SIMULATION OF AN UNCONDITIONAL PREEMPTION BUS PRIORITY SYSTEM

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An urban network traffic model has been modified to simulate a bus priority technique that automatically grants a green signal to buses as they approach an intersection. Such a technique could be implemented at individual intersections. Bus routes along 18th and 19th Streets in downtown Washington, D.C., were simulated, and traffic data representing the morning peak were used as model input. Repeated simulation runs tested the effect that the bus priority system had on bus and nonbus traffic for combinations of bus headways (from 0.5 to 4 min) and near-side and far-side bus stop locations. The technique substantially improved many aspects of bus operations, including reduction of the mean number of unnecessary stops, and the mean, 90th percentile, and standard deviation of travel time. An improvement of 15 to 20 percent in bus travel time was supported by statistical test. Other vehicles on bus streets also benefited from this type of system. Cross-street traffic was adversely affected by shorter headways, but far-side stops were far superior to near-side stops under those conditions. Under the conditions simulated, the bus priority system would have the least impact on other vehicles in applications with far-side bus stops when headways were 2 min and greater. However, a consideration of passenger movement rather than vehicle movement may indicate that the system should be operated at shorter than optimum headways.

•TODAY'S urban commuters spend up to 25 percent of their weekday free time traveling to and from work. The natural pattern of urban growth has resulted in an almost perfect negative correlation between the traffic attraction of the central business district and the traffic handling capability of the central business district's street network. Future technologies will provide unique solutions to the problem; in the meantime, however, the existing corridors must be used most efficiently to enable movement of as many people as possible. This can be accomplished by increasing the bus-to-car ratio. During peak travel hours, the average occupancy of a bus is equivalent to that of 35 cars, but its size is equivalent to merely 3 cars. Even after one allows for reasonable bus headways, 1 lane of bus traffic can carry the equivalent of 3 lanes of automobile traffic on city streets. However, to increase the bus-to-car ratio, commuters must be attracted to the bus from their cars. One way to accomplish this would be to ensure that transit service provides origin-to-destination travel time that is comparable with, or better than, that for automobiles.

Overall bus travel time begins with a built-in time handicap that results from the walk from trip origin to bus stop, the wait for the bus, stops for loading along the route, and the walk to the destination from the bus stop. If, in addition, the bus encounters the same traffic conditions as the car does, trip time cannot improve. This implies that some type of bus priority system (BPS) is necessary. Bus priority systems can use completely new roads, reserved lanes during peak periods, or expressway exits and bypasses for congested areas. Another bus priority technique, which is the one

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this paper will discuss, depends on recognizing buses in the traffic stream and changing traffic signals to benefit them. This can be done by automatically granting green lights or weighing supplementary data before making such a decision.

Such a system, from a people-moving viewpoint, could be justified even if it caused large delays to other traffic. In fact, this might even be seen as desirable, as it would favor the bus in the bus-to-car travel-time ratio. But a BPS should not unduly affect other traffic, and the tolerable value of inconvenience varies among communities. Implementing a BPS scheme is not a minor undertaking, and system effectiveness is difficult to predict for other than simple applications.

Although various bus priority techniques have been tested, the effectiveness of a given system depends as much on characteristics of the bus routes as it does on BPS technique. It may be necessary to relocate bus routes or bus stops to take best advantage of different BPS strategies.

An existing urban traffic model has been modified to simulate various bus preemption techniques involving traffic signals. The effects of various operating conditions were separated in simulations of local-service bus routes that had a range of headways and different bus-stop locations. The results help to identify conditions particularly favorable to BPS application.

Some terminology that will be used throughout the paper is defined as follows:

1. A near-side bus stop is located on the near side of the downstream intersection.
2. A far-side bus stop is located on the far side of the downstream intersection.
3. Preemption of a traffic signal overrides the existing signal pattern and substitutes a new signal pattern to benefit buses.
4. Unconditional preemption results if preemption is granted whenever a bus "requests" it.
5. Conditional preemption results if other factors (such as side street queues, time since last preemption, or expected bus travel and dwell time) are considered in determining whether a preemption will be granted.
6. A green extension preemption holds a green phase in the bus direction at the end of the normal green phase.
7. A red truncation preemption terminates a red phase in the bus direction and replaces it with a green phase.

SUMMARY

Computer simulation runs tested a number of unconditional preemption BPS cases, including combinations of various bus headways that ranged from 0.5 to 4 min, near-side and far-side bus stops, and 1 route per street and multiple routes. The following, subject to the constraints of the simulation, were found:

1. The BPS algorithm provided substantial benefits to buses regardless of headways or bus stop location;
2. When BPS was operative, other vehicles on bus streets benefited;
3. BPS use resulted in a penalty to cross-street traffic; and
4. The greatest penalty occurred with short headways and near-side bus stops.

The simulation results show that a BPS with medium and long headways and using far-side bus stops holds most promise. However, stable network operation results at headways as short as 0.5 min.

BPS ALGORITHM

The unconditional signal preemption strategy discussed here provides a green extension or red truncation. [A conditional 10-s green-extension strategy was simulated and was found to provide little benefit (4).] The algorithm guarantees a green signal to a bus approaching an instrumented intersection. If the signal is green at the time, it is held green until the bus clears the intersection; if it is not green, it is changed to green. The technique requires an indication of when a bus is in a detection zone, which extends upstream from an intersection. If no priority is in effect when a bus enters the zone, the signal facing the proper approach is checked. If the signal is not green, the sequence of phases at the intersection is scanned until 1 is found that will provide a green signal. This is the priority phase. A 4-s yellow signal is then provided for all green-signal faces that would not be green in the priority phase. This is the standard caution signal and is adequate to safely stop a vehicle. If a bus is still in the zone at the end of this time, the priority phase is initiated and remains in effect until all buses leave the zone. The phase that would have been in effect at that time, if no priority had been granted, is then determined, and a 4-s yellow signal is provided for all green-signal faces that would not be green in the normal phase. If, at the end of this time, no more buses have entered the zone, the normal phase is restored. Any signal synchronization in the network is thus maintained after the departure of all buses. This type of preemption technique could be used at individual intersections.

The preceding description illustrates typical operation during long-headway bus operations. During short-headway operations, other buses may enter or leave the zone during the 4-s yellow periods, and a different sequence of control will result.

MODEL

The Urban Traffic Control System-1 (UTCS-1) program is an urban network traffic simulation model that can be used for testing and evaluating traffic control techniques; it was specifically sized to be able to simulate the area of the UTCS-BPS in Washington, D.C. The model is discussed in detail by Bruggeman, Lieberman, and Worrall (5). Only an overview is presented here. Development of the UTCS-1 program has been evolutionary. It was based on the DYNET model, which had been based on the TRANS model developed for the Bureau of Public Roads. Later versions have revised and expanded the original UTCS-1 model (6, 7). The model flexibility allows simulation of virtually any geometric configuration and many forms of traffic control. The model has been extended to provide the capability of simulating and evaluating a wide variety of control systems that give buses preferential treatment at traffic signals.

Model Operation

The UTCS-1 model microscopically simulates the action of vehicle traffic in an urban network. Vehicles move through the network, change lanes, accelerate, and decelerate based on car-following and queuing logic to satisfy specified traffic-signal timing and network topology. Each vehicle is given an identification number, and its position is updated once every time period, which is usually 1 s. Vehicles enter the network at locations and times selected by random number to satisfy given input flow rates. Random numbers also are used to determine the type of vehicle entering the network according to specified entry link proportions and assigned driver characteristics related to reaction time and desired cruising speed. Acceleration characteristics of vehicles differ according to type of vehicle. When a vehicle enters a link, stochastic distributions are used to determine the turning movement that it will make at the downstream node and the pedestrian blockage that it will cause when it turns. The dwell times of buses at bus stops also fit predetermined distributions. However, location and time of entry of buses, as well as the sequence of links traversed, is set when bus route and headway are provided.

During the course of the simulation statistics are collected by type of vehicle and link; they may be printed out at various intervals during simulation. The statistics include moving, delay, and total time, which are measured in vehicle minutes and seconds/vehicle mile (seconds/vehicle kilometer); average speed; stops per vehicle;

and volume, occupancy, and number of cycle failures. Obviously, a large amount of input data is required to simulate a desired network accurately.

Modifications for BPS Simulation

Modifications were made to the model to add BPS logic to the traffic-signal timing and to provide additional output data for analysis of BPS operation. The BPS logic gives the choice of a conditional, fixed-time, green-extension preemption or an unconditional green-extension and red-truncation preemption. In either case, signal patterns remain coordinated after buses leave the network. Output summaries now put together vehicle data by bus street and cross street and include equivalent statistics for buses. For example, travel time/vehicle mile (travel time/vehicle kilometer) is given for all vehicle traffic on bus streets, for all vehicle traffic on cross streets, and for buses on bus streets to allow rapid determination of significant changes in traffic flow resulting from different combinations of scheduling conditions. (Bus streets and cross streets are selected by input data cards.) Queue-length data on selected links are output regularly, and moving and delay times of individual buses and the number of bus priorities requested and used are totaled. A bus-trace feature that stores the position of all buses in a time period and prints out the progress of each bus through the network at the end of the simulation helps one to visualize the dynamics of BPS operation.

Other modifications were made to provide greater statistical validity for the analysis of bus behavior. For example, the model originally used the current value of the random number generator to choose the dwell time of a bus at a bus stop. To determine the difference in travel time, later analysis paired each bus run not using BPS with a run using BPS; the initial random number was the same in each case. As soon as BPS influences the signal timing on any link, the situations will diverge, and the random number used to assign dwell time to a given bus at a given bus stop will not be the same in both cases. The resultant large variations in dwell time can mask the effects of bus priority operations. Of course, with a large enough number of runs, the effects will average out, but, for greater resource efficiency, the random number now used to choose the dwell time is formed by combining the initial random number, the entry time of the bus into the network, and the bus stop served. (The resulting sequence of numbers meets statistical criteria for randomness.) This process ensures that the sequence of bus dwell times occurring when BPS is operative will be the same as when no bus priority is simulated.

In the UTCS-1 model, it was noted that buses entered the network at the same times during every run. Of course, random events caused by changing the initial random number will cause the position of the bus at a given time to vary from run to run. However, a bus entering a given route at a given time has a good chance of encountering the same sequence of traffic signals on each run, which could unduly influence the BPS statistics. Again, a large number of runs would alleviate the problem, but another model change will randomize the initial signal timing based on the input random number and ensure that a given bus will encounter a variety of signal sequences for different runs.

NETWORK CHARACTERISTICS

The network used for the analysis is shown in Figure 1. It is the central grid portion of the Washington, D.C., UTCS-BPS network, which runs from G to K Streets and 17th to 20th Streets. Traffic-flow and signal-timing data are typical of the morning peak. A bus priority system with a large number of crossing bus routes will only reallocate delays among the routes in inverse ratio to the bus traffic intensity on those routes. Therefore, the routes selected were on parallel 3- and 4-lane 1-way streets: northbound 18th Street and southbound 19th Street. These streets have approximately equal signal splits (40 s green and 40 s red). Average traffic volume is approximately the same for 19th Street and its cross streets (200 vehicles/hour/lane). The average

Figure 1. Simulation network.

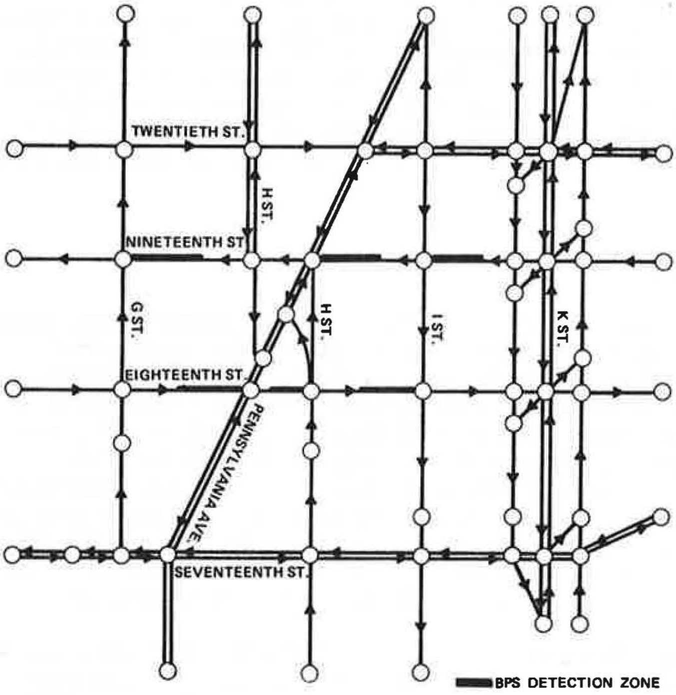
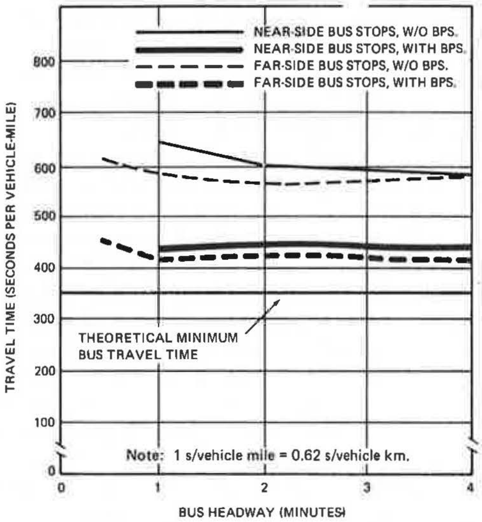
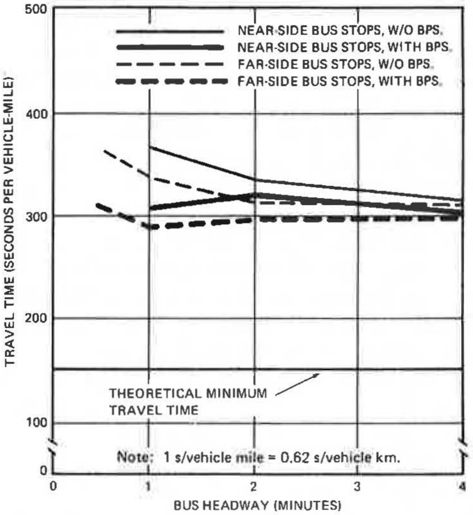


Figure 2. Bus-street travel time, buses only.



Note: 1 s/vehicle mile = 0.62 s/vehicle km.

Figure 3. Bus-street travel time, all vehicles.



Note: 1 s/vehicle mile = 0.62 s/vehicle km.

traffic volume for 18th Street is approximately twice as heavy as that for its cross streets. Eighteenth Street serves 2 bus stops and 19th Street serves 3.

Each bus street has 3 intersections instrumented for bus priority. Because K Street is itself a major east-west bus street, its intersection with 18th Street northbound is not instrumented. All other signalized intersections are instrumented. Bus detection zones begin 210 ft (64 m) upstream from the instrumented intersection and extend to within 5 ft (1.5 m) of the intersection. Therefore, near-side bus stops are completely within the zones and, for the streets chosen, no part of the far side bus stops are within a zone.

MEASURES OF EFFECTIVENESS

A large number of statistics are now available from the model that permit comparisons to be made of different runs. However, as the number of cases to be examined increases, it becomes more difficult to assess the overall effects of these comparisons. Although all of the measures of effectiveness resulting from each run were examined for possible inconsistencies, travel time/vehicle mile (travel time/vehicle kilometer) and stops/vehicle mile (stops/vehicle kilometer) were selected initially for close scrutiny. It should be noted that, although these measures are easily determined from the model, they are not easily measured in the field. Consequently, measures such as volume and occupancy, which are more closely related to measuring instrumentation, are often used. A major reason for stressing travel times and stops is that these measures can be directly related to system benefits, and many other measures are related only indirectly.

Travel time and delay time are important measures in determining the efficiency of vehicle traffic flow. Analyses of traffic control systems often assign monetary value to an individual's time and determine system benefit by multiplying that value by the total time saved when the system is used. The number of stops is a measure that can be related to air pollution and accidents. In fact, the Washington, D.C., and San Jose, California, traffic control systems use a weighted function of stops and delays as an indication of the efficiency of the signal-timing plan chosen. Also both measures can be related to vehicle operating efficiency and, thus, energy consumption. At first glance, it may seem that these 2 measures of effectiveness are the same, but this is not the case. For example, a vehicle in stop-and-go traffic may have a shorter travel time than does a vehicle stopping only a few times for longer periods of time.

For bus operations, travel-time statistics probably provide the most important measures of a system's effectiveness. In addition to the mean value, the 90th percentile of travel time is of interest because one method of specifying schedule time is based on the travel time that is not exceeded in 90 percent of the cases; sufficient improvement in this time could result in fewer buses being required for the same level of service. Although travel-time improvement is most important, BPS also could be of use if the variance of travel times from run to run were decreased. Failure to adhere closely to a schedule compounds inefficiencies. Buses that arrive early tend to gain time because of the decreased loading time required for fewer waiting passengers; late buses tend to lose time picking up more passengers at each stop. The result is a dynamic instability that causes buses to pair up. The magnitude of this statistic is also important to the bus commuters' satisfaction; if travel time varies greatly from day to day, they may return to their cars for a more consistent trip time. The considerations previously cited concerning stops and reduction of pollution and accidents also apply to buses.

ANALYSIS OF RESULTS

Figures 2, 3, and 4 summarize mean travel-time data resulting from the simulation runs. Data are presented separately for buses, all vehicles on bus streets, and all vehicles on cross streets. Bus headways of approximately 0.5, 1, 2, and 4 min were used. Headways were offset slightly from these values to prevent multiples of a head-

Figure 4. Cross-street travel time, all vehicles.

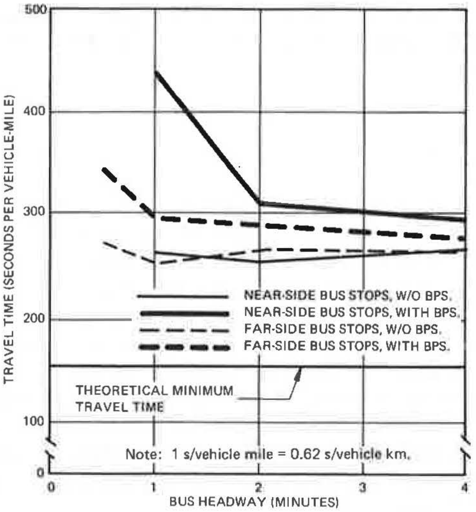


Table 1. Bus statistics.

		Travel Time											
		Mean			90th Percentile			Standard Deviation			Stops, Mean		
Headway (min)	Bus Stop Location	Without BPS (s/ vehicle mile)	With BPS (s/ vehicle mile)	Change (percent)	Without BPS (s/ vehicle mile)	With BPS (s/ vehicle mile)	Change (percent)	Without BPS (s/ vehicle mile)	With BPS (s/ vehicle mile)	Change (percent)	Without BPS (stops/ vehicle mile)	With BPS (stops/ vehicle mile)	Change (percent)
0.5	Near side	—	—	—	—	—	—	—	—	—	—	—	—
	Far side	606	471	-22	690	570	-17	95	67	-29	13.0	17.7	-25
1	Near side	657	450	-32	774	506	-35	113	67	-40	19.5	14.5	-26
	Far side	594	438	-26	658	500	-24	99	50	-49	16.0	11.0	-31
2	Near side	606	474	-22	665	517	-22	113	60	-47	17.9	14.5	-19
	Far side	546	438	-20	665	514	-23	113	74	-35	13.5	11.0	-19
4	Near side	588	447	-24	711	535	-25	92	64	-30	19.5	15.5	-21
	Far side	585	417	-29	672	503	-25	77	60	-22	16.0	10.2	-37

Note: 1 s/vehicle mile = 0.62 s/vehicle km. 1 stop/vehicle mile = 0.62 stop/vehicle km.

Table 2. Statistics for all vehicles.

			Travel Time			Stops		
Bus Headway (min)	Street	Bus Stop Location	Without BPS (s/vehicle mile)	With BPS (s/vehicle mile)	Change (percent)	Without BPS (stops/vehicle mile)	With BPS (stops/vehicle mile)	Change (percent)
0.5	Bus	Near side	—	—	—	—	—	—
		Far side	345	315	-9	8.5	7.5	-12
0.5	Cross	Near side	—	—	—	—	—	—
		Far side	270	350	+30	4.5	7.3	+62
1	Bus	Near side	365	310	-15	8.5	7.6	-11
		Far side	335	290	-13	7.3	7.0	-4
1	Cross	Near side	265	440	+66	4.6	7.3	+59
		Far side	250	295	+18	4.5	5.5	+22
2	Bus	Near side	340	325	-4	8.1	7.5	-7
		Far side	315	295	-6	7.5	6.4	-15
2	Cross	Near side	250	310	+24	4.7	5.7	+21
		Far side	270	310	+15	4.4	5.4	+23
4	Bus	Near side	320	300	-6	7.3	6.9	-5
		Far side	315	290	-8	6.8	6.2	-9
4	Cross	Near side	265	290	+9	4.6	5.5	+20
		Far side	260	275	+6	4.4	4.8	+9

Note: 1 s/vehicle mile = 0.62 s/vehicle km. 1 stop/vehicle mile ≐ 0.62 stop/vehicle km.

way from coinciding with multiples of a signal cycle. Each data point represents the output of 4 model runs; each run has a different random number and different initial signal timing.

Mean Travel Time

As shown in Figure 2, bus travel time is improved substantially when BPS is used, and the location of bus stops has little effect on travel time. In fact, individual bus travel times with and without BPS were compared by using the Wilcoxon matched-pairs test. At least 15 percent improvement (more than 20 percent for some combinations of headway and bus stops) was shown at the 0.05 level of significance. The same test comparing travel times for near- and far-side bus stops showed no statistically significant difference. Figure 3 shows the adverse effect of short-headway bus operation on other vehicles on the bus streets under normal conditions (without BPS). When BPS is used, other vehicles also benefit. Figure 4 shows the corresponding travel-time penalty for cross-street traffic when BPS is used. When headways are shorter than 2 min, far-side bus stops are far superior to near-side bus stops although 0.5-min headways result in substantial delays.

The lowest line on each graph indicates the shortest average travel time attainable for the given vehicles on the given streets. For all vehicles, this is 150 s/vehicle mile (83 s/vehicle km); it is derived from the free-flow speed of the appropriate links although an individual vehicle's speed may range from 0.75 to 1.27 times this value. For the bus-only case, the additional time required to decelerate to a halt at a bus stop, to pick up and drop off passengers, and to accelerate to free-flow speed was also considered. A minimum travel time of 365 s/vehicle mile (226 s/vehicle km) resulted. When BPS is operative, mean bus travel time improves to within 15 percent of the minimum.

The near-side, 0.5-min headway case is not shown because the runs encountered severe traffic congestion. Without BPS, buses at bus stops accumulate queues of right-turning vehicles and other buses behind them. If buses enter the network infrequently enough, queues have time to dissipate before additional buses arrive. At 0.5-min headways, however, queues do not have time to dissipate, and eventually the storage capacity of the right lane of short links is exceeded. This causes spillovers (vehicles entering intersections that are not clear). Spillovers, in turn, block cross streets and prevent bus-street vehicles from entering the bus links. When BPS is operative, congestion on bus links is minimized, but cross-street congestion at controlled intersections is increased because the signal remains red for cross streets while a bus is in the detection zone. Cross-street queues eventually cause spillovers at their upstream intersections, some of which are, in turn, bus streets. It is obvious that near-side bus stops will cause this during some short headway conditions; the simulation gives an indication of the critical headway value. For far-side bus stops, 0.5-min headways result in a stable operation without BPS because vehicles approaching a bus dwelling at a far-side bus stop can pass it if there is space ahead of the bus. Although vehicles on cross streets are delayed by 30 percent, conditions will remain stable at 0.5-min headways with BPS because instrumented intersections are held green for only that amount of time required for the bus to travel through the detection zone, not for the dwell time.

Other Statistics

Additional travel-time and stop data are given in Tables 1 and 2. As the model records individual bus travel times, not only standard deviations and 90th percentiles of bus travel times but also the percentage differences in each statistic are presented when BPS is used. Only the mean travel time is available for other vehicles because the paths followed by them are randomly chosen during a simulation run and only link totals are available. Similarly, only link and bus-stop data are available from the model, so no measure of vehicle variation can be derived.

In summary, buses receive substantial benefits over the entire range of headways tested when BPS is used (20 to 30 percent improvement in mean and 90th percentile travel times, 25 to 50 percent improvement in travel-time standard deviation, and 15 to 20 percent improvement in stops). Data on other-vehicle traffic show headway differences that can be separated into 3 regions:

1. A long-headway range (4 min or more) that shows almost no difference whether BPS is or is not used,
2. A short-headway range (1 min or less), in which extreme effects occur when BPS is used, and
3. A medium-headway range in which effects decrease with increasing headways.

For short headways, far-side bus stops caused much less disruption to cross-street traffic than did near-side bus stops (travel time and stops were at least 30 percent better). However, even with far-side bus stops, BPS operation with short headways caused significant degradation to cross-street traffic. For medium headways, far-side bus stops were slightly superior to near-side bus stops (10 percent or less improvement in bus travel time and stops) and caused less degradation to cross-street traffic. At long headways, BPS had little effect on other-vehicle traffic.

Multiple Routes per Street

Cases with multiple routes per street that were tested indicated that the previously mentioned headway definitions also would apply when average bus headway, not route headway, is used. Thus, even though long headways may seem relatively short, equivalent route headways are not unreasonable if they are viewed as bus headways multiplied by the number of routes operating on a street.

Short Headways

Two points concerning the results of the short-headway case require discussion. First, the assumption that a street with 4-min headways would have the same amount of other vehicles as it would if it had 0.5-min headways may be questioned. There would be some trade-off between modes of passenger travel, so that a passenger demand requiring 0.5-min headways would result in fewer other vehicles being required than when 4-min headways would be used. Another factor stems from the commuter's choice of routes to minimize travel time (or perceived travel time). That is, if bus streets result in great congestion for right-turning vehicles, the commuter who wishes to make a right turn will choose a nonbus street that has less congestion.

Second, the realism of the model's handling of right-turning traffic at near-side bus stops is pertinent. The objection may be made that a link of car traffic may not queue up behind a bus at a bus stop if the drivers realize that the signal will remain green until the bus has left the zone, but the model modifications required to realistically simulate what would actually happen are considerable.

The net result of these 2 points is to simulate a kind of worst-case condition. That is, very short headway bus traffic would probably result in (or be a result of) fewer other vehicles being on the bus streets; therefore, congestion would not be as bad as simulated. Also actual right-turning traffic would not increasingly queue up behind buses at a near-side bus stop. Some vehicles would change lanes and turn in front of the bus and cause shorter queues than those measured.

CONCLUSION

Simulation results have indicated that an unconditional preemption bus priority system can provide substantial benefits to buses in an environment representative of many cities. However, successful application of the technique requires more than just modifications to traffic-signal hardware; relocation of bus stops and bus routes may also be necessary. In some applications, BPS will have little effect on other vehicles. In other applications, BPS may cause substantial delay to cross-street traffic. The urban planner must determine the acceptable trade-off between overall passenger movement and inconvenience to automobile passengers.

ACKNOWLEDGMENTS

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