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CANADIAN TRANSPORTATION RESEARCH FORUM

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A MODEL FOR SIMULATING the behaviour of traffic along a heavily travelled roadway whose curb lane is reserved for buses has been developed and programmed in the GPSS computer simulation language. Its accuracy of representation and sensitivity to changes in inputs have been demonstrated by application to the Eglinton Reserved Bus Lane System between Bathurst and Yonge Streets in Toronto. This programme can be used to study the relative effects of various reserved bus lane strategies. Measures of effectiveness can be quoted in terms of such factors as bus time, car time, total passenger time, and/or adherence to bus schedules. Vehicles intending to make right turns can be allowed to enter the bus lane in a common bus-car section, of some specific length just upstream of the intersection. The simulation model can be applied to determine an optimal length for this common section. In addition, the effects of bus bays, left turning storage areas, alternative bus stop locations, various turning movement percentages, and traffic signal operations can be estimated.

Application of the model in simulating various combinations of bus stop locations, bus volumes and right turning movements has led to a set of tentative general guidelines for planning and design of a reserved bus lane system.

Introduction

We appear to be moving back in the direction of partial dedication of road lanes to transit. We are, in fact, on the verge of completing the circle which has gone from streetcar to bus to private auto, gradually returning to bus and moving increasingly to reserved bus lanes, even back to streetcars. In the past, buses replaced streetcars due to their flexibility and the nuisance of tracks to the preferred private auto. The bus in turn largely gave way to the automobile, a consequence of affluence and urban sprawl. However, increased congestion and shortage of parking in our larger cities, along with the threat of fuel shortage, are causing us to reconsider the relative advantages and efficiencies of transit. The dominance of the auto has diminished, and there seems to be an increasing tendency to give preferential treatment to buses, at least in the downtown areas, and especially during peak periods of traffic flow. An example of this is the comeback being made by the streetcar in Toronto. Compared to buses operating in mixed traffic, streetcars have advantages in capacity and a right-of-way relatively free of cars.

In an attempt to make buses emulate the streetcar without the expense of a guideway, a lane is often reserved for their use. Reserved bus lanes are presently operating in Toronto and Ottawa, with more streets planned for such operation in both cities. Other cities are using and/or planning reserved bus lane operation. Buses on a reserved bus lane operate somewhat similar to streetcars. The major difference is that the reserved bus lane has generally been the right hand lane while streetcar tracks are placed in the left lane. The streetcar conflicts with vehicles which must bear left to turn left, while the bus must at some point share its reserved lane with right turners. Since left turn restrictions are generally easy to implement, the streetcar can conceivably be given an almost, if not completely exclusive right-of-way, except for crossing traffic. In contrast, it is not very likely that right turns could be banned along a roadway in favour of dedicating the right-hand lane for the exclusive use of buses.

Therefore, buses, even in a reserved lane, will generally have to interact to some extent with cars. Right turning vehicles will have to be allowed into the bus lane at some distance prior to certain intersections. But what distance and at which intersections? Prior to setting up a reserved bus lane system along a roadway, the traffic planner should have the answers to such questions. For example, he should have some indication of the extent to which this car-bus interaction will delay both cars and buses and their respective passengers. If he can estimate the effects of the various possible operating strategies on the cars and buses, he can weigh their respective delays under each strategy and choose the best one.

This paper describes a methodology developed to aid the traffic planner in weighing the relative merits of various alternative operating strategies. Included is a GPSS simulation model developed to simulate the operation of a roadway with a reserved bus lane, and in particular, the above car-bus interaction. This model can quantitatively estimate car and bus travel times, speeds and delays for each of the various combinations of strategies and data inputs. Each strategy can be evaluated and the optimal one found. If the predicted results indicate that implementation would be worthwhile and advisable this optimal strategy would then be implemented.

The Simulation Model

The requirement for accurately modelling phenomena such as car-bus interaction and the operation of bus stop sections dictated that computer simulation be used as opposed to a strictly mathematical approach combining flow theory and queuing analysis. The selection of

Aids for Planning and Evaluating Reserved Bus Lane Strategies

by S. Yagar and G. F. W. Chan**

computer simulation is discussed in reference (1).

The simulation model has been programmed in the GPSS (General Purpose Simulation System) computer simulation language (2, 3), which was developed by I.B.M. to aid computer simulation. The programme can simulate the operation of a roadway with two lanes in each direction in addition to a reserved bus lane in one direction. Other configurations would involve straightforward programming modifications. Basically, the simulation model consists of the following three major components:

(1) Generation of the individual vehicles into the traffic stream.

(2) Movement of the vehicles through time and space.

(3) Registering the traffic statistics.

The generation of cars for entry into the network is a stochastic process. In this case exponentially distributed headways were used at all points of entry. Once vehicles are in the network their travel patterns are governed by the traffic system and interactions with other vehicles. For example, traffic signals filter the arrival patterns from one intersection to the next and queues affect the movements of individual cars. Bus arrivals are generated according to a schedule pre-determined by the transit authority. There is also provision for some random variation in the schedule. The simulated behaviour of a car depends on its intended movement (left, thru, or right) at the immediate downstream intersection. The behaviour of a bus depends on the bus route that it must follow (i.e., where it enters and leaves the network).

Various traffic phenomena such as turning movements, gap acceptance, bus stop location, delays at intersection and lane queuing discipline have been included in the model to simulate in detail the traffic movement in the network (1). In particular, separate routines were developed to represent sections with near side, far side, and mid-block bus stops. There is also a routine for sections without any bus stop. Each of these types of section can be simulated in conjunction with a signalized or unsignalized intersection.

To accommodate right turning movements, vehicles intending to make right turns are allowed to use the bus lane only in a specified car-bus section, referred to as a "common section," just upstream of the intersection. It was felt that the car-bus conflicts associated with the common section would have a great influence on the performance of a reserved bus lane system. Consequently, considerable effort has been devoted to describe the operation of this "common section."

To simulate the interference caused by vehicles entering and leaving the main stream of traffic, the minor street traffic at each intersection is also simulated.

The data required by the model are generally available from traffic or transit authorities. The output of the model includes detailed descriptions of the delay statistics at each intersection such as average delay and maximum queue length. Average travel time by vehicle type over the entire reserved bus lane network and/or between any pair of signalized intersections can also be obtained. Average travelling speeds can be calculated quite simply from these. The number of right turners accepted by and/or refused entry into the bus lane can also be identified (see Assumptions below). In addition, a timing routine is included at the end of the network to record the individual bus arrivals. These times can be compared to the bus schedules to determine how well the schedules are adhered to for each transit route with reserved bus lane operation.

Assumptions Used in the Model

(1) All right turners will try to enter the bus lane at the beginning of the common section. If the common section is full of vehicles when a car reaches that entry point, it will be forced to go straight through at that intersection and attempt to turn right at the next intersection.

(2) The reserved bus lane operation can be strictly enforced, i.e., no non-priority vehicles will attempt to enter the bus lane.

(3) Through vehicles choose the lane with the shortest queue.

(4) All queued automobiles have a fixed space headway of 20 feet; buses require 40 feet.

(5) Pedestrian interference is not considered in the model.

(6) All left turns are made from the

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inside lane and all right turns are made from the curb lane.

(7) Buses use only the bus lane.

Validation of the Simulation Model

The model was validated against field results from the Eglinton Avenue reserved bus lane experiment in Toronto. The Eglinton reserved bus lane operates in the east bound direction only, i.e., from Bathurst Street to Yonge Street from 7:00-9:00 A.M. and from Yonge Street to Brentcliffe Road from 4:00-6:00 P.M. The roadway has been restriped to allow the curb lane to be reserved for buses plus two lanes for cars in each direction. The model has been applied to simulate the 7:45-8:45 A.M. peak hour traffic between Bathurst Street and Yonge Street. Bus route #32 runs the entire length of the reserved bus lane, while route #33 and #61 enter the network at Vesta and Avenue Road respectively and terminate at Yonge Street.

The field results were obtained by a floating car survey covering the section of Eglinton Avenue between Bathurst Street and Duplex Avenue. For comparative purposes, the model gathers car statistics as far east as Duplex Avenue which is about 540 feet west of Yonge. Buses travel a further 200 feet after leaving Duplex to enter the subway terminal area, and the model simulates this.

The simulation run produced average travel times for cars and buses of 294 seconds and 538 seconds respectively. The corresponding average speeds are 16.3 and 9.1 m.p.h. From field observations, travel times for cars and buses are 276 seconds and 495 seconds, with average speeds of 18.3 and 10.3 m.p.h. respectively.

The simulation results indicate higher travel times for both cars and buses than were observed in the field. This is due to the fact that the simulation used flow rates corresponding to the 7:45-8:45 A.M. peak hour whereas the field survey was performed from 7:00 A.M. to 9:00 A.M., during which lower average flows were encountered.

On the basis of the above results the model was tentatively accepted as valid. However, to further test whether the model can indeed describe the operation accurately, a second validation procedure was carried out. The delay at each signalized intersection and travel time between each pair of intersections, as estimated by the simulation model, were compared to theoretical values obtained from a simple fluid approximation queuing analysis in which arrivals are approximated at their average rates. Newell (4) discusses analysis by fluid approximations.

In the fluid approximation queuing analysis, traffic movement is considered as a fluid rather than a stream of individual vehicles. To illustrate how this can be used to represent traffic movement along the simulated roadway, the cumulative car arrivals and departures at each intersection were plotted over time in Figure 1. The arrivals of cars into the network are approximated as having a constant average rate (i.e., cumulative arrivals to Bathurst are linear with time). The departures from each intersection are determined by the signal timing scheme at that intersection. The departures from an intersection, shifted by average travel time to the next intersection, represent arrivals at the downstream intersection. The departures from the latter intersection again depend upon its signal timing. The procedure is repeated to obtain arrival and departure patterns from one end of the system (Bathurst) to the other (Duplex). The path of a car can be traced by a horizontal line in Figure 1. The total delay at an intersection is the area between its cumulative arrivals and departures. To obtain average delay, divide by the number of vehicles that contributed to this total delay.

Table 1 compares the simulation results for car delay and travel time to estimates from fluid approximation queuing analysis. The total delay and travel time estimated by simulation are respectively 3.8% and 3.2% higher than the corresponding fluid approximation values. The simulation results include delay due to randomness while fluid approximations do not. For a series of intersections with good platoon behaviour the portion of delay attributed to randomness would be relatively small. The 3.8% excess therefore seems to be a reasonable measure of this added delay, so that the model's predictions are very encouraging.

COMPARISON OF SIMULATED RESULTS TO FLUID APPROXIMATION QUEUING ANALYSIS

INTERSECTION	AVERAGE INTERSECTION DELAY FOR CARS (Seconds)		AVERAGE TRAVEL TIME BETWEEN INTERSECTIONS FOR CARS (Seconds)	
	SIMULATION	FLUID QUEUING ANALYSIS	SIMULATION	FLUID QUEUING ANALYSIS
Bathurst	19.0	18	-	-
Spadina	10.4	12	54.2	52
Chaplin	10.1	11	21.5	22
Castleknock	21.3	19	54.9	52
Beddington	3.6	3	18.9	16
Avenue	28.1	26	52.0	48
Oriole	23.0	21	41.9	[illegible]
Duplex	14.0	15	51.9	[illegible]
Totals:	111	107	292	28[illegible]

TABLE 1

ILLUSTRATION OF FLUID QUEUING ANALYSIS

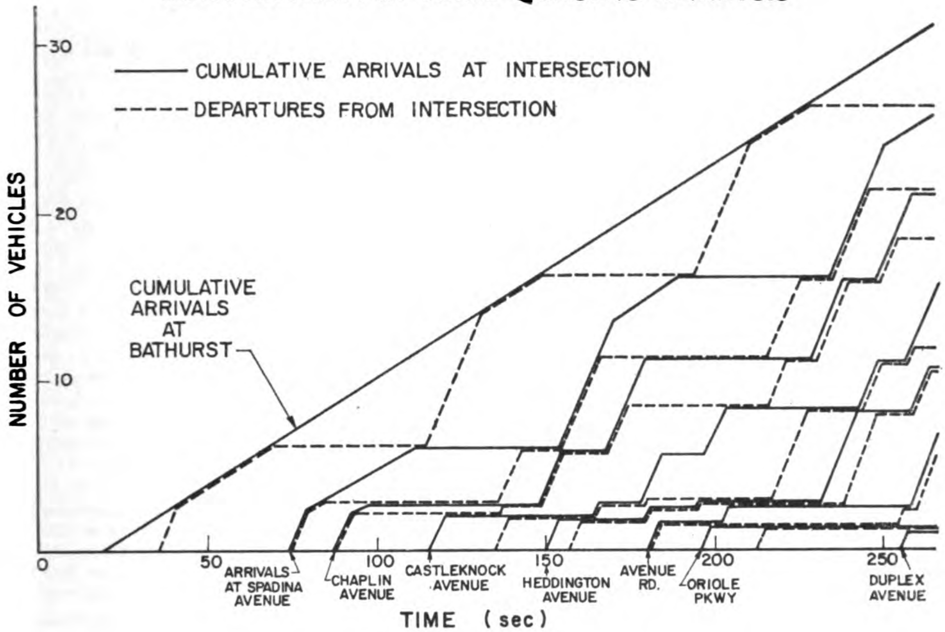

FIGURE 1

Sensitivity of the Model

To determine how well the model responds to a change in operation or data input, the green phase at Avenue Road was delayed by 35 seconds. This changed its offset relative to the upstream intersection from 20 seconds to 55 seconds. It also changed the offset between Avenue Road and the downstream intersection, Oriole Parkway, by 35 seconds, having the effect of advancing the green time at Oriole relative to Avenue Road.

Estimates of the effect of this timing change on network travel times and delays, especially at the Avenue Road and Oriole Parkway traffic signals, were obtained by both simulation and fluid queuing analysis. The queuing analysis involved diagrams of the form used in Figure 1 corresponding to "before" and "after" conditions. The difference in their queuing times served as control results against which the simulation results could be quantitatively tested. Since the offsets before Avenue Road are not disturbed, there would be no changes in delay for those upstream sections. However, the combined average delay per car for Avenue Road, Oriole Parkway, and Duplex was estimated to have decreased from 62 seconds to 42 seconds, or 32%. The corresponding effect estimated by the simulation model was a decrease from 65.1 to 45.0 seconds or 31%. These results indicate that the simulation model is quite sensitive in quantifying the effects of operational changes. The above delay values are broken down by intersection in Table 2.

The fluid queuing analysis indicated that the offset change at Avenue Road would cause the platoon at Oriole Parkway to be very well co-ordinated with the timing of the green phase. This would generate most of the 20 second saving in delay.

Effects of Growth in Traffic Demand

The model was applied to the Eglinton Avenue system to estimate the effects

SENSITIVITY OF THE SIMULATION MODEL TO CHANGE IN SIGNAL TIMING OPERATIONS

AVERAGE DELAY PER CAR (IN SECONDS)				
	BY SIMULATION MODEL		BY FLUID APPROXIMATION ANALYSIS	
INTERSECTION	EXISTING CONDITION	AVENUE ROAD GREEN PHASE DELAYED BY 35 SECONDS	EXISTING CONDITION	AVENUE ROAD GREEN PHASE DELAYED BY 35 SECONDS
Avenue	28.1	21.5	26	21
Oriole	23.0	3.9	21	2
Duplex	14.0	19.6	15	19
Totals:	65.1	45.0	62	42

TABLE 2

of increased bus and car flows respectively. The purpose was twofold; to illustrate the model's applicability for this type of purpose and to quantitatively estimate the effects of growth in demand on the viability of reserved bus lane operation. The model predicted that a 50% increase in the volume of cars on Eglinton Avenue would increase the car travel time for the 1.4 mile Bathurst to Yonge section by 60 seconds or 20% and the bus travel time by 10 seconds or 2%. It was judged that a reserved bus lane system would have even greater merit with the higher car volumes. For a 100% increase in bus volume, from 60 per hour to 120 per hour, the average travel time for buses was predicted to increase by 134 seconds, or 25% from the present 538 seconds. This corresponds to a decrease in average speed for the 1.4 mile section from 0.1 to 7.4 m.p.h. This indicates that effective reserved bus lane operation is limited to somewhat less than 120 buses per hour under present operating conditions.

TOTAL BUS PASSENGER DELAYS VS. COMMON SECTION LENGTHS (Near-side bus stop, average bus headway = 60 sec.)

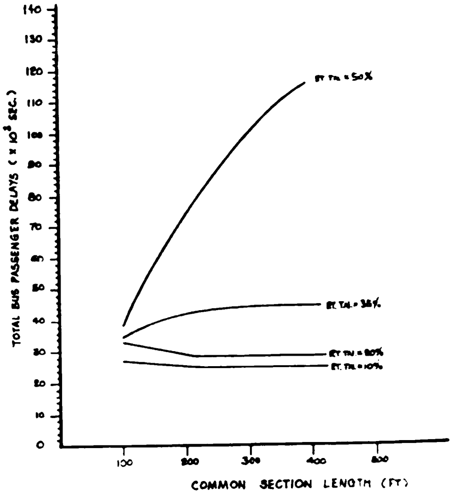

FIGURE 2

Determination of Some General Guidelines for Reserved Bus Lane Operation

One of the objectives of the paper is to develop some guidelines for the planning and evaluation of reserved bus lane strategies. To accomplish this objective, the operation of a hypothetical section containing an isolated signalized intersection was simulated employing the logic of the model, and the assumptions and lane configuration described above. Volumes of 60 and 120 buses per hour were considered. Cars were assumed to enter the system at exponential headways with an average of 4 seconds. The effects of near side and far side bus stops on the right turning movements and bus stop interactions were estimated by simulation of the corresponding routines. 10%, 20%, 35%, and 50% right turners were each used with common section lengths varied from 100 feet to 400 feet. These simulations were used to obtain an optimal length of common section corresponding to each combination of average bus headway and right turning percentage. The criterion for optimality was minimum total passenger delay (assuming bus and car occupancies of 40 and 1.4 passengers respectively). Although car arrival distributions and signal operations will vary with specific locations, these results should provide some initial guidelines prior to more extensive investigations. In Figure 2, the total delay to bus passengers is plotted as a function of common section length for each of the simulated right turn percentages, using a near side bus stop and 60 buses per hour. The similar case, but with 120 buses per hour was simulated but not plotted. The curves for total passenger delay are similar to those for bus passengers only and are not plotted. For a near side stop with 60 buses per hour and 10% or 20% right turners, total passenger delay decreases slightly with increased length of common section. For higher right turning percentages of 35% and 50%, total passenger delay increases dramatically with increased length of common section. For 120 buses per hour, total passenger delay increases with common section length for 10-50% right turns.

The above results are converted to suggested lengths of common section as functions of right turning percentages, given a near side bus stop. These are illustrated in Figures 3 and 4 for bus volumes of 60 and 120 per hour respectively. Figures 3 and 4 are summarized into the following guidelines. For 120 buses per hour the common section should not exceed 100 feet. For 60 buses per hour the common section should be kept at 200 feet for 10% to 20% right turning movements. For higher right turn percentages, a length of 100 feet should be used. The optional paths shown dashed in Figures 3 and 4 provide some alternatives for those traffic planners who may wish to accommodate all desired right turns, as far as possible.

Total bus passenger delays are plotted against common section length in Figure 5 for a far-side bus stop and 60 buses per hour. As before the curves of total delays to bus and car passengers are similar to those for just bus passengers and are not shown. For both bus vol-

OPTIMAL COMMON SECTION FOR VARIOUS RIGHT TURNING PERCENTAGES (Near-side bus stop, average bus headway = 60 sec.)

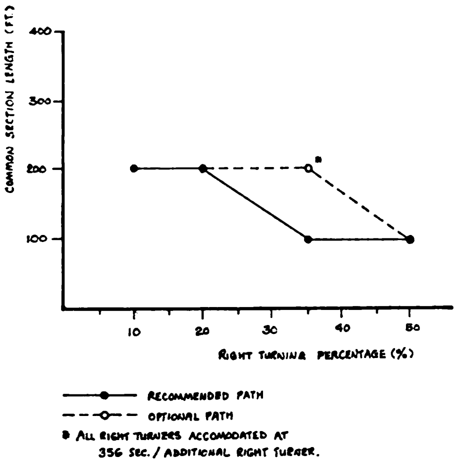

FIGURE 3

umes, delays increase with common section length. Figures 6 and 7 given recommended common section lengths as functions of right turning percentages for 60 and 120 buses per hour respectively. As in Figures 3 and 4 optional dashed paths are included for trading off delay savings in favour of accommodating additional drivers wishing to make right turns.

Discussion

The accuracy and sensitivity of the simulation model have been tested and validated against field data from the Eglinton Avenue system in Toronto. The

OPTIMAL COMMON SECTION FOR VARIOUS RIGHT TURNING PERCENTAGES (Near-side bus stop, average bus headway = 30 sec.)

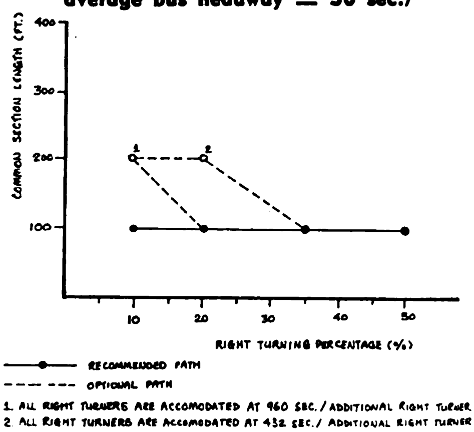

FIGURE 4

TOTAL BUS PASSENGER DELAYS VS. COMMON SECTION LENGTHS (Far-side bus stop, average bus headway = 60 sec.)

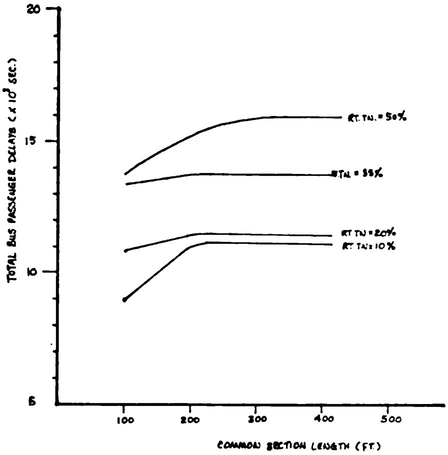

FIGURE 5

model has then been used to develop some guidelines for locating bus stops and defining the common sections where right turners can join the bus lane. These guidelines can aid the traffic planner in developing one or more alternative designs for operation. Any designs can then be tested using the GPSS computer programme of the model. It is noted that the above guidelines were developed for a specific section and should only be considered as initial guidelines. Final design decisions should be made with considerations to specific traffic requirements and characteristics.

OPTIMAL COMMON SECTION FOR VARIOUS RIGHT TURNING PERCENTAGES (Far-side bus stop, average bus headway = 60 sec.)

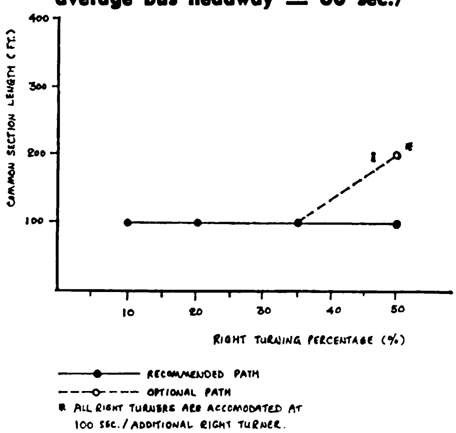

FIGURE 6

OPTIMAL COMMON SECTION FOR VARIOUS RIGHT TURNING PERCENTAGES
(Far-side bus stop, average bus headway = 30 sec.)

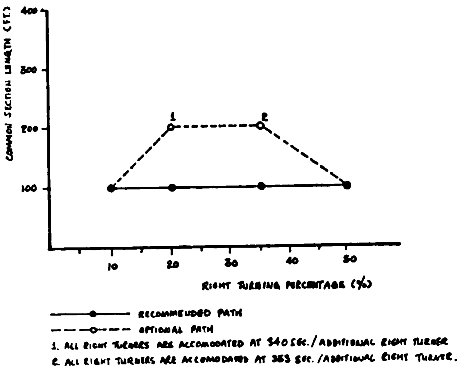

FIGURE 7

Although it was outside the scope of this paper, the model could be used in further analyses. For example, the predicted service levels for bus and car under reserved bus lane operation could be used as input data to modal choice models for estimating the amount of modal shift of travellers from car to bus due to the improved bus operation. The operation of the system could then be re-simulated with the new levels of bus and car demands. In a similar way, the model could be used to predict operation for growth in demand of either car, bus or turning movements.

The operation of a roadway without a reserved bus lane has not been modelled and programmed. Although this would be a straightforward offshoot of the bus lane model it was not considered essential to the requirements of this paper, as existing operation can be readily observed.

There is provision for easy inclusion of special geometrics such as bus bays and left turn storage areas.

Conclusions

A simulation model and some operational guidelines have been developed to aid in the planning and operation of reserved bus lane systems. The computer programme for application of the model has demonstrated an ability to predict travel times and delays with reasonable accuracy. The model is also capable of responding quite accurately to changes in various input parameters or data such as signal phasing operations and traffic demand growths. Some tentative guidelines for the planning of a reserved bus lane system are as follows:

(1) Bus stops should be located at the far side of a signalized intersection wherever possible.

(2) For near side bus stops and 60 buses per hour, common sections should be 200 feet long for right turning percentages of up to 20%. For higher right turning movements the common section should not be longer than 100 feet.

(3) For near side bus stops and 120 buses per hour, common section lengths should not exceed 100 feet.

(4) For far side bus stops and between 60 and 120 buses per hour a common section length of not more than 100 feet should be selected.

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FOOTNOTES

1 Suppliers might include employers, cooperatives, private entrepreneurs or the public transit authority.

2 Useful life means the time before traffic density requires the addition of more physical capacity to the highway.

3 Development density—the concentration of business or residential populations served by one link of the highway network.

4 Tennessee determines the property tax base (the valuation) at 55 percent of market value on public utility property and 25 percent on residential property.