Bus Priority Strategies and Traffic Simulation

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Simulation of corridor traffic (SCOT), a recently developed computer model that simulates traffic flow within a specified traffic system, has been used to predict the effect on bus service and general traffic performance of implementing candidate bus priority strategies. Numerical values of standard traffic performance measures were determined from computation of network vehicle trajectories. SCOT was calibrated to current peak-hour traffic conditions within an urban street grid representative of the central business district of Minneapolis. Data from city agencies were used in conjunction with field experiments to verify SCOT simulations. Various bus priority strategies designed to increase bus speeds by providing bus-only lanes were evaluated. The significant elements in bus travel time were shown to be frequency of station stops and red light signals. Further studies planned include identifying optimum bus station locations, developing bus progressive traffic signal timings, and evaluating various bus preemption of traffic signal strategies. Demonstration projects are under consideration to evaluate the simulation technique as a transit operations tool.

Until recently, traffic engineers were given the responsibility of moving vehicles safely and efficiently through city streets and highways. The bus operates at great disadvantage in the general traffic stream. If the objective of a transportation system is to move people and freight, and not simply vehicles, then the assignment of priority to buses and trucks in the traffic system must be evaluated. There is considerable activity in the transit industry to provide buses with priorities on the roadway and within the traffic control system commensurate with their people-moving capability. Some bus priority strategies already in effect or planned for early implementation are downtown bus-only streets, both direct-flow and counterflow bus-only lanes, bus bypass lanes for ramp-metered freeways, and bus preemption of traffic signals.

Before a proposed bus priority strategy is implemented, a preliminary analysis is conducted to estimate the expected benefits for the bus system and the disadvantages for the automobile and truck system. Experiments are conducted before and after the bus priority system is put into effect, and comparative bus and automobile-truck performance indexes are measured. Because traffic performance depends very much on weather conditions, time of day, day of the week, special events, and holidays, field observations must be made over a time span sufficient for statistical validity. In addition, driver adaptability makes properly controlled experiments difficult to design.

Computer simulation affords an ideal method for evaluation of candidate bus priority strategies, as well as general traffic control systems. The public is not inconvenienced, nor can it interfere with a computer experiment. Traffic conditions can be controlled to determine the systemwide effect of varying any individual component. Time can be compressed so that many strategies may be evaluated in a few weeks and only the most promising ones selected for eventual field test. Computer simulation can prove to be a valuable traffic engineering tool. However, it is, at best, an approximation to the real world and cannot replace field experiments. But it can provide the insight necessary to identify problem areas and lead to more successful demonstration projects.

STUDY PLAN

The objectives of this study were as follows:

1. To predict the changes in traffic performance and bus service caused by implementing various bus priority strategies,
2. To conduct a demonstration and thereby determine the validity of the preliminary analyses performed, and
3. To evaluate the usefulness of the computer model as a transit operations tool and to formulate an appropriate training program if the decision is made to recommend widespread use of the model.

The study area selected was the Minneapolis central business district. Most of the data needed to model the current traffic and bus system were made available by the traffic engineer of the City of Minneapolis and the operations authorities of the Twin-Cities Metropolitan Transit Commission. They cooperated in conducting experiments to acquire the remaining necessary data and selecting the candidate bus priority strategies. These strategies specified designation of bus-only lanes on two one-way streets. The first strategy specified that one lane be assigned to buses on the five middle blocks of two 10-block streets in the direction of traffic. This constraint required that passenger cars and trucks not be permitted to make right turns or to stop within this region. The second strategy specified that one counterflow lane be assigned to buses for the entire 10 blocks of two streets. No restrictions on turning movements were made, but one lane (of five) was used to separate the two directions of flow.

The study plan included using the computer model SCOT to simulate current traffic flow patterns for the morning and afternoon peaks. These would be the base or before cases and provide the quantitative traffic performance and bus service data. Once the model was calibrated to the study area, each bus priority strategy would be simulated under the same traffic conditions and the changes in traffic performance would be determined. Recommendations would then be made for a demonstration project for the more promising strategy.

COMPUTER MODEL

SCOT (1, 2, 3) is the amalgam of two computer programs: UTCS-1, urban traffic control system (4, 5), and DAFT, dynamic analysis of freeway traffic (6). In this study, the urban, microscopic part of the model was used because traffic flow within only the Minneapolis CBD was to be simulated. This traffic flow is characterized by different trajectories for passenger cars, trucks, and buses, governed by driver types, roadway geometry, presence of queues, downstream signal phase, and driver destination. Thus the trajectory of each vehicle must be individually computed. From these trajectories, traffic performance measures may be determined for each street. The traffic engineer can then identify the bottlenecks and the time and duration of congestion for each candidate bus priority and/or control system. Traffic demand can be held fixed, resulting in a controlled computer experiment—the ideal condition for evaluating a proposed change in bus service. Any component in the system may be systematically increased and the breaking point of the candidate strategy determined without public inconvenience.

The model logic specified vehicles entering the network at various points on the periphery, their flow rates, and automobile-truck ratios determined by field observations. As each vehicle enters the system, it is designated as a passenger car or a truck and randomly assigned one of 10 driver types. The driver set ranges from extremely conservative to reckless. These designations stay with the vehicle for the duration of its network trip and influence the selection of such quantities as acceleration (more sluggish for trucks) and desired cruising speed (highest for reckless). The vehicle speed profile includes acceleration, cruise, and deceleration segments. The desired cruising speed is selected on the basis of driver type from a statistical distribution about a mean free-flow speed observed for each network link. Crusing continues until deceleration is indicated. This mode is triggered by the presence of an obstacle in the vehicle's path (a slow-moving vehicle or a queue), a red or amber traffic signal downstream, or the need to make a right or left turn at the next intersection. The driver may change lanes when his lane is obstructed and an acceptable gap exists in an adjacent lane. The position and speed of each car are updated every second, and collisions do not occur. The deceleration regime is designed to ensure a safe stop. As a vehicle approaches an intersection, it may turn right or left, proceed through, or stop. Turning movements are in conformity with field site traffic statistics. Movement at an intersection depends on the traffic demand there and the signal currently displayed. The response of a driver to an amber signal depends on his speed and proximity to the intersection and which of the 10 driver types he is. Delays caused by pedestrian movement and determined from field data are added to the trajectories of right- and left-turning vehicles. Queues are discharged in a systematic way so that vehicles start up sequentially and arrive at the intersection at times and with speeds dependent on their position in the queue. Buses move through the network and stop at their assigned stations, which, in general, interferes with traffic. Their dwell times are computed from a statistical distribution about a specified mean value. Provision is made for intralink lane-blocking events. These simulate predictable temporary lane blockages, such as double parkers, taxi pickups, parking garage queues, and unloading trucks.

MODEL CALIBRATION: THE INPUT

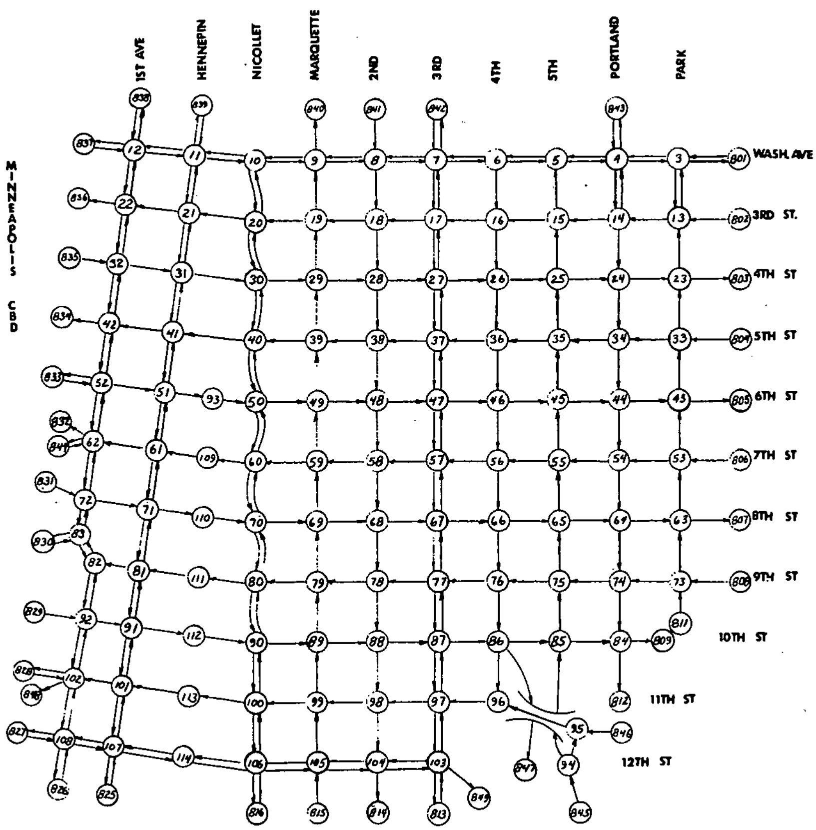
Before SCOT can generate traffic patterns, it must be calibrated to the study area. This means that the data describing the traffic system must be obtained and keypunched for input to the computer program. The study area selected was a portion of the Minneapolis CBD and is approximately a rectangle of 10 by 11 streets. It includes one- and two-way streets, a bus-only street, midblock and intersection traffic signals, parking lots, downtown and crosstown buses, pedestrians, and the downtown exit ramp of an urban freeway. This study area is modeled by a grid consisting of a set of unidirectional links that represent the street roadway and a set of nodes that represent the intersections. The information required to describe the study area traffic system falls into four sets: geometric, traffic demand, control system, and bus service data.

Geometric Data

The network model (Fig. 1) consists of 251 network links, 27 entry links, 27 exit links, and 114 network nodes. A two-way street requires two links. Two streets between Hennepin and Nicollet were not modeled as links, but their effects were represented by traffic sources and sinks.

For each street, the stop-line to stop-line span, the number of travel lanes, and the storage capacity of left- and right-turn pockets are needed. In this case the number of

Figure 1. Network model.



lanes per link varied from one to five; the spans varied from 254 to 1,114 ft, with the average span about 400 ft. The dimensions of the entire network are approximately 4,300 by 4,300 ft. Grades were not significant in this study area. The capacity of turning pockets ranged from two to 10 passenger cars.

Traffic Demand Data

The traffic conditions simulated were those occurring on a weekday morning between 7:30 and 8:30 a.m. and on a weekday afternoon between 4:30 and 5:30 p.m. From traffic counts at each intersection, turning movements and pedestrian counts were determined. Turning movements are assigned to each vehicle randomly at each intersection but in conformity with the field data; e.g., if the field data showed that 78 percent of the vehicles went straight through, 10 percent turned left, and 12 percent turned right, then a 100-sided die is cast for each vehicle as it enters a given link and, if the number lies in the set 1 to 10, the vehicle turns left at the downstream end of the link; if the number lies in the set 11 to 88, the movement is straight; and, if in the set 89 to 100, the vehicle turns right. Thus the turning movements are random, as in reality, and not uniform. Pedestrian volumes at each intersection are classified as negligible, 100 to 250, 250 to 500, and over 500 pedestrians per hour. Vehicles making right and left turns in conflict with pedestrians are given delays, and the amount of delay depends on the volume of pedestrian activity and the time within the green phase (heaviest at the beginning of the green phase).

The entry links bring vehicles into the network at observed uniform rates and with the observed truck-passenger car ratio. For the morning peak hour, the entry flow rates at the 27 entry points ranged from 21 to 3,165 vehicles per hour, the largest coming from the exit ramp of I-35W. Truck volumes ranged from 3 to 34 percent. Total entry volume was 19,999 vph. For the afternoon peak hour, the entry flow rates ranged from 24 to 1,509 vph, and total entry volume was 12,544 vph. Truck volumes ranged from 0 to 13 percent.

Minneapolis has many parking lots and structures that subtract vehicles from the traffic stream during the morning peak hour and add vehicles to the traffic stream during the afternoon peak hour. The total capacity of off-street parking within the study area is about 25,000 vehicles for 29 structures and 111 surface lots. This inflow-outflow activity was simulated by developing a sink model for the morning cases and a source model for the afternoon cases. This required identifying the location of each parking facility and the number of vehicles entering (or exiting) the lot from (or onto) each street during the morning (or afternoon) peak hour. The computer model subtracts (or adds) vehicles at the observed rate from each network link uniformly during the simulation period. The total morning parking lot inflow rate is 10,000 vph or 50 percent of the vehicles entering the network. In the afternoon, the parking lot outflow rate is 9,000 vph or 42 percent of the vehicles leaving the network.

Two minor streets that were not modeled geometrically as links were presented as sources and sinks in the streets they intersected. In particular, one dead-end street onto a major arterial provided a source of 486 vph to this artery. In this way, computer storage can be conserved.

Experiments were conducted at the field site to determine the free-flow speeds, driver reaction time (lost green time for the first driver in the queue), and queue discharge rates. These quantities can be specified individually for each link and are functions of local driving behavior, link geometry, and traffic demand. From the observations, free-flow speeds of 30 mph for the morning and 25 mph for the afternoon were designated for each street. The reaction time and queue discharge rates were both 2.3 sec for the morning period and were 2.2 and 2.5 sec for the afternoon period for each street. These data are averages for the desired cruising speed for the driver type and rates at which the queue at a red light dissipates during the green phase.

Field experiments were also conducted to determine the characteristics of lane-blocking events, such as passenger pickup or drop-off and truck loading. Short-term events are those lasting less than one traffic signal cycle length, here 90 sec. They can be specified for each network link. The mean duration of the short-term events was 15 sec, and the frequency of occurrence ranged from one event every 48 sec to one event every 900 sec, depending on location and time of day. The duration simulated is the mean duration multiplied by a factor ranging from 0.10 to 3.70 chosen randomly from a uniform decile distribution. Long-term events have specified durations, starting times, and locations, and ranged from 2 to 5 min. As vehicles traverse a blocked lane, delays are added to their trajectories as they seek and maneuver into gaps in an adjacent lane.

Control System

The traffic control system consists of fixed-time traffic signals at each intersection with a cycle length of 90 sec. Most of the signals have four phases with equal splits and 4-sec amber phases. During the peak hours, most offsets are zero. The timings of each phase and the offset for each signal were simulated as specified by the Minneapolis traffic engineer. There are two fixed-time midblock signals at pedestrian crossings. In addition, five intersections are modeled as nodes with no cross links because the traffic on the cross street could be modeled as sources and sinks and it was computer efficient to do so. There are 110 network traffic signals, and they have a maximum of seven phases, although the computer model can accommodate nine.

The control system also includes lane channelization, e.g., right-turn-only lane or bus-only lane. In addition, the turning movement may produce a de facto right- or left-turn lane, and these are specified as such even when the roadway is not so painted. Parking restrictions are taken into consideration by counting only travel lanes and adding right-turn pockets to model the downstream part of the curb lane at which parking is prohibited during the simulation period. In this way, the number of travel lanes is a function of the time of day and not simply of the road geometry.

Dual turning movements are common in the study area and were simulated. This refers to the practice of prescribing the curb lane to be right-turn-only (or left-turn-only) and vehicles in the adjacent lane may turn left (or right) or proceed straight. It is useful where heavy pedestrian volumes or turning movements occur.

Bus System

More than 50 bus routes traverse the study area during peak hours, and many routes have identical paths. The computer model now can accommodate at most 30 distinct bus routes. The Minneapolis bus system was therefore consolidated into 30 simulation bus routes, and headways were adjusted accordingly. This procedure affects only the statistics relating to bus routes and not those relating to bus activity on a street or at a bus station. The length of bus routes within the study area ranges from 3,972 to 9,610 ft, a total of 26 route-miles. The adjusted or simulation bus route headways ranged from 1.8 to 27.5 min. During peak hours, 350 buses enter the study area.

There are 99 bus stations in the study area, which is the maximum number the model can now accommodate. The term station does not imply an enclosure but merely differentiates from bus stops, which refer to the number of instances in which the bus came to rest, whether to serve passengers at stations, to join a queue, or to comply with a red traffic signal. Bus routes through the study area serve from 4 to 10 stations. A bus need not stop at every station on its route. The mean dwell time is specified for each station together with one of six decile distributions. Two of these distributions do not permit zero dwell times, but the other four do, thus simulating the skipping of a bus station with different probabilities. Experiments were conducted at the field site to measure dwell times. These data were reduced, mean dwell times were determined, and the appropriate distribution was selected. The afternoon mean dwell times ranged from 14 to 82 sec, more than three times longer than corresponding morning service durations.

In addition, the distance of each bus stop from the downstream intersection is needed to compute each bus trajectory. The capacity of each station, i.e., the number of buses that can service passengers simultaneously, is used to determine how long the station is overloaded and buses must wait in queue. This time period is part of the output as is the time during which each station is empty. Station capacities ranged from one to six buses. The computer model distinguishes between bus stations that permit the bus to pull out of traffic when serving passengers and those that do not and thereby produce lane blockages. This information is needed to ensure a realistic simulation and an accurate measure of the interference between buses and other vehicles.

RESULTS: THE OUTPUT

Performance Measures

The function of SCOT is to simulate traffic at a specific field site for a given traffic demand and control system. Trajectories for each vehicle (passenger automobile, truck, or bus) are computed, and, from these data, the numerical values of a set of performance measures are determined. These quantities are then displayed in the computer printout. Sixteen quantities are listed for each street in the network, averaged over the simulation period, e.g., 8:00-8:15 a.m. These quantities include average speed, average delay per vehicle, vehicle-miles, vehicle trips, average number of vehicles on the street, and average number of stops per vehicle. Similar quantities are listed for the network as a whole. Bus statistics are computed and listed separately. These statistics describe the bus activity on each street and at each bus station and include delay time, number of stops, and the time interval during which the capacity of each bus station was exceeded and during which it was empty. In addition, for each completed bus route, the total travel time, total dwell time, and average speed are listed.

Two important performance measures are worth special attention. The time, location, and duration of each instance of spillback are recorded. Spillback is the condition that occurs when a queue on a street is so long that it extends into the upstream intersection and blocks cross traffic. The number of cycle failures at each intersection is also listed. Cycle failure occurs when the green phase is too short to discharge the entire queue and some vehicles must sit out another red phase.

It is extremely useful to be able to plot each bus trajectory in order to identify the reason that each bus comes to a complete stop. These include scheduled station stops, midblock queues or lane blockages, and downstream red traffic signals. The information printed for each bus includes the time, location, duration, and reason for each stop.

With this extremely detailed printout, the city traffic engineer and transit operator have a bird's-eye view of what has happened on each street during the simulation period. They can thus identify bottlenecks and underutilized streets for each candidate control strategy. The candidate control strategy can then be improved, another simulation run made, and the performance observed. Through repetition, the control strategy can be adjusted until it merits field implementation.

Tabulation of Results

The bus priority strategies selected were confined to two adjacent streets, Marquette and Second Avenues. It was then found adequate and computer efficient to use smaller study networks.

The morning peak traffic demand was simulated for the 15-min period 8:00 to 8:15 a.m. The results, averaged over this period, are given in Table 1. The afternoon peak traffic demand was simulated for 4:30 to 4:45 p.m. The results, averaged over this period, are given in Table 2.

A typical afternoon bus trajectory was selected (Fig. 2).

Bus Route and Network Performance

Tables 1 and 2 give the changes in bus performance over completed routes. Each entry is an average of all buses completing a route during the 15-min period, and these range from 17 to 20 buses. Dwell times are not identical because dwell time distributions are stipulated at each bus station. The average dwell time per bus route includes all scheduled station stops. Average moving times can be compared by subtracting average dwell times from average travel times. From Tables 1 and 2 it is seen that providing a reserved bus lane in the direction of flow on the five middle blocks of these two 10-block streets for either the morning or afternoon peak traffic conditions results in no significant decrease in route travel time. Data given in the tables show that, when the two streets have 10 blocks of exclusive counterflow lanes, average moving time decreases 9.5 percent in the morning and 4.6 percent in the afternoon; this amounts to only 39 sec in the morning and 16 sec in the afternoon.

Tables 1 and 2 also show the changes in automobile and truck traffic performance for the entire network. Morning results are averaged for 2,840 vehicle trips and afternoon results for 3,330 vehicle trips completed during the 15-min simulation periods. In the morning, removing a lane from use by general traffic resulted in a 20 percent improvement in average delay per vehicle. The reason for the suprising development was that the direct-flow bus lane strategy restricts right-turning movements. The base case had two large right-turning movements that conflicted with heavy pedestrian movements. Eliminating them could only improve the traffic flow. This conclusion is reinforced by the elimination of 13 cycle failures also caused by these right turners.

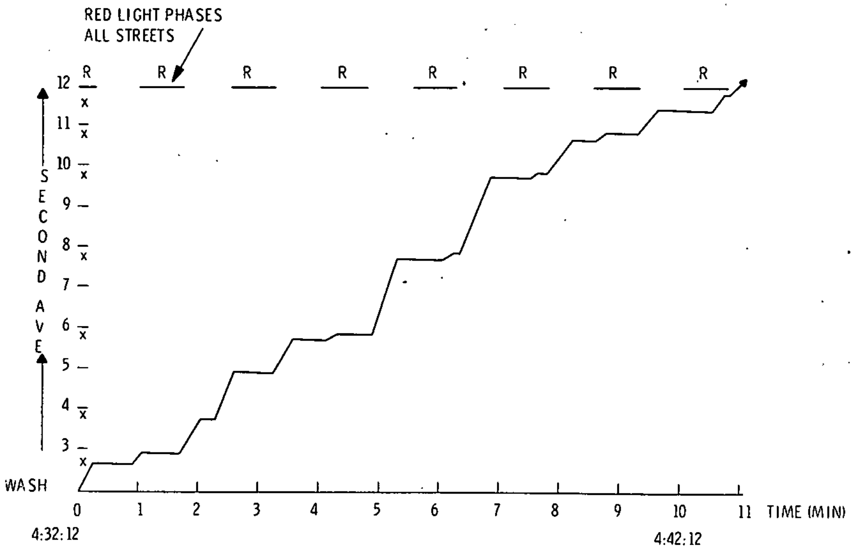
Table 1. Bus route and general traffic performance for 8:00 to 8:15 a.m. peak.

Traffic	Statistic	Base Case	Direct-Flow Bus Lane	Counterflow Bus Lane
Bus	Average travel time per bus route, minutes	8.14	8.00	7.29
	Average dwell time per bus route, minutes	1.26	1.16	1.06
	Average speed, mph	5.8	6.1	6.6
Automobile-truck	Average speed, mph	11.1	12.0	10.9
	Average delay per vehicle, seconds	44	35	46
	Average stops per vehicle	1.12	0.96	1.20
	Stopped delay per total delay	0.71	0.67	0.71
	Cycle failures at link location	7 at 48, 58 6 at 79, 69 1 at 58, 59	1 at 58, 59	3 at 79, 69 4 at 58, 59
	Spillback	None	None	None

Table 2. Bus route and general traffic performance for 4:30 to 4:45 p.m. peak.

Traffic	Statistic	Base Case	Direct-Flow Bus Lane	Counterflow Bus Lane
Bus	Average travel time per bus route, minutes	9.75	9.91	9.65
	Average dwell time per bus route, minutes	4.02	3.89	4.19
	Average speed, mph	4.9	4.8	5.2
Automobile-truck	Average speed, mph	11.1	9.8	9.7
	Average delay per vehicle, seconds	36	41	46
	Average stops per vehicle	1.16	1.13	1.29
	Stopped delay per total delay	0.73	0.77	0.76
	Cycle failures at link location	1 at 38, 39	2 at 48, 58 4 at 58, 68 2 at 89, 79 10 at 49, 39	3 at 48, 58 2 at 79, 69 5 at 69, 59 1 at 59, 49
	Spillback at link location, seconds	None	24 at 48, 58 10 at 49, 39	70 at 48, 58

Figure 2. Bus 142 trajectory simulation along Second Avenue from Washington Avenue to 12th Street at 4:32:12 to 4:42:53 p.m.



In the afternoon, the situation is different because of the increased general traffic volumes and pedestrian conflicts. Table 2 shows a 12 percent decrease in average speed and a 14 percent increase in average delay per vehicle for the direct-flow bus lanes and a 13 percent decrease and 28 percent increase for these quantities for the counterflow bus lanes. For both strategies, there is a marked increase in cycle failures and spillback. The afternoon volumes cannot afford to lose a lane to either strategy. The direct-flow bus lane strategy forbidding right turns included a provision for a left loop (one left turn followed by two right turns) to achieve equivalent vehicle destinations. These heavy left turns conflicted in the afternoon with heavy pedestrian movements, a condition not occurring in the morning. It seems clear that drivers will find better maneuvers than the left loop assumed here and the flow will not be so poor in the field.

Link Bus Performance

For direct-flow bus lanes within the priority region, right-turning vehicles have not proved to impede bus movements strongly enough to degrade trip times significantly. In the afternoon peak period, bus performance is again not consistently better for the direct-flow bus lane strategy either in the priority region or on the entire route.

For the counterflow bus lane strategy, improvements in bus performance are consistent: Bus speeds increased by as much as 26 percent (from 5.4 to 6.8 mph) for morning northbound buses. The inability of buses to pass each other in this mode does not appear to be significant at these headways.

Bus Station Activity

The time that a bus station is empty seems to decrease when station capacity is increased. For southbound buses, the average empty time is 6.5 min out of the 15 for the counterflow bus lanes where the entire block is a bus stop. This contrasts with 9.9 min for the base case and 9.2 min for the direct-flow bus lanes where two out of the seven bus stations are a full block long. The northbound bus stations are empty about 11 minutes for all three cases.

Bus Trajectories

We plotted bus trajectories to determine why the provision of reserved bus lanes did not decrease the average bus travel time significantly and consistently. Bus trajectories are computed in the model, so all information regarding the time, location, duration, and reason that each bus stopped was available and printed.

A typical bus trajectory is shown in Figure 2. The X's on the vertical axis denote the locations of the seven bus stations on Second Avenue. The horizontal bars at the top of the figure, marked with R's, represent the duration of the red signal phase. The cycle length is 90 sec and the red phase is 45 sec long. The signals turn red simultaneously at all streets from 3rd St. to 12th St.; there is no progression during the peak periods.

Bus 142 stopped at each of the seven bus stations for 13 to 52 sec of dwell time. It made seven stops for red lights for durations of from 5 to 38 sec. At no time was it impeded midblock by queues. Travel time for the 10-block route was 10 min 41 sec for an average speed of 4.4 mph. The total dwell time was 4 min, and total red light stopped time 2 min 40 sec. This leaves a moving time of 10:41 - 4:00 - 2:40 = 4 min 1 sec. In the model bus acceleration profile, the minimum moving time to touch base at each bus station when all lights are green is 3 min. This is for the acceleration-deceleration travel path.

Providing Bus 142 with its own lane would do nothing to decrease the time used in accelerating and decelerating at the seven stations and seven red lights. In this case slow bus speeds are caused by frequent service and red light stops and long dwell times, not by general traffic interference.

CONCLUSIONS

For the traffic conditions described in this study, including street geometry, traffic inflow rates, turning volumes, parking lot volumes, pedestrian movements, predictable lane blockages, traffic signal timings, bus routes, headways, and bus station dwell times, the provision of either direct-flow or counterflow bus-only lanes cannot significantly decrease the route travel time. The dominant factors in these low bus speeds are the frequent number of bus stations (seven in 10 blocks), the probability of encountering red traffic signals, and long dwell times. General traffic tends to avoid the right curb lane where buses travel, except right-turning vehicles and passenger drop-offs. Also, bus drivers are efficient in maneuvering around lane blockages. Traffic volumes would have to be considerably higher than those examined here before their effect on bus speeds could be determined and the provision of bus lanes would be expected to improve bus speeds significantly.

CURRENT PROJECTS

Plans are being made to validate this simulation study in Minneapolis. Experiments will be designed to compare before and after general traffic and bus performance at the field site with simulation predictions.

SCOT is being expanded to accept traffic demand described by origin-destination data as well as intersection turning movements. Vehicle movements are determined by computing current minimum time paths. Such a simulation will yield the time-optimal traffic pattern for a given control strategy. It will identify the ceiling or the best obtainable from a candidate control system. Once the necessary origin-destination data are collected, another simulation study will be made.

SCOT also has the ability to simulate bus preemption of traffic signals; i.e., under specified safety constraints, buses may extend the green phase of the downstream traffic signal long enough to permit them to pass through the intersection, or they may shorten the red phase and decrease their delay time. A study is planned to show the benefits to be expected from this bus priority strategy.

A study is under way to design fixed-time bus progression traffic signal schedules. These timings will be based on estimated time of arrival of buses at the intersection determined by mean station dwell times and distributions and the kinematics of bus trajectories. The design will be evaluated by simulation and, if the results are promising, tested at a field site.

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