Model to Evaluate the Impacts of Bus Priority on Signalized Intersections

Srinivasa R. Sunkari
Texas Transportation Institute
College Station, TX 77843-3135
Phone: (409) 845-5685
Fax: (409) 845-6481

Phillip S. Beasley
Texas Transportation Institute
College Station, TX 77843-3135
Phone: (409) 845-8545

Thomas Urbanik II
Texas Transportation Institute
College Station, TX 77843-3135
Phone: (409) 845-8545
Fax: (409) 845-6008

Daniel B. Fambro
Texas Transportation Institute
College Station, TX 77843-3135
Phone: (409) 845-1717
Fax: (409) 845-6481

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Transit service is being increasingly viewed as a reliable travel demand measure. Various means of trying to attract the motorist to move from the car to transit are being tried all over the country. It has been found that delay at intersections is the primary cause of delay for buses. 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 could not 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 was 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.
INTRODUCTION

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 better match 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 was soon followed by other similar demonstrations across the U.S. (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 (3,4,5,6,7,8,9,10,11,12). However, priority may increase delay to traffic on the cross-street. Since the concept emerged, however, experimentation and research have produced few operational systems.

A surge in transportation and communication technology has renewed interest in the potential benefits of bus priority. These benefits include the long term reduction of vehicular demand as drivers are enticed from their vehicles onto buses, reduction of fuel consumption and emissions, as well as a general improvement in transit system performance, including travel time savings, increases in average bus speed and the improvement of bus schedule adherence.

Problem Statement

Early active priority strategies accommodated buses with unconditional measures which give buses priority each time it is requested, with little concern for other traffic. Although these
strategies were shown to reduce bus delay, it was done so at the expense of other traffic. Because of the negative reactions received by early demonstrations, bus priority has not been generally accepted as a traffic control strategy. Another obstacle to the widespread implementation of bus priority strategies is their incompatibility with some coordinated signal 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. The model will enable the traffic analyst to evaluate the feasibility of implementing a bus priority strategy. 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.

**Priority at Traffic Signals**

Signal priority is a method of providing preferential treatment to buses and other high occupancy vehicles (HOV) at traffic signals by altering the signal timing plan in a way that benefits those vehicles. However, due to passenger loading and unloading operations and other characteristics, average bus speeds are typically slower and more variable than the traffic stream. Slower speeds result in the inability of the bus to stay in the traffic stream,
which presents problems in coordinated systems. 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. This phenomenon is graphically illustrated in Figure 1 (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. Bus priority can make transit a more attractive mode of transportation and may increase the passenger carrying capacity of arterial streets (14). On the other hand, at high levels of demand, bus priority may disrupt other traffic, especially on the cross-street.

Signal priority treatments can be divided into two major categories, passive priority and active priority. Furthermore, active priority treatments can be subdivided into unconditional and conditional signal priority strategies. The following section provides a discussion of the basic differences in the two major types of priority.

Passive Priority

Passive priority techniques do not explicitly recognize the actual presence of a bus. 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. The effect of reducing delay is a potential reduction in intersection capacity. Therefore, care must be taken so that cycle lengths are not reduced to the point that the resulting congestion affects bus operations.

**Splitting phases.** Splitting a priority phase movement into multiple phases within a cycle can reduce transit delays without necessarily reducing the cycle length. By repeating the priority phase within the same cycle, transit vehicles delay may be reduced at the intersection.

**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. Converting buses into auto equivalents may be used to justify the allocation of more green time to the bus movements.

**Metering vehicles.** Metering regulates the flow of vehicles through a network by limiting the number of vehicles allowed into the system. Buses benefit from metering by allowing buses to bypass metered signals with special reserved bus lanes, special signal phases, or by rerouting buses to non-metered signals.

**Active Priority**

Active priority occurs when the detection of a bus causes the activation of a new signal timing pattern which overrides the existing pattern. In general, active priority treatments
improve upon the passive priority concept in that priority is given only when the bus is actually present. There are mainly four types of active priority treatments.

**Phase extension (13).** A phase extension is an elongation of the green indication for the priority movement and is usually limited to some maximum value. A phase extension is useful when the bus will arrive at the intersection just after the end of the normal green period.

**Early start (13).** An early start priority advances the bus street green phase by prematurely terminating all other non-bus phases. An early start period is used when the bus arrives at the intersection during a red indication, while non-bus phases are active.

**Special phase (13,16).** A special phase occurs when a short green phase is injected into the normal phase sequence. Generally, special phases allow exclusive movement through the intersection in that the bus can make its movement while all other phases are stopped. Special bus phases may appear at any point in the cycle. Thus, adequate safety clearances must be provided when transitioning from the active phase to the bus phase.

**Phase suppression (16).** To facilitate the provision of the priority bus phase, one or more non-priority phases may be omitted from the normal phase sequence. This treatment should only be used when demand on the skipped phase(s) is low. Thus, to avoid disrupting operations on the non-bus phases, some logic must be provided such that no phases with heavy demand are skipped.

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. Most of the priority schemes combine phase extensions and early starts to provide priority to buses.
Priority schemes sometimes also include the concept of compensation \((16)\). Compensation is a priority strategy designed to limit the adverse effects priority has on the non-priority movements. In compensation, the non-priority movements can be allocated additional green time in the form of a non-priority phase extension following a priority. By compensating the non-priority movements with extra green time and by limiting the number of consecutive times priority is granted, the deterioration of non-priority traffic can be minimized.

**Unconditional Priority.**

Unconditional signal priority (or preemption) describes the provision of signal priority each time it is requested by a bus. In other words, 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 not a very attractive strategy. Now, most signal priority strategies are conditional in nature. However, unconditional signal priority strategies are still used for emergency vehicle preemption of traffic signals.

**Conditional Priority.**

Conditional signal priority strategies consider other factors in determining when or if priority will be granted to approaching vehicles. This form of signal priority attempts to limit the
undesirable effects caused by unconditional priority through selective consideration of various factors.

Several factors can be used in conditional signal priority algorithms. These 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. Conditional priority requires a more complex form of signal control than is needed for unconditional preemption. While both fixed-time and advanced traffic signal control systems have priority capabilities, the consideration of a variety of inputs or factors requires some form of computer algorithm capable of implementing the appropriate signal plan. Because advanced traffic signal control systems have the ability to adapt to changing traffic demands and patterns, these control systems may be more sensitive to the factors that may be considered (occupancies, cross-street traffic conditions, schedule adherence) in a conditional active priority strategy.

DEVELOPMENT OF A PRIORITY MODEL

A model to simulate and evaluate the operating strategy was developed (17). The model can be used as a tool to estimate the effects of the priority scheme on intersection operation. 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 safely be assumed 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 quantitatively examined using the input-output models shown in Figure 2.

Five cases have been defined and illustrated in Figure 2. 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 since the non-priority phases are least disrupted and also the bus would have had maximum waiting time to go through the intersection if no priority was provided.

Case 3 provides maximum extension (predefined) to the priority phase. Maximum extension usually depends on the travel time of the bus from the detection zone to the intersection. A bus detected just before the arterial phase (priority phase) terminates, can go through the intersection if an extension of the travel time is provided. A 10 second 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 non-priority phase(s) on at that time, and the priority phase comes on early. The non-priority 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 non-priority phases are provided minimum times and the priority phase comes on early.

Figure 2 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. The area of the triangles represent the delay experienced by vehicles in a typical cycle. 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 which delay is reduced. The effects on the cross-street are similar, but opposite. A short extension will likely 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 similar to an extension, as illustrated in Figure 2. The amount which the cross-street period is shortened should also have an affect on the delay to other traffic.

Analytical Tool to Evaluate Priority Scheme

The simple model developed uses the delay equation found in the 1985 Highway Capacity Manual (HCM). Several geometric, traffic, and signal timing values are required as input to the model. These include the number of lanes for each movement, hourly volumes, saturation flow rates, cycle length, and effective green times. While the number of lanes and cycle length will be obtained from plans, actual hourly volumes and green times will be obtained during the field study. Saturation flow rates will be computed either by using the Highway Capacity Manual procedure or by collecting discharge headway data in the field under saturated conditions.

The model simulates and evaluates the operation of the intersection with and without priority. 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 can be converted to person-seconds of delay per cycle knowing the number of vehicles per cycle and the average automobile occupancy.

The following values were used by the model to evaluate the operation of the intersection with and without priority:

- **Volume** = volume recorded during field study, in veh/hr
- **Saturation Flow Rate** = calculated using HCM or collected from the field, in veh/hr/lane group
- **Effective Green** = average phase green time, in sec
- **Stopped Delay** = calculated by the HCM equation, in sec/veh
- **Vehicle Delay/Cycle** = converted from HCM delay value
  
  \( (\text{sec/veh} \times \text{veh/cycle}) \), in veh-sec/cycle
- **Person Delay/Cycle** = veh-sec/cycle \( \times \) average auto occupancy, in person-sec/cycle
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 safely pass 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. This relationship is quantitatively represented in Figure 3.

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 sake, an assumption is made that buses are arriving only on Phase 2 and priority is being provided only to the coordinate phases (Phases 2 and 6). The duration the bus has to wait determines the delay savings obtained in person-sec/cycle when priority is provided.

The model calculates the savings obtained by providing priority through a number of steps. Various terms employed in the spreadsheet which 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. They are person delay/cycle with no bus for original splits and person delay/cycle with no bus for modified splits.

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

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

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

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

Waiting Period

It 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 or not priority is provided.

Person Delay/Cycle with One Bus and No Priority ($D_{(IB\cdot NP)}$)

$D_{(IB\cdot NP)}$ is obtained for each case of priority. $D_{(IB\cdot NP)}$ is the same as $D_{(NB\cdot OS)}$ 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 $D_{(NB\cdot OS)}$ with the product of the bus occupancy (40) and the period for which the bus has to
wait. Thus, the delay experienced by the bus in person seconds per vehicle is accounted for. However, in $D_{(IB\cdot NP)}$ we are assuming that a bus is arriving every cycle. Hence, the delay values obtained, represent the case when a bus is arriving every cycle and no priority is being provided.

Person Delay/Cycle with One Bus and With Priority ($D_{(IB\cdot P)}$)

$D_{(IB\cdot P)}$ is obtained for each scenario of priority that is provided. The various scenarios are obtained by modifying the green splits (adding to priority phases and reducing from non-priority phases). First the delay with modified splits is calculated assuming there is no bus arrival in the cycle ($D_{(NB\cdot MS)}$). 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 $D_{(IB\cdot P)}$ are the same as in $D_{(NB\cdot MS)}$ except the bus phase. The delay for the bus phase is obtained by summing the delay in $D_{(NB\cdot MS)}$ with the product of the bus occupancy (40) and the waiting period for the bus when priority is provided. Hence, these delay values are obtained from modified splits and the delay due to bus waiting (if it has to wait) to clear the intersection. However, in $D_{(IB\cdot P)}$ we are assuming that a bus is arriving every cycle. Hence, the delay values obtained, represent the case when a bus is arriving every cycle and priority is being provided every cycle.

The delay values in $D_{(IB\cdot NP)}$ and $D_{(IB\cdot P)}$ 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 will try to correct itself and second, the delays for some cross-street phases may get very high. A few cycles without priority will allow any phases disrupted due to 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 is being disrupted (i.e., v/c ratio is increasing over it's normal value).

Weighted Normal Delay (W.D_{NP})

W.D_{NP} is the delay experienced in person sec/cyc 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_{(IB-NP)} with the number of bus arrival cycles and the product of the delays in D_{(NB-OS)} with the number of normal cycles (non-bus arrival cycles) and dividing the sum by the total number of cycles in an hour. Thus, a weighted delay is obtained for the delay experienced when buses are arriving every 4 or 5 cycles and no priority is provided.

\[
W.D_{NP} = \frac{(D_{(IB-NP)} \times No: \text{Bus Arr. Cyc.}) + (D_{(NB-OS)} \times No: \text{Non-bus Arr. Cyc.})}{No: \text{of Cyc. per hr}}
\]
Weighted Delay with Priority (W.D_{(p)})

W.D_{(p)} is the delay experienced in person sec/cyc 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 $D_{(1B-p)}$ with the number of bus arrival cycles and the product of the delays in $D_{(NB-os)}$ with the number of normal cycles (non-bus arrival cycles) and dividing the sum by the total number of cycles in an hour. Thus, a weighted delay is obtained for the delay experienced when buses are arriving every 4 or 5 cycles and appropriate priority is provided to them.

\[
W.D_{p} = \frac{(D_{(1B-p)} * \text{No: Bus Arr. Cyc.}) + (D_{(NB-os)} * \text{No: Non-bus Arr. Cyc.})}{\text{No: of Cyc. per hr}}
\]

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 disbenefits to other traffic due to the priority strategy. Stopped delay was the chosen measure of performance for several reasons. First, intersection delay studies are very common. Delay data can be used to measure the quality of traffic flow at an intersection. Secondly, stopped delay is used because of its relative ease of collection and its precision.

The 1985 Highway Capacity Manual (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 HCM stopped delay field measurement method is a point sampling technique which is based on the direct observation of "stopped-vehicle counts" at the
intersection and a knowledge of the total approach volume during the same period (18).
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/veh
- \( \sum V_s \) = sum of stopped vehicle counts
- \( I \) = length of interval, in seconds
- \( V \) = total volume observed during study period

Site Selection and Description

A demonstration site was chosen among several candidate locations. The following criteria were considered in the decision:

- 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
- 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 south bound approach of Texas Avenue. Engineers and signal technicians of the city of College Station were consulted and their assistance was sought in the field implementation of the bus priority scheme. Some hardware and software modifications in the signal controller were required. Engineers at Automatic Signal/Eagle Signal assisted in modifications in the controller.

Two minor modifications were made in the traffic signal controller before data was collected in the field. Stopped vehicle counts were recorded for Case 1, Case 3, and Case 5 of the following five conditions:

- Case 1: No priority (before condition)
- Case 2: Priority with a minimum extension period
- Case 3: Priority with a maximum extension period
- Case 4: Priority with a minimum early start period
- Case 5: Priority with a maximum early start period
Case 2 did not warrant a separate study, as the benefits to the bus phase were apparent and at the same time, the affect of priority on the non-priority phases was not significant. In Case 4, only one or two sets of phases were influenced and hence did not require a separate study. Also, in Case 4 it was difficult to predict and control a fixed minimum early start while operating a semi-actuated controller in a coordinated system.

To determine the delay when priority was not provided, stopped vehicles were recorded for a period of approximately 30 consecutive minutes using 15 second intervals. McShane and Roess (19), maintain that the use of 15 second intervals is adequate for most studies, although a smaller interval may increase the accuracy of the delay estimate.

After the priority scheme was implemented at the demonstration site, stopped delay counts were performed during cycles in which buses were granted priority (Case 3 and Case 5). Ten cycles should provide an adequate number of data points to estimate the number of seconds of delay per cycle for each case.

The data collected for each of the cases was 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 which may not accurately apply to the existing local conditions. Also while 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 completely match the field results.

Field Data Collection

NEMA phase designation (Figure 4) with phases 2 and 6 as coordinated phases was used to denote phases. Data were collected in three parts. First, stopped vehicle counts were collected manually. Data collectors were positioned on each approach to record the number of vehicles stopped at 15 second intervals. In Case 1 (No Priority), the stopped vehicle counts were recorded for 30 minutes.

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 scheme was devised to activate the priority strategy by simulating the arrival of a bus. A push button was manually activated 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. Ten cycles with priority actuation provided adequate data to estimate the amount of vehicular stopped delay per cycle.

Secondly, the intersection was videotaped using two video cameras located on opposite corners of the intersection. Traffic volumes could be determined by observing the videotapes later. 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 was used to obtain green splits during the study.
The data collection was performed independently for Case 3 and Case 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 proportionately reduced from the subsequent non-coordinated phases. Thus, while coordination was not disrupted due to a single extension, quick and successive extensions can cause the controller to go off-sink and then correct itself. Thus, extensions were obtained only once every 4 to 5 cycles.

For Case 5 (maximum early start), it was decided to provide a maximum of 7 seconds for phases 3 and 7, a maximum of 15 seconds for phases 4 and 8, and maximum of 5 seconds for phases 1 and 5. The push button was energized seven seconds 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 non-priority phases after providing the earlier specified green times.

About 10 sample priority cycles were obtained for each of the two cases. Stopped delay data was collected for 4 intervals of 20 minutes each. Since, the cycle length of the intersection was 115 seconds, each 20 minute period facilitated in getting 2 to 3 cycles in which priority was provided. Hence, the target of 10 priority cycles was achieved.
Data Reduction

The final task in the study design was the reduction and analysis of the data collected. Data reduction involved estimation of the green splits, volumes, and stopped delay data. This data was reduced for each case separately. The objective of reducing the field data was to obtain the volumes and green splits to input into the model and to estimate the stopped delay in the field in seconds per vehicle.

The data collected was reduced in order to obtain stopped delay on a cycle by cycle basis. This meant that, green splits, volumes and stopped delay data were reduced to a cycle by cycle basis. This was done to maintain uniformity in data reduction with the other cases. As mentioned earlier, in Case 3 and Case 5, only the cycles in which priority was provided were considered.

Green splits were identified for each of the cycles. Average of these splits were input into the model. Volumes were obtained from the video tapes. These volumes were input into the model and also used to estimate delays in the field. The same procedure was used for all the cases (Case 1, Case 3 and Case 5).

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

RESULTS

The results of the field data collected to determine the effect a conditional bus priority strategy has on intersection operation are discussed below. In addition, the results of the model generated to estimate the impacts of the bus priority strategy on delay are also
examined. The following sections describe the results of the field study and the model, and the effectiveness of the model in estimating delay.

Comparing Field and Model Results

The field study consisted of collection, reduction and analysis of various data collected during the demonstration. The demonstration was conducted over a four week period. The three cases were tested on the same day of the week during the same time period to reduce variability in traffic conditions.

The data collected includes traffic volumes, stopped vehicle counts, and signal timing information. Traffic volumes and stopped vehicle counts were used to compute stop delay according to the Highway Capacity Manual field method. Although the signal timing information was collected during the field study, it was used by the model in the estimation of stop delay.

Field data was 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 indicates 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 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 Highway Capacity Manual overestimates the delay at high v/c ratios.

A regression analysis was done with the field delay values as independent values and the model values as dependant values. The constant was forced to pass through the origin. The analysis resulted in the following values:

\[
\begin{align*}
R^2 &= 0.830 \\
\text{Intercept} &= 0 \\
\text{X-coefficient} &= 1.437
\end{align*}
\]

The desirable values for \(R^2\) and X-coefficient are 1. While, a \(R^2\) 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 reasonably strong linear relationship between the delay observed in the field and the delay predicted by the model.

Based on the regression analysis, it can be said that the delay predicted by the model is about 44 percent higher than what we can expect in the field. This level of overestimation can result because of the high v/c ratios for some approaches. Hence, the approaches with v/c ratios greater than 0.85 were removed (refer Table 1) and regression analysis was performed again. Following is the result of the revised analysis.

\[
\begin{align*}
R^2 &= 0.904 \\
\text{Intercept} &= 0 \\
\text{X-coefficient} &= 1.413
\end{align*}
\]
The revised 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 still overestimating delay by about 41 percent.

In order to investigate the overestimation of the delay by the model, the data was further reduced 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 while 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-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. A regression analysis performed on the data in Table 2 gave the following results.

\[
\begin{align*}
R^2 &= 0.398 \\
\text{Intercept} &= 0 \\
\text{X-coefficient} &= 1.273
\end{align*}
\]

The results of the regression analysis indicate that while the X-coefficient is lower than found in earlier analyses, the $R^2$ value is very low. This low value of $R^2$ indicates a lack of a linear relationship between the delay values observed in the field and delay values predicted in the model.
In order to examine if the model is predicting delay reasonable well 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.

<table>
<thead>
<tr>
<th>R²</th>
<th>0.911</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>0</td>
</tr>
<tr>
<td>X-coefficient</td>
<td>1.249</td>
</tr>
</tbody>
</table>

Results of the regression analysis indicate that while the model is overestimating delay by about 25 percent, there is a strong linear relationship between the field delay and model delay. Figure 5 illustrates a scatter plot of the data used in the analysis and a line having a slope equal to 1. It shows that, while 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. While 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 affect of a bus priority strategy on the intersection operations. The model is very simple to use and estimates the affects 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 which is worse than what actually is in the field, i.e., 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 significantly worsen the intersection operation, it may not be the case. The results of the model should be looked at closely, and engineering judgement should be used to evaluate the feasibility of any priority strategy.

ACKNOWLEDGEMENTS

The authors wish to thank the Southwest Region University Transportation Center for sponsoring this project. Acknowledgements are also due to the engineers and technicians from Eagle Signal and the City of College Station for assisting in conducting this research.
REFERENCES


TABLE 1. COMPARISON OF FIELD DELAY WITH MODEL DELAY

<table>
<thead>
<tr>
<th>Cases</th>
<th>Approach</th>
<th>v/c Ratio</th>
<th>Field Delay (sec/veh)</th>
<th>Model Delay (sec/veh)</th>
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<td>Case 1</td>
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<td>12.0</td>
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<td>S. Bound</td>
<td>0.43</td>
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<td>Total Intersection Delay</td>
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TABLE 2. COMPARISON OF FIELD DELAY WITH MODEL DELAY FOR EACH PHASE

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<th>Model Delay (sec/veh)</th>
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Table Titles and Figure Captions

TABLE 1. COMPARISON OF FIELD DELAY WITH MODEL DELAY

TABLE 2. COMPARISON OF FIELD DELAY WITH MODEL DELAY FOR EACH PHASE

FIGURE 1. Time-Distance Diagram Showing the Different Typical Movements of a Platoon of Traffic and a Bus

FIGURE 2. Illustrated of the Expected Effects of the Priority Scheme on Main and Cross-Street Traffic

FIGURE 3. Delay to the Bus in Terms of its Point of Detection

FIGURE 4. Relationship of Field Delay with the Model Delay
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FIGURE 2. Illustration of the Expected Effects of the Priority Scheme on Main and Cross-Street Traffic.
Figure 3. Delay Savings to the Bus in Terms of its Point of Detection.
FIGURE 4. NEMA Configuration for Numbering Phase Movements.
FIGURE 5. Relationship of Field Delay with the Model Delay.