Model to Evaluate the Impacts of Bus Priority on Signalized Intersections

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Transit service is being viewed increasingly as a reliable travel demand measure. Various means of attracting the motorist to move from the car to transit are being attempted all over the country. It has been found that delay at intersections is the primary cause of bus delay. Reducing delay at intersections can reduce overall trip time, improve schedule reliability, and reduce overall congestion. Providing priority for buses at signalized intersections is one way to reduce delay at intersections. Numerous organizations have developed priority strategies to do the same. But most of them cannot be operational for a long time for various reasons. Improved technology has prompted traffic engineers to renew efforts to develop newer bus priority strategies. This paper discusses the development of a model to evaluate the impacts of implementing a priority strategy at signalized intersections. The model uses the delay equation for signalized intersections in the *1985 Highway Capacity Manual.* A priority strategy was developed and implemented in the field. Data were collected, and delay in the field was measured. The model seems to be predicting delay reasonably accurately. In some cases, however, the model was overestimating delay. The model can be a useful tool to traffic engineers to evaluate the impacts and the feasibility of implementing a priority strategy.

The concept of providing priority to buses at traffic signals is by no means a newly conceived notion. In fact, as early as 1962 an experiment was conducted in Washington, D.C. in which the offsets of a signalized network were adjusted to match better the lower average speed of buses (*1*). The first bus-actuated, or active, signal priority experiment for buses occurred in Los Angeles in 1970 and soon was followed by other similar demonstrations across the United States (*2*). These early experiments concentrated on moving buses through an intersection as quickly as possible with little or no concern for other traffic. In general, experimentation with bus priority has yielded positive results for buses and traffic on the bus street (*3–12*). However, priority may increase delay to traffic on the cross-street. Since the concept emerged, however, experimentation and research have produced few operational systems.

RESEARCH OBJECTIVE

The primary objective of this research was to develop a model to evaluate a conditional, active bus priority strategy for a traffic signal in a coordinated signal system. An effective priority strategy would provide significant benefits to buses in terms of reduced travel time, delay incurred at an intersection, and increase in schedule reliability. The strategy should not disrupt the progression along the arterial and should not affect the cross-street operation seriously. The model was evaluated by implementing the strategy at a local intersection and observing the impacts of the strategy.

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Priority at Traffic Signals

Signal priority is a method of providing preferential treatment to buses at traffic signals by altering the signal timing plan in a way that benefits buses. Buses may begin a movement within a vehicle platoon, but loading and unloading requirements may cause them to fall behind the platoon and become delayed at downstream traffic signals (*13*).

Delay at traffic signals is one of the largest components of bus delay on arterial streets. Bus delay at traffic signals comprises between 10 and 20 percent of overall bus trip times and nearly 50 percent of the delay experienced by a bus (*2*). Thus, by giving priority to buses at traffic signals, bus delay can be reduced. Potential short-term advantages of bus priority also include the decrease in bus travel times and increased speeds, decrease in schedule variability, and the improvement of non-bus traffic on the bus phase. At reasonable demand levels, bus priority can make transit a more attractive mode of transportation and may increase the passenger-carrying capacity of arterial streets (*14*). Signal priority treatments can be categorized as follows.

Passive Priority

In passive priority, predetermined timing plans are used to provide some benefit to the transit movements but do not require the presence of the transit vehicle to be active. The following passive priority treatments are low-cost methods aimed at improving transit operations (*15*).

Adjustment of Cycle Length

Reducing cycle lengths can provide benefits to transit vehicles by reducing the delay.

Splitting Phases

Splitting a priority phase movement into multiple phases and repeating it within a cycle can reduce transit delays without necessarily reducing the cycle length.

Areawide Timing Plans

Areawide timing plans provide priority treatment to buses through preferential progression, which can be accomplished simply by

designing the signal offsets in a coordinated signal system using bus travel times.

Metering Vehicles

Buses benefit from metering by allowing buses to bypass metered signals with special reserved bus lanes, special signal phases, or by rerouting buses to nonmetered signals.

Active Priority

In active priority treatments, priority is given only when the bus is actually present. There are mainly four types of active priority treatments.

Phase Extension

A phase extension is useful when the bus will arrive at the intersection just after the end of the normal green period and is usually limited to a maximum value (*13*).

Early Start

An early start priority is used when the bus arrives at the intersection during a red indication by truncating all non-bus phases (*13*).

Special Phase

A special phase occurs when a short green phase is injected into the normal phase sequence while all other phases are stopped (*13,16*).

Phase Suppression

To facilitate the provision of the priority bus phase, one or more nonpriority phases with low demand may be omitted from the normal phase sequence (*16*).

The four previous strategies are the most widely used forms of active priority. These strategies can be used alone or can be combined to provide priority to buses. Priority schemes sometimes also include the concept of compensation (*16*). In compensation, the nonpriority movements can be allocated additional green time in the form of a nonpriority phase extension after a priority to minimize deterioration of nonpriority phases.

Unconditional Priority

In unconditional signal priority (or preemption), priority is given whenever the bus detector places a call to the signal controller. After the bus is detected, the bus movement is given a green indication after all other vehicular and pedestrian clearance intervals are satisfied for safety reasons. Because unconditional priority is so disruptive to cross-street traffic, it is used mainly for emergency vehicle preemption of traffic signals only.

Conditional Priority

Conditional signal priority strategies attempt to limit the undesirable effects caused by unconditional priority through selective consideration of various factors. These factors include schedule adherence, bus occupancy, cross-street (or non-bus street) queue length, current traffic conditions, time since last priority, effect on coordination, and point in cycle at which the bus is detected.

DEVELOPMENT OF A PRIORITY MODEL

A model to simulate, evaluate, and estimate the effects of the priority scheme on intersection operation was developed (*17*). Priority is provided by phase extensions and early start of the priority phase at regular intervals. The development of the model is described in the following paragraphs.

It can be assumed safely that when a priority is granted to a bus on the coordinated approach, the result will be a decrease in delay to the bus and the vehicles on the coordinated approach. Similarly, because green time is taken from the cross-street, an increase in delay to the vehicles on the cross-street approaches is expected. These effects can be examined quantitatively using the input-output models shown in Figure 1.

Five cases have been defined and illustrated in Figure 1. Case 1 does not provide any priority. In Case 2, the priority phase gets a minimum extension to allow the bus to go through the intersection. Case 2 is most beneficial because the nonpriority phases are disrupted least and the bus would have had maximum waiting time to go through the intersection if no priority were provided.

Case 3 provides maximum extension (predefined) to the priority phase. A bus detected just before the arterial phase (priority phase) terminates can go through the intersection if the phase is extended by the travel time from the detection zone to the intersection. A 10-sec maximum extension was used in the model.

In Case 4, a minimum early start is provided. When a bus arrives on red very late in the cycle, a minimum phase time is provided for the nonpriority phase(s) on at that time, and the priority phase comes on early. The nonpriority phases are not affected seriously. Case 5 illustrates a maximum early start for the priority phase. When a bus arrives just after the termination of the arterial phase (priority phase), all of the nonpriority phases are provided minimum times and the priority phase comes on early.

Figure 1 illustrates the arrivals and departures for both the main street and the cross-street and the effects of priority phase extensions and early starts on delay. Extending the main street phase to accommodate the bus should cause a reduction in delay (reduction in size of triangle) for the vehicles on this approach. The length of the extension affects the amount by which delay is reduced. The effects on the cross-street are similar but opposite. A short extension likely will cause a small increase in delay (increase in size of triangle), whereas a large extension should cause a larger increase in delay. An early start priority affects delay similarly to an extension, as illustrated in Figure 1.

Analytical Tool to Evaluate Priority Scheme

The simple model developed uses the delay equation found in the *1985 Highway Capacity Manual* (HCM). Geometric, traffic, and signal timing values as required for the HCM model are obtained

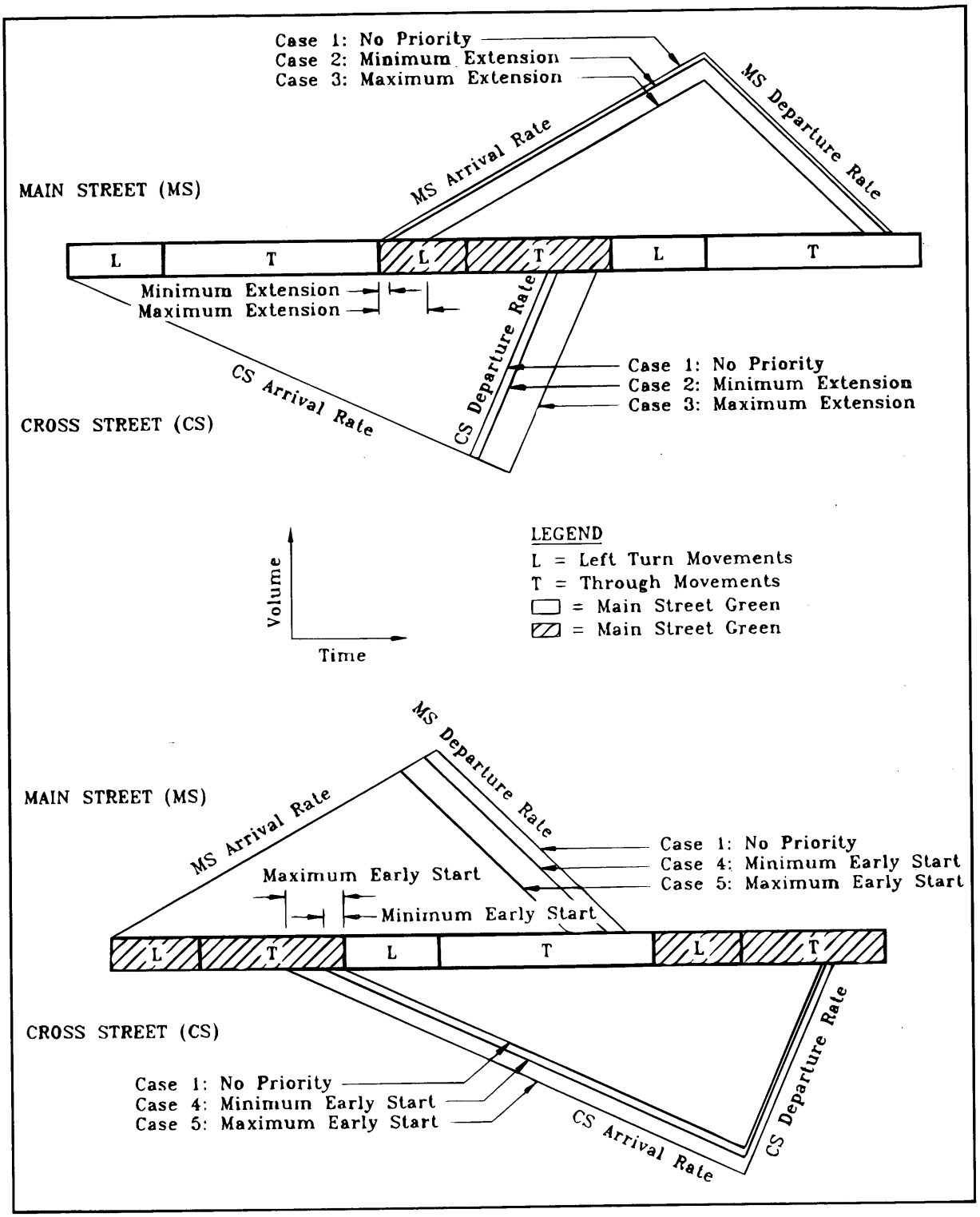

FIGURE 1 Illustration of the expected effects of the priority scheme on main and cross-street traffic.

from either the plans or the field observations. Different types of priority are modeled by adjusting the green times to represent the desired condition (no priority, phase extension, or early start). For example, to model the intersection without priority, the green times used in the spreadsheet would match average green times in the field. Similarly, for an extension or early start the cross-street green times would be decreased (and the coordinated phase green time increased) according to the type of priority and the length of the priority phase.

The HCM delay equation calculates the average seconds of delay per vehicle. These units are adequate for many applications. The increase in delay is experienced by a large number of vehicles with

small occupancies (passenger cars). But the benefits are presumably experienced by a large number of passengers in the bus. Thus, person delay is a more appropriate measure of effectiveness. Also, to compare the benefits gained by buses to the increase in delay to the cross-street, the effects are compared on a cycle-by-cycle basis. The HCM delay value is converted to person-sec of delay per cycle knowing the number of vehicles per cycle and the average automobile occupancy.

The magnitude of delay savings to the bus depends on the time at which it arrives at the intersection or is detected by a priority detector. If it arrives during the green portion and can pass safely through the intersection without an extension, then there is no delay savings to the bus. However, if the bus arrives at the intersection such that it can be accommodated by an extension, then the bus is saved an amount of time equal to the length of the cross-street period. If the bus arrives during the cross-street period, the delay savings to the bus increases the earlier it is detected in the phase.

Based on the green splits, the model estimates the period the bus has to wait when no priority is provided as well as when priority is provided. This is done for the buses arriving at different points in the cycle. For simplicity, an assumption is made that buses are arriving only on Phase 2 approach and priority is being provided only to the coordinate phases (Phases 2 and 6).

The model calculates the savings obtained by providing priority through a number of steps. Various terms used in the spreadsheet that is used in the model are defined and described below.

Person Delay/Cycle with No Bus

Person delay/cycle with no bus has been defined for two cases in the spreadsheet.

Person Delay/Cycle with No Bus for Original Splits ($D_{(NB\text{-}OS)}$)

$D_{(NB\text{-}OS)}$ is obtained by simply converting vehicle-stopped delay without modifying the green splits in sec/vehicle to sec/cycle and multiplying by the average auto occupancy. The average auto occupancy is assumed to be 1.25 and does not consider any bus arriving in that particular cycle.

Person Delay/Cycle with No Bus for Modified Splits ($D_{(NB\text{-}MS)}$)

$D_{(NB\text{-}MS)}$ is the same as $D_{(NB\text{-}OS)}$ except that the splits used to calculate stopped delay are modified as required for providing priority to bus.

Waiting Period

Waiting period is the period the bus has to wait at the intersection. It depends on the point in cycle at which the bus arrives and also whether priority is provided.

Person Delay/Cycle with One Bus and No Priority ($D_{(1B\text{-}NP)}$)

$D_{(1B\text{-}NP)}$ is obtained for each case of priority. $D_{(1B\text{-}NP)}$ is the same as $D_{(NB\text{-}OS)}$ for all phases except the Bus Phase (Phase 2), where a bus is assumed to arrive in the cycle. The delay for the bus phase is obtained by summing the bus phase delay in $D_{(NB\text{-}OS)}$ with the product of the bus occupancy (*40*) and the period for which the bus has to wait.

Person Delay/Cycle with One Bus and With Priority ($D_{(1B\text{-}P)}$)

$D_{(1B\text{-}P)}$ is obtained for each case of priority. Various scenarios are obtained by modifying the green splits (adding to priority phases and reducing from nonpriority phases). First, the delay with modified splits is calculated assuming there is no bus arrival in the cycle ($D_{(NB\text{-}MS)}$). The waiting period for the bus when priority is provided as well as when no priority is provided was calculated earlier. The delay values in $D_{(1B\text{-}P)}$ are the same as in $D_{(NB\text{-}MS)}$ except the bus phase. The delay for the bus phase is obtained by summing the delay in $D_{(NB\text{-}MS)}$ with the product of the bus occupancy (*40*) and the waiting period for the bus when priority is provided.

The delay values in $D_{(1B\text{-}NP)}$ and $D_{(1B\text{-}P)}$ are obtained assuming that a bus is arriving every cycle. However, a bus is arriving only once every 4 or 5 cycles or priority for the bus is being provided every 4 to 5 cycles. Providing priority in quick succession is harmful for two reasons. First, the controller may lose coordination and arterial progression is disrupted; second, the delays for some cross-street phases may get very high. A few cycles without priority will allow any phases disrupted caused by providing priority to recover. The cycles in which the bus is arriving (priority is being provided) can be called *bus arrival cycles.* Thus, there are only a limited number of *bus arrival cycles* in an hour, and their number depends on the cycle length of the intersection and the extent to which the cross-street can be disrupted.

Weighted Normal Delay ($W.D_{(NP)}$)

$W.D_{(NP)}$ is the delay experienced in person sec/cycle for an hour, in which buses are arriving every 4 or 5 cycles and no priority is provided. $W.D_{(NP)}$ is obtained by summing the product of the delays in $D_{(1B\text{-}NP)}$ with the number of bus arrival cycles and the product of the delays in $D_{(NB\text{-}OS)}$ with the number of normal cycles (non-bus arrival cycles) and dividing the sum by the total number of cycles in an hour:

$$W.D_{NP} = \frac{(D_{(1B\text{-}NP)} * \textit{No. Bus Arr. Cyc.}) + (D_{(NB\text{-}OS)} * \textit{No. Non-bus Arr. Cyc.})}{\textit{No. Cyc./hr}}$$

Weighted Delay with Priority ($W.D_{(P)}$)

$W.D_{(P)}$ is the delay experienced in person sec/cycle for an hour, in which buses are arriving every 4 or 5 cycles and the appropriate priority is provided. $W.D_{(P)}$ is obtained by summing the product of the delays in $D_{(1B\text{-}P)}$ with the number of bus arrival cycles and the product of the delays in $D_{(NB\text{-}OS)}$ with the number of normal cycles (non-bus arrival cycles) and dividing the sum by the total number of cycles in an hour:

$$W.D_{P} = \frac{(D_{(1B\text{-}P)} * \textit{No. Bus Arr. Cyc.}) + (D_{(NB\text{-}OS)} * \textit{No. Non-bus Arr. Cyc.})}{\textit{No. Cyc./hr}}$$

FIELD EVALUATION OF THE MODEL

The objective of the field evaluation was to investigate the reliability of the results predicted by the model and document any benefits to the bus and possible detriments to other traffic caused by the priority strategy. Stopped delay was the chosen measure of performance because intersection delay studies are very common and it is relatively easy to collect; it is also precise.

The HCM field delay measurement technique was used to collect stopped delay data for each of the approaches to the intersection for each of the cases. The number of seconds of delay per vehicle can then be calculated according to the following equation (*18*):

$$Delay = \frac{\sum V_s \times I}{V},$$

where

$Delay$ = stopped delay, in sec/vehicle,
ΣV_s = sum of stopped vehicle counts,
I = length of interval (sec), and
V = total volume observed during study period.

Site Selection

The following criteria were considered in the decision to choose the site:

- the intersection must be signalized;
- the intersection must be part of a coordinated system;
- intersection geometrics and signal phasing should be relatively simple such that priority is feasible;
- the site allows for the collection of the necessary data; and
- the intersection is not critical such that priority would disrupt traffic operations to a great degree.

Careful consideration of the above criteria resulted in the selection of the intersection of Texas Avenue and Southwest Parkway in College Station, Texas. The site is located at the intersection of a major north-south arterial (Texas Avenue) and a major east-west collector (Southwest Parkway). The intersection is controlled by an EPAC 300-actuated controller unit manufactured by Automatic Signal/Eagle Signal.

Data Collection

It was decided to simulate bus operation in the field for different types of bus arrivals on the southbound approach of Texas Avenue. Stopped vehicle counts were recorded for Case 1, Case 3, and Case 5 of the five conditions described earlier. Case 2 and Case 4 did not warrant a separate study, because the effect of providing priority on the nonpriority phases was not significant.

The data collected for each of the cases were reduced and input into the model. The green splits were obtained from the data downloaded from the controller, and their average values were used for each case. Field studies were used to calibrate the model to the local conditions. The progression factors specified in HCM were incorporated. Various factors defined in HCM were used to calculate the saturation flow rate. However, it should be noted that calibration may not result in very similar values of delays from the model and field studies. The HCM delay equation is suitable for fixed time operation. It is based on a number of empirical factors that may not apply accurately to the existing local conditions. Also, although every effort was made to maintain consistency and accuracy in the field data collection, there could be some minor errors. Hence, it is necessary to recognize that the model results may not match completely the field results.

Field Data Collection

NEMA phase designation (Figure 2) with phases 2 and 6 as coordinated phases was used to denote phases. Data collectors were positioned on each approach to record the number of vehicles stopped at 15-sec intervals. In Case 1 (No Priority) the stopped vehicle counts were recorded for 30 min.

In Cases 3 and 5 the stopped vehicle counts were required only during cycles in which the priority scheme was activated. Buses do not operate along Texas Avenue. Therefore, a push button was activated manually to simulate the arrival of the bus for various cases. To minimize the disruption to non-bus traffic, the intersection was allowed to recover between successive activations of the scheme.

The intersection was videotaped using two video cameras to determine the traffic volumes. Data were also collected from the traffic signal controller via a laptop computer. This information included the status of each detector and the current signal phase every 1/10 of a second. The phase status data were used to obtain green splits during the study.

The data collection was performed independently for Cases 3 and 5 on separate days. For each day a similar type of bus arrival was simulated. For Case 3 (maximum extension) the point in the cycle at which the coordinated phase would terminate (i.e., if no priority was to be provided) was determined. The push button was energized a few seconds before that point in the cycle and held for about 10 seconds after the point. The coordinated phase would be extended as long as the push button was held. The duration by which the coordinated phase was extended was reduced proportionately from the subsequent noncoordinated phases.

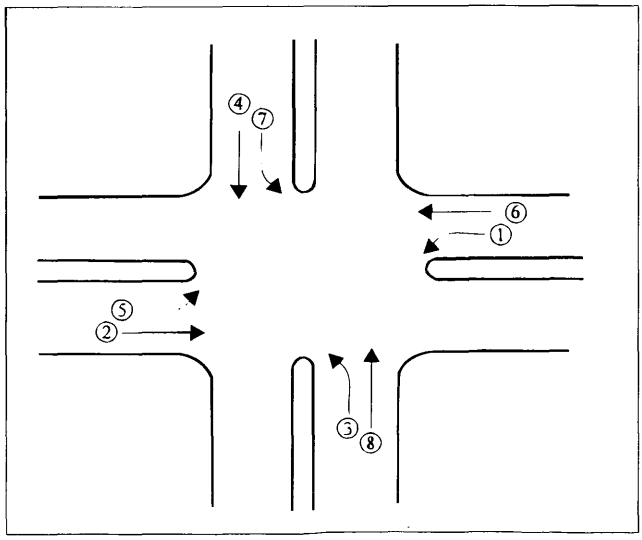

FIGURE 2 NEMA configuration for numbering phase movements.

For Case 5 (maximum early start) it was decided to provide a maximum of 7 sec for Phases 3 and 7, a maximum of 15 sec for Phases 4 and 8, and maximum of 5 seconds for Phases 1 and 5. The push button was energized 7 sec after the coordinated phase terminated and Phases 3 and 7 came on. This actuation forces Phases 3 and 7 to the subsequent phases. The push button was energized in a similar fashion to force out of other nonpriority phases after providing the earlier specified green times.

About 10 sample priority cycles were obtained for each of the two cases. Stopped delay data were collected for 4 intervals of 20 min each. Because the cycle length of the intersection was 115 sec, each 20-min period facilitated in getting two to three cycles in which priority was provided. Hence, the target of 10 priority cycles was achieved.

Data Reduction

The data collected (green splits, volumes, and stopped delay data) were reduced for each case separately to obtain stopped delay on a cycle-by-cycle basis. This was done to maintain uniformity in data reduction with the other cases. As mentioned earlier, in Cases 3 and 5 only the cycles in which priority was provided were considered.

Averages of the green splits (for each cycle) were input into the model. Volumes were obtained from the video tapes. These volumes were input into the model and used to estimate delays in the field. The same procedure was used for all of the cases (Cases 1, 3, and 5).

Stopped delay values obtained in the field were then compared with the delay values obtained from the model.

COMPARING FIELD AND MODEL RESULTS

Field data were reduced as described earlier. The average volumes and splits were input into the spreadsheet model. Intersection stopped delay observed in the field and predicted by the model were computed and compared by approach as well as for the entire intersection. Table 1 illustrates the comparison of these delays.

Data in Table 1 indicate that the delay predicted by the model is slightly higher than the delay observed in the field. The difference in delays is more apparent at higher vehicle-to-cycle (v/c) ratios ($v/c >$ 0.85). This indicates that the model is good at predicting delays with low v/c ratios and as v/c ratios increase, the model overestimates the delay values. This finding is consistent with the belief that the delay equation in the HCM overestimates the delay at high v/c ratios.

The approaches with v/c ratios > 0.85 were removed (refer to Table 1), and a regression analysis was performed with the field delay values as independent values and the model values as dependent values. The result of the regression analysis follows:

$$R^2 = 0.904$$
$$\text{Intercept} = 0$$
$$X\text{-coefficient} = 1.413$$

The desirable values for R^2 and X-coefficient are 1. Although an R^2 of 1 indicates that there is a strong linear relationship between the field delay and model delay, an X-coefficient of 1 indicates that model delay is equal to field delay.

The regression analysis indicates that there is a strong linear relationship between the delay predicted by the model and the delay observed in the field. However, the model is overestimating delay by about 41 percent.

To investigate the overestimation of the delay by the model, the data were reduced further to obtain stop delay for each phase for all the three cases. Table 2 illustrates the delay experienced by each phase along with their v/c ratios. It is seen that although the delay predicted by the model is slightly higher than the delay observed in the field for most of the phases, the difference is more apparent for phases with high v/c ratios and for left-turn phases. The difference can be attributed to two reasons. First, the HCM delay equation used in the model overestimates delay at high v/c ratios. Second, delay observed in the field for left-turn phases (mainly Phases 1 and 5) is higher than delay predicted by the model. This is because left-

TABLE 1 Comparison of Field Delay with Model Delay

Cases	Approach	v/c Ratio	Field Delay (sec/veh)	Model Delay (sec/veh)
Case 1	N. Bound	0.39	11.7	12.0
	S. Bound	0.43	6.8	12.0
	E. Bound	0.73	21.7	41.8
	W. Bound	0.71	35.5	46.9
	Total Intersection Delay		19.1	21.1
Case 3	N. Bound	0.37	13.1	11.0
	S. Bound	0.49	4.4	11.0
	E. Bound	0.97	39.9	77.7
	W. Bound	0.79	39.1	55.4
	Total Intersection Delay		18.1	26.0
Case 5	N. Bound	0.39	9.9	10.4
	S. Bound	0.42	4.9	10.9
	E. Bound	0.86	55.2	57.8
	W. Bound	0.85	40.6	69.7
	Total Intersection Delay		19.2	20.2

TABLE 2 Comparison of Field Delay with Model Delay for Each Phase

Case	Phase	Volume to Capacity Ratio	Field Delay (sec/veh)	Model Delay (sec/veh)
Case 1	1	0.26	20.7	41.5
	6	0.42	10.8	8.8
	5	0.26	16.5	41.0
	2	0.47	5.70	5.9
	3	0.78	61.0	48.8
	8	0.71	37.3	38.0
	7	0.59	37.8	42.5
	4	0.78	35.2	48.7
Case 3	1	0.36	24.7	41.1
	6	0.43	11.8	7.2
	5	0.24	15.3	42.2
	2	0.53	3.40	8.6
	3	1.07	44.9	115.5
	8	0.92	37.0	55.9
	7	0.71	43.5	49.2
	4	0.84	37.2	57.9
Case 5	1	0.29	16.1	41.2
	6	0.41	9.20	6.7
	5	0.31	18.4	41.7
	2	0.44	3.20	7.0
	3	0.92	80.4	73.5
	8	0.84	41.8	49.4
	7	0.70	56.1	46.4
	4	0.93	34.7	77.9

turning vehicles have protected-permitted operation and, thus, have the long duration of arterial through movements to make left turns. The model does not estimate delay very well for left turns having protected-permitted operation.

To examine the model under less complicated conditions, delays for left-turn phases and phases with high *v/c* ratios were removed from the data in Table 2. A regression analysis performed on the remaining data gave the following results:

$$R^2 = 0.904$$
$$\text{Intercept} = 0$$
$$X\text{-coefficient} = 1.413$$

Results of the regression analysis indicate that although the model is overestimating delay by about 25 percent, there is a strong linear relationship between the field delay and model delay. Although the delay estimation is very good at lower values, the model is overestimating the delay at higher values. The delay for the arterial phases are the low values and are being predicted very well. However, delay for the cross-street phases may be estimated by using the *X*-coefficient as a reduction factor. Although it is recognized that using only 10 observations to perform a regression analysis may not be ideal, lack of more data did not allow a more thorough analysis.

CONCLUSIONS

Based on data collected and reduced and analysis performed with the model, it can be said that a model has been developed to evaluate the effect of a bus priority strategy on the intersection operations. The model is very simple to use and estimates the effects of bus priority at an intersection reasonably accurately. The model seems to overestimate delay for some phases. Overestimation of delay, however, will only present a picture that is worse than what actually is in the field, that is, the delay experienced by the critical phases is less than the delay predicted by the model. Hence, even if the model predicts that the implementation of a priority strategy may worsen significantly the intersection operation, it may not be the case. The results of the model should be looked at closely, and engineering judgment should be used to evaluate the feasibility of any priority strategy.

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