicle, is 30, the demand would be $X_{a,b} = 40$, $X_{a,c} = 20$, and $X_{a,d} = 0$, and the number of passengers loaded would be $P_{a,b} = 20$, $P_{a,c} = 10$, and $P_{a,d} = 0$. The remaining passengers that are not loaded are added to an overflow matrix. The boarded passengers and their time values are then added to the vehicle matrix. The temporal demand matrix is subsequently reduced to indicate that passengers are loaded on the vehicles or added to the overflow matrix. These load and off-load subroutines are repeated for all vehicles located at a node during the time interval.

Performance Characteristics

As TSCS moves vehicles through the network, the effectiveness of the system's design must be measured. This final stage of the TSCS process determines, catalogs, and stores certain performance characteristics for the total system, individual routes, and each vehicle.

System Performance

The description of system performance characteristics is given in Table 1 as mentioned previously. In addition, the overflow matrix is a principal indicator of the system's performance since it shows which nodes and routes need more vehicles or shorter headways. This matrix also shows removal of passengers not initially served by the transit system and serves to prevent passenger queues at the nodes from becoming too large. The removal of the passengers not served by the first available vehicle is assumed to give a realistic representation of a working system. It is hypothesized that, if a potential passenger is forced to wait for a transit vehicle while full vehicles are passing the stop, the passenger will find another mode of transportation for the trip.

The system time matrix and average system time are measures of the system's performance from the user's point of view; thus, the time values in the matrix and the total average travel time give the planner an indication of the system's effectiveness as measured by the passenger.

Route Performance

The route performance characteristics are used to describe each route and the way in which each affects the performance of the system. These characteristics include number of vehicles per route, round-trip time per route, route headways, and route load factors. The route load factor is an average of the vehicle load factors on that route and is an indicator of the route's ability to meet the travel demand.

Vehicle Performance

The vehicle performance characteristics are similar to the route performance characteristics and are used to determine some of the route characteristics. The vehicle load factor indicates the average number of passengers on the vehicle. This value is also expressed as a percentage of the seated capacity. The total number of passengers carried, the number of passengers on each vehicle, and the position of each vehicle are determined. This information identifies which vehicles can be removed and determines which routes are overloaded or underloaded.

The following application of the transit simulator will clarify and further explain the operational qualities of the model and will define the demand measures and system variables that serve as the initial model inputs. It will also exhibit some typical performance characteristics that can be produced.

APPLICATION

An application of TSCS is demonstrated by an analysis of alternative rubber-tired transit system designs for the University of Virginia. This system will function as a line-haul system (morning and afternoon peak periods) and a circulation system. The following design constraints prevailed in this application of the model:

1. The maximum demand of first trip passengers during the 8 a.m. to 10 a.m. peak period will be met.
2. The transit system will provide service to all areas of the university grounds as well as nearby residential areas.
3. The transit simulator will test the designs during the 7 a.m. to 11 a.m. time period; the peak demand for service is included within this time period.
4. The time the average passenger spends in the transit system, waiting and traveling, during a trip from origin to destination will be less than 10 min.
5. Location of routes will make maximum use of the existing roadways.
6. All nodes will be located at areas of maximum potential ridership, i.e., parking lots, dormitories, residences, and other locations.
7. The system will be designed for a 40-passenger bus; maximum number of vehicles available to the transit system will be 25 buses.
8. The system will average 20 mph (32 km/h) between transit nodes; loading and off-loading times are not included.

Specification of Demand

Nine transit nodes are selected, and their locations are shown in Figure 5. The demand data for the interchanges among the nine nodes are given in Table 3. The distances [miles (kilometers)] between all nodal pairs are given in Table 4.

The arrival rate for transit service is assumed to be uniform for each of the nine

Figure 4. Load and off-load procedures.

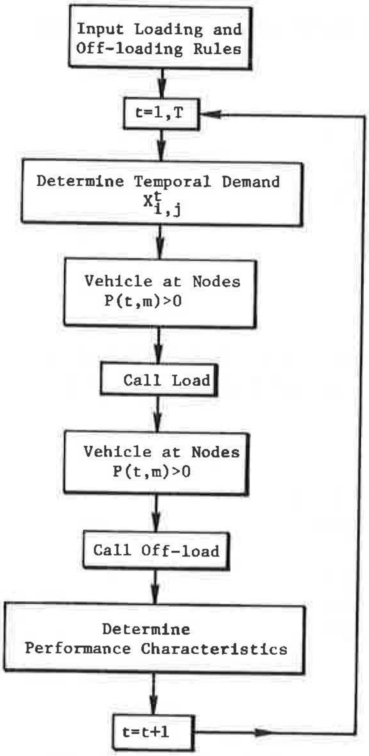

Figure 5. Transit nodes.

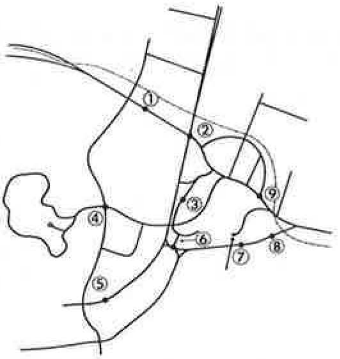

Table 3. Total demand for first trip.

	Destination Node								
Origin Node	1	2	3	4	5	6	7	8	9
1. University Hall	0	190	450	120	0	1,320	970	400	10
2. Fine Arts	40	0	360	100	0	1,060	780	310	10
3. Newcomb	10	50	0	30	0	580	270	110	0
4. Alderman	80	250	530	0	0	1,560	1,080	480	10
5. Stadium	40	140	240	70	0	750	570	230	10
6. Grounds	20	70	140	500	0	0	3,300	1,400	0
7. Brandon	10	40	30	30	0	240	0	80	10
8. Medical	10	50	120	40	0	370	270	0	0
9. Elliewood	40	200	430	130	0	1,220	830	360	0

Note: Values are in miles. 1 mile = 1.6 km.

Table 4. Distance node to node.

	Destination Node								
Origin Node	1	2	3	4	5	6	7	8	9
1. University Hall	0.0	0.70	1.20	1.00	1.70	1.50	1.75	2.10	1.00
2. Fine Arts	0.70	0.0	0.50	1.10	1.20	0.80	1.05	0.85	0.30
3. Newcomb	1.20	0.50	0.0	0.60	0.70	0.30	0.55	0.90	1.45
4. Alderman	1.00	1.10	0.60	0.0	0.70	0.50	0.75	1.10	1.45
5. Stadium	1.70	1.20	0.70	0.70	0.0	0.50	0.75	1.10	1.45
6. Grounds	1.50	0.80	0.30	0.50	0.50	0.0	0.25	0.60	1.15
7. Brandon	2.10	0.85	0.90	1.10	1.10	0.60	0.35	0.0	0.55
9. Elliewood	1.00	0.30	1.45	1.45	1.45	1.15	0.90	0.55	0.0

Note: Values are in miles. 1 mile = 1.6 km.

transit nodes in the system. The arrival rate is divided into two components:

1. The hourly load factors, as given below, represent the percentage of the total number of trips made during the hour.

Hour	Load Factor (percent)	Hour	Load Factor (percent)
7 to 8 a.m.	20	9 to 10 a.m.	30
8 to 9 a.m.	30	10 to 11 a.m.	20

2. The arrival ratios of the passengers, as given below, are centered around the change of classes within the hour time periods. The hour is divided into six 10-min intervals.

Time (min)	Arrival Ratio	Time (min)	Arrival Ratio
0 to 10	0.25	30 to 40	0.15
10 to 20	0.10	40 to 50	0.15
20 to 30	0.10	50 to 60	0.25

System Variables

The alternatives evaluated are shown in Figures 6 and 7. Each network is evaluated with the number of vehicles per route varied, but the route network and all other design constraints are held constant. Each change in the number of vehicles per route is referred to as a transit plan; these transit plans are given in Table 5 for networks A and B.

Evaluation Criteria

After the design constraints were reviewed, the following evaluation criteria were used to determine the best alternative transit plan:

1. System performance criteria include delivery of maximum number of passengers, in-system time (waiting and traveling time) less than 10 min, and average vehicle load factor greater than 10 passengers/vehicle/min.
2. Route performance criteria include headways less than 10 min and route load factors greater than 10 passengers/vehicle/min.

The results of these evaluations are given in Table 6. Based on the evaluation criteria, plan A-4 would be selected. It meets all of the route and system criteria and delivers the maximum numbers of passengers. Plan A-6 delivers more passengers but does not meet the route load factor criterion of maintaining a minimum of 10 passengers/vehicle/min. The evaluation criteria given in this application are not intended to limit the simulator but are only examples of the many possible evaluation criteria. TSCS output can be included within a cost-benefit analysis or combined with nonuser impacts to provide for a comprehensive evaluation of transit system designs.

Figure 6. Network A.

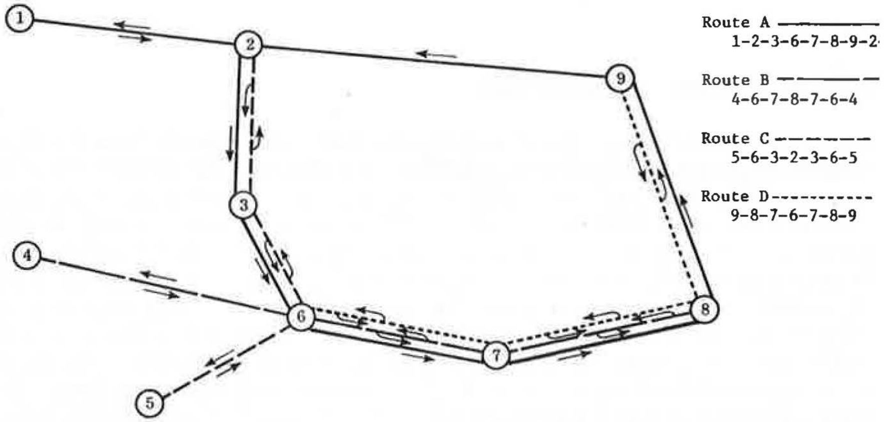

Figure 7. Network B.

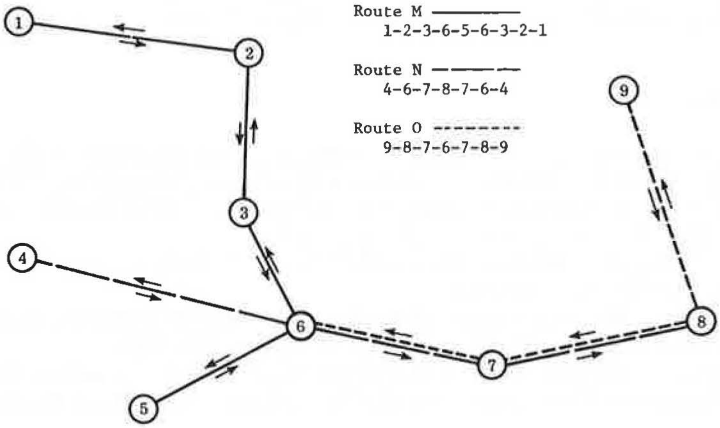

Table 5. Number of buses per route.

	Network A Routes				Network B Routes		
Plan	A	B	C	D	M	N	O
A-1	4	4	4	4			
A-2	6	4	4	4			
A-3	8	6	4	4			
A-4	10	7	5	3			
A-5	12	6	3	4			
A-6	10	7	4	4			
B-1					3	3	3
B-2					5	5	5
B-3					7	6	6
B-4					8	7	7
B-5					10	7	7

Table 6. Evaluation matrix of alternative transit plans.

Plan	Number of Passengers Delivered	In-System Time (min)	Average Load Factor	Headways (min)	Route Load Factor
Network A[a]					
A-1	11,843	8.6	15	7, 5, 6, 6	20, 16, 11, 14
A-2	12,473	8.5	14	5, 5, 5, 6	17, 16, 11, 14
A-3	13,313	8.3	13	4, 4, 5, 6	15, 17, 8, 12
A-4	14,191	8.1	12	3, 3, 4, 7	14, 10, 10, 12
A-5	14,031	8.3	11	3, 4, 7, 6	14, 9, 9, 11
A-6	14,250	8.1	11	3, 3, 5, 6	14, 9, 9, 11
Network B[b]					
B-1	8,829	9.7	22	9, 7, 7	26, 18, 22
B-2	11,134	8.7	17	6, 5, 5	21, 15, 16
B-3	12,632	8.5	16	4, 4, 4	19, 13, 16
B-4	13,485	8.2	14	4, 3, 3	15, 13, 12
B-5	13,798	8.1	14	3, 3, 3	15, 13, 12

[a] Routes A, B, C, D in Figure 6.
[b] Routes M, N, O in Figure 7.

SUMMARY AND CONCLUSIONS

The TSCS model uses a person-computer interaction procedure for testing alternative transit systems and operating policies. By showing the sensitivity of various system components, this analytical tool aids in selection of optimal circulation routes, vehicular designs, and transfer points. TSCS needs only readily available data as inputs (demand and system variables), and the output information (performance characteristics) is designed to indicate the effectiveness of the system in a relatively simple manner. The number of transit nodes and the size and number of the time intervals are limited only by the storage capacity of the computer. The present stage of development of TSCS limits the average in-system-time values to approximations based on groups of passengers and not on an average of each individual passenger trip. A method for inventorying individual trips would improve the accuracy of the simulator. An additional improvement would be to key the arrival rate of the vehicles to the arrival of passengers at pickup points. An interactive computerized format using data displays and light-screen mapping can also be developed to greatly improve the synthesis process.

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