1. Report No. SWUTC/94/60041-1	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle A Model to Evaluate the Impacts of Bus Priority on Signalized Intersection		5. Report Date August 1994
		6. Performing Organization Code
7. Author(s) Srinivasa R. Sunkari, Phillip S. Beasley, Thomas Urbanik II, and Daniel B. Fambro.		8. Performing Organization Report No.
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135		10. Work Unit No.
		11. Contract or Grant No. 0079
12. Sponsoring Agency Name and Address Southwest Region University Transportation Center Texas Transportation Institute Texas A&M University System College Station, Texas 77843-3135		13. Type of Report and Period Covered Final - September 1993 August 1994
		14. Sponsoring Agency Code

15. Supplementary Notes

Supported by a grant from the Office of the Governor of the State of Texas, Energy Management Center.

16. Abstract

The concept of providing bus priority at signals is not new. Numerous cities have implemented bus priority strategies at signals with varying degree of success. Many of these cities have however discontinued using the priority measures. The advent of newer technology and an increased awareness for energy conservation and environmental problems due to emissions has prompted renewed interest in providing priority to buses at traffic signals. Reducing delay to the buses at signals can reduce overall travel time and improve schedule reliability.

This report documents the efforts to develop a model to estimate the impacts of providing priority to buses at signalized intersections. The existing strategies to provide priority to buses were reviewed. A priority strategy compatible with the local signal controllers was developed. A model using the delay equation in the 1985 Highway Capacity Manual was developed to simulate the intersection operations with bus priority. The priority strategy was implemented in a signal controller at an intersection in College Station. Bus arrivals were simulated and priority was provided manually.

Stopped delay data were collected for various scenarios of bus arrivals at the intersection when priority was provided. Data was also down loaded from the controller to obtain green split information. Volume data were obtained from video at the intersection. Stopped delay was obtained using the field data. Data were also input into the model and stopped delay values were obtained.

Delay values from the field were compared with the delay values obtained from the model. It was found that the model predicted delay very well at low v/c ratios but was slightly overestimating delays at high v/c ratios. The model can be used to estimate the impacts of implementing the priority strategy on intersection operation reasonably accurately.

The model can be a useful tool to traffic engineers to estimate the feasibility of implementing bus priority strategies. The model could encourage the increased use of bus priority measures. Better bus operations can lead to the bus being a viable alternative to the car. This in turn can lead to a reduction in vehicle miles of travel (VMT) and energy conservation, and improvement in pollution emissions.

17. Key Words Bus Priority, Green Extension, Early Green, Compensation, Fuel Consumption	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, 5285 Port Royal Road Springfield, Virginia 22161	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 60	22. Price

Form DOT F 1700.7 (8-69)

A MODEL TO EVALUATE THE IMPACTS OF

BUS PRIORITY ON SIGNALIZED INTERSECTIONS

Project 60041 Final Report

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EXECUTIVE SUMMARY

The concept of providing bus priority at signals is not new. Numerous cities have implemented bus priority strategies at signals with varying degree of success. Many of these cities have however discontinued using the priority measures. The advent of newer technology and an increased awareness for energy conservation and environmental problems due to emissions has prompted renewed interest in providing priority to buses at traffic signals. Reducing delay to the buses at signals can reduce overall travel time and improve schedule reliability.

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1. INTRODUCTION

The concept of providing priority to buses at traffic signals is by no means new. 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. 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 traffic signal systems.

Research Objective

The primary objective of this research is to develop, implement and evaluate a conditional active bus priority strategy for a traffic signal in a coordinated signal system. An effective priority strategy would provide a significant benefit to buses in terms of reduced travel time through or delay incurred at an intersection and also would be compatible with a coordinated signal system, such that it does not disrupt progression. Improved transit performance would be expected to increase transit usage which would have positive impacts on energy consumption and the environment. Another objective was to obtain a working knowledge of various priority strategies for buses at traffic signals. The project focused on the implementation of the strategy at a local intersection.

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2. RESEARCH BACKGROUND

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, bus operating characteristics are, by nature of their function, different than general (automobile) traffic operating characteristics. Due to passenger loading and unloading operations and other characteristics, average bus speeds are typically slower and more variable than the traffic stream in general. Slower speeds result in the inability of the bus to stay in the traffic platoon, 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 (3).

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 may make transit a more attractive mode of transportation and may increase the passenger carrying capacity of arterial streets (4). 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. Since this report emphasizes active priority treatments, more detailed discussions are provided for unconditional and conditional priority strategies.

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. Rather, passive priority treatments operate independent of the transit vehicles that they are designed to benefit. The following passive priority treatments are low cost methods aimed at improving transit operations (5).
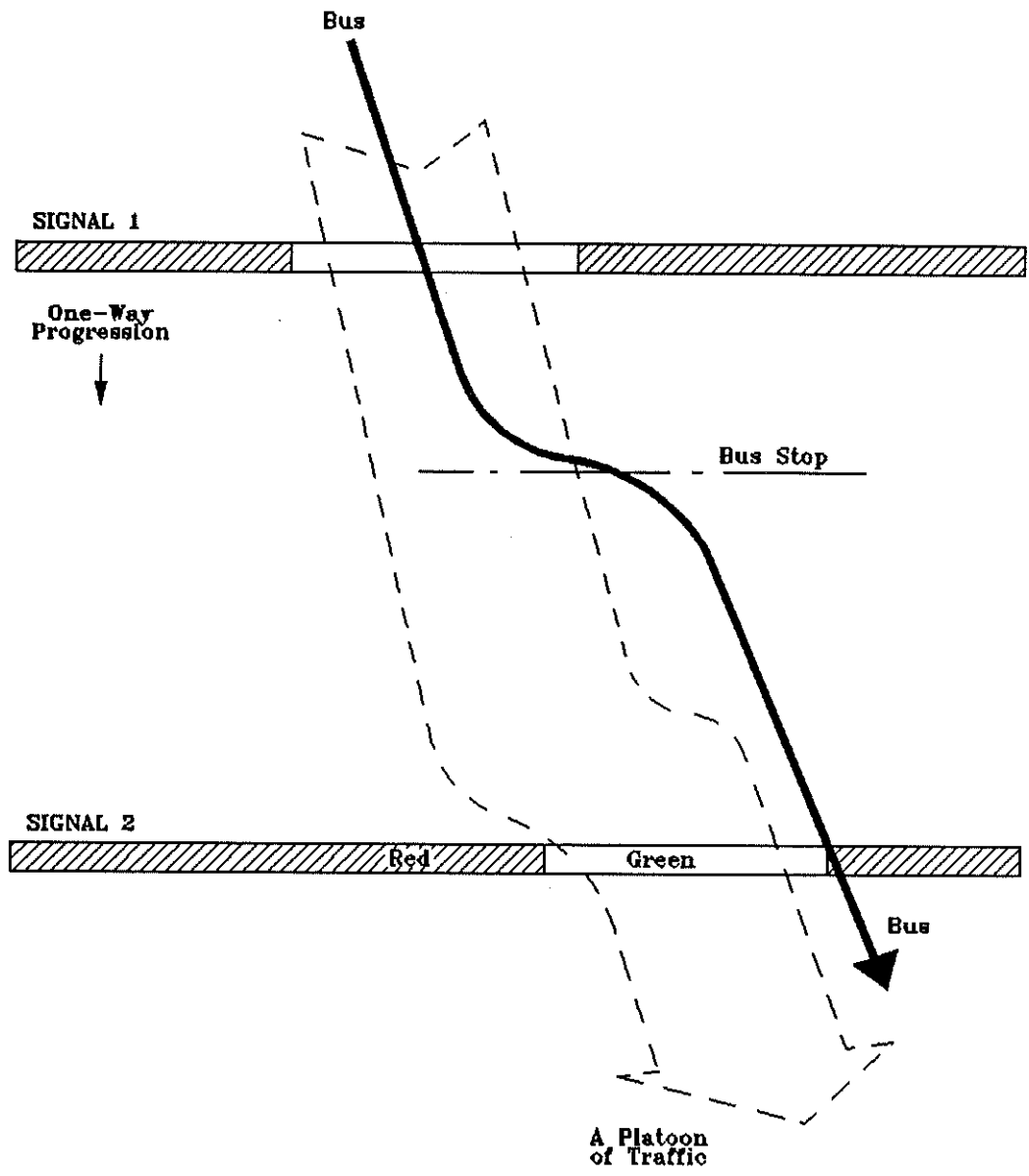
3

Figure 1. Time-Distance Diagram Showing the Different Typical Movements of a Platoon of Traffic and a Bus (*3*).

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 or conversion of buses into auto equivalents. Preferential progression for buses 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. Thus, the operating conditions at critical intersections can be controlled by metering vehicles at the perimeter. 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. Several active priority treatments are discussed in the following paragraphs.

Green extension (Phase extension) (3). A green extension is an elongation of the green indication for the priority movement and is usually limited to some maximum value. Many factors are considered when determining the maximum extension value such as detector location and near- or far-side transit stops. A green extension is useful when the bus will arrive at the intersection just after the end of the normal green period.

Early green (Early start) (3). An early green priority advances the bus street green phase by prematurely terminating all other non-bus phases. An early green period is used when the bus arrives at the intersection during a red indication, while non-bus phases are active. This type of priority treatment can be used to clear vehicles queued ahead of the bus, so that when the bus arrives it will not be forced to wait for a green indication.

Special phase (red interruption) (3,6). 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. Because a special phase may violate the normal phase sequence, it possibly may contribute to driver confusion.

Phase suppression (6). 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.

Compensation (6). 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 green 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.

The strategies mentioned are the basic alternatives of active priority. These strategies can be used alone or can be combined to provide priority to buses. The strategies can also sometimes be combined with compensation. A few examples of the priority routines obtained by combining the above mentioned strategies are Window Stretching (6) and Flexible Window Stretching (6).

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.

Previous experience indicates that cross-street traffic can be penalized by the nature of unconditional priority treatments. Simulations of a modified version of the Urban Traffic Control System-1st generation (UTCS-1) which used an unconditional bus preemption strategy benefitted buses but greatly penalized cross-street traffic. These penalties occurred in the form of unacceptable delays, especially when bus headways were small and when near-side bus stops were used. These simulations also showed that bus preemption systems using far-side bus stops with medium to long headways were most beneficial (7).

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. Bus signal priority system designers may consider any combination of the above conditions depending on the particular characteristics of their system. It is interesting to note that the Federal Transit Administration suggests that signal priority should be based on schedule adherence of the buses (*8*). Although the use of schedule adherence seems logical, only advanced systems are capable of determining whether or not a bus is on schedule.

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.

PAST PRIORITY PROJECTS

Although many early bus priority experiments resulted in travel time or delay savings to buses and an overall improvement in total person throughput, these strategies often significantly increased delays on the cross-street (*9,10,11*). A lack of experimentation with bus priority strategies in the U.S. in the 1980's seems to indicate that it was not considered a viable traffic control strategy. Now, technological advances and increasing emphasis on public transit afford another look at bus signal priority strategies.

Some early bus priority experiments used unconditional, or preemptive, control strategies (*3*). In an unconditional priority strategy, each detected bus is awarded priority movement through the intersection. Thus, traffic flow could be significantly disrupted at traffic signals with closely spaced bus arrivals. However, some more recent demonstrations have employed more sophisticated (conditional) control strategies to provide priority to buses while minimizing the effects to non-bus traffic (*12,13*). The following section discusses several of the more noteworthy demonstrations of bus signal priority in the U.S.

The LA priority system mentioned earlier (2) was manually activated to provide either an early green or an extended green so the bus could proceed with little delay. In the experiment, bus delay decreased between 70 and 76 percent and the cross street delay increased by an average of 38 percent. The result of the experiment was a net savings to travelers of approximately 35 percent.

In the early 1970's a large scale bus priority experiment was conducted in Washington, D.C. (3). A complex traffic management system with priority capabilities, the Urban Traffic Control System-Bus Priority System (UTCS-BPS), had 114 interconnected intersections and approximately 512 vehicle detectors. Thirty-nine of the intersections were equipped for bus priority. The project was performed in two phases.

The first phase of the project utilized a conditional priority routine which gave buses a conditional 10 second green extension. The constraints used in the algorithm to minimize the effects to non-bus traffic included degree of network saturation, queue lengths, flow volumes, and number of successive priority actions. However, this system was abandoned due to preliminary tests which indicated no significant improvement in bus travel time.

In the second phase of the UTCS-BPS project, an unconditional scheme awarded priority movement to buses with green extensions, early greens (red truncation), and special phases (red interruption). After a priority phase was activated, it remained in effect until all buses cleared the detection zone subject to a maximum period of two times the normal green phase. After all buses cleared the zone, control returned to the phase which would have been in effect had no priority been given. Thus, signal coordination was maintained.

In 1975, a three-month preemption experiment was conducted in Sacramento County, California on a 3.8 mile section of a suburban arterial, Greenback Lane (9). In the experiment, two express buses and the nine intersections were equipped with traffic signal priority equipment, 3M Company's Opticom system. The equipment gave the buses the ability to alter each of the nine signal's normal timing pattern in favor of a timing plan which could benefit the bus. Once detected, the bus phase could have either a green extension or an early green.

Based on the results of the experiment, average bus trip time was reduced an average of 23 percent. In addition, trip times became more reliable and bus speeds increased slightly. Experimenters noted that no hazardous conditions were created and that delays for both the arterial and the cross-street traffic did not increase. However, only two express bus trips were made in each direction per day.

A larger demonstration of bus priority was conducted in Miami, Florida from 1974 to 1976 (10). In the demonstration, the following four bus priority treatments were evaluated:

1) Bus preemption of traffic signals in mixed traffic.

2)   Bus preemption of traffic signals in an exclusive bus lane.
3)   Bus operation in an exclusive lane with signal progression.
4)   Bus preemption of traffic signals in an exclusive lane with signal progression.

During the stages with signal priority treatment (stages 1,2, and 4), buses could hold the green phase for up to 120 seconds. Thus, practically all buses could clear the intersection with little or no delay. This guarantee of passage may have led to a decrease in schedule adherence because buses could clear the intersection at any desired speed.

The results of the evaluation indicated bus travel time values were smallest in the stages when exclusive bus lanes were used. However, bus travel times were also improved when buses could preempt the signals in mixed traffic. Intersection delay analyses showed little change in delay between the original operation (without priority) and the introduction of the priority strategy.

Despite the positive results achieved by early bus priority projects, the concept appears to have not been accepted by traffic engineers and the general public. Conversely, transit operators regard bus priority as a benefit to their operations. Because cross-street green time is reallocated to serve buses, cross-street traffic may experience some excess delay. The delay to the cross-street is more apparent and severe during saturated conditions because of the absence of slack time for the cross-street phase i.e., cross-street traffic is using the phase time completely.

More recent experience with bus priority treatments has been mixed, even though priority strategies can be more easily implemented due to advances in signal control and communication technologies. Few systems are in operation today, although several systems have recently been tested and several are proposed.

The Ventura Boulevard Bus Priority Traffic Signal Preemption Demonstration Project began in 1983, although the system did not become operational until 1986 (*11*). Due to operational and mechanical difficulties the Ventura Boulevard priority system was not evaluated until 1989. The priority strategy gave buses priority movement through traffic signals with green extensions or advancement of the bus street green phase (early green) of up to 10 seconds.

The demonstration was evaluated using bus travel times and delays. The results showed a 3.2 minute reduction in average travel time for a 77.1 minute round trip, amounting to a 4.2 percent improvement. However, average bus delays at intersections were reduced from 10.2 minutes to 8 minutes for a 21.6 percent improvement. The difference between the before and after bus travel time and delay data was statistically significant for most conditions (time of day and bus line) at a 90% confidence level. Student T tests were used to evaluate the data. Impacts on passenger vehicles resulting from the bus priority scheme were not measured in this study.

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The City of Bremerton, Washington and Kitsap Transit implemented a bus priority system in July of 1992 (14). Utilizing Opticom priority hardware, the priority scheme provides buses with green extensions or early greens at 42 traffic signals. The system offers a more cost efficient improvement to bus services than other more costly alternative. The total cost of equipping all 42 intersections was $250,000, compared to an average cost of $5,000,000 per mile to construct HOV lanes in King County, Washington. To date, no results have been released for this demonstration project.

Since 1985, the City of Charlotte, North Carolina, has operated a bus priority system for express buses along Central Avenue (12). The system was designed to address several problems that older priority systems experienced, such as unexpected phase skipping, development of large queues on the side streets, and disruption of progression in a coordinated system. Although Charlotte's current bus priority system has solved several known problems, it still is unable to provide priority to buses without disrupting progression to some degree.

In an attempt to address Chicago's congestion problems, the Chicago Area Transportation Study (CATS) formed Operation Green Light (15). One goal of Operation Green Light is to reduce congestion on Chicago's arterial street system. To achieve this goal, one method under observation is signal priority. Operation Green Light is considering signal priority systems for two arterial corridors, the Cermack Road corridor and the South Michigan/119th Street Corridor. The proposed systems will likely use advanced (European) technologies to provide sophisticated control. Such advanced technologies will allow the provision of priority to buses based on their schedule performance. Thus, late buses can be given priority movement while early buses can be held up.

One other project deserving mention is a bus preemption project initiated by the Maryland Department of Transportation in 1993 (13). In the Maryland bus preemption system, bus phase can either have a green extension or an early start to reduce delays incurred by buses at traffic signals. This project was one of the first signal priority projects to be funded by the 1991 Intermodal Surface Transportation Efficiency Act (ISTEA). ISTEA allocated a total of $155,000, the cost to equip 14 signalized intersections and nine transit buses with Opticom priority hardware (16).

Maryland's priority system is different in that the early green period is an exclusive special phase during which only the bus can proceed through the intersection. During the special phase a special overhead signal notifies the driver when it is safe to proceed (all other phases are red) via the right-most shoulder. This feature is called a "queue jump." The system was designed to operate without disrupting progression utilizing signal controllers which aren't "set free" when a priority is granted. Thus, the controller does not have to transition back into coordinated operation. Transitioning back into coordinated operation can take up to three cycles.

In summary, experience with bus priority systems in the U.S. is mixed, at best. Although non-bus traffic was sometimes disrupted, many of the early demonstrations were successful in improving bus operations while also improving overall person throughput. In recent times, few projects have been initiated, probably due to the residual effect of the early demonstrations. New advancements in signal and communication technologies, IVHS initiatives and the increased attention toward public transit may have a positive effect on the use of signal priority strategies in the near future.

3. BUS PRIORITY SCHEME

This chapter describes the study design that was used to achieve the research objectives which were to develop, implement and evaluate a conditional active bus priority strategy for a traffic signal in a coordinated signal system. The study consisted of the following eight tasks:

1.   Investigation of Problem: the information needed to develop a working knowledge of bus priority strategies was obtained.

2.   Development of Operational Strategy: based on the information obtained in the task above, a control scheme to provide priority movement to a bus was developed. Constraints used in the decision to grant priority were determined in this task.

3.   Development of Analytical Tool: a model of the priority strategy was generated to estimate its effects on intersection operation.

4.   Development of Field Study Evaluation Plan: an evaluation plan to determine the effectiveness of the operational strategy was developed.

5.   Selection of Demonstration Site: a suitable demonstration site was chosen among several area intersections.

6.   Implementation of Strategy: modifications to the existing traffic signal control equipment were performed to activate the priority strategy.

7.   Compilation of Data: a field study to obtain various data regarding vehicle and bus performance was performed.

8.   Analysis of Data: the priority strategy was analyzed qualitatively and quantitatively using data collected in the above task to determine its effectiveness.

The following sections provide a discussion of the major activities and the issues associated with each of the eight tasks in the study design.

Investigation of Problem

The status of the problem and an understanding of the literature had to be determined first. With this information, an operational plan to provide priority to buses could be determined. This information was obtained in a search of the literature and was discussed in detail in Section 2, Research Background. The literature provided the following information:

- types of active bus priority strategies;
- measures of effectiveness used to evaluate bus priority systems; and
- case studies of previous and ongoing demonstrations.

DEVELOPMENT OF OPERATIONAL STRATEGY

The second task consisted of the development of the specifications for the operation of conditional active bus priority strategy. This task required an understanding of the types of priority treatments and how these treatments could be applied to accomplish the objectives of this thesis. Several approaches were taken to develop a suitable scheme. The following paragraphs explain this process.

Optimum Priority Scheme

Initially, a sophisticated priority strategy was considered. The proposed strategy provided priority movement to buses with green extension and early greens. In addition, the strategy compensated cross-street traffic when feasible.

An additional feature was a variable green extension period. This green extension period varied according to the amount of time required by the bus, subject to a maximum constraint. A two detector scheme is required for the strategy. The first, or upstream, detector would place a call for an extension if the bus was detected during the coordinated phase green. The second detector, placed at the stop line, had two main functions. First, this detector canceled priority requests if the bus was accommodated during the green period. Secondly, the stop line detector was used to terminate the priority green extension when the bus entered the intersection. Thus, the priority extension could be terminated when no longer required.

If the bus arrived in the coordinated red phase, it would be given an early green. To do so, the controller would provide minimum periods to all the cross-street phases thus expediting the early return of the coordinated green phase. The early green period also varies in length according to when the bus is detected. Finally, the strategy provided compensation of the cross-street phases when feasible. This feature gave time lost back to the cross-street in the cycle immediately following one in which priority had been given. To

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do so, the coordinated phase was to be composed of two parts: a non-actuated portion and an actuated portion. During normal operation, the actuated portion would be on recall. However, in a cycle succeeding one in which priority was awarded to a bus, this portion would not be on recall. Thus, this portion of the coordinated phase could be transferred to the cross-street in the absence of traffic on the coordinated phase detectors.

Final Priority Scheme

The original plan was modified for several reasons, including monetary and time constraints. It was decided to design a priority scheme using the capabilities of an Eagle EPAC 300 series signal controller (*17*). The objective of the strategy is to provide conditional active priority treatment to buses without disrupting progression.

Additional research and consultation with various professionals led to the development of a scheme which closely matched the original strategy, minus the provision of cross-street compensation. This low cost alternative strategy requires minor modifications to the software and hardware in the signal controller.

This third and final strategy provides priority to buses with green extensions and early greens. Buses detected at the end of coordinated phase green will be granted an extension with a maximum value of 10 seconds. The extension period will terminate when the bus clears the intersection, as described in the original strategy. Buses detected during the coordinated red phase will receive an early green. In such a situation, the coordinated phase will be advanced by providing user defined maximum green splits (due to constant extensions) to the non-priority phases. The length of the early green period will vary according to when the bus is detected in the cycle.

Constraints of the Scheme

Cross-Street Queues not Considered. One of the objectives of the project was to consider the traffic conditions on the cross-street before providing any priority. However, time constraints as well as the hardware constraints did not allow us to so. However, not considering the cross-street queues is not very critical as priority is being provided only once every 4 to 5 cycles. Any deterioration in the traffic conditions due to priority being provided will be overcome in the next few cycles.

Schedule not Considered. The schedule of the bus is also not being considered automatically. If the bus is ahead of schedule, providing priority is not necessary. It may even be detrimental to bus operations if bus is significantly ahead of the schedule.

4. DEVELOPMENT OF THE PRIORITY MODEL

In the third task of the project, a model of the operating strategy was developed. The model can be used as a tool to estimate the effects of the priority scheme on intersection operation. 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.

Figure 2 illustrates the arrivals and departures for both the main street and the cross-street and the effects of priority green extensions and early greens 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 green extension affects the amount which delay is reduced. The effects on the cross-street are similar, but opposite. A short green extension will likely cause a small increase in delay (increase in size of triangle), whereas a large green extension should cause a larger increase in delay. An early green priority affects delay similar to an green 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

With these relationships in mind, a model of the priority strategy was developed to quantitatively estimate the impact of the different types of priority on delay. The simple model uses the delay equation found in the 1985 Highway Capacity Manual (HCM), as shown below:

$$d = 0.38C\frac{[1-g/C]^2}{[1-(g/C)(X)]} + 173X^2[(X-1)+\sqrt{(X-1)^2+(16X/c)}]$$

where: d   =   average stopped delay per vehicle for the lane group, in sec/veh;

                 C   =   cycle length, in sec;

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Case 1: No Priority
Case 2: Minimum Green Extension
Case 3: Maximum Green Extension

MS Arrival Rate

MS Departure Rate

MAIN STREET (MS)

| L | T | L | T | L | T |

Minimum Green Extension →||←
Maximum Green Extension →| |→

CS Departure Rate

Case 1: No Priority
Case 2: Minimum Green Extension
Case 3: Maximum Green Extension

CROSS-STREET (CS)

CS Arrival Rate

Volume

Time

LEGEND
L = Left Turn Movements
T = Through Movements
☐ = Main Street Green
▨ = Main Street Red

MS Departure Rate

MS Arrival Rate

Case 1: No Priority
Case 4: Minimum Early Green
Case 5: Maximum Early Green

MAIN STREET (MS)

Maximum Early Green

→| |← Minimum Early Green

| L | T |

CROSS-STREET (CS)

Case 1: No Priority
Case 4: Minimum Early Green
Case 5: Maximum Early Green
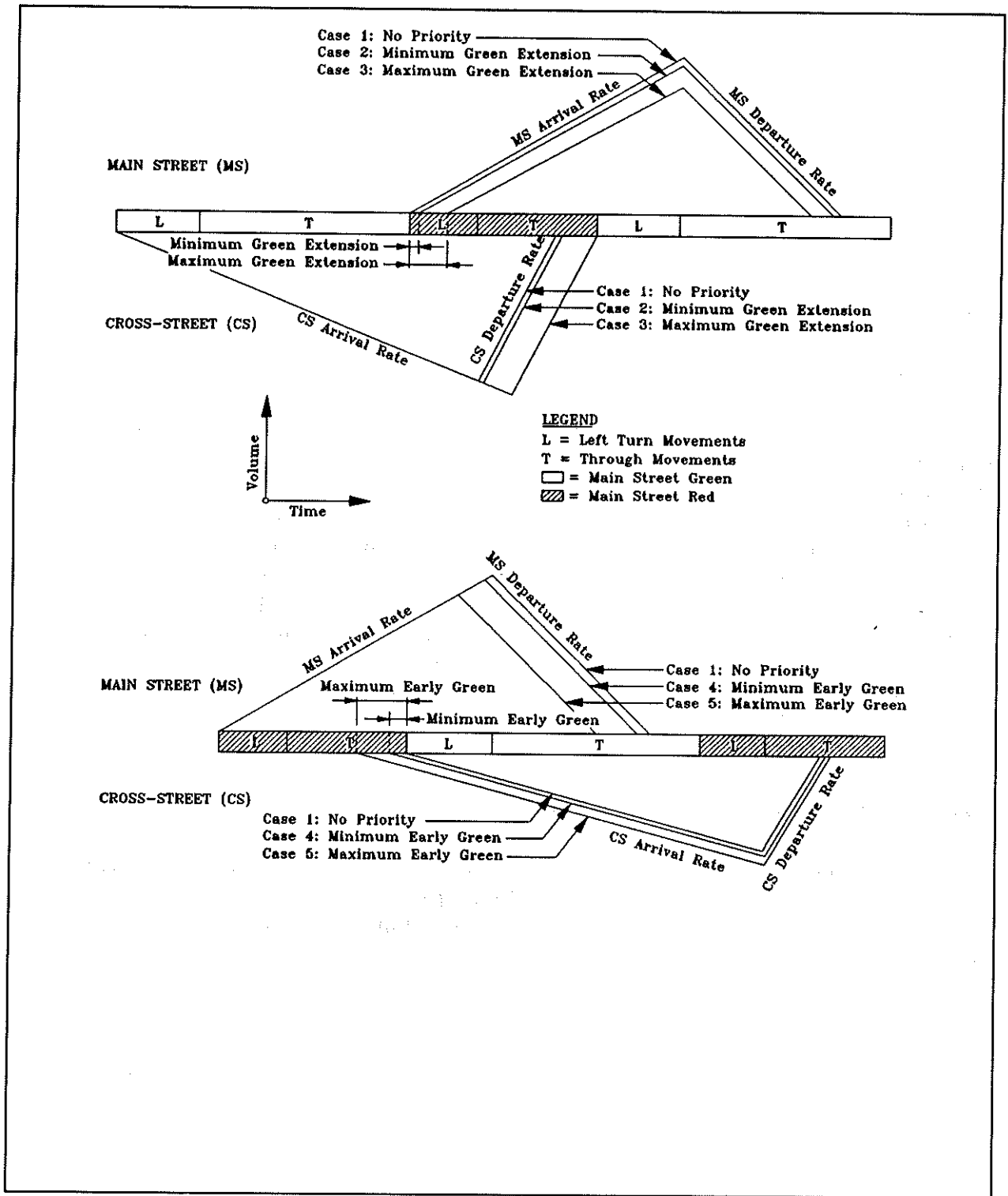
CS Arrival Rate

CS Departure Rate

Figure 2.   Illustration of the Expected Effects of the Priority Scheme on Main and Cross-Street Traffic.

g/C   =   green ratio for the lane group, the ratio of effective green time to cycle length;

X   =   v/c ratio for the lane group; and

c   =   capacity of the lane group.

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 the 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.

A spreadsheet was generated to calculate various measures of effectiveness for different input conditions and model 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, green extension, or early green). 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 a green extension or early green, 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 spreadsheet was used to calculate delay. 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 and equations were used by the spreadsheet to model 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
  (sec/veh x veh/cycle), in veh-sec/cycle

- Person Delay/Cycle   =   veh-sec/cycle x average auto occupancy, in
  person-sec/cycle

- Auto Occupancy   =   1.25, in persons/veh

- Bus Occupancy   =   40, in persons/bus

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 a green 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 a green 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, then 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 spreadsheet 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 spreadsheet calculates the savings obtained by providing priority through a number of steps. The spreadsheet is illustrated in Figure 4 and various terms in it are 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 ($D_{(NB-OS)}$)
        $D_{(NB-OS)}$ 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.

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Sum of
Cross–Street
Phases

BENEFIT TO BUS
(Delay Savings)

| ←——— NO BENEFIT ———→ |
| (Bus doesn't need priority) |

0

| L | T | L | T | |

POINT IN CYCLE WHEN BUS IS DETECTED

LEGEND

L = Left Turn Movements
T = Through Movements
☐ = Main Street Green
▨ = Fixed Portion of Cross–Street Phase
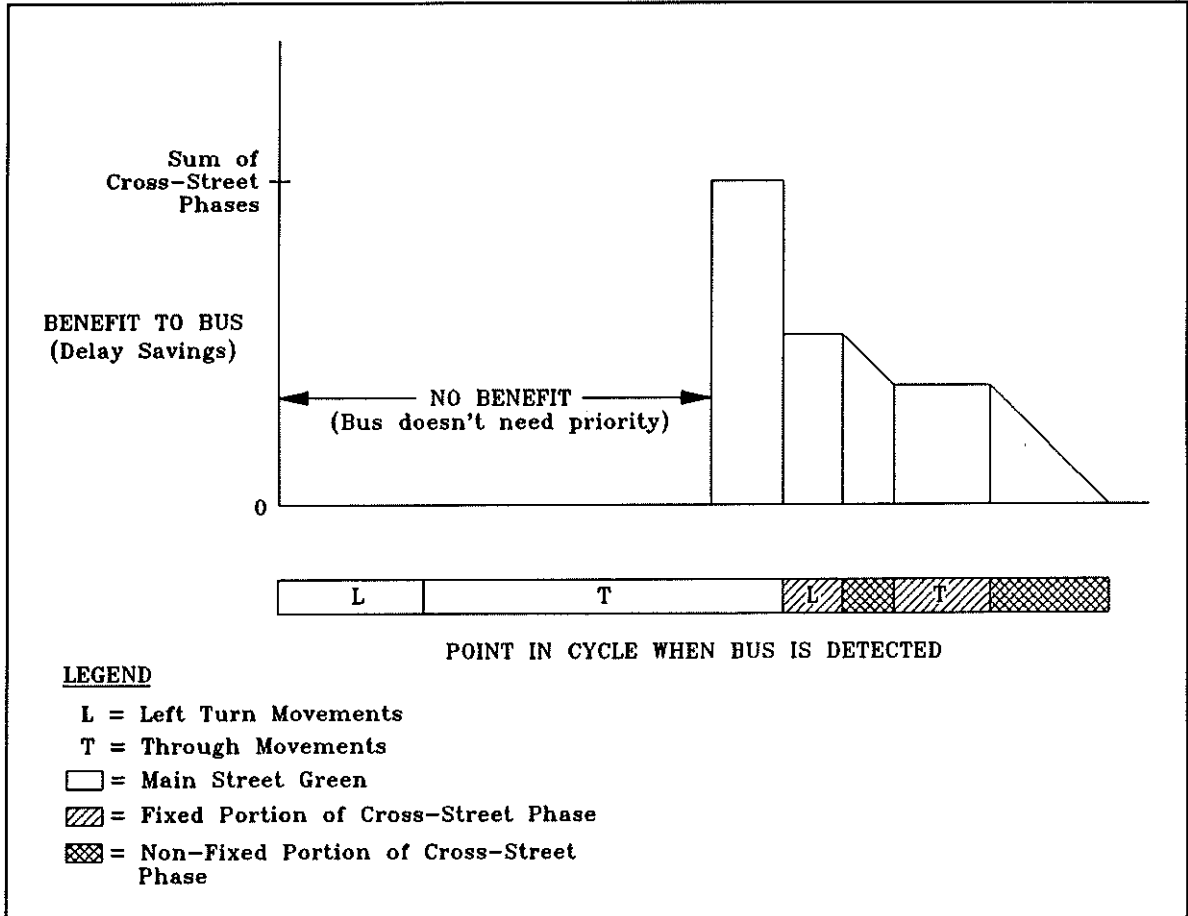▩ = Non–Fixed Portion of Cross–Street
    Phase

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

Intersection	Direction	Movement	# Lanes	Hourly Volume, v	Sat Flow Rate, Sp	Cycle C	Eff. Green, g	Flow Ratio, y	Cap. c	X or v/c	du	dr	Stopped Delay, d sec/veh	Delay/Cycle, sec/cyc	Cycle, sec/cyc (No Bus)	Waiting Per. (W.O Prio.)	Waiting Per. (With Prio.)	Person Delay/Cycle, sec/cyc (1 Bus No Prio.)	Person Delay/Cycle, sec/cyc (1 Bus With Prio.)	Normal Delay	Prio. Delay	Percent Reduction
Texas/SWP	NB (Texas)	L (1)	1	88	1843	115	3.5	0.05	341	0.26	41.4	0.1	41.5	116.7	145.8							
		T (6)	2	820	3645	115	61.8	0.22	1959	0.42	12.1	0.1	8.8	229.3	286.6							
	SB (Texas)	L (5)	1	100	1843	115	4.2	0.05	380	0.26	41.0	0.1	41.0	131.1	163.9							
NO PRIORITY		T (2)	2	912	3593	115	62.5	0.25	1953	0.47	12.2	0.1	8.9	258.9	323.6							
	EB (SWP)	L (3)	1	184	1676	115	11	0.11	236	0.78	38.6	10.2	48.8	287.1	358.9			Person Delay/ Cycle, sec/cyc	Person Delay/ Cycle, sec/cyc			
		T (8)	2	338	2953	115	18.6	0.11	478	0.71	34.7	3.3	38.0	410.0	512.5							
	WB (SWP)	L (7)	1	132	1676	115	8	0.08	223	0.59	39.5	3.0	42.5	179.1	223.8			Cycle, sec/cyc	Cycle, sec/cyc			
		T (4)	1	190	1676	115	15.6	0.11	227	0.84	36.8	15.5	52.4	317.8	397.3			(1 Bus No Prio.)	(1 Bus With Prio.)	Normal Delay	Prio. Delay	Percent Reduction
		R (4)	1	130	1372	115	15.6	0.09	186	0.70	36.1	7.3	43.4	180.3	225.3	Waiting Per. (W.O Prio.)	Waiting Per. (With Prio.)					
													21.2	1929.9	2412.4							
Texas/SWP	NB (Texas)	L (1)	1	117	1843	115	4.8	0.06	324	0.36	40.7	0.3	41.1	153.4	191.8			145.8	191.8	145.8	159.2	-9%
		T (6)	2	921	3645	115	67.7	0.25	2146	0.43	9.9	0.1	7.2	211.4	264.3			286.6	264.3	286.6	280.1	2%
	SB (Texas)	L (5)	1	85	1843	115	2.3	0.05	353	0.24	42.2	0.1	42.2	114.7	143.4			163.9	143.4	163.9	158.0	4%
MAX. EXTENSION		T (2)	2	1087	3593	115	65.2	0.30	2037	0.53	11.7	0.2	8.6	299.3	374.1	52.8	0	2435.6	374.1	936.7	338.2	64%
(10 SECOND)	EB (SWP)	L (3)	1	215	1676	115	8.8	0.13	200	1.07	40.6	74.9	115.5	793.4	991.8			358.9	991.8	358.9	542.6	-51%
		T (8)	2	371	2953	115	15.7	0.13	403	0.92	37.3	18.7	55.9	662.7	828.4			512.5	828.4	512.5	604.2	-18%
	WB (SWP)	L (7)	1	121	1676	115	6.9	0.07	170	0.71	40.3	8.8	49.2	190.0	237.5			223.8	237.5	223.8	227.8	-2%
		T (4)	1	156	1676	115	13.8	0.09	201	0.78	37.3	11.5	48.8	243.2	304.0			397.3	304.0	397.3	370.2	7%
		R (4)	1	148	1372	115	13.8	0.11	165	0.90	37.9	29.5	67.5	319.0	398.7			225.3	398.7	225.3	275.7	-22%
													26.0	2668.2	3335.2				Sum	3025.6	2680.3	11%
Texas/SWP	NB (Texas)	L (1)	1	110	1843	115	4.1	0.06	380	0.29	41.1	0.1	41.2	144.7	180.9			145.8	180.9	145.8	156.0	-7%
		T (6)	2	905	3645	115	69.2	0.25	2193	0.41	9.2	0.1	6.7	193.5	241.9			286.6	241.9	286.6	273.6	5%
MAX. E.S.	SB (Texas)	L (5)	1	118	1843	115	3.4	0.06	385	0.31	41.5	0.1	41.7	157.1	196.4			163.9	196.4	163.9	173.3	-6%
(Arr. at Yel.)		T (2)	2	939	3593	115	68.5	0.26	2140	0.44	9.7	0.1	7.0	211.0	263.7	52.6	46	2427.6	2103.7	934.4	840.4	10%
Ph 3,7 = 7 sec	EB (SWP)	L (3)	1	152	1676	115	7.8	0.09	166	0.92	40.5	33.0	73.5	356.7	445.8			358.9	445.8	358.9	384.1	-7%
Ph 4,8 = 15 sec		T (8)	2	284	2953	115	13.2	0.10	339	0.84	37.9	11.5	49.4	447.8	559.8			512.5	559.8	512.5	526.2	-3%
Ph 1,5 = 5 sec	WB (SWP)	L (7)	1	115	1676	115	6.8	0.07	165	0.70	40.3	8.1	48.4	177.8	222.3			223.8	222.3	223.8	223.4	0%
		T (4)	1	157	1676	115	12.2	0.09	178	0.88	38.5	25.4	63.9	320.6	400.7			397.3	400.7	397.3	398.3	-0%
		R (4)	1	144	1372	115	12.2	0.10	146	0.99	39.0	54.1	93.1	428.2	535.2			225.3	535.2	225.3	315.3	-40%
													20.2	2009.2	2511.5				Sum	3023.2	2975.4	2%

Figure 4. Spreadsheet Developed to Evaluate the Benefits due to Bus Priority.

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

$D_{(NB - MS)}$ is the same as $D_{(NB - OS)}$, 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 on not priority is provided.

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

$D_{(1B - NP)}$ is obtained for each case of priority. $D_{(1B - NP)}$ is the same as $D_{(NB - OS)}$ 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 $D_{(NB - OS)}$ 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 $D_{(1B - NP)}$ 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 ($D_{(1B - P)}$)

$D_{(1B - P)}$ 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 ($D_{(NB - MS)}$). 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 $D_{(1B - P)}$ are the same as in $D_{(NB - MS)}$ except the bus phase. The delay for the bus phase is obtained by summing the delay in $D_{(NB - MS)}$ 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 $D_{(1B - P)}$ 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 $D_{(1B - NP)}$ and $D_{(1B - P)}$ 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$_{(1B-NP)}$ 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.

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

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.

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

Field Evaluation of the Model

One of the first activities performed in the fourth task was to determine the measures of effectiveness (MOE) with which the demonstration would be evaluated. This project focuses on the operational evaluation of the priority strategy described in the second task. Hence, it was proposed that various cases with and without priority be studied to evaluate the effective field implementation of the priority strategy.

The objective of the evaluation was to 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.

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Point sampling delay measurement techniques, in which stopped vehicles are recorded at regular intervals, provide accurate estimates of the actual intersection stopped delay. Greater accuracies can be achieved with longer observation periods and smaller intervals (18). However, the use of small (less than 10 seconds) intervals is not practical in field situations. Field-collected stopped delay data should be used with caution, especially when delays are short or volumes are low (19). Stopped delay values can also be used to estimate approach, or total, delay by applying a factor of 1.3 (18).

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 (20). The number of seconds of delay per vehicle can then be calculated according to the following equation (20):

$$Delay = \frac{\Sigma V_s \times I}{V}$$

where: Delay $=$ stopped delay, in sec/veh
         ΣV_s $=$ sum of stopped vehicle counts
         I $=$ length of interval, in seconds
         V $=$ total volume observed during study period

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 green extension period
- Case 3: Priority with a maximum green extension period
- Case 4: Priority with a minimum early green period
- Case 5: Priority with a maximum early green 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 green 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 (*18*), 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 used in the spreadsheet. 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 spreadsheet 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 spreadsheet 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 spreadsheet results should not be expected to exactly match the field results. The methods employed to reduce the data collected in the field are discussed in Section 5.

5. FIELD INSTALLATION

SITE SELECTION AND DESCRIPTION

In the next task, 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 (Figure 5). In addition to satisfying the above criteria, this intersection is also the site of other research projects. Thus, some data collected for this project can be used in other projects.

The site is located at the intersection of a major north-south arterial (Texas Avenue) and a major east-west collector (Southwest Parkway) (Figure 5). The northbound and southbound approaches to the intersection on Texas Avenue have three lanes: an exclusive left turn lane, an exclusive through lane, and a shared through-right turn lane. On Southwest Parkway, the eastbound approach has three lanes (an exclusive left turn lane, an exclusive through lane, and a shared through-right turn lane). The westbound approach geometrics differ slightly in that there is an exclusive left turn lane, an exclusive through lane, and an exclusive right turn lane. Lane widths vary greatly, from 9.5 feet on Southwest Parkway to 15 feet on Texas Avenue (Refer to Figure 6).

The intersection is controlled by an EPAC 300 actuated controller unit manufactured by Automatic Signal/Eagle Signal. Currently 15 detectors are in operation at the intersection. Presence loops are located in three of the left turn lanes (NB, SB, and EB). The presence loops measure 6' x 30', and are located in the turn lane close to the stop line. In addition, 6' x 6' loop detectors are located in each of the three lanes of each approach. These loops are located approximately 125 feet upstream of the intersection (Refer to Figure 6).
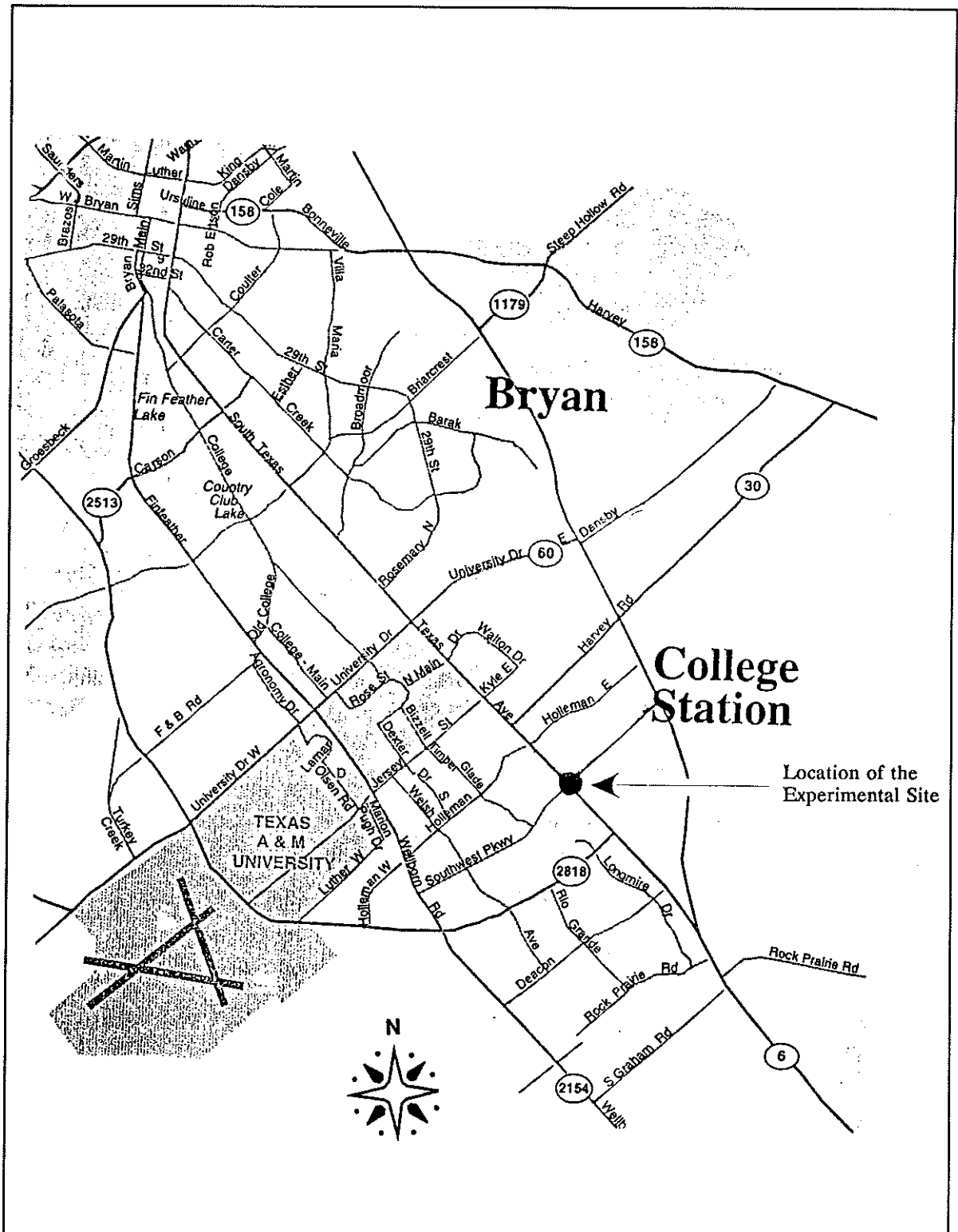
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Figure 5. Map of the City of College Station Showing the Location of the Site.
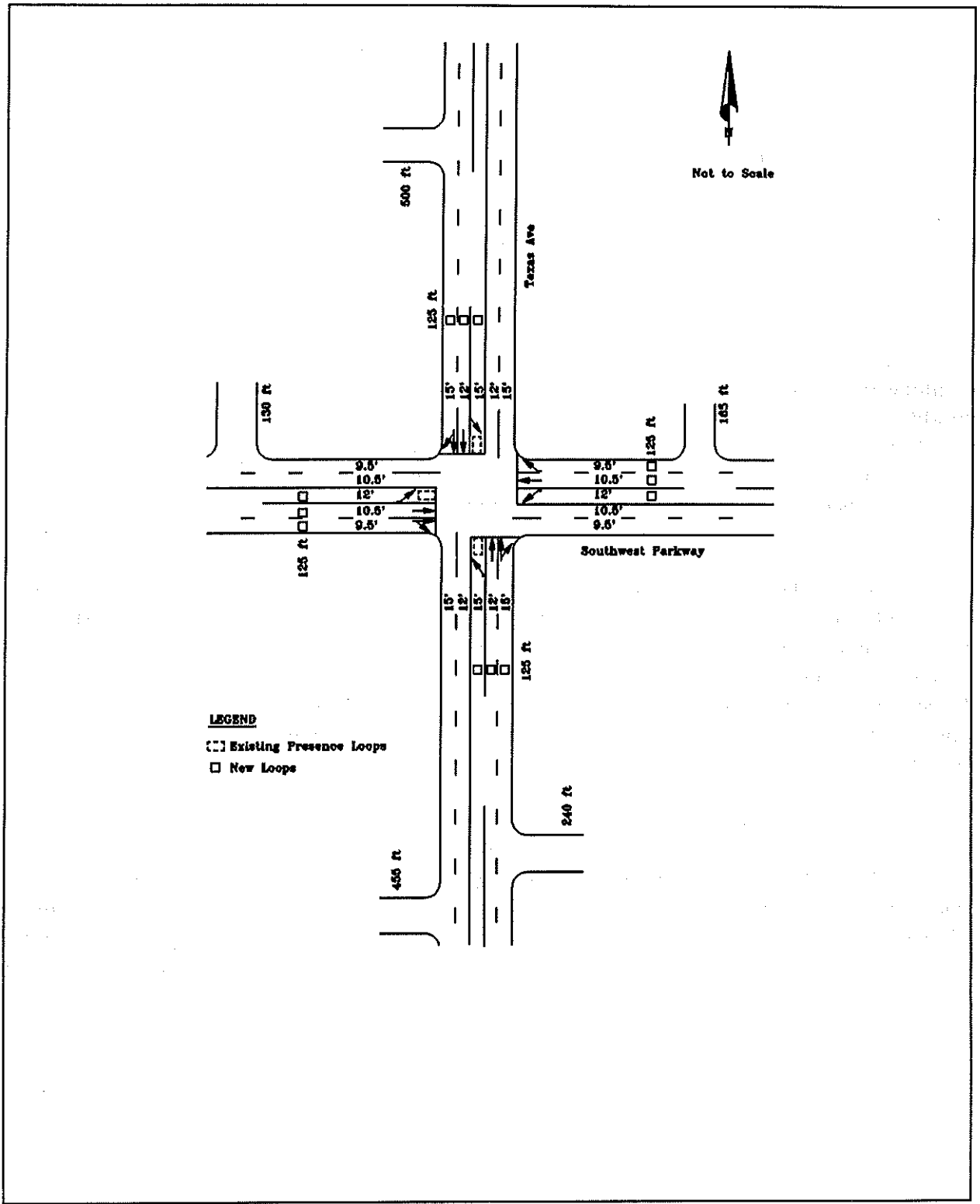
Not to Scale

Texas Ave

500 ft

125 ft

130 ft

185 ft

125 ft

15' 12' 15' 15'

9.5'
10.5'
12'
10.5'
9.5'

9.5'
10.5'
12'
10.5'
9.5'

125 ft

Southwest Parkway

15' 12' 15' 15'

125 ft

LEGEND

[::] Existing Presence Loops

☐ New Loops

455 ft

240 ft

Figure 6. Illustration of the Study Site.

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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. Assistance from the signal technicians was also sought in the field data collection for the various cases.

Modifications to the Existing Setup

The fifth task in the study design of this project is the implementation of the priority strategy and the compilation of data. Implementing the priority strategy required two minor modifications to the signal control at the intersection. The first modification was the addition of special hardware to the signal cabinet. Two relays were wired in the controller cabinet to provide additional logic and a push button was used to place a call for a priority green extension or an early green. The second modification was a change in the controller's mode of coordination.

Specifically, the additional hardware provided the following functions. The first relay (TR1) places a call on phases 2 and 6, the coordinated through movements, when the push button is energized. This holds the coordinated phases (2 and 6) as long as the push button is held till a maximum limit. The second relay (TR2) forces ring 1 off if phase 2 is red and forces ring 2 off if phase 6 is red. In other words, if the push button is activated when the coordinated phases are red, then the cross-street phases will be terminated after the minimum cross-street green period elapses.

EPAC 300 signal controllers currently have four different types of modes of coordination. The city currently uses permissive mode of operation to operate this intersection. In order to obtain the priority for the coordinated phase, the mode of coordination was changed from permissive to permissive-yield. The permissive-yield mode allows the coordinated phase to be extended by monitoring the detectors on the coordinated phase approaches. In the presence of traffic on the coordinated phase detectors or an actuation by the push button, the coordinated phase will be extended, subject to a maximum green extension.

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Field Data Collection

Data were collected to estimate the stopped delay for buses and vehicles as a measure of evaluating traffic behavior before and after the implementation of the priority strategy. This effort was performed 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. In order to avoid any confusion, the stopped delay data collectors collected the data continuously for all the cycles and the cycles of interest were later selected from the data collected. In Case 3 and 5, the push button was energized (priority scheme activated) to provide different types of priority. 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. Figure 7 illustrates the approximate location and coverage areas of the video cameras and the approximate location of data collection personnel. Various information can also be collected from the traffic signal controller via a laptop computer. This information includes the status of each detector and the current signal phase every 1/10 of a second.

Buses do not operate along Texas Avenue. Therefore, a scheme was devised to activate the priority strategy by simulating the arrival of a bus. Manual activation of the priority strategy by a push button allows it to be activated as necessary to simulate the various cases being studied.

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 green 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 green extension, quick and successive extensions can cause the controller to go off-line and then correct itself. Thus, green extensions were obtained only once every 4 to 5 cycles.
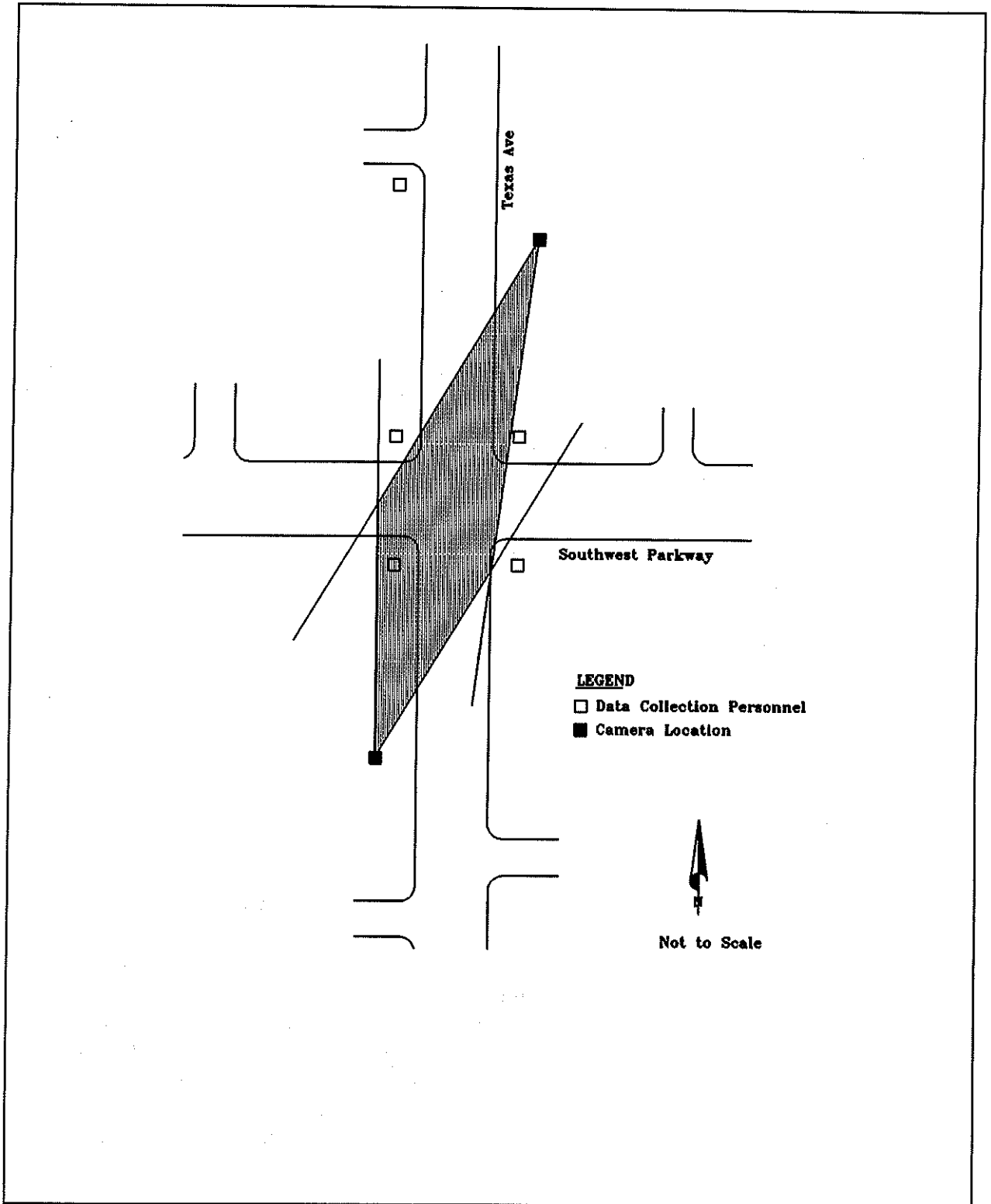
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Figure 7. Location of Cameras and Data Collection Personnel.

For Case 5 (maximum early green), 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 phase 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. The video cameras were filming the intersection for the entire duration of the study. Hence, volumes could be obtained from the video tape. The field data reduction is described in the next section.

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 and is discussed in the following paragraphs. The objective of reducing the field data was to obtain the volumes and green splits to input into the spreadsheet and to estimate the stopped delay in the field in seconds per vehicle.

Before starting the data collection, the clocks in the video cameras were synchronized with the clock in the controller. The clock time was displayed in the video tape while recording. The stopped delay data was collected based on the same clock time. The controller data being down loaded also has the time stamp on data collected every second. Hence, it was possible to accurately pinpoint a point in time in all the data collected.

Case 1. The data collected is being reduced in order to obtain 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.

First the cycle was defined. As there was a continuous demand for phases 3 and 7, the coordinated phases (phases 2 and 6) were terminating at a fixed point in the cycle. Hence, phases 3 and 7 were coming on every cycle at a fixed point in the cycle. It was decided to define a cycle from the onset of the phases 3 and 7 till the termination of the clearance interval for the subsequent coordinated phases (phases 2 and 6). This ensured that the cycle length was 115 seconds even though the duration of the individual phases was not uniform.

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Once the cycle was defined, the green splits for each cycle were identified in the controller data. Green splits were listed by cycle for every complete cycle and the average of each of the phase times was calculated. Average phase times were slightly adjusted to obtain a cycle length of 115 seconds to be input in the spreadsheet.

The time in the clock at which the defined cycle started was noted. Volumes were obtained from that time for a duration of 115 seconds (1 cycle length) from the video tapes. This was done for every cycle in the 30 minute study period. Thus, volumes for each phase per cycle were obtained. These volumes were then converted to vehicles per hour for each phase and input into the model.

Stopped delay data was reduced next. Stopped delay data too was reduced on a cycle by cycle basis. This was however a little more complicated. Stopped delay data was collected every 15 seconds from a point in time to a point in time (for example from 2:00 pm to 2:20 pm). Hence, stopped vehicles were counted at 2:00:00, 2:00:15, 2:00:30, 2:00:45, etc. in actual clock time. On the other hand, cycles were not usually starting at any of the points the stopped vehicles were being counted i.e., the start and the end of the cycle was partially overlapping over the 15 second intervals. In order to maintain the stopped delay data for 115 seconds, the duration of partial overlapping portions of the 15 second intervals were noted in each case and multiplied by the number of stopped vehicles in that interval. For the remaining intervals (completely overlapping), the number of stopped vehicles were multiplied by the interval duration (15 seconds). Hence, the number of stopped vehicles in vehicle seconds were obtained per cycle. Dividing the number of stopped vehicles for each cycle by the total volume for the same cycle gives the stopped delay in seconds per vehicle for each cycle. The average of these delays was then calculated. Thus, average stopped delay for the intersection was obtained.

Volumes and stopped delay data values were then calculated for each approach. Thus, the approach delay as observed in the field was calculated. Stopped delay values obtained from the model (which were by phase) were also converted to stopped delay per approach.

Case 3. In Case 3, the coordinated phases (2 and 6) were extended by 10 seconds. These 10 seconds are proportionately reduced only from the subsequent non-coordinated phases. The subsequent coordinated phase is of normal duration. The phases of interest are the subsequent non-coordinated phases and the extended coordinated phase. Hence, the defined cycle started at exactly 10 seconds before the termination of the extended coordinated phase (phase 2 and 6) and ended at the end of subsequent cycle (at the end of the subsequent phase 2 and 6). This ensured that the extended portion of the coordinated phase as well as the affected non-coordinated phases were included in the defined cycle. The defined cycle is illustrated in Figure 8.

Once the cycle was defined, the green splits, volumes as well as the stopped delay data was reduced as described earlier for Case 1.
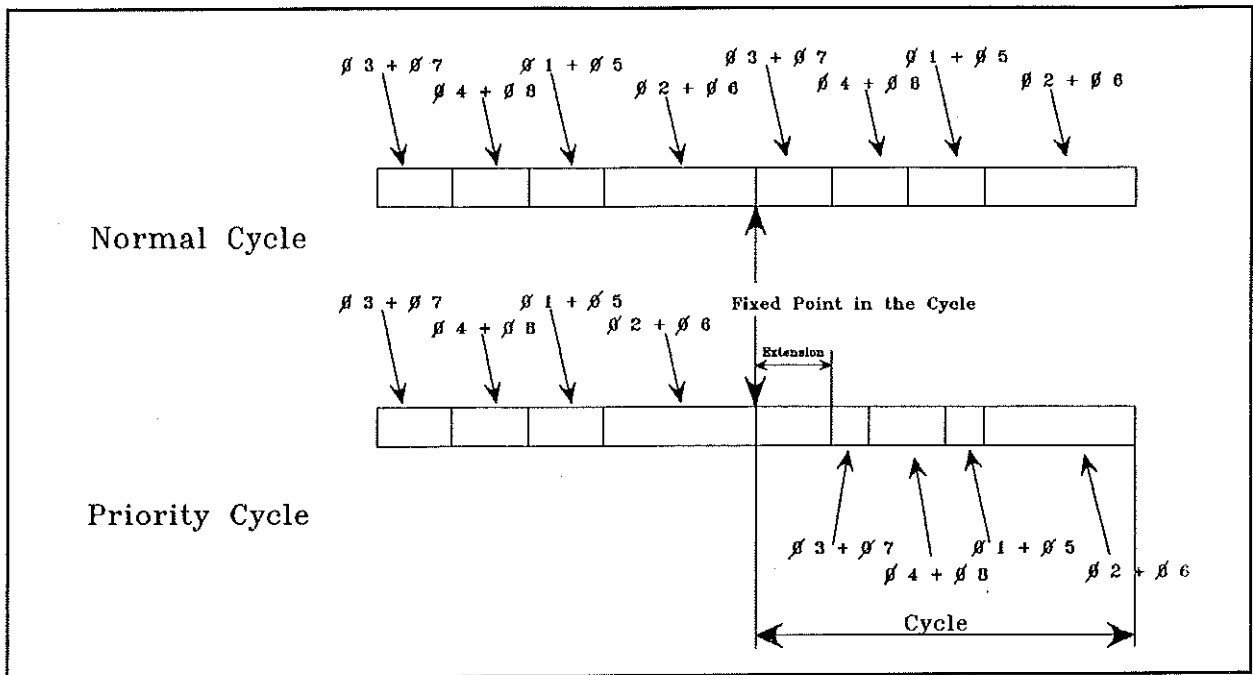
Figure 8. Cycle as Defined in Case 2.

Case 5. In Case 5, the non-coordinated phases were terminated (forced off) after providing a maximum split (specified earlier), if the phase was extending till that point. As mentioned earlier a maximum of 7 seconds was provided for phases 3 and 7, a maximum of 15 seconds was provided for phases 4 and 8, and a maximum of 5 seconds was provided for phases 1 and 5. Forcing off the non-priority phases allowed the early return of the coordinated phase. The cycle was defined as starting at the onset of the cross street (phases 3 and 7) till the end of the main street (phases 2 and 6). Thus, all the forced off phases as well as the coordinated phase (which returned early) were included in the defined cycle.

Once the cycle was defined, the green splits, volumes as well as the stopped delay data was reduced as described earlier for Case 1.

6. RESULTS

This section documents and discusses the results of the field data collected to determine the effect a conditional bus priority strategy has on intersection operation. In addition, the section contains the results of a spreadsheet model generated to estimate the impacts of the bus priority strategy on delay. 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 (Table 1). The following sections present the results of the data collection effort.

Table 1. Dates on which Field Data was Collected

Case	Date
Case 1 (No Priority)	April 27th, 1994
Case 3 (Maximum Extension)	April 13th, 1994
Case 5 (Maximum Early Start)	April 6th, 1994

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 in Section 5. The average volumes and splits were input into the spreadsheet model. Total intersection stopped delay values from the field and the model were computed and compared. Table 2 and Figure 9 illustrate the comparison of these two delays.

Table 2. Comparison of Field Delay with Model Delay for Total Intersection

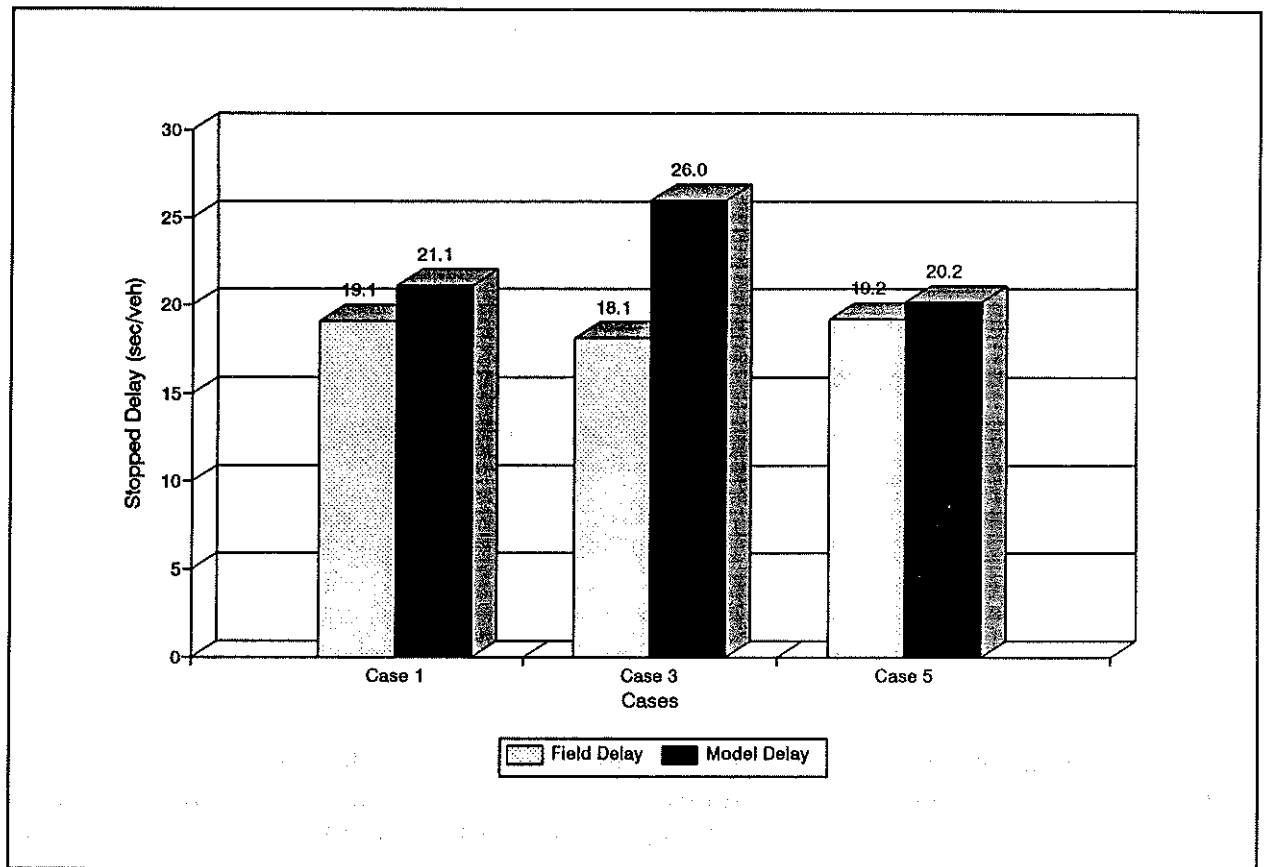| Case	Field Delay (sec/veh)	Model Delay (sec/veh)
Case 1	19.1	21.1
Case 3	18.1	26.0
Case 5	19.2	20.2

Figure 9. Comparison of Model Delay with Field Delay for Total Intersection.

The results indicate that the delay predicted by the model closely matches the delay observed in the field for Case 1 (no priority) and Case 5 (maximum early green). However for Case 3 (maximum green extension), there is a significant difference between the model delay and field delay.

In order to investigate the discrepancy in delay estimation, the data was further reduced. Stopped delay for each approach was obtained for all the three cases. The field delay and the delay predicted by the model per approach for the three cases were then compared. Table 3 illustrates the approach delay as observed in the field and as predicted by the model. The volume to capacity ratios for each of the approaches is also indicated.

Table 3. Comparison of Field Delay with Model Delay for Each Approach

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	39.4	41.8
	W. Bound	0.71	35.5	46.9
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
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

Data in Table 3 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).

A scatter plot was plotted (Figure 10) with delay observed in the field on the X-axis and delay predicted by the model on the Y-axis. A line with a slope of 1 was also plotted from the origin. The graph indicates that, while at low delay values, data points lie close to the line, at high delay values, the data points are further away from the line. 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.
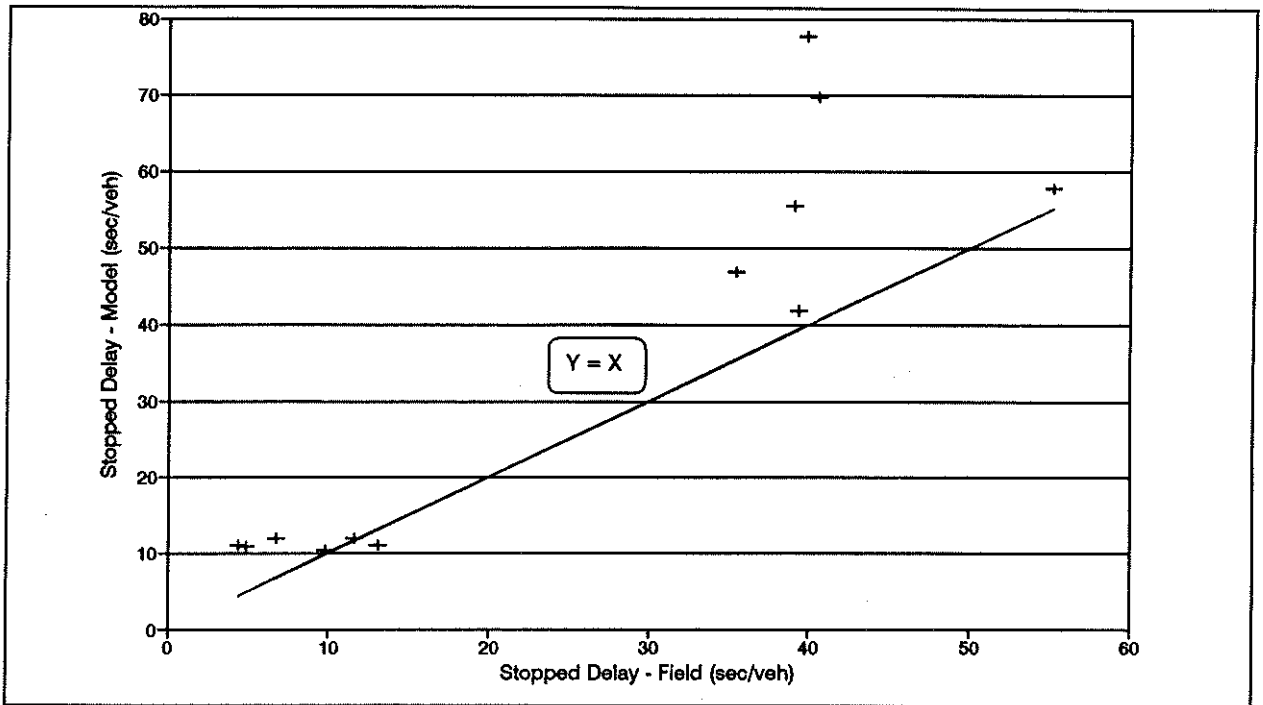
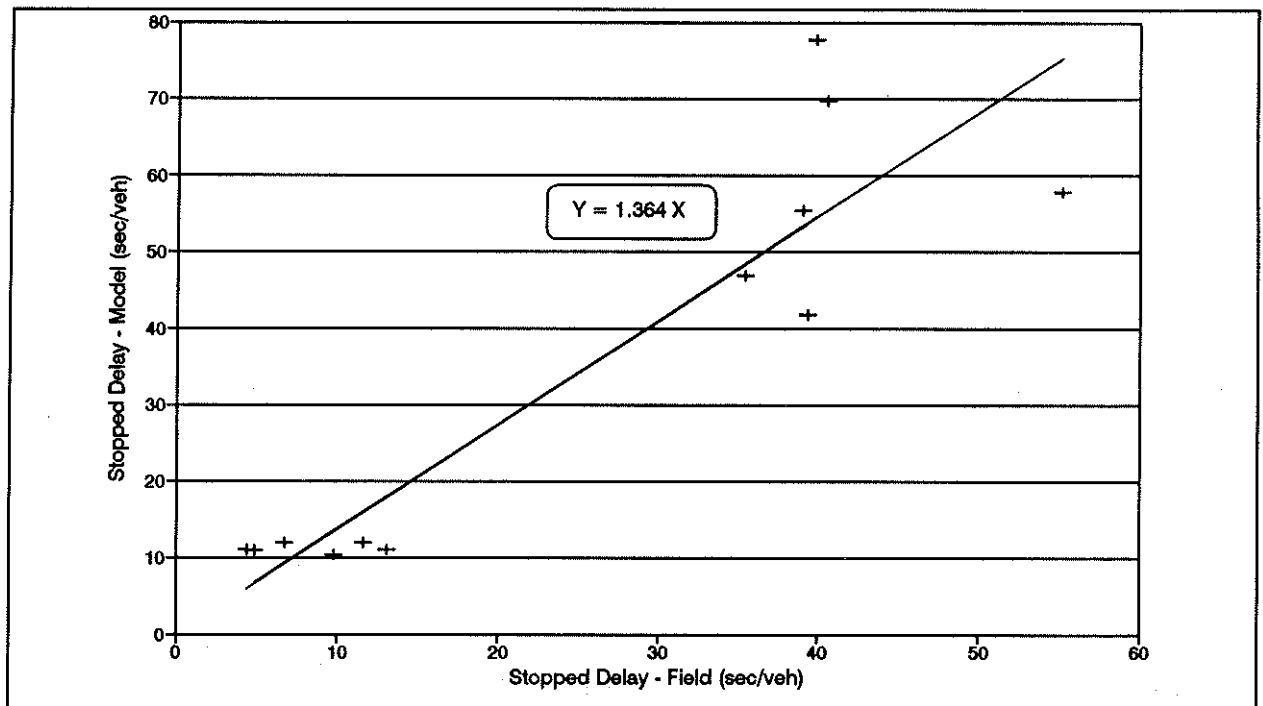Figure 10. Relationship of Field Delay with the Model Delay.

Figure 11. Regression Line to Estimate Delay.

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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:

$$R^2 \qquad = \qquad 0.824$$
$$\text{Intercept} \qquad = \qquad 0$$
$$\text{X-coefficient} \qquad = \qquad 1.364$$

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. A line was plotted with the obtained X-coefficient on the scatter plot (Figure 11). The equation used is shown below. The plot shows that the regression line passes close to most of the data points.

Model Delay = Field Delay * 1.364

Based on the regression analysis, it can be said that the delay predicted by the model is about 36% 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 3) and regression analysis was performed again. Following is the result of the revised analysis.

$$R^2 \qquad = \qquad 0.925$$
$$\text{Intercept} \qquad = \qquad 0$$
$$\text{X-coefficient} \qquad = \qquad 1.250$$

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 25%.

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 4 indicates the stop delay for each phase for all the three cases. The v/c ratios for each of the phases is also indicated.

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Table 4. 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	8.9
	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	48.4
	4	0.93	34.7	77.9

Table 4 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. A regression analysis performed on the data in Table 4 gave the following results.

$$R^2 \quad = \quad 0.398$$
$$\text{Intercept} \quad = \quad 0$$
$$\text{X-coefficient} \quad = \quad 1.273$$

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 4. A regression analysis performed on the remaining data gave the following results.

$$R^2 \quad = \quad 0.911$$
$$\text{Intercept} \quad = \quad 0$$
$$\text{X-coefficient} \quad = \quad 1.249$$

The results of the regression analysis indicates that while the model is overestimating delay for the through movements with low v/c ratios by about 25%, there is a strong linear relationship between the field delay and model delay. Figure 12 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.
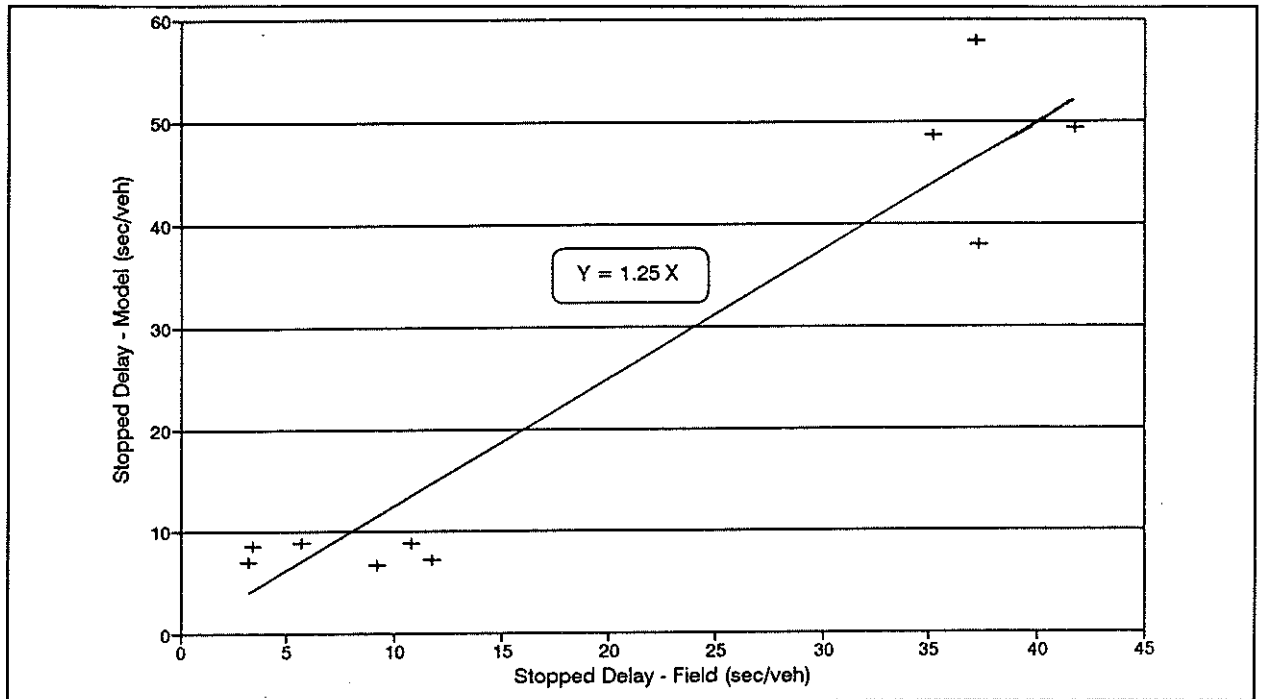
Figure 12. Relationship of Field Delay with the Model Delay (Revised Data).

ENERGY SAVINGS

A successful bus priority scheme will result in a reduction in travel time and an improvement in reliability of bus schedules. A reduction in travel time is dependant on the type of priority treatment as well as existing traffic conditions. For example, priority treatments like exclusive lanes show a significant reduction in travel times only at congested levels. When congestion is lacking, reductions in travel times are minimal. Signal priority treatments however demonstrate reductions in travel times independent of the congestion levels. Reduction in travel time has shown to significantly increase the number of trips arriving early or on time.

Improvement in the schedule reliability i.e., "arrival at the intended time" is shown to be one of the most important travel attribute by commuters. A reduction in the standard deviation of the headway from 6 minutes to 4 minutes and 2 minutes can result in an increase in patronage of 8 percent and 14 percent respectively (21). An improvement in the schedule reliability also reduces the passenger waiting time at the transit stops.

Reduced travel time and improved schedule reliability are the characteristics of a successful priority treatment. These attributes are perceived by the commuter as favorable characteristics of transit. A successful priority treatment results in a change in traffic volumes. There is a significant increase in person volumes. On the other hand, vehicle

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volumes show only a marginal increase if not a decrease. This indicates a diversion of commuters to high occupancy vehicles (HOV) which directly results in a reduction in vehicle miles of travel (VMT). The decrease in VMT results in savings of energy and reduction of pollutant emissions. Table 5 illustrates the energy savings and emissions reduction when a 25 percent reduction in bus headway was modeled.

Table 5. Areawide Change in Ridership, VMT, Fuel Consumption, and Emissions (20)

	Transit Rides	Auto VMT	Auto Fuel	Auto Emissions HC	CO	NOx
Denver	+21.0 %	-0.4 %	-0.4 %	-0.4 %	-0.4 %	-0.3 %
Fort Worth	+21.6 %	-0.3 %	-0.3 %	-0.4 %	-0.4 %	-0.3 %
San Francisco	+18.3 %	-2.0 %	-2.2 %	-2.3 %	-2.4 %	-1.9 %

As discussed above, it is clear that signal priority is a very useful tool to move more people. The priority has got the potential to decrease vehicle volumes and VMT. This can lead to a decrease in energy consumption and pollutant emissions. The model developed in the project is a simple tool to evaluate priority strategies and can encourage an increase in the implementation of low cost signal priorities.

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 adversely affect 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.

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