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Development and Evaluation of Transit Signal Priority Strategies

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16. Abstract

Research on the effectiveness of providing signal priority to transit vehicles is presented in this report. Results from previous studies indicate the effectiveness of transit signal priority depends on a number of factors, including the type of transit route, the level of transit usage, and the time of day priority is used. This research describes and evaluates several methods for providing transit signal priority during both peak and off-peak times.

Results indicate that providing signal priority during off-peak times is often justified, due to the excess capacity available within the transit network. However, during peak times, use of transit signal priority is only justified when the level of transit usage is high.

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DEVELOPMENT AND EVALUATION OF TRANSIT SIGNAL PRIORITY STRATEGIES

by

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Research Report SWUTC/97/472840-00068-1

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EXECUTIVE SUMMARY

Provision of arterial street signal timing favoring bus transit vehicle passage describes a family of techniques called transit signal priority strategies. These include passive priority concepts requiring no special signal hardware, as well as, active concepts requiring real time vehicle detection and signal controller modification.

This study evaluates a wide variety of bus transit signal priority concepts using an arterial street bus route where an active priority system is operational. In order to easily implement each priority condition and gather appropriate network level measures of effectiveness, the TRAFNETSIM micro-simulation model was used. The test corridor was authentically described within the simulation and test traffic conditions were modified according to an experiment design. Evaluation was based on system performance including effects upon transit users, as well as, auto users both on the arterial and cross streets.

Testing indicated priority systems produce overall positive effects if transit demand is high and cross street auto traffic demands are not approaching capacity. Within this corridor, these conditions existed during off-peak times. However, during peak hours, major cross streets were heavily congested and arterial priority signal timing produced incremental cross street delays that were greater than arterial transit plus auto delay savings. Obviously, conditions at which overall effects change from positive to negative depends upon arterial versus cross street auto demand, and importantly, upon transit patronage level.

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ABSTRACT

Research on the effectiveness of providing signal priority to transit vehicles is presented in this report. Results from previous studies indicate the effectiveness of transit signal priority depends on a number of factors, including the type of transit route, the level of transit usage, and the time of day priority is used. This research describes and evaluates several methods for providing transit signal priority during both peak and off-peak times.

Results indicate that providing signal priority during off-peak times is often justified, due to the excess capacity available within the transportation network. However, during peak times, use of transit signal priority is only justified when the level of transit usage is high.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1. INTRODUCTION

BACKGROUND

In recent years, rising population levels coupled with low density development outside center cities has created a large increase in demand placed upon transportation networks in many urban areas. Building additional infrastructure to meet these increasing demand levels is expensive, time consuming, and often encourages more travel. Therefore, in recent years, transportation professionals have shifted their efforts from building additional transportation infrastructure, to operating the existing infrastructure more efficiently.

Encouraging travel in high occupancy vehicles, such as public transit, is one way to meet growing levels of travel demand while building little or no additional transportation capacity. However, low public transit usage plagues many urban areas, especially urban areas with low density development. In low density urban areas, travelers do not share many common origins or destinations, making it hard for public transit to provide service levels competitive with the private automobile.

Therefore, policies providing priority to high occupancy vehicles have been initiated in many urban areas. The use of car-pooling, for instance, has been encouraged with high occupancy vehicle (HOV) lanes and van-pooling programs. Priority for public transit vehicles has also been initiated in many urban areas over the past 25 to 30 years. Traditionally, priority for transit vehicles has been provided through signal timing advantages at signalized intersections. However, methods for providing signal priority for transit vehicles which consider the well-being of the transportation network as a whole should be developed.

RESEARCH OBJECTIVES

This study will examine work which has previously been performed in the transit signal priority arena, and will also propose and evaluate methods of providing transit signal priority, during both peak and off-peak times.

Based on past transit signal priority studies, conditions favorable for transit signal priority success and strategies for its use will be identified. These strategies will be tested with both peak and off-peak traffic levels along a case study arterial network using computer simulation. Results from the computer simulation will be evaluated over the entire arterial network to determine whether the various transit signal priority strategies provide an overall arterial network benefit.

Once this evaluation has been conducted, recommendations for future transit signal priority use for both peak and off-peak times will be given.

STRUCTURE OF REPORT

A review of the literature on transit signal priority follows this chapter. This literature review will identify the nature of past research efforts, including algorithms for transit signal priority which have been proposed. In addition, results from field tests and simulations evaluating these algorithms will be discussed.

Chapter 3 describes the development of simulation models used in this study to evaluate various signal priority strategies. Data input into these models, as well as characteristics of the simulation software selected for the analysis, will be described.

Chapter 4 will describe and evaluate several signal priority strategies proposed for use during off-peak times. Strategies for use with both local and express transit service will be evaluated separately.

Chapter 5 will begin by describing and evaluating factors impacting peak period signal priority for local transit operations. These factors will then be taken into consideration while evaluating signal priority along the case study arterial network on a system-wide basis.

Finally, Chapter 6 will summarize study findings, and will also give recommendations for future research.

CHAPTER 2. LITERATURE REVIEW

INTRODUCTION

This literature review main objective is to determine whether giving transit vehicles signal priority has potential usefulness. To answer this question, the literature review is broken down into the following three parts: 1) the identification of past research performed on transit signal priority 2) the identification of algorithms developed for use with signal priority and 3) the identification of results of various field tests and simulations which evaluate the effectiveness of these algorithms.

PAST RESEARCH EFFORTS

Research on awarding signal priority to transit vehicles has been conducted world-wide over the past 20 to 30 years. A 1995 report by Sunkari [Ref 19] gives basic background on different types of signal priority available and subsequently describes the development and testing of a model which estimates delay resulting at approaches and movements within an intersection receiving different types of signal priority. This report was published through research conducted at the Texas Transportation Institute (TTI) at Texas A&M University. A related report published through TTI in 1977 [Ref 1] evaluates various techniques used to give priority to high occupancy vehicles along urban arterials.

Signal priority has been tested in various urban areas throughout the United States. Signal Priority for light rail transit (LRT) vehicles has been used in various California cities, including Sacramento, San Jose, Los Angeles/Long Beach and San Diego. The algorithms used in conjunction with the Los Angeles/Long Beach LRT line have been described by Fehon [Ref 4] while an algorithm which gives trolleys signal progression in downtown San Diego has been described by Celniker [Ref 8]. Further research on the use of signal progression for light rail vehicles in Baltimore has been performed by Kuah [Ref 9]. A report by Jacobson [Ref 11] written in 1993 indicates that signal priority using 3M's Opticom priority system has been in use along express bus routes in Charlotte, North Carolina since 1985. Additional research has been performed on use of the Opticom system in the Seattle area [Ref 14].

In addition, a great emphasis has been placed upon designing infrastructure with public transportation in mind in Canadian cities. Presently in Calgary, traffic signals at grade-level crossings outside of downtown are preempted by LRT vehicles, allowing for unimpeded movement through intersections between stations. Green time taken away from pedestrians and private vehicles is then restored once the LRT vehicle crosses the intersection. In downtown

Calgary, light rail is not given active signal priority (signal priority upon request). However, the signal settings along Calgary's downtown 7th Avenue transit mall have been designed to allow for LRT vehicle progression when traveling between stops [Ref 27].

Field testing to determine the effects of transit signal priority was conducted extensively in 1991 by the Municipality of Metropolitan Toronto [Ref 6]. This field testing was performed to determine the effectiveness of providing priority to streetcars traveling in mixed traffic along a selected corridor in Toronto. Extensive field measurements of the resulting delay on the arterial and its various cross streets resulted in an evaluation of the net present worth of the signal priority system along the selected corridor.

Priority systems for public transportation have also been used extensively abroad. Recently in Japan, collaboration by the Universal Traffic Management Society of Japan and the Hokkaido Prefectural Police Headquarters enabled field testing of a recently developed signal priority system for buses in Sapporo, Japan [Ref 29]. Efforts to skew modal split towards public transportation have been undertaken by providing significant priority to public transit in European cities such as Zurich and Stuttgart. While in other European cities such as Turin (Italy), the emphasis has been placed upon optimization of traffic signal settings by providing limited preferential treatment to transit vehicles [Ref 12].

In London, buses along a selected route have been given priority by metering private vehicles, in addition to providing signal priority to buses along their routes [Ref 26]. Also in London and in Southampton and other cities in the United Kingdom, bus priority has been incorporated into each city's urban traffic control system which controls signal timings [Ref 15, 18]. In addition, work on providing priority for buses in real time has been performed in London and other European cities such as Turin and Gothenburg (Sweden) [Ref 25].

Simulation has also been used extensively to model the effects of introducing various priority measures for transit vehicles. In 1995, two separate simulation models were used in conjunction with one another by Bauer [Ref 24] to simulate the effects of several LRT priority measures in downtown Chicago. In 1988, the TRANSYT simulation model was modified and used by Yagar [Ref 3] to determine the potential effectiveness of setting traffic signals to allow for streetcar progression along a major arterial in Toronto. In addition, extensive simulation using TRAF-Netsim was performed by Al-Sahili of Michigan State University in 1995 [Ref 23] to assess the impacts of introducing various bus priority strategies into a range of traffic conditions along a selected arterial in Ann Arbor, Michigan.

In the most recent research on signal priority, an emphasis has been placed on the use of adaptive signal control environments [Ref 7, 10, 22], as opposed to the use of pre-determined signal timing strategies. Real-time algorithms which monitor various intersection level of service measures are utilized within adaptive signal control environments. The initial results of research within this field has been presented by Yagar and Chang. Chang has also conducted further unpublished research on adaptive signal control measures using neural network traffic prediction models and automated vehicle location (AVL) systems.

ALGORITHMS USED WITH TRANSIT SIGNAL PRIORITY

A variety of signal priority algorithms are identified in a 1995 report by Sunkari of TTI [Ref 19]. These include passive priority algorithms, which use pre-timed signalization plans to benefit transit vehicles. With passive priority, signalization plans are not affected by the presence or absence of transit vehicles. Passive priority algorithms are attractive because little or no capital investment is required to implement most passive priority algorithms, only engineering design is needed. Passive priority algorithms include 1) adjustment of the cycle length, 2) splitting phases, 3) areawide timing plans, and 4) metering vehicles. These algorithms are explained in greater detail in a related 1977 report by Urbanik [Ref 1], also from TTI.

Urbanik notes that shortening the cycle lengths at intersections along transit routes aids in reducing transit vehicle delay. However, the merits of shortening cycle lengths to reduce delay must be weighed against the costs associated with the intersection's reduced capacity resulting from shorter cycle lengths.

Splitting phases refers to splitting priority phases into multiple phases and repeating these phases within one cycle. As shown in Figure 2.1, phase A (the phase which the transit vehicle uses) can be split into two separate phases whose total time equals phase A's original duration. The net result is a reduction in the phase A effective cycle length without changing the overall cycle length. Bus delay is reduced by such a timing plan, without seriously reducing the intersection capacity.

Areawide timing plans come in two forms. First, area-wide timing plans can be generated by allocating green time based on the number of passengers, rather than vehicles, which pass through the network's intersections. Vehicle occupancies, or a proxy for these occupancies, must be known to allow passenger delay to be minimized. A network of intersection timings can be established which minimizes delay per passenger with the aid of computer programs, such as SIGOP and TRANSYT.

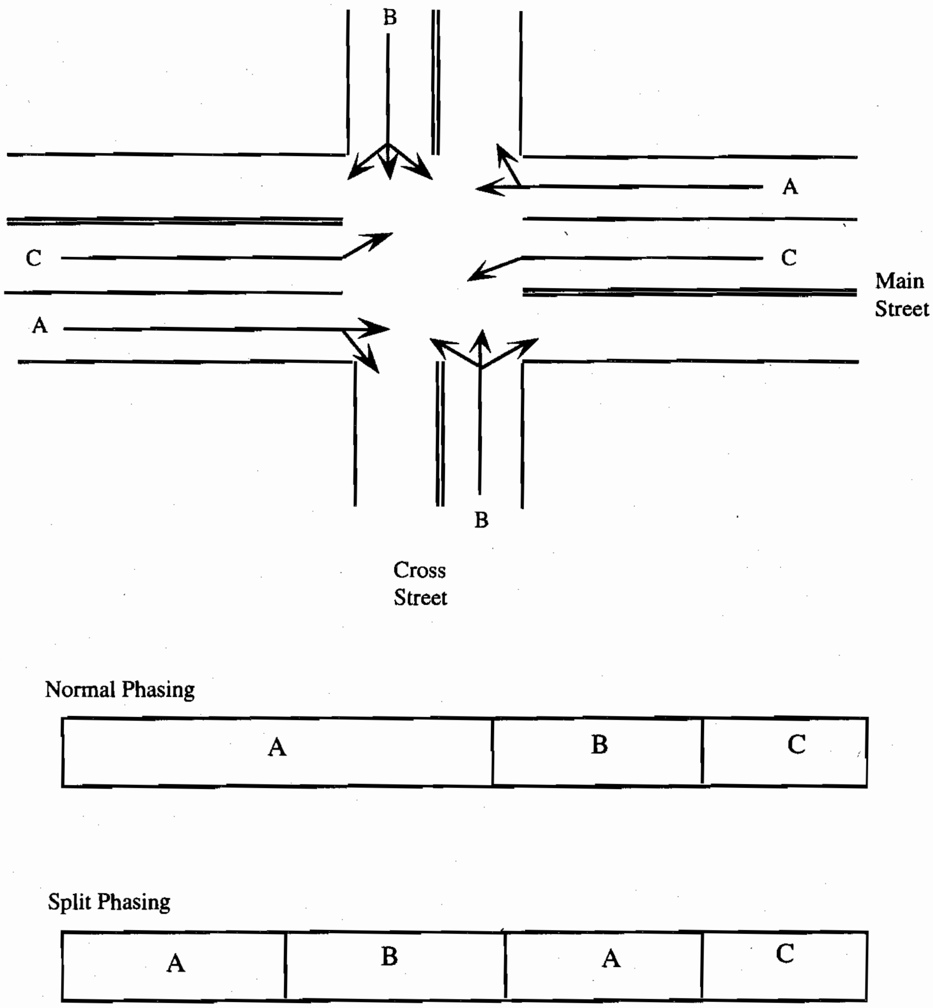


Figure 2.1 Illustration of split phasing [Ref 1]

Areawide timing plans can also be designed to give priority to transit vehicles by coordinating intersection signal plans to allow for transit vehicle progression through the network. This technique is simplified when working within a grid of one-way streets, as progression is then only needed in one direction. Also, because transit vehicles must frequently stop to allow passengers to board and deboard, the effectiveness of this technique is highly dependent on the ability to forecast the bus travel times between the network intersections. As a result, Urbanik notes that areawide timing plans providing progression to transit vehicles are best suited for use along express transit routes, because these routes are less prone to variability in their travel time between intersections.

The last passive priority measure explained by Urbanik is metering. The flow of vehicles into a designated link in the road network can be restricted by metering a signal phase (analogous to freeway metering). Priority can be given to transit vehicles to bypass the metered signal phase in a number of ways. For instance, a lane which bypasses the metered signal can be reserved for transit vehicles, or transit vehicles may be given their own lane and signal phases at the metered signal.

Urbanik notes that active priority algorithms are different than passive priority algorithms in that active priority measures are only taken in response to a transit vehicle signal priority request. Active priority algorithms include 1) phase extension (green extension), 2) early start of a phase (red truncation), 3) introduction of a special phase (red interruption), 4) phase suppression, and 5) green truncation. Since interaction between the transit vehicle and the signal controller is necessary for active priority measures to work, a communication link between the two is needed to support active priority. As a result, an initial capital investment, followed by periodic maintenance costs, are required to operate active priority algorithms.

With green extensions, additional green time is allocated to the end of the transit vehicle's normal green phase to allow it to pass through the intersection without stopping. Similarly, additional green time is allocated to the beginning of the transit vehicle's green phase with red truncations. With red interruption, a short green phase on the transit vehicle's approach is inserted into its normal red phase while conflicting approaches are forced to stop. With the use of phase suppression, a low-volume non-priority phase is eliminated from the intersection's cycle.

Urbanik notes that if a transit vehicle is detected far from the intersection, truncating the transit vehicle's green as it is detected will increase the likelihood that the transit vehicle will receive a green during the next cycle as it arrives at the intersection. In addition, delay to the cross street may be reduced through green truncation. With green truncation, the additional green given to the transit vehicle is truncated once the transit vehicle passes through the intersection.

Active priority measures can be grouped into two categories: 1) unconditional priority and 2) conditional priority. With unconditional priority (or preemption), a priority measure is granted whenever the transit vehicle calls for priority, subject to safety considerations (minimum clearance intervals must be observed). When using conditional priority, the transit vehicle is not necessarily given priority at the intersection every time it is requested. Several criteria, such as the time since priority was last given at the intersection, the number of queued cross street vehicles, or constraints due to the road network's areawide timing, must be considered before priority is granted to the transit vehicle. Conditional priority is used more often at locations within a network of closely spaced traffic signals, because intersections do not perform independently in this environment. Therefore, the benefit to the network as a whole must be considered before priority is granted to a transit vehicle at a single intersection.

Urbanik notes that computer simulation of unconditional priority over a range of bus headways, and bus stop locations (near-side and far-side) was performed by the Mitre Corporation. Results from the simulation indicate that buses, as well as non-bus vehicles, receiving unconditional priority benefit substantially from the unconditional priority regardless of the bus headway or the bus stop locations. However, cross street traffic was adversely impacted by the use of unconditional priority, especially when short headways and near side bus stop locations were simulated.

The simulation model TRANSYT was modified and subsequently used by Yagar [Ref 3] in 1988 to determine the potential effectiveness of setting signals to minimize streetcar delay along a major arterial in Toronto.

Both private vehicles and transit vehicles can be modeled with the use of TRANSYT. However, the interaction between transit vehicles and private vehicles is modeled somewhat unrealistically. According to TRANSYT, when a transit vehicle stops for boarding and deboarding purposes, the private vehicles are unimpeded by the stopped transit vehicle. Although this assumption is realistic when a transit vehicle enjoys its own fixed guideway, it breaks down when private vehicles and transit vehicles operate in a mixed environment.

The operational environment which Yagar analyzed was the Queen Street arterial in downtown Toronto, where streetcars and private vehicles operate on the same guideway. Private vehicles traveling along Queen Street are forced to stop behind a streetcar which is stopped prior to the intersection for boarding and deboarding (near-side transit stops are primarily used). The TRANSYT model was modified by Yagar from its original form, which models intersections as nodes and street sections as links. Additional dummy links were introduced in the modified TRANSYT network. The effect of delay felt by private vehicles stopped behind a streetcar is modeled through these additional dummy links, giving TRANSYT the capability to more properly model traffic flow along Queen Street.

The improved TRANSYT simulation model was then used by Yagar to address the feasibility of setting intersection timings along Queen Street to accommodate streetcars. Since fixed signal settings operate most effectively in environments where streetcar arrival times are known with certainty, streetcar dwell times were assumed to be fixed and known for purposes of the analysis. Therefore, the "best case scenario" of setting signal timings to accommodate streetcars was analyzed. Two scenarios were modeled within the analysis, one in which streetcars were given a weight equivalent to 5 private vehicles in the modified TRANSYT model and one where streetcars were given a weight equivalent to 100 private vehicles. The effect of setting traffic signals to give passive priority to streetcars is modeled in the latter scenario, while the "no priority" condition is modeled with the former scenario.

Streetcar delays were shown to decrease by about 25 percent with the introduction of passive priority compared to the base case, while private vehicle delays did not change substantially from the base case to the passive priority case. Although these results seem promising, the stochastic nature of the boarding and deboarding times were ignored by the analysis.

To account for this simplification, Yagar hypothesized that a policy of fixed boarding and deboarding times may enhance overall transit operations. In other words, the frustration felt by some transit users because of the inability to board a transit vehicle might be more than compensated by the improved schedule adherence and potentially lower costs of the new transit service. After discussions with transit officials, Yagar abandoned this hypothesis. However, Yagar states that if the assumption of fixed dwell times is lifted, a fraction of the benefits realized in the previous analysis would be achieved. Therefore if the stochastic nature of the transit vehicle dwell times can be incorporated into the model, marginal benefits might be realized by simply resetting the signal timings along an arterial.

A 1990 report by Fehon [Ref 4] describes development of two algorithms which are proposed for use with the LRT system linking Los Angeles with Long Beach (LB/LA). Due to the vast number of at grade intersections which cross the LB/LA line, complex active signal priority algorithms were needed to minimize delays to cross-street traffic while providing priority to the LRT vehicles.

The need for active signal priority was identified due to the nature of the corridor along which the LB/LA line runs. A passive signal priority algorithm, such as a coordinated signal timing plan which matched the expected LRT vehicle trajectory, was considered infeasible for several reasons. Typically, this type of passive priority is expected to prosper when used with transit lines having little variability in their dwell times and when signals in the area are coordinated only along the transit line. Because many coordinated signal timing routes crossed the LB/LA line, and its dwell times were expected to be highly variable, the need for active signal priority was identified.

In response to this need, two algorithms were developed. These two algorithms were made possible through the use of an integrated signal system comprised of the following five components: 1) LRT detectors 2) travel time predictors 3) signal and sign controllers 4) central master computers and 5) the LRT System Control and Data Acquisition Center (SCADA).

The first algorithm is called partial priority. The partial priority algorithm lengthens compatible (or shortens non-compatible) signal phases giving LRT vehicles greater likelihood of traversing intersections without stopping. Once detected by the LRT detectors, the LRT's expected arrival time at the intersection is estimated and compared with the signal it is expected to receive at arrival time. If a compatible phase is expected for the LRT vehicle, then no additional action need be taken by the partial priority algorithm. If, however, a non-compatible phase is expected for the LRT vehicle, the compatible phase will be lengthened or intermediate non-compatible phases will be shortened by pre-determined amounts as specified in the algorithm's current parameters. Each phase's maximum allowable lengthening or shortening is specified by the user prior to system use.

The second algorithm is called full priority. Signal phases are not only lengthened or shortened with the full priority algorithm, in some instances phases are skipped or presented in a different sequence allowing an even higher level of LRT priority. Partial priority is first attempted by the full priority algorithm. If movement of the LRT vehicle through the intersection is found to be impossible with partial priority alone, then additional measures are taken by the full priority algorithm. Non-compatible phases (including the pedestrian phase) which cannot be terminated prior to LRT vehicle arrival at the intersection will be shortened or omitted by the full priority algorithm.

The parameters which can be specified by the user of the full priority algorithm include selection of pedestrian and normal phases that can be skipped, the minimum green time to be used when inserting a phase, the method of signal recovery, and the hours of operation.

The logic necessary to deal with the stochastic nature of random bus arrivals at selected intersections is addressed in a 1991 report by Khasnabis [Ref 5]. It is noted that, in general, buses cannot be platooned through intersections with normal traffic because of the random nature of boarding and deboarding times at various intersections. Express bus service is less subject to large variations in the time needed for boarding and deboarding, but this stochastic component exists nonetheless. Therefore, the components of a successful transit priority system were identified as 1) buses equipped with transmitters to allow for their identification and/or loop detectors within the pavement and 2) a real-time control system which estimates the arrival times of buses at intersections and determines whether signal priority will be granted. Two questions should be answered by the real-time control system. First, is the approaching bus in need of signal priority (typically a green extension, red truncation, or red interruption)? Secondly, will the bus be able to make use of this priority if it is indeed granted? Since upper bounds typically are set for the green extension, red truncation, or red interruption available, not all buses will be able to utilize the signal priority which is awarded to them. Only if the bus arrival time satisfies the two constraints mentioned previously, should priority be granted.

Khasnabis notes that use of near-side bus stops limits the effectiveness of this type of algorithm. The prediction of bus arrival times at intersections is complicated by the presence of a near-side bus stop. Finally, Khasnabis notes that intersections are treated independently within this type of real-time algorithm. However, since intersections do not function independently within most urban operating environments, an algorithm which operates at the network level may be helpful in minimizing overall network delay.

These issues are dealt with in greater detail in a 1992 report by Yagar [Ref 7]. A computer program entitled SPPORT (Signal Priority Procedure for Optimization in Real Time) is presented by Yagar which attempts to minimize the overall cost (or delay) to all bus and private vehicle passengers at an intersection. The SPPORT model uses detectors located about 150 and 1000 meters upstream from an intersection to determine the presence or absence of both streetcars and private vehicles. Information on the current queue lengths and the future arrivals of vehicles is provided by these detectors. Given this information the SPPORT model generates a short term (5 second) plan which minimizes total intersection delay. This plan is then re-evaluated after a 5 second duration and a new plan is implemented. This process is repeated continuously. The listing of possible new plans from which the model can choose is not all-inclusive. Only feasible plans based on the traffic conditions present when the intersection was last evaluated are considered, and these plans can be prioritized in order to meet a certain objective. Priority for transit vehicles can be embedded into the SPPORT model by giving high priority to timing plans conducive to transit operations.

The SPPORT model was tested through simulation to determine its effectiveness compared to a normal fixed timing plan. The intersection which was simulated was the Queen and Bathurst Street intersection in Toronto. At this intersection, streetcars are operated alongside normal traffic. Typical streetcar and private vehicle volumes were used to model the intersection under 3 sets of timing plans: 1) fixed timing plan, 2) SPPORT generated timing plan (no priority given to streetcars), and 3) SPPORT generated timing plan (priority given to streetcars). The simulation results indicate the delay per person was reduced by about 50 percent with the SPPORT model which gives priority to transit vehicles. This same strategy also reduced the delay per vehicle for both private vehicles and streetcars by roughly 50 percent.

Finally, Yagar notes that the SPPORT model helps effectively deal with the stochastic nature of boarding and deboarding operations at transit stops. The streetcars seem to be guided to the intersection by the SPPORT real-time signal control. Then, when the streetcar began to board and deboard, the competing phases were called and the SPPORT model returned the green to the streetcar when boarding and deboarding was expected to be complete.

The SPPORT model currently is designed to minimize overall cost at an individual intersection. However, the development of a model which integrates intersections within a network for real-time signal coordination is planned for the future.

The use of passive priority to provide signal progression for trolleys in downtown San Diego is described in a 1992 report by Celniker [Ref 8]. Originally, in 1981, trolleys in downtown San Diego were given signal preemption, an active priority measure, to reduce delays when traveling through downtown San Diego. However, Celniker notes that preemption initially worked well because the service frequency of the trolleys was not too high (maximum of 8 trolleys per hour). As the service grew, however, headways were shortened and, by 1992, a maximum of 27 trains per hour could cross a given intersection. Because signal preemption could only be awarded to a trolley traveling in one direction at a time, delays were encountered by many trolleys as they competed with each other for preemption at intersections. In addition, pedestrians and cross street traffic were often forced to endure lengthy delays due to the increased number of intersection preemption requests.

This problem was solved by abandoning active signal priority in favor of an areawide timing plan designed to give signal progression to trolleys as they traveled between transit stops. This timing plan was built into the overall San Diego network of signal timings and is continuously in effect. In addition, the timing plan changes automatically throughout the day to accommodate differences in travel patterns occurring during peak and off-peak hours. As part of the passive priority plan, trolley drivers are instructed to wait until a fresh green appears after boarding and deboarding operations are completed at a transit stop. As long as the trolley departs to the next transit stop within the first 5 seconds of green time, the trolley is ensured signal progression to the next transit stop.

Travel time savings of roughly 2 to 3 minutes through the 4.8 km corridor in downtown San Diego have been achieved through the use of passive signal priority as opposed to active signal priority. However, the passive priority methodology is not without its drawbacks. If trolley departure is impossible within the first 5 seconds of green time, the trolley is forced to wait until the beginning of the next green phase. However, consideration is being given to shortening the cycle lengths at intersections along the trolley's path through downtown to reduce the impacts of this problem.

Areawide timing which provides signal progression to LRT vehicles operating in downtown Baltimore was investigated in a 1992 report by Kuah [Ref 9]. In 1988, the feasibility of providing signal progression to the Central Light Rail Line (CLRL) running through about 2.4 km of downtown Baltimore along Howard Street was examined. The benefits of enhanced transit service provided through signal progression were weighed against potentially negative impacts which may occur to cross street traffic which had previously enjoyed signal progression.

To make this assessment, data on the base year (1988) signal timings, turning movement counts, intersection geometries and traffic signal control types were collected for intersections within the study area. An assessment of the degree to which progression was utilized at the various cross streets and along Howard Street was then made. Using assumptions regarding the proposed operational characteristics of the CLRL, the predicted CLRL trajectory along Howard Street was superimposed upon the existing time-space diagram of Howard Street obtained from measurements of base year signal timings. The assumptions which were made to obtain the CLRL trajectory included constant station dwell times of 30 seconds, headways of 7.5 minutes in each direction along Howard Street, cruise speeds of 40 to 48 km/hr along straight track sections, cruise speeds of 24 to 32 km/hr along curved track sections, and acceleration and deceleration rates of 0.84 and 0.76 m/s^2, respectively.

The existing time-space diagram for Howard Street was then manually altered to give progression to the CLRL running along Howard Street within the study area. A 30 second bandwidth was decided upon for the CLRL line based on expected travel time variability for the CLRL line, and the expected light rail train lengths and intersection crossing speeds. The negative impacts to the cross streets were considered while adjustments to the Howard Street time-space diagram were made. Cross streets which were shown to have good or excellent progression based on the base year timing plan were given high priority to maintain their progression. The existing bandwidths for these cross streets were maintained by manually adjusting their new (they had been altered from the introduction of progression for the CLRL) time-space diagrams.

The study area was simulated using TRANSYT-7F under two scenarios; with and without the CLRL for the study year of 1992. The simulation results were mixed. Bandwidths at some cross streets remained unchanged after adjustments were made to their time-space diagrams while other bandwidths were reduced in order to provide CLRL progression.

Intersection levels of service were also examined through TRANSYT-7F simulations of the two scenarios mentioned previously. In general, little or no degradations in level of service were encountered with the introduction of the CLRL. However, the level of service was predicted by simulation to decline from B to F at one intersection (Centre Street and Howard Street).

Finally, the overall effects which the CLRL introduced into the network were identified through the TRANSYT-7F simulations. Several measures of effectiveness (MOEs) were identified to help assess CLRL impacts and its revised signal timing upon present conditions. Among the MOEs found, individual vehicle delay was predicted to increase by 2.3 seconds (14 percent increase) while average operating speeds of vehicles in the study area were predicted to decrease by 1.3 km/hr (7 percent decrease) with the introduction of the CLRL. In general, introducing the CLRL into the study area resulted in moderate impacts to present traffic conditions.

The advantages of using advanced traffic control systems, as opposed to fixed timed traffic control systems, in conjunction with signal priority for transit are addressed in a 1992 report by Daniel [Ref 10]. The advanced traffic control systems which were addressed within the report include the Automated Traffic Surveillance and Control System (ATSAC) which has been used in Los Angeles, the Sydney Coordinated Adaptive Traffic System (SCATS) used in Australia, and the Split Cycle Offset Optimization Technique (SCOOT) developed in the United Kingdom.

Priority is assigned to public transit vehicles by these advanced traffic control systems with the realization that cross street traffic may be adversely affected by favoring the public transit vehicles. As a result, a parameter which reflects the present status of the intersection is measured at regular intervals within each of the 3 systems to determine the consequences of providing public transit vehicle priority. Traffic volumes and occupancies determined through loop detectors are monitored by the ATSAC system in determining the optimum cycle lengths, phase splits, and offsets to be used. While the degree of saturation is used in a similar manner by both SCAT and SCOOT, respectively.

If the need for priority is indicated by the respective parameters of ATSAC and SCAT, priority is granted in the form of either a green extension or a red truncation. On the other hand, priority is granted through the SCOOT system using passive priority, favoring the green time of approaches serving transit vehicles. However, the needs of cross street traffic are recognized because the degree of saturation is not allowed to climb above pre-specified limits along all approaches.

The benefits gained by using advanced traffic control systems, such as ATSAC, SCAT, and SCOOT include a more flexible and adaptive form of signal control as opposed to fixed signal timings. In addition, the needs of cross street traffic are recognized by these traffic control systems when granting priority to public transit vehicles.

Two strategies for rewarding active signal priority to buses which have been tested in studies in the Seattle area are identified in a 1993 report by Jacobson [Ref 11]. With the first methodology, entitled the HOV-Weighted OPAC strategy, the flow of people or vehicles through an intersection is maximized through the use of a dynamic programming algorithm. Traditional signal timing constraints such as cycle lengths, signal splits, and offsets, are ignored by the dynamic programming algorithm in its attempt to minimize delay encountered by people or vehicles. In initial studies, the OPAC strategy has been shown to outperform conventional signal timing methods. The OPAC strategy, however, is relatively new and has been tested to only a limited degree. However, Jacobson notes that further research is warranted by its potential effectiveness.

The second methodology identified by Jacobson is called the "lift" strategy. In the "lift" strategy, loop detectors placed at a given distance from a traffic signal identify the presence of buses and send a corresponding signal to the traffic controller downstream. Upon receiving an indication from the loop detector, the traffic signal is programmed to respond as if all traffic on approaches non-concurrent with the bus' phase does not exist (or is "lifted") for a given amount of time. Placement of bus detectors at an intersection and the amount of time traffic is "lifted" are the algorithm control parameters. These control parameters can be adjusted depending on the intersection geometry, time of day, traffic volumes, or other site-specific conditions. Jacobson notes, however, that the "lift" strategy should not be used in an environment of closely spaced intersections operating at, or near, capacity. In these situations, Jacobson notes that attempts should be made to provide signal progression for buses and private vehicles.

The effectiveness of the "lift" strategy was simulated under several types of environments using TRAF-Netsim. First, the "lift" strategy was applied to an isolated intersection in the Seattle area. Traffic volumes representative of existing traffic conditions were input into TRAF-Netsim. Results of the simulation show a 33 percent decrease in bus delay with the use of the "lift" strategy. In addition, the resulting impacts to private vehicles were not found to be statistically significant. However, when the "lift" strategy was simulated at 3 adjacent intersections consecutively, only marginal benefits to buses were realized while the negative impacts to private vehicles increased.

The approaches taken to provide priority to public transit vehicles in several European cities are identified in a 1993 report by Nelson [Ref 12]. In Turin, Italy the UTOPIA (Urban Traffic Optimisation by Integrated Automation) traffic control system has been used to monitor the position, occupancies, and potential defects of its public transit vehicles in real time (vehicle information is updated every 10 to 15 seconds). This information is used by Turin's urban traffic control system to provide priority to public transit vehicles by weighting transit approaches more heavily when determining signal splits on a real-time basis. The UTOPIA system is operated at the network level. Therefore, Turin's urban transportation network has been divided into overlapping zones. The interactions among the various zones are taken into account by the UTOPIA system when determining the optimum signalization strategy. The selected strategy is implemented for 3 seconds, followed by implementation of a new strategy which takes information on the updated network into account. In its trial run during the years of 1985 and 1986, a 19 percent increase in speed over all vehicle types was realized through UTOPIA system use.

In Wil, priority is granted to transit vehicles through the use of advanced information technologies. This technology consists of three main components: 1) an on-vehicle computer, 2) a passenger information system, and 3) an infrared information system. Information regarding schedule adherence, transit vehicle destination, and transit vehicle occupancies are maintained and communicated to a central controller within the on-vehicle computer, while the presence of a transit vehicle near an intersection is communicated to the signal controller through the infrared information system. Three messages are communicated between the signal controller and the transit vehicle through the infrared information system. These messages include a "get ready" message which warns the signal controller of an approaching transit vehicle, a "change lights" message which is sent when the transit vehicle nears the intersection, and a "cancel" message sent after the transit vehicle passes through the intersection.

In Zurich, the traffic control system is operated in an attempt to provide priority to public transit vehicles to maximize the overall safety of Zurich's transportation network. This is accomplished through the use of a computer-controlled traffic system which obtains information on vehicle locations through inductive loop detectors. At most intersections, public transit vehicles are given absolute priority over general traffic. A 2 second window of green is provided to the transit vehicle by the absolute priority algorithm upon arrival at an intersection. If the transit vehicle misses its opportunity to cross the intersection during the 2 seconds, the absolute priority algorithm terminates and regular traffic control is returned. When near-side transit stops are encountered, the absolute priority call occurs at the end of transit vehicle's dwell time, allowing the transit vehicle to cross the intersection when boarding and deboarding operations have finished.

Finally, Nelson notes that in Stuttgart, a policy has been developed to encourage the use of public transit by using three priority levels within their light rail system. In the first level (limited preferential treatment), green extensions are provided to LRT vehicles only when necessary. This technique has been shown to reduce LRT delay by 50 percent, with little negative impact on private vehicles. In the second level, full preferential treatment, LRT vehicles are given priority in most circumstances upon arrival at an intersection. However, the green extension awarded to the LRT vehicle is constrained by an upper bound. Within the final level, absolute preferential treatment, complete priority is given to LRT vehicles at all intersections, with no upper bound on the green extension awarded to the transit vehicle. The detection of LRT vehicles is accomplished primarily through inductive loops, supplemented by an infrared information system. Currently, limited preferential treatment is awarded to LRT vehicles. However, in the future, public transit use might be further encouraged by implementing either full or absolute preferential treatment for LRT vehicles.

A 1993 report by Duncan [Ref 13] describes the use of the green extension and red truncation methods for transit buses in Maryland. The Opticom priority detection system from 3M is used in conjunction with ASC/2-2100 signal controllers to detect a bus call for priority and allot added green time for the bus travel direction. This added green may come in the form of an advanced green solely for the transit bus (the "queue jump" technique) or may come in the form of a green phase extension, giving the transit bus a better chance of progressing through the intersection without stopping.

If a transit bus is detected while the signal controller along the bus travel path is red, an advanced green phase solely for the bus is inserted before the coordinated green phase begins. Alternatively, if a transit bus is detected while the signal controller along the bus travel path is green, the ASC/2-2100 signal controller communicates with the transit bus to ensure that only the minimum amount of additional green needed by the transit bus to traverse the intersection is used. As a result, green time may be extended by the transit bus up to the pre-specified maximum extension limit. If the transit bus is traveling within a platoon of vehicles, only a short extension (if any) will likely be required. If, however, the transit bus has been left behind by its platoon, a longer extension will be needed. The main advantage noted by Duncan with using the green extension or red truncation methods is the absence of signal preemption (instantaneously switching one phase to the next at the request of a transit vehicle). Therefore, signal coordination can be more readily maintained within the street network while giving priority to transit vehicles.

The inclusion of active bus priority within the SCOOT traffic control systems of London and Southampton are described in a 1994 report by Bowen [Ref 15]. Priority is granted to buses in London and Southampton by programming the bus priority algorithms into the SCOOT software, and implementing these algorithms upon bus detection. Bus detection may be accomplished in several ways. In London, buses are detected through selective vehicle detection (SVD). With SVD, buses equipped with transponder units are detected as they pass over inductive loops embedded in the pavement at selected locations. The position of these inductive loops must be downstream from a bus stop, yet upstream from an intersection as SCOOT does not attempt to predict the bus dwell time at a stop in order to predict its intersection arrival time. In

Southampton, buses are detected through automatic vehicle location (AVL). With AVL, buses are fitted with equipment which enables the central computer to determine the bus location at regular (20 seconds in Southampton) time intervals.

Upon bus detection, signal priority may be awarded to buses by SCOOT through either green extensions or red truncations. SCOOT determines whether priority will be granted to buses by evaluating the present traffic conditions and selecting the optimum implementation strategy. When buses are furnished with a green extension or a red truncation, the local traffic signal is temporarily removed from control of the centrally located urban traffic control system (UTC). This eliminates the threat of a false alarm the UTC may have furnished as it runs a system check and encounters the green extension or red truncation.

Several important parameters must be established before the SCOOT system can effectively grant priority to transit vehicles. The degree of intersection saturation below which priority may be granted is a highly important parameter when determining whether signal priority is feasible. If this cutoff value is set too high, the usefulness of green extensions or red truncations will be lost when used in heavily congested environments. In addition, the intersection level of service may be further sacrificed through the excessive use of signal priority. If this cutoff value is set too low, then buses which could have benefited from signal priority will not be granted a green extension or a red truncation. Bowen reports that this cutoff level of saturation will be found through simulation and tested in the field in the future.

Green extension and red truncation lengths are also highly important variables. According to Bowen, the amount of priority should vary from intersection to intersection based on the amount of spare capacity at the intersection.

Finally, it is noted that red truncations are more disruptive to normal traffic operations than green extensions, as signals are switched between approaches with red truncations. This will also be considered when determining the optimum strategy to implement upon bus detection. Simulation will be used to evaluate some of the variables mentioned above, such as the cutoff degree of saturation. Once proper values of some of the system variables have been found through simulation, field testing was proposed in London and Southampton for 1994.

The use of priority for LRT vehicles in Sheffield, England is explained in a 1994 report by Saffer [Ref 16]. In Sheffield, LRT vehicles are forced to share their guideway with normal traffic. As a result, priority is granted to LRT vehicles through a transponder-detector loop system. Four loops are used to determine when and if priority should be granted to an LRT vehicle. The four loops are designated as prepare, demand, stopline, and exit loops, respectively. By triggering each loop successively, the LRT vehicle is granted signal priority while delays to cross street traffic are maintained at reasonable levels.

In a 1995 report, Machemehl [Ref 20] identified and examined a number of methodologies for determining the additional green times which should be allocated to transit vehicles receiving signal priority at an intersection through either green extensions or red truncations. These methodologies are as follows:

1. Minimize Total Vehicular Delay at Each Intersection: This methodology selects the green time to cycle ratio (g/C) for each approach at an intersection which minimizes the sum of arterial and cross street delays. The delay which is minimized is measured in units of delay per vehicle. In theory this methodology should work. However, Machemehl had difficulty finding this optimal g/C ratio for several experimental intersections using the equations of the highway capacity manual.

2. Green Time Allocation According to Passenger Demand at an Intersection: This methodology allocates green time associated with the priority timing plan on the basis of the total number of passengers at the various intersection approaches. The methodology uses observed vehicle counts and estimated occupancy rates to estimate the passenger demands at the major arterial (receiving priority) and the cross streets. Then, a passenger demand equivalent to one bus is added to the arterial's total demand (to mimic the presence of a bus in need of signal priority) and green times are calculated accordingly. This methodology appears to work well as the results often closely matched existing priority timing plans which were observed working well and recommends more reasonable priority timing plans at intersections which performed poorly.

3. Signal Priority Scheme which Utilizes Progression Bands: This methodology was identified, but not analyzed as part of this project. The basic methodology involves establishing green extension or red truncation lengths at various intersections to allow transit vehicles to maintain progression along an arterial even when stopping to board and deboard passengers. This methodology assigns probabilities of stopping at various bus stops along the arterial to determine whether additional green time should be added to the beginning or end of the existing green, and the duration of this additional green time. Variability associated with bus dwell times at bus stops is critically important within this methodology, as it will perform better on transit routes less prone to dwell time variability.

The effects of introducing signal priority techniques are evaluated over a range of traffic conditions in a 1995 report by Cisco [Ref 21]. These deterministic techniques use queuing theory to determine the delay and queue length consequences of using signal priority strategies. Two methods, method 1 and method 2, have been developed to address the consequences of using priority signal timing. Method 1 analyzes vehicles macroscopically, while method 2 looks at vehicles microscopically by addressing the priority signal timing effects for each individual vehicle. The 3 signal priority strategies which are evaluated include use of 1) green extensions, 2) red truncations, and 3) red interruptions. In all cases, the additional green time given to the bus lane is assumed to be 10 seconds.

After development of deterministic techniques for evaluating the changes in queue length and delay due to priority signal timings, data was collected on 3 intersections in Ann Arbor, Michigan. Although all 3 intersections are located along the same major arterial (Washtenaw Avenue), a range of cross street volumes (low, medium, and high) are represented by the 3 intersections. Data on arrival rates and processing rates were collected at the 3 intersections using video tape.

The deterministic equations from both method 1 and method 2 were then used with the field data to predict the queue length and delay consequences resulting from the use of the 3 types of signal priority. At the low volume intersection, the predicted consequences of using the various signal priority techniques were found to differ considerably between method 1 and method 2. Typically, method 1 (macroscopic) predicts more significant reductions in queue lengths and delays with the introduction of the priority signal timings than method 2. However, because of the inherent randomness associated with low volume intersections, method 2's microscopic analysis might be considered more feasible. Likewise, at high volume intersections the use of method 1 might be considered more feasible as arrival patterns become more homogeneous. In general, however, the results of the 2 methods were found to differ from one another with no apparent pattern. As a result, the relative effectiveness of the 3 priority strategies is not readily apparent.

According to Cisco, the relative effectiveness of these techniques might be addressed by determining how many vehicles pass with a bus receiving priority through the intersection during the added green phase in comparison to how many vehicles are forced to stop along the cross street due to the priority signal timing. A larger sample size would inherently be needed at low volume intersections to discern any of these trends since low volume intersections are subject to more randomness.

A new methodology for granting priority to transit vehicles which operates on a real-time basis is presented in a 1995 report by Chang [Ref 22]. Research has been conducted by Chang on the use of adaptive signal control environments in granting priority to transit vehicles. Adaptive signal control environments incorporate real-time algorithms which evaluate the present consequences of granting or disallowing signal priority. Decisions regarding the use of signal priority are taken based on evaluation of these consequences.

Vehicle and bus detectors are both used by Chang's adaptive signal control algorithm. Vehicle detectors are placed about 37 meters upstream from the stop line and about 15 meters downstream from the upstream intersection to allow estimation of queue lengths and vehicle arrivals, respectively. Bus detectors are also placed about 37 meters upstream of the stop line and also at the stop line to detect bus arrivals and departures, respectively. Vehicle and bus detectors are positioned in this manner along the arterial and also along the cross streets. Both vehicle and bus detectors are placed in all approach lanes.

Data from the detectors is used within the algorithm's traffic state estimation module to estimate the current queue length, expected demand, and anticipated discharge flow at an intersection's various approaches. In addition, this data is used in the following module to estimate allowable minimum green times for the various phases. These measures are estimated by the algorithm every 3 seconds.

The signal's present state (green phase or red phase), elapsed green time (if applicable), minimum green and maximum green are all found within the signal state estimation module. Because the green times are determined using queue length calculations in real-time (every 3 seconds), maximum green times can be input as constants by the user to limit the green time given to an oversaturated approach. In addition, the maximum green times can be programmed to change based on the time of operation (morning peak, evening off-peak, etc.).

Information from the signal state estimation module and the bus detectors are fed into the bus preemption module. Within the bus preemption module, a performance index (PI) is computed for all competing phases (normal intersection control phases and the bus preemption control phase at all relevant approaches). The PI is the summation of three separate measures: passenger delay, vehicle delay, and schedule delay. Minimum green times, yellow intervals, all red times and average bus occupancy rates are taken into account to determine passenger delay resulting from the set of potential signal control decisions. Similarly, the number of detected buses, current queue lengths, and starting delay estimates are used to measure the vehicle delay resulting from possible signal control decisions. Finally, the duration of a proposed green extension (3 seconds), is used in conjunction with various delay measures to determine the schedule delay resulting from the possible signal control decisions.

In the presence of buses, this PI function is evaluated every three seconds. Based on the value of the PI function, a decision will be made by the system whether to extend the green an additional 3 seconds, or switch the green to another approach.

The adaptive control algorithm was tested by comparing its effectiveness (when it doesn't give priority to buses) with that of an actuated signal which also doesn't give priority to buses. In addition, the effects of the adaptive control algorithm when priority is, and is not, given to buses was examined. All scenarios were simulated within TRAF-Netsim. The evaluation criteria used to compare the effectiveness of the adaptive and actuated controls (both without priority for buses) was total queue length over the entire intersection at 3 second intervals. These two methodologies were compared over a range of traffic volumes and bus headways.

Results indicate that the adaptive control logic resulted in smaller total queue lengths over the entire intersection for all traffic situations. The results were more pronounced at high traffic levels, where the total queue lengths were reduced by about 40 to 45 percent with the use of the adaptive control algorithm.

Passenger delay was used to compare the effects of using and neglecting bus priority within the adaptive control algorithm. Simulation results indicate passenger delay decreases with the use of bus priority in the adaptive control algorithm. However, the added benefit gained from using bus priority seemed to diminish as volume increased. Chang postulates that this occurs because the competition between the number of bus passengers and vehicles in the queue at the intersection stiffens when traffic volumes increase. Thus, drastic priority measures cannot be taken by the adaptive control algorithm.

OPERATIONAL FIELD TEST RESULTS

A 1977 report by Wattleworth [Ref 2] presents the results of a series of field tests run along a 16 km section of the I-95 and Northwest Seventh Avenue corridor in Miami in 1973. Express bus service called the Orange Streaker was used to test the effectiveness of 3 bus priority techniques which included 1) a reversible, exclusive bus lane, 2) a traffic signal preemption system for buses, and 3) a coordinated signal system which gave express buses signal progression. These 3 priority measures were tested with regard to the following 5 scenarios.

Scenario 0:	No bus priority measures taken
Scenario 1:	Signal preemption for buses
Scenario 2:	Signal preemption for buses, exclusive bus lane

Scenario 3: Signal progression for buses, exclusive bus lane

Scenario 4: Signal progression for buses, signal preemption for buses, exclusive bus lane

The effects of the various bus priority measures on bus operations, signal timing, traffic flows, and transit service were identified as follows:

- All bus priority measures decreased bus travel times and delay.
- The use of an exclusive bus lane yielded the fastest bus travel times. The use of signal preemption yielded slightly faster bus travel times than use of signal progression.
- Strong cooperation is needed on the part of other motorists when the center left turn lane is used as an exclusive bus lane. Wattleworth found that motorists often violated the no left turn restriction, limiting the effectiveness of the exclusive bus lane.
- All the bus priority measures except for the use of signal preemption resulted in improved bus schedule adherence. Wattleworth hypothesized that the use of signal preemption resulted in a greater variation in bus travel times because preemption allows the bus driver to essentially travel at any desired speed.
- The impact upon traffic flow was influenced more strongly by the signal system's control parameters (isolated versus interconnected timing plans, pre-timed versus semi-actuated controllers) than the various signal priority measures.
- In general, the traffic streams along the study corridor and the cross streets were not adversely impacted to a large extent by the use of various bus priority measures. The most favorable combination of bus priority measures with regard to minimizing automobile delay was signal progression with an exclusive bus lane (scenario 3).
- The number of people who were moved through the study corridor increased by 26.8 percent with the introduction of the Orange Streaker.
- Orange Streaker ridership increased from roughly 1050 passengers/day to about 1450 passengers/day during the course of the project. This was a larger growth rate than the overall growth rate in Miami's transit ridership.
- The majority (almost three fourths) of the Orange Streaker's ridership was comprised of choice riders, many of whom had previously traveled in a single occupant vehicle.

- The effectiveness of the Orange Streaker (an express route) was heavily dependent upon the availability of park and ride facilities.

The methodology and results of a demonstration project which was conducted by the Municipality of Metropolitan Toronto is presented in a final report submitted in 1991 [Ref 6]. This demonstration project was intended to determine the effectiveness of implementing a non-optimizing signal priority strategy for streetcars along Queen St. in Toronto, and also to aid in determining the feasibility of this methodology elsewhere.

Queen St. in Toronto is comprised of two-way streetcar transit service in addition to 4 regular traffic lanes. The area is relatively dense, with strip/storefront commercial areas abutting most of Queen St. Streetcars are operated at headways of roughly 4 minutes during peak hours and 5 to 6 minutes during off-peak hours, with streetcars forced to share their right of way with normal traffic. In addition, near-side transit stops are typically used by streetcars and, by law, normal traffic is forced to stop at least 2 meters behind a streetcar stopped for boarding or deboarding. The use of signal priority was examined along a 1.6 km section of Queen St. West for the demonstration project. Six signalized intersections (3 T intersections and 3 four-way intersections) and 7 streetcar stops (6 near-side and 1 far-side) are included within this study area.

Active transponders, which are installed on all the streetcars to allow for track switching, were used in conjunction with track switch receiver loops buried within the pavement at an upstream and downstream (just downstream from the stop line) location at each of the 6 intersections to identify streetcars for priority. Signal priority was awarded to streetcars in 2 forms: green extensions and red truncations. Green extensions up to 14 seconds in length are provided to streetcars in jeopardy of failing to reach an intersection prior to the end of their green time. Further, the status of the streetcar (still in need of priority or downstream from the intersection) is checked at 2 second intervals during the green extension. When an intersection is traversed by a streetcar, a receiver loop is crossed which indicates that the streetcar is no longer in need of signal priority. In this way, the green extension time can be limited to only a duration necessary to enable a streetcar to pass, uninhibited, through an intersection.

Conversely, if a streetcar arrives at an intersection in the latter part of its green phase or during its red phase, a red truncation is used to reduce the streetcar delay. Red truncations shorten the green time at the cross street to allow the green to return to the streetcar approach more quickly. At most intersections in the study, the red truncations were fixed at 6 seconds. As a result, pedestrian safety was maintained by conserving minimum cross street green times.

The signalized intersections along Queen St. are controlled by a central computer which coordinates the various signals, allowing for traffic progression. Upon granting signal priority to a streetcar, the intersection is released from central computer control. When priority has been granted to a streetcar, or the maximum allowable duration of priority has expired, the control of the intersection is shifted back to the central computer. A few of the intersection's subsequent cycles will then be shortened by the central computer to allow the intersection's offsets to resume coordination with Queen Street's other intersections. This methodology for providing signal priority to transit vehicles is an example of "non-optimizing priority". Priority is not optimized because the signal priority is only responsive to the presence or absence of streetcars, while the current queue lengths, the presence of transit on cross streets, and other important factors are ignored.

Extensive data collection was established to test the signal priority algorithm previously described. Data was collected during 2 hour intervals of the morning peak period (7 am to 9 am), the off-peak period (1 pm to 3 pm) and the evening peak period (4 pm to 6 pm). The priority algorithm was activated during 1 of the hours in each 2 hour interval, and disabled the remaining hour. Data was collected on Tuesdays, Wednesdays, and Thursdays for a 2 week period. Due to the short streetcar headways in the study area, 75 streetcar observations with priority and 75 streetcar observations without priority were collected at each of the 3 data collection times (morning peak, off-peak, evening peak) during the 2 week period. This resulted in a total of 450 observations, a sufficiently large sample size to yield statistically significant results.

An extremely large data collection effort was conducted over the 2 week period, resulting in data on the following: 1) streetcar speed and delay, 2) auto speeds and delay, 3) cross street queue delay, 4) traffic volumes, and 5) miscellaneous data (weather, traffic incidents, etc.).

Based on the data collected during the two week demonstration, streetcar delays and travel times were shown to decrease with the introduction of priority. Due to high transit usage in Toronto, the reduction in delay translates into a substantial savings in passenger-minutes of delay. Finally, an increase in streetcar schedule adherence and reliability was realized though the decreases in streetcar delay.

Negative impacts to the cross streets resulting from priority were found to be minimal. Changes in average delay per vehicle along non-transit cross streets were shown to be statistically insignificant. In addition, corresponding changes in delay along cross streets supporting transit were also found to be minimal, with one exception (Bathurst Street). Significant traffic volumes are carried along Bathurst Street and a high volume intersection (Bathurst and Richmond) is located only about 60 meters south of Queen Street. As a result, the signal priority awarded to Queen Street disrupted the signal coordination between the intersections of Queen and Bathurst Streets and Richmond and Bathurst Streets. Consequently, spillback from the Richmond/Bathurst intersection into the Queen/Bathurst intersection was occasionally cited. As a result, the need for investigation into the potential for simultaneous priority at these 2 intersections was identified.

Finally, the green extensions were found to be far more effective than red truncations. Often, red truncations were "lost", or could not be used by the streetcars along Queen Street. Only 12 percent of the red truncations were fully used by a streetcar. As a result, the average time savings per red truncation was found to be only 1.2 seconds, compared with an average time savings of 20 seconds per green extension.

Based on findings from the 2 week priority demonstration, recommendations given by the Municipality of Metropolitan Toronto include: 1) the use of green extensions, as opposed to red truncations, 2) the selection of signal priority at intersections whose cross streets have excess capacity as characterized by low v/c ratios and adequate levels of service, and 3) the introduction of signal priority on a staged basis (one transit route at a time).

The results of a series of field tests on the effectiveness of 3M's Opticom priority control system in Bremerton, Washington was submitted by Williams through The University of Washington in 1993 [Ref 14]. The Opticom priority system allows buses to request signal priority at intersections by sending optical signals to traffic controllers. Once the request is received, either a green extension or a red truncation is provided to the bus, allowing the bus to traverse the intersection with less chance of stopping. In the Bremerton system, once the bus traverses the intersection, Opticom releases control of the traffic signal and the signal regains coordination with other signals within 30 seconds. This is usually accomplished by skipping phases. (The Opticom system can be operated in different ways, however. In Charlotte, North Carolina, for instance, phases are not skipped because officials in Charlotte feel that accidents may result. Therefore, signals in Charlotte are not returned to coordination in 30 seconds.)

The 2 main objectives of the study in Bremerton were to determine the effects which the Opticom system had on bus travel times along various routes and to assess the impact which the Opticom system had upon traffic delays at cross streets.

Four bus routes were examined in the study, namely the numbers 11, 24, 25, and 26 bus routes. Bus travel times along these routes were examined under 2 scenarios. Under the first scenario, the Opticom priority system was activated continuously, providing either a green extension or red truncation for the bus at all intersections. Under normal operations, the use of the Opticom priority system would be restricted only to situations where the bus was running behind schedule. Thirty observations of bus travel time were made along each of the 4 bus routes when the Opticom system was continuously activated (15 observations from the off-peak time period and 15 from the p.m. peak time). Under the second scenario, the Opticom priority system was not used, and 30 observations were also made of bus travel times along each of the 4 routes.

The results of the testing indicate that, on average, a statistically significant reduction in bus travel times of about 10 percent was introduced through the use of the Opticom priority system. In addition, the percent reduction in travel times increased as the number of traffic signals present along the bus routes increased, as shown in Table 2.1.

TABLE 2.1 COMPARISON OF BUS TRAVEL TIME SAVINGS BY ROUTE

Route	Traffic Lights on Route	Average Travel Time Without Opticom	Average Travel Time With Opticom	Change in Travel Time
Route 11	52	46.21	38.72	-16%
Route 24	32	54.29	50.04	-8%
Route 25	18	49.54	46.97	-5%
Route 26	36	45.93	40.57	-12%
Average		48.99	44.07	-10%

[Ref 14]

The delay to cross streets along the 4 bus routes was also examined to determine whether the Opticom priority system had any significant negative impacts to cross street traffic. To do so, the stopped delay per vehicle was found at 8 selected intersections. These intersections represented a range of cross street traffic volumes, from moderate to heavy. Four intersections were observed during a peak travel time while 4 intersections were observed during off-peak times. Each intersection was observed for a total of 4 hours, while the Opticom system was in use for 2 of the 4 hours.

The results of these observations were inconclusive. Increases in stopped delay were observed at the cross streets of 4 intersections while decreases in stopped delay were observed at the remaining 4 intersections. Overall, the stopped delay decreased by 3.9 percent with the use of the Opticom signal priority system. However, these results are not statistically significant. Williams notes that these inconclusive results are probably due to the small sample size (preemptions could only be observed whenever buses arrived at the intersections, 3 or 4 times per hour).

A 1994 report by Hunter-Zaworski [Ref 17] examines the results of a pilot project which occurred at 4 intersections traversing 3.2 km of SE Powell Blvd. in Portland, Oregon. The study was conducted through the joint cooperation of the Transportation Research Institute of Oregon State University, the city of Portland, Oregon, and the Tri-County Metropolitan Transportation District of Oregon. The resulting report assesses the effectiveness of 2 bus priority techniques and 2 bus detection technologies. The arterial examined for this pilot project, Powell Blvd., is a major five-lane arterial which typically carries between 40,000 and 50,000 vehicles per day.

The 2 bus priority techniques evaluated in this project include the green extension-red truncation technique and the queue jump technique. The green extension-red truncation technique was used exclusively at the 3 intersections with far-side bus stop locations, while the queue jump technique was used at the remaining intersection which had near-side bus stop locations.

The green extension-red truncation technique either adds additional green time to the existing green, increasing the bus' chances of passing through the intersection without stopping, or returns the green to the bus lane more quickly if the bus lane has a red signal as the bus approaches. Up to 10 seconds of additional green time per cycle was allocated to the buses during the off-peak period, while up to 20 seconds of additional green time was given to buses during the peak period. The methodology used to establish the amount of additional green was not specified. In order to maintain a constant cycle length, the additional green time given to the arterial carrying the buses was taken from the cross streets at each intersection.

The queue jump technique was used at an intersection which had a lane designated "Right Turn Only Except Buses". When buses equipped with appropriate sensors were stopped at this intersection, a signal visible only to vehicles in the bus lane begins its green time before the other lanes at the approach. This allows buses to advance from the intersection ahead of the queued traffic.

These 2 techniques were implemented at the 4 intersections along the study corridor. Data collected include turning movement counts, approach vehicle delay measurements, bus travel time and delay measurements, private vehicle occupancy counts, and bus passenger counts. Data was collected for 3 days apiece when the priority system was, and was not, activated. Data was collected each day during the hours of 7:00 a.m. to 9:00 a.m., 11:30 a.m. to 1:30 p.m., and 4:00 p.m. to 6:00 p.m.

The 2 types of bus detection technologies which were tested were labeled System A and System B. The System A technology used RF tag readers mounted on lighting and signal poles roughly 122 to 183 meters before the intersection to identify buses. As a tagged bus passed the tag readers, System A's controller activated a priority call to the intersection signal. System A collected "in" and "out" times for each bus and also logged the amount of green which Powell Street received for every cycle where signal priority was used. System B made use of loop detectors embedded in the pavement to identify the presence of buses.

Data collected on bus travel times through the study area indicate that buses enjoyed travel time reductions of 5 percent and 7.8 percent, respectively, during the a.m. inbound and p.m. outbound peak travel periods. Additionally, the signal priority system seemed to have no significant impact on total vehicular delay or total delay per person at the 4 intersections studied, with the exception of a slight increase in total delay per person when signal priority was used during the off-peak period (11:30 a.m. to 1:30 p.m.). However, the bus passenger delay per person decreased by 12.3 percent with the use of signal priority. Finally, Hunter-Zaworski, indicated that System A was harder to work with than System B, as System A was still in a development stage.

The integration of the SCOOT urban traffic control system with active and passive bus priority in Swansea, England in 1992 and 1993 is described in a 1994 report by Evans [Ref 18]. Prior to 1992, traffic congestion had been prevalent along the Carmarthen Road/Dyfatty Street junctions in Swansea. Therefore, an exclusive bus lane, complimented by bus priority integrated within SCOOT, were introduced as measures to alleviate traffic congestion.

In Swansea, buses are detected through selective vehicle detection (SVD) using transponder units attached to the buses and inductive loops embedded in the pavement. Upon detection, buses are given priority in one of 3 ways: 1) green extension, 2) red truncation, or 3) insertion of a green bus phase. Further, under normal operating conditions, the degree of saturation on all approaches to an intersection will be balanced by SCOOT. However, passive priority can be granted to buses by biasing the bus approaches within SCOOT.

Based on observations from field testing, the total person-delay of bus users was reduced significantly with the introduction of the exclusive bus lane. In addition, with passive priority awarded to buses in the form of biases within SCOOT, bus delays were found to decrease by about 2 percent, with delays to other road users increasing by about 17 percent. When active priority was awarded to buses in the form of green extensions or red truncations, delays to bus passengers decreased by 9 percent and 13 percent during the morning and evening peak periods, respectively. This was accompanied by an increase in the delay to private vehicles of roughly 7 percent during the evening peak with no increase in delay noted during the morning peak. Finally, upon providing active priority in the form of a green insertion, increases in delays to private vehicles of 13 percent and 16 percent in the morning and evening peak periods were encountered, with no significant benefits for buses.

A model developed through a 1995 report by Sunkari [Ref 19] attempts to estimate delay occurring through the use of green extensions or red truncations. The model was developed with regard to 5 situations, 4 corresponding to maximum and minimum amounts of additional green time needed for green extensions and red truncations respectively, and one situation where no signal priority is used.

The model uses the delay equation from the 1985 Highway Capacity Manual (HCM) to predict delay per vehicle given green splits and volumes as inputs. In addition, the model converts the HCM's delay value into a delay per passenger per cycle value, using vehicle occupancy rates, the number of vehicles per cycle, and a number of per person delay measures which account for the various possible scenarios occurring at the intersection (presence of a bus with priority, presence of a bus without priority, absence of bus, etc.).

To test the model, an intersection was selected for data collection, and field tests were run on 2 signal priority scenarios (maximum green extension and maximum red truncation). Data was collected on the intersection's green splits with and without priority, the volume at the intersection, and the number of stopped vehicles at the intersection at 15 second intervals. Signal priority was modeled by manually activating the priority timing with a push button, as no buses run through the intersection examined in the field. In order to allow the field testing to resemble actual signal priority operations as closely as possible, the priority timing was manually activated only when the intersection recovered from the last activation of priority signal timing. The data collection yielded the observation of 10 priority cycles for the 2 priority scenarios in question. The volumes and green splits observed in the field were input into the model, yielding estimates of delay. These delay estimates were than compared to actual field delay measures.

Comparisons of the 2 delay measures indicate that the model over-estimates delay by about 41 percent. In addition, the model performs better at approaches with low volume to capacity (v/c) ratios. Sunkari notes that this reinforces the belief that the HCM delay equation (which the model uses) overestimates delay when high v/c ratios are present.

Extensive simulation with TRAF-Netsim was used by Al-Sahili of Michigan State University [Ref 23] in 1995 to determine the effectiveness of various signal priority strategies for buses over a range of traffic conditions on a selected arterial (Washtenaw Avenue) in Ann Arbor, Michigan. The selected arterial is about 9.7 km long with 13 intersections. Typically, far-side bus stops and 2 phase timing plans were present throughout the arterial, with buses operating at 15 minute headways during peak times and 30 minute headways during off-peak times.

Situations where buses needed signal priority were identified using TRAF-Netsim's graphical animation. Use of bus detectors embedded within the pavement is simulated for near-side and far-side bus stops using TRAF-Netsim according to the 2 schemes shown in Figures 2.2 and 2.3.

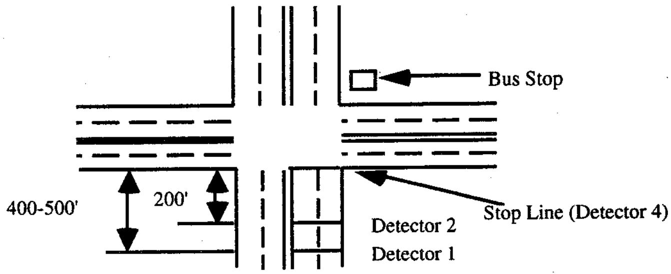


Figure 2.2 Far-side bus stop intersection and detector configuration [Ref 23]

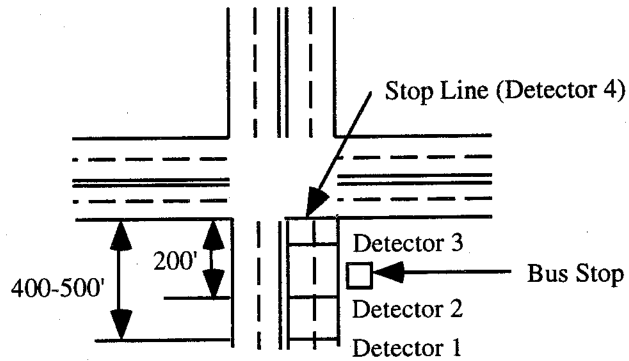


Figure 2.3 Near-side bus stop intersection and detector configuration [Ref 23]

The following bus priority methodologies were tested by Al-Sahili using simulation:

Base Case: No preemption used; Traffic operates according to optimal traffic signal timings generated through TRANSYT-7F.

Case 1: Green extension and red truncations used without compensation; No compensation is given to the cross street after green time is taken from it to provide priority to buses along Washtenaw Avenue.

Case 2: Green extension and red truncations used with compensation; Compensation is only granted when cycle failure is imminent upon the cross street due to the use of signal priority upon Washtenaw Avenue.

Case 3: Skip Phase without compensation; If green extensions or red truncations are not sufficient to allow passage of the bus through the intersection, the cross street green phase is completely skipped for one cycle, without providing compensation to the cross street.

Case 4: Skip Phase with compensation; Similar to Case 3, except compensation is provided in the same manner as in Case 2.

Case 5: Selective Plans; The most suitable form of signal priority among the 4 listed previously is used at each individual intersection. The form of priority which is least prone to causing excessive delays based upon simulation results is selected.

Case 6: Conditional Priority; Case 5 priority plans are used at each intersection only if the bus arrives to an intersection behind schedule.

Finally, all previous bus priority algorithms operate under the following constraints: 1) bus priority cannot be called in 2 consecutive cycles, 2) the minimum green time for any signal phase is 10 seconds, and 3) the maximum possible green extension or red truncation is 10 seconds.

Results of the simulation in terms of vehicle delay indicate that use of compensation is not advisable when the arterial traffic volume is significant. Results from Case 4 indicate that when compensation is used in conjunction with substantial arterial traffic volumes, the resulting delays caused to the bus approach outweigh the initial benefits awarded to the bus approach through signal priority.

In addition, Eastbound traffic along Washtenaw Avenue suffered from overall increased delays (when measured in delay per vehicle) with the introduction of any of the 6 priority algorithms. Traffic volumes along Eastbound Washtenaw Avenue were rather high. Therefore, upon receiving signal priority, signal progression along Eastbound Washtenaw Avenue was lost, resulting in increased downstream intersection delay. Therefore, along heavily traveled sections of Washtenaw Avenue, signal progression, rather than signal priority, appears to be of prime importance. The base case, where no signal priority is used, enjoys the least overall delay per vehicle according to the simulation. This, however, is not surprising since the base case represents the optimal signal timings as calculated through TRANSYT-7F, while the various priority algorithms deviate from this optimum timing plan.

Performance measures of the 6 priority algorithms were also computed in terms of person-delay, rather than vehicle-delay. These statistics were calculated using TRAF-Netsim while assuming an average auto occupancy of 1.3 persons per vehicle and an average bus occupancy of 25 persons per vehicle.

Results of this analysis are similar to the previous analysis. Once again, delay (delay per person) was found to be smallest for the base case and largest for Case 4. Al-Sahili attributes this finding to the rather long bus headways (15 minutes during peak periods and 30 minutes during off-peak periods). The longer the headway, the less impact bus priority will have on delay per person for a given bus occupancy.

The effect of skipping phases as a means of providing priority to buses was observed using TRAF-Netsim's graphical animation. It was found that buses benefited from signal priority through phase skipping, as they could almost certainly pass through the intersection with the added green time received through the skipped phase. However, under heavy traffic conditions, other vehicles sharing the bus approach would also benefit from the skipped phase, resulting in longer queues at the downstream intersection. Bus travel times were negatively impacted by these long queues at the downstream intersection, especially when signal priority was unavailable there (due to priority's operational constraints mentioned previously).

Overall, the most beneficial priority algorithm based on the simulation results appears to be Case 5 (selective signal priority at each individual intersection). Bus travel distances and delays were the largest and smallest, respectively, during the 45 minute simulation time when Case 5 was used. The success of Case 5 is attributed to its ability to minimize the negative impacts (excessive delays and long queues) which are introduced through signal priority, as Case 5 utilizes the most beneficial priority technique at each intersection to minimize cross street delays. Al-Sahili notes that the whole network, including buses, may be negatively impacted if improper bus priority measures are taken. Therefore, it is in the bus' best interest to disrupt the optimal flow of traffic as little as possible.

In addition to testing the effectiveness of the various signal priority techniques under Washtenaw Avenue's existing traffic conditions, sensitivity analyses were performed through simulation to measure the effects which different traffic volumes, arterial to cross street volume ratios, traffic mixes (percentage of carpools), and random number seeds used in the simulation have on the bus priority effectiveness.

Sensitivity analysis of traffic volume throughout the network was performed by varying the volume from 20 percent less than the original volume to 20 percent greater than the original using 10 percent increments. These 5 volumes were used in 45 minute simulations with Case 5 signal priority, only.

Al-Sahili found that additional delay imposed upon the network (in terms of delay per vehicle) through use of Case 5 signal priority tended to increase at higher volumes. This reflects the importance of signal progression, rather than signal priority, in moving vehicles through intersections during periods of high volume. TRAF-Netsim animation showed that benefits gained though signal priority at one intersection were lost at the downstream intersection under high volume conditions, as the downstream intersection's already saturated (or near saturated) conditions were worsened by the influx of vehicles receiving signal priority at the upstream intersection.

Delay per person was essentially the same with and without the use of Case 5 signal priority with the exception of the simulation run with the lowest volume. In this simulation (volume 20 percent below average) delay per person was reduced from 29.7 seconds to 28.3 seconds with the introduction of signal priority. Finally, it was found that buses generally benefited from the use of Case 5 signal priority as bus travel time and delay both decreased with signal priority usage. Also, as expected, bus travel time and delay decreased with decreasing traffic volumes, but leveled off at very low traffic volumes (20 percent less than normal).

The sensitivity of all the previously mentioned signal priority techniques to the ratio of arterial and cross street traffic volumes was also examined. This type of analysis for the entire network is not possible within TRAF-Netsim. Therefore, the effects of varying the arterial to cross street volumes was simulated for an isolated intersection within TRAF-Netsim. Therefore, a 5 minute bus headway was assumed in the simulation to ensure that the effect of the bus priority calls was felt on the overall network. The ratios of arterial traffic volumes to cross street traffic volumes selected for the analysis were 2:1, 3:1, and 5:1. In addition, the arterial traffic volume ranged from 1000 vehicles per hour to 2000 vehicles per hour, with the cross street volume calculated according to the ratio used.

Results of the simulation indicate that negative impacts (in terms of increased delay per vehicle) introduced through the various signal priority techniques are significant at low volume ratios (2:1), but insignificant at high volume ratios (5:1). In addition, the 3:1 ratio of arterial to cross street traffic appeared to be the cutoff value for which compensation should be used in conjunction with signal priority. At ratios above 3:1, compensation is not recommended based on the calculated delay statistics (delay per vehicle and delay per person). At volume ratios below 3:1, the use of signal priority was found to be suspect, but if priority is used, then compensation is recommended. However, under conditions of high volumes and low arterial to cross street volume ratios, the benefits of signal priority may be negated by compensating the cross street with additional green time after a priority call. Under high volume conditions, considerable queues may form along the arterial as the cross street is compensated for the signal priority call. The next bus may be caught in this queue and experience delays, along with other vehicles along the arterial. These findings indicate that perhaps compensation is best suited for low volume conditions at intersections where low arterial to cross street volume ratios are present.

The effectiveness of the various signal priority strategies identified previously was also examined in lieu of changing volume ratios and overall volumes. The effectiveness of green extensions and red truncations in terms of overall intersection delay was inconclusive. One set of simulations indicated generally positive results over a range of volumes and volume ratios, while a negative impact was measured due to green extensions and red truncations in a second set of simulations. In general, delay was found to increase with the use of skip phase signal priority methodologies (Case 3 and Case 4). However, these methodologies were effective under high volume ratio conditions (5:1 volume ratios).

As might be expected, benefits from signal priority in terms of reduced bus travel times and delays decreases with increasing volume ratios. At high volume ratios, signals are already timed to favor the bus approaches. Therefore, less signal priority calls are required under these conditions.

The sensitivity to random variations within the simulation was tested by using different random number "seeds" within TRAF-Netsim. Results of this sensitivity analysis indicate that network statistics (vehicle delay, person delay, bus delay, and bus travel time) were not significantly affected by the use of different random number seeds. These statistics were generally not influenced by randomness by more than 5 percent.

The following conclusions are made by Al-Sahili:

- bus signal priority provides little, if any, overall benefits to an arterial with volumes (about 1500 vehicles per hour) and bus frequencies (15 minute peak headways) similar to those of Washtenaw Avenue

- Bus priority might be justified if bus headways were more frequent
- If bus priority is to be used, the Case 5 bus priority (selecting the most appropriate bus priority scheme at each intersection) is recommended
- Signal priority is not recommended at intersections operating at or near saturation. The negative effects of a single signal priority call at saturated intersections was often found to continue to the end of the simulation
- In terms of sensitivity to traffic volumes, general vehicular delay was not significantly influenced by the various bus priority measures at very high and very low volumes
- Above the 3:1 arterial to cross street volume ratio, preemption with no compensation is recommended while compensation is recommended if signal priority is used when the arterial to cross street volume ratio falls below 3:1
- Signal priority tends to increase delay when arterial to cross street volume ratios fall below 3:1
- Skip phase priority methodologies were found to be effective at high volume ratios (5:1), but ineffective at lower volume ratios
- Intersection delay is not affected by compensation at low volumes, but is negatively influenced by compensation at high volumes.

A 1995 report by Machemehl [Ref 20] describes the results of a series of tests which were run with 3M's Opticom signal priority system for Capital Metro buses along the Guadalupe-N. Lamar corridor in Austin, Texas by a graduate student class at The University of Texas at Austin.

To test the effects of the Opticom signal priority system, the system was triggered for 30 minutes continuously at each of the 6 intersections examined in the study during both peak on off-peak time periods (each intersection was examined separately). This enabled field data to be collected on experimental stopped time delay at each intersection with and without priority signalization. Similarly, bus travel time data was collected in the field which compared a variety (buses stopping and not stopping to board/deboard passengers) of bus travel times with and without signal priority. Theoretical stopped time delay was determined using traffic volume and signalization timing data as inputs into the Highway Capacity Software (HCS). The study yielded the following findings:

- The HCS is insufficient as an analysis tool to assess the impacts of the signal priority system. The HCS does not compute values of stopped time delay corresponding to lane groups with volume to capacity ratios (v/c ratios) in excess of 1.2. This prevents the subsequent calculation of that approach and intersection delay even if only 1 lane group exhibits v/c ratios above 1.2. In addition, the HCS only models pre-timed signalization plans, as opposed to priority signalization schemes which often change from cycle to cycle. Therefore, the HCS is not recommended for use as a tool to address the effects of signal priority upon stopped time delay. Field measurements, instead, are recommended.

- Triggering the Opticom system continuously for 30 minutes has a significant impact on the intersection approach levels of service at high volume intersections (improved levels of service for approaches with priority and reduced levels of service for the cross street) and little impact on intersection approach levels of service at low volume intersections. Intersections with moderate volumes felt moderate impacts from the continuous use of the Opticom priority system.
- Analysis of stopped time delay collected in the field showed that the continuous use of the Opticom system did not have large impacts on average stopped time delay for most approaches during the off-peak time period. Of the 22 approaches examined in the study, only data from 6 was found to have statistically significant increases in average stopped time delay at a 5 percent level of significance.
- Data collected during the peak time period shows that continuous use of the Opticom system produced significant increases in average stopped time delay at high volume intersection approaches not receiving priority. This increase in stopped time delay during the peak period was found to be far greater than the corresponding increase in stopped time delay occurring at these same approaches during off-peak times.
- Opticom signal priority didn't significantly reduce bus travel times during the off-peak period when stops were made. The effects of Opticom signal priority on bus travel times could not be examined during the peak period as the priority signalization could not be utilized during peak times at the time of the project's data collection.
- The Opticom signal priority system significantly reduces average trip times of buses which make no stops. With this in mind, a recommendation was given to use Opticom signal priority with express bus routes, or bus routes which carry the majority of its passengers to and from common origins and destinations.

- Far-side bus stops are more effective than near-side bus stops in conjunction with signal priority. With far-side bus stops, transit vehicles can take advantage of their additional green time to traverse the intersection before stopping to board and deboard.

It should be noted that the results of this analysis represent a worst case scenario where the Opticom system was triggered continuously for 30 minutes. In reality, this would never occur since buses would never arrive at an intersection during every cycle over 30 minutes. Therefore, when used with moderation, the Opticom priority system should have impacts similar to those described previously, but to a significantly smaller degree.

A 1995 report by Bauer explains how providing priority to LRT vehicles in downtown Chicago was simulated with the aid of two simulation models [Ref 24]. The Chicago Central Area Circulator (CAC) was simulated by Bauer. The CAC is a LRT system scheduled to begin operations in the year 2000 which will be operated amongst pedestrians, automobile traffic, and buses. The CAC will be given its own travel lane, but will interact with traffic at intersections. As a result, signal priority measures are being planned for the CAC.

TransSim II and TRAF-Netsim were used in conjunction with one another to simulate the effects of 3 potential LRT priority measures for the CAC. TransSim II is a link-node based tool which models both LRT and bus operations. With TransSim II, transit operations are modeled at the microscopic level, while other traffic is modeled macroscopically. In addition, transit operations are modeled on a real-time basis. Most importantly, most types of signal controllers (fixed time to fully actuated) and signal priority can be modeled by TransSim II. LRT performance measures such as total LRT travel time, station dwell time, and average travel speed are calculated by TransSim II. The only apparent disadvantage to TransSim II is its inability to model the effects of queue spillbacks or heavy pedestrian flows. However, since intersections are located along a closely spaced grid and pedestrian traffic is heavy in downtown Chicago, the limitations of TransSim II could not be ignored.

As a result, the use of TRAF-Netsim was proposed as a solution. TRAF-Netsim simulates traffic throughout a street network at a microscopic level. Nodes and directional links are used by TRAF-Netsim to model the network topology. Inputs such as traffic volumes, average traffic headways, and pedestrian volumes are used by TRAF-Netsim. Performance measures used to evaluate the effects of various LRT priority measures on non-LRT traffic included maximum queue lengths and stopped delay.

A link between the two simulation programs was established by way of signal phasing and timing. Signal phasings and timings were calculated by TransSim II based on various signal priority measures and subsequently input into TRAF-Netsim to allow the effects of the priority measures upon non-LRT traffic to be modeled.

The 3 LRT priority strategies which were simulated allot priority in the following manner:

Strategy 1: Fixed time controllers at intersections and semi-actuated controllers at junctions are used in attempts to give progression to LRT and automobiles.

Strategy 2: In addition to the priority measures taken in Strategy 1, green times for LRT vehicles can be lengthened through the use of green extensions or red truncations should the LRT vehicle request this additional priority.

Strategy 3: Delay of LRT vehicles is minimized through the use of interactive communication between the LRT vehicle and the signal controllers which allows LRT arrival times at intersections to be predicted.

Results of the simulations show that average LRT travel speeds are substantially higher using Strategy 3 (roughly 18 km/hr), than when using Strategies 1 and 2 (roughly 14.5 km/hr). Likewise, the total systemwide delay was shown to increase from roughly 830 seconds with the use of Strategy 1 to about 940 seconds with the use of Strategies 2 and 3.

The development of signal priority systems for buses in London, Turin (Italy), and Gothenburg (Sweden) lead Hounsell [Ref 25] to identify several key issues involved with signal priority, in a 1995 report. Ideally, buses should be detected by a signal priority system far enough upstream from the intersection to allow for the signal to gradually adjust timings for bus priority. This will minimize the disruptions to other intersection traffic. However, the further upstream a bus is detected, the more variable its forecasted arrival time will be. This variability increases as traffic and the number of transit stops between the bus and the intersection increases. The problem may be further complicated by the use of near-side bus stops, making the bus arrival time to the intersection that much harder to predict.

In addition, the frequency of bus arrivals was identified by Hounsell as a key variable in determining appropriate signal priority strategies. In London, when buses were operated with 1 minute headways, providing green extensions only was identified as the optimum strategy. When operating at headways shorter than 1 minute, adjusting signal timings to allow for bus progression is recommended.

Finally, the bus operating environment was identified as a determining factor for the degree of success signal priority affords. In London, bus delay savings from priority averaged 10 seconds per bus per intersection when the intersection degree of saturation ranged from 50 percent to 70 percent. However under more congested conditions (degree of saturation greater than 85 percent), delay savings to buses were reduced to only 2 to 3 seconds per bus per intersection. This 2 to 3 second savings in delay was accomplished through the use of green extensions, which did not significantly impact private vehicles.

Results of simulation and field testing in London from 1995 are explained in greater detail in a 1996 report by Hounsell [Ref 28]. The effectiveness of an active bus priority scheme integrated into the SCOOT urban traffic control system of London was tested first with simulation, and subsequently through field testing. Active bus priority is operated within SCOOT by equipping buses with transponders, allowing for bus detection with inductive loops embedded in the pavement at selected points (typically 70 - 100 meters upstream from the intersection). Priority is granted to buses in the form of a green extension or a red truncation on the condition that levels of saturation for non-priority approaches do not rise above pre-specified limits.

Simulation was used to test the effectiveness of signal priority within SCOOT using the microsimulation model STEP (SCOOT Testing and Evaluation Program). Over 2000 simulation runs were conducted on 2 road networks in London; the Camden SCOOT network and the Edgware Road SCOOT network. Conclusions reached from the simulation runs include the following:

- bus delay savings of 20-30 percent are possible, without significant impacts to general traffic, when appropriate control settings (cutoff degree of saturation for priority use, etc.) are used with signal priority
- bus delay savings increase as the intersection's degree of saturation decreases
- the appropriate cutoff degrees of saturation beyond which priority should not be used are 110 percent and 90 percent for green extensions and red truncations, respectively
- green extensions typically provide more overall benefit than red truncations because they are less disruptive to traffic flow
- the spacing of inductive loops embedded within the pavement is important, as loops should be far enough upstream to allow buses to be detected as soon as possible, while not sacrificing the ability to accurately predict the bus arrival time at the intersection

- higher benefits to buses accrue along links where bus stops are present because, without priority, these buses often loose the benefits of signal coordination due to their frequent stops
- bus benefits from priority decrease as the frequency of bus arrivals increases, due to conflicting priority calls

Field testing was also conducted at the same two road networks within London. In order to obtain statistically significant results, 20 hours of data collection was conducted along the Camden SCOOT network. Data collected included bus journey times, traffic flows at intersections, intersection delays and congestion, signal timings, degrees of saturation, bus detections, predicted bus journey times (from SCOOT), and continuous video recording of traffic conditions.

Four priority methods were compared during field testing: 1) use of green extensions subject to central computer control, 2) use of green extensions and red truncations subject to central computer control, 3) use of green extensions subject to control from the local signal controller, and 4) use of green extensions and red truncations subject to control from the local signal controller.

Results of the field testing for these 4 alternatives within the Camden SCOOT network are shown in Table 2.2. As shown in the table, the most beneficial results are produced through the use of green extensions subject to control from the local signal controller. The delay savings to buses are increased by supplementing green extensions with red truncations, but at a high cost to the general traffic. Similar results were encountered with the Edgware Road SCOOT network.

TABLE 2.2 BUS PRIORITY EVALUATION IN CAMDEN

Strategy	Change in Bus Delay (sec/bus/link)	Change in Auto Delay (sec/veh/link)
Green Extensions with Central Control	-0.2 (-1%)	+1.7
Green Extensions and Red Truncations, Central Control	-3.7 (-17%)	+5.3
Green Extensions with Local Control	-4.2 (-19%)	+0.4
Green Extensions and Red Truncations, Local Control	-4.8 (-22%)	+5.0

[Ref 28]

In addition, a passive priority technique using SCOOT cycle lengths and offsets to favor bus approaches was also tested with the Edgware Road SCOOT network. Field data, however, indicated that the delay savings to buses were higher with the use of the active priority techniques.

Simulation results regarding increased effectiveness of bus priority at low traffic levels was supported by the field test results. Decreases in delay over 40 percent were encountered under all 4 of the priority schemes tested, accompanied by slight decreases in delay to general traffic when priority was used under light traffic conditions. Future research is planned for bus priority within SCOOT using automatic vehicle location, as opposed to vehicle detection with induction loops.

A signal priority system called PTPS (Public Transportation Priority System) has been developed and has undergone its initial field testing in Sapporo, Japan. Japan's PTPS is supported with the use of roadside Infrared Vehicle Detectors (IRVDs) with associated electrical system components and an exclusive bus lane. Results of the field tests and the methodology behind PTPS is described in a 1996 report by Ikeda [Ref 29].

When a bus is detected by an IRVD, the traffic signals at the next series of intersections are altered to allow non-stop passage of the bus through these intersections. This is done by either extending bus green phases, or truncating bus red phases. In addition, the bus driver is given a recommended driving speed by the system, which is based on a time-space diagram of the priority timing at the upcoming intersections. This recommended driving speed is displayed through an in-vehicle display, which also transmits estimated arrival times for the benefit of passengers.

This system was tested in April and May of 1996 along 6 km of National Highway Route 36 (a heavily traveled arterial). Thirty three intersections and 12 bus stops are located along this 6 km stretch of road. At 1 intersection, buses were given right turn priority by devoting a right turn phase exclusively to the bus only lane. In addition, regular vehicles were kept out of the bus only lane through the use of 3 Variable Message Signs (VMS) which ordered regular vehicles to leave the bus only lane.

Data collected in the field on bus travel times shows that the PTPS reduced bus travel times, but not to a level believed to be possible. Theoretically, the bus travel times could be reduced to 20 minutes, should the PTPS's parameters be adjusted to further give priority to buses. Most of the bus travel times were found to be slightly longer than 20 minutes during the field test.

CONCLUSIONS

Signal priority systems for public transit vehicles appear to offer significant potential benefits to transit vehicles, without seriously compromising competing traffic if the priority system is developed and implemented with the needs of the entire transportation network, not just transit vehicles, in mind.

Mixed success of various signal priority systems across different transportation networks implies the success of a signal priority system depends on various parameters within the transportation network. Transportation networks which accommodate the needs of public transit within their infrastructure, or enjoy high levels of transit usage are likely to benefit from signal priority systems, while successfully developing and implementing signal priority strategies within a transportation network built solely for the automobile is more challenging.

Parameters within a transportation network which affect the success of a signal priority system include: 1) frequency of transit vehicle arrivals, 2) transit vehicle occupancies, 3) traffic volumes, 4) capacity of the transportation network, and 5) the amount and quality of Intelligent Transportation System (ITS) technologies available to the transportation network using signal priority.

Before implementing a particular signal priority strategy, the effects of the previous parameters on its implementation should be considered. Sensitivity analyses which examine the effects of changes in one or more of these parameters on the effectiveness of signal priority may prove useful in determining optimum signal priority strategies in a given transportation network.

CHAPTER 3. TRAFFIC SIMULATION MODEL BASED DATA COLLECTION

INTRODUCTION

As seen in the literature review, previous studies of transit signal priority have used field testing, traffic simulation models, or both, to observe transit signal priority effects. Field testing offers the advantage of observing the effect of a signal priority strategy first hand, but often requires extensive time and effort to collect even a limited amount of data.

Computer simulation models cannot completely capture the real-world variability of traffic operations. However, simulation models allow for a more extensive data collection effort in a given amount of time. In addition, simulation models allow one to perform sensitivity analyses of parameters affecting signal priority, which is difficult or impossible to do with field tests. For these reasons, the TRAF-Netsim computer simulation model was chosen to aid in the evaluation of alternative signal priority strategies.

This chapter describes TRAF-Netsim Version 5.0, as well as the data collected to model the Guadalupe-N. Lamar case study arterial network in Austin, Texas.

TRAF-NETSIM

TRAF-Netsim is a link-node based micro-simulation model [Ref 30]. By definition, micro-simulation models simulate all vehicles individually as they respond to traffic controls and other vehicles in the network. Directional street segments running between intersections are represented in TRAF-Netsim by links, while intersections are represented as nodes.

Figure 3.1 shows a link-node representation of a hypothetical arterial street network. Nodes 8001 through 8010 are entry/exit nodes. All vehicles entering or leaving the network must do so through these nodes. Links originating at entry/exit nodes are entry links. All vehicles enter the network through entry links. Likewise, links terminating at entry/exit nodes are exit links. Unlike other links in the network, TRAF-Netsim does not gather statistics on the performance of entry or exit links.

Nodes 1 through 4 represent intersections along the arterial street. Directional links between these nodes represent arterial street segments. Nodes 5 through 12 are dummy cross street nodes having perpetual green signal indications. The dummy nodes create cross street non-entry/exit links which allow TRAF-Netsim to gather cross street performance measures. Without cross street dummy nodes, cross street links would be represented only as entry or exit links. For instance, without the presence of node 6, link (8003, 1) would model a cross street. However, TRAF-Netsim could not collect statistics for this link, as it would also be an entry link.

Therefore, links running between dummy nodes and arterial nodes, such as link (6, 1) represent cross street approaches.

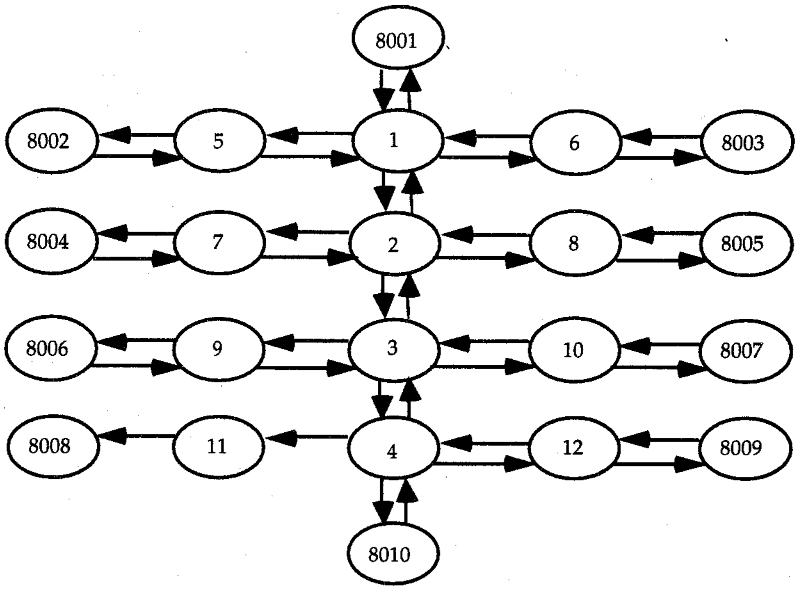


Figure 3.1 Sample link-node network

Inputs required by TRAF-Netsim for an analysis of transit signal priority along an arterial include the following [Ref 30]:

1. Network topology (link-node representation of the network)
2. Roadway geometry and traffic channelizations along links
3. Traffic control specifications at all nodes other than entry/exit nodes
4. Traffic volumes along entry links
5. Turning movement percentages and
6. Bus specifications (bus route paths, bus stop locations, bus headways, bus stop dwell time distribution, bus stop bypass parameters)

By altering some of these input parameters, one can simulate alternative transportation control strategies. TRAF-Netsim expresses the effectiveness of alternative transportation control strategies through various measures of effectiveness (MOE). MOE are collected over all links in the network, with the exception of entry and exit links. These MOE include vehicle speeds, cumulative delays, vehicle stops, queue lengths, vehicle-hours of travel time, vehicle-miles of travel, pollution emissions, and fuel consumption [Ref 30]. The cumulative delay measure is especially useful in comparing the effectiveness of transit signal priority strategies.

TRAF-Netsim has several other features which make it ideal for simulating transit signal priority. First, since TRAF-Netsim is a micro-simulation model, it simulates the effects of various signal priority strategies in more detail than macroscopic models (which simulate groups of vehicles, rather than individual vehicles). Therefore, simulation results from TRAF-Netsim are more robust than simulation results from macroscopic models.

In addition, TRAF-Netsim allows one to use multiple time periods within each simulation. Within each time period, one can alter input parameters such as signal timings, traffic volumes, lane channelizations, and turning percentages [Ref 30]. This feature is very useful when modeling active transit signal priority. With active signal priority, an intersection signal timing is temporarily altered to provide priority for a transit vehicle, and then restored to its original timing after the transit vehicle departs the intersection.

Figure 3.2 shows how an active signal priority call can be modeled with multiple time periods using TRAF-Netsim. In the example, 600 seconds pass between bus arrivals and the signal cycle length is 120 seconds.

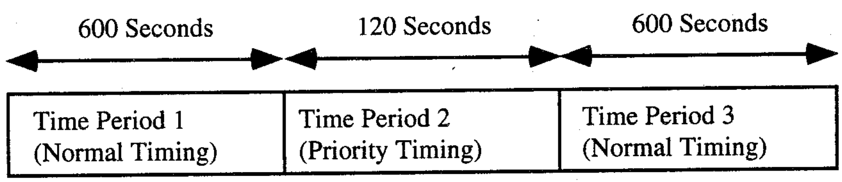


Figure 3.2 Modeling signal priority with multiple time periods in TRAF-Netsim

During the first time period prior to the bus arrival, the intersection is controlled by its normal signal timing plan. During the second time period as the bus arrives, the intersection signal timing is altered, allowing the transit vehicle to pass through the intersection. Finally, the intersection's original timing plan is restored in the third time period as the transit vehicle departs the intersection.

Time periods within TRAF-Netsim are further subdivided into time intervals. TRAF-Netsim updates its MOE along non entry or exit links after every time interval. The suggested time interval length corresponds to the most frequently used signal cycle length over all nodes in the network. Each time period length must be an integer multiple of the time interval length. In the example, the time interval length is 120 seconds.

The graphical animation feature in TRAF-Netsim is also helpful when evaluating transit signal priority strategies. The animation feature displays a plan view of the network, where traffic movements and signal indications can be observed over the duration of the simulation. This graphical animation feature allows one to track the progress of buses through the network to determine where and when active signal priority is needed. Once a need for signal priority is identified, a time period can be inserted to initiate transit signal priority.

In addition, the mechanism behind strange or unexpected results can often be identified with TRAF-Netsim's graphical animation. For instance, graphical animation helped uncover a bug in the bus operations module of TRAF-Netsim. This bug affects the bus stop bypass parameter specified for bus stops along all bus routes. This parameter indicates the probability of a bus bypassing a bus stop, due to the absence of boarding and deboarding passengers at the stop. However, no matter what probability is entered, buses stop at each bus stop along their routes all the time. This bug is taken into consideration as needed in analyses to follow.

Finally, replicate runs can be performed using TRAF-Netsim by specifying different random number seeds for different simulations. TRAF-Netsim employs 2 random number seeds which control the driver/vehicle characteristics and driver responses to traffic choices, respectively [Ref 30]. Changing the random number seed models the effect of observing the impact of a set of traffic controls on one day and then observing the effect of this same set of controls on a different day. This feature will be used extensively in analyses which follow, accounting for traffic operations variability.

GUADALUPE-N. LAMAR CASE STUDY ARTERIAL MODELS

Figure 3.3 shows the link-node representation of the Guadalupe-N. Lamar case study arterial in Austin, Texas used for the transit signal priority analysis. Nodes 1 through 11 represent signalized intersections along the arterial, which extends roughly 4.1 km from the Koenig Lane and Lamar Boulevard intersection to the 27th Street and Guadalupe Street intersection. The geometry at each of these 11 intersections was collected through field observations, while timing plans for these intersections were obtained from the City of Austin.

Nodes 12 through 35 represent either dummy nodes or uncontrolled intersections. Like dummy nodes, perpetual green indications exist at uncontrolled intersections. Uncontrolled intersections allow one to model geometry changes occurring along links, such as a lane drop.

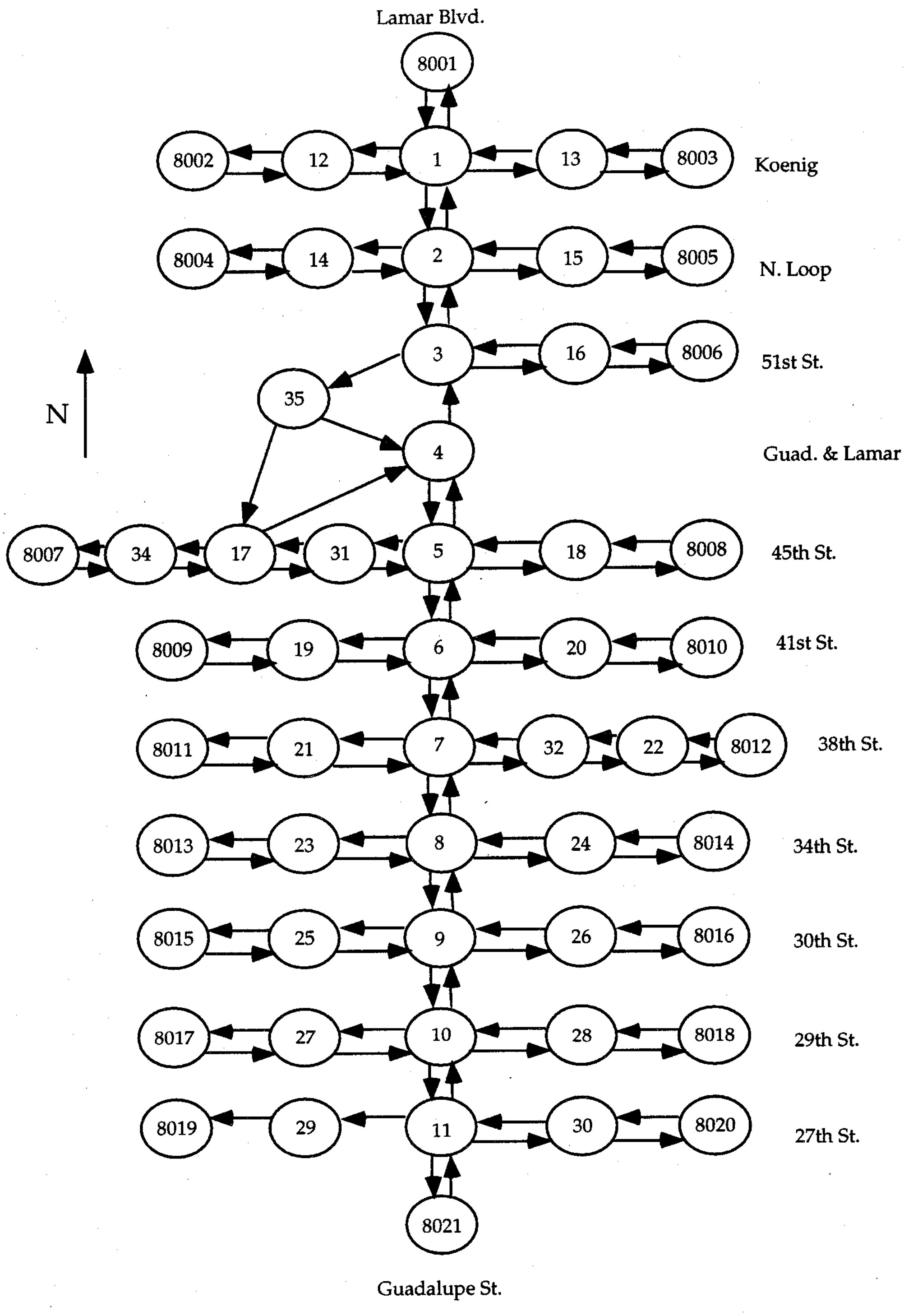


Figure 3.3 Link-node representation of Guadalupe-N. Lamar arterial

For instance, node 32 is an uncontrolled intersection which models a lane drop from 2 to 1 in the Eastbound direction of 38th Street.

Arterial and cross street link lengths were collected by driving the arterial and cross streets and noting odometer readings. In addition, arterial and cross street lane channelizations were collected by walking or driving these links and noting appropriate channelization features. Typically, both Northbound and Southbound arterial links enjoy 2 lanes apiece, as well as a shared continuous left turn lane. The number of lanes along cross streets varies, as traffic on major cross streets is carried by 2 lanes in both directions, accompanied by a continuous shared left turn lane, while minor cross street traffic is carried by only a single lane in each direction.

Most traffic volumes and turning percentages for the evening peak period, as well as the off-peak period, had already been collected through a previous study conducted for a class project at The University of Texas at Austin [Ref 20]. Traffic counts from that study indicate arterial links carry between roughly 900 and 1800 Northbound vehicles per hour and between roughly 700 and 1100 Southbound vehicles per hour during the evening peak period. Northbound and Southbound off-peak volumes along arterial links range from roughly 400 to 900 vehicles per hour [Ref 20].

Cross street traffic volumes vary significantly. Major cross streets, such as 38th Street and Koenig Lane, carry roughly 1200 and 800 vehicles per hour during peak and off-peak times, respectively. Minor cross streets, such as 34th Street and 30th Street, carry about 300 and 100 vehicles per hour during peak and off-peak times, respectively [Ref 20].

Capital Metro, the transit agency in Austin, Texas, operates Northbound and Southbound local bus service along the Guadalupe-N. Lamar arterial. Thirty bus stops are present between Koenig Lane and 27th Street, with 15 bus stops along both Northbound and Southbound routes, respectively. Near-side bus stop configurations are used for most bus stops. In addition, buses share their guideway with private automobiles and the absence of bus turnouts causes buses to block a lane while dwelling at bus stops. Bus stop locations were observed in the field, while measurements of bus stop dwell times were obtained from the study mentioned previously.

The data collected on signal timings, link lengths, traffic volumes, turning percentages, lane channelizations, and bus operations was used to create 3 TRAF-Netsim models. These 3 models simulate the following 3 bus operating environments:

Model 1: Peak period local bus
Model 2: Off-peak period local bus
Model 3: Off-peak period express bus

Model 1 was initially developed. Then, Model 2 was developed by matching off-peak condition entry link volumes, turning percentages, signal timing plans, and bus characteristics.

In reality, only local buses operate along the Guadalupe-N. Lamar case study arterial. Therefore, Model 3 was created from Model 2 by eliminating 12 of the 15 bus stops along both Northbound and Southbound bus routes and adjusting the bus dwell times and headways accordingly.

MODEL CALIBRATION

After developing TRAF-Netsim models for both peak and off-peak times, results from these models were examined to identify any obvious discrepancies between simulated and existing traffic conditions.

In particular, simulated delays along selected links were compared to field measured delays. Field measured delays were obtained from the University of Texas class project mentioned previously which examined signal priority along the Guadalupe-N. Lamar arterial [Ref 20]. In this project, delay was measured in the field only along select approaches, mostly at high volume intersections along the Guadalupe-N. Lamar arterial.

Discrepancies in trends between delay measurements from the field and the simulation models were corrected by making appropriate adjustments to signal timings within TRAF-Netsim. Table 3.1 shows the comparison of field measured delay with delay from a TRAF-Netsim simulation after necessary modifications were made to the peak period simulation model.

TABLE 3.1 COMPARISON OF FIELD MEASURED AND SIMULATED DELAY DURING PEAK TIMES

		Measured Delay (sec/veh)	Simulated Delay (sec/veh)
Lamar Blvd. and Koenig Lane			
	Eastbound Approach	95	56
	Westbound Approach	59	49
Lamar Blvd. and North Loop			
	Eastbound Approach	79	61
	Northbound Approach	68	26
	Southbound Approach	9	28
45th Street and Guadalupe Street			
	Eastbound Approach	110	70
	Westbound Approach	50	59
	Northbound Approach	31	52
	Southbound Approach	36	52
38th Street and Guadalupe Street			
	Eastbound Approach	26	35
	Westbound Approach	29	43
	Northbound Approach	27	40
	Southbound Approach	34	34

As shown in Table 3.1, simulation delay measurements seem to be "smoothed" in comparison to field measured delay. The variation in the simulated delays across different approaches is smaller than the variation in delays occurring in the field. However, the peak period TRAF-Netsim model seems to capture performance trends over different approaches, such as the high delay occurring along the Eastbound approach of 45th Street. Therefore, this model seems capable of capturing the impacts of various transit signal priority strategies.

Table 3.2 shows the results of the calibration for the off-peak TRAF-Netsim models. As shown in Table 3.2, the off-peak simulation models behave similarly to the peak period simulation model. Unlike the field measured delay statistics, simulated delay measurements do not exhibit large variations across different approaches.

TABLE 3.2 COMPARISON OF FIELD MEASURED AND SIMULATED DELAY DURING OFF-PEAK TIMES

		Measured Delay (sec/veh)	Simulated Delay (sec/veh)
Lamar Blvd. and Koenig Lane			
	Eastbound Approach	23	39
	Westbound Approach	23	35
Lamar Blvd. and North Loop			
	Eastbound Approach	30	37
	Northbound Approach	22	12
	Southbound Approach	8	20
45th Street and Guadalupe Street			
	Eastbound Approach	31	26
	Westbound Approach	26	33
	Northbound Approach	16	27
	Southbound Approach	22	33
38th Street and Guadalupe Street			
	Eastbound Approach	24	25
	Westbound Approach	23	35
	Northbound Approach	17	13
	Southbound Approach	19	17

However, trends in delay over different approaches are captured by the off-peak TRAF-Netsim model. Therefore, this model seems equipped to simulate transit signal priority consequences.

SUMMARY

Computer simulation was chosen to assist the evaluation of transit signal priority because of the analysis richness and time savings it affords. Computer simulation models allow one to analyze alternative signal priority strategies, and the sensitivity of these strategies to various traffic parameters, in a fraction of the time required by a comparable field testing plan.

TRAF-Netsim was chosen to simulate the effects of transit signal priority for a number of reasons. As a micro-simulation model, TRAF-Netsim offers a clear look at the potential effects of implementing various signal priority strategies. In addition, active transit signal priority can be readily modeled with TRAF-Netsim using multiple time periods, while the graphical animation feature aids in determining where and when buses need signal priority. Finally, variability in results over numerous simulations can be observed using multiple random number seeds within TRAF-Netsim.

Traffic simulation models for local bus operations during the peak hours, and local and express bus operations during the off-peak hours were developed. Traffic volumes and turning percentages along the Guadalupe-N. Lamar case study arterial taken from a previous study were combined with data on signal timings, link lengths, lane channelizations, and bus operations to create 3 simulation models. Once developed, these models were calibrated using field measured delay statistics along selected approaches during both peak and off-peak times.

CHAPTER 4. OFF-PEAK TIME PERIOD TRANSIT SIGNAL PRIORITY

INTRODUCTION

Use of transit signal priority during the off-peak hours is promising because excess capacity available within the transportation network can be used for transit's advantage. This chapter will describe and evaluate several strategies for providing signal priority for local and express transit service during off-peak times.

These strategies include two passive priority techniques, reduced signal cycle lengths and split phasing, which will be evaluated with respect to local transit service. In addition, unconditional priority, an active form of transit signal priority, will be evaluated in conjunction with express transit service.

LOCAL TRANSIT SERVICE

Capital Metro, which is the transit agency that operates buses along the Guadalupe-N. Lamar case study arterial in Austin, Texas, provides local bus service using 10 minute headways during off-peak times. Therefore, 10 minute bus headways will be assumed within subsequent analyses involving off-peak hour local bus service.

Reducing Traffic Signal Cycle Lengths

If traffic signals along an arterial share common cycle lengths, signal progression can be implemented along the arterial. The duration of this common cycle length is a parameter crucial to operational effectiveness. Long cycle lengths (cycle lengths greater than 100 seconds) tend to maximize vehicle throughput along an arterial for several reasons. First, the percentage of "lost" time (start-up time and amber time) at intersections decreases with increasing cycle lengths. In addition, long cycle lengths help widen arterial progression through bands.

However, the drawback to this large throughput is substantial stopped delay experienced by many vehicles at intersections along the arterial. Long red phases result from long cycle lengths, causing expected intersection stopped times to grow as the cycle length grows [Ref 31].

Traditionally, the use of long cycle lengths is reserved for peak hours, while shorter cycle lengths are used during off-peak hours. During peak hours, high vehicle throughput is necessary to accommodate high peak period traffic volumes. However, during off-peak hours, shorter cycle lengths may be used because less vehicle throughput is needed to accommodate lower off-peak traffic volumes. These short cycle lengths help maintain reasonable stopped delay levels for vehicles along the arterial and cross streets.

In addition, short cycle lengths can also be used as a passive priority strategy for transit vehicles [Ref 1]. By minimizing stopped time delay incurred by a transit vehicle along its route, short cycle lengths allow transit vehicles to traverse their routes in a timely fashion.

Using short cycle lengths as a passive transit signal priority strategy is appealing for several reasons. First, benefits to transit can be realized with little monetary cost. Active transit signal priority usually requires installation and maintenance of expensive electronic devices which detect the presence of transit vehicles and alter intersection signal timing favoring transit vehicles. However, implementing a policy of short cycle lengths along an arterial is a passive form of transit signal priority and is, therefore, in effect even in the absence of transit vehicles. Therefore, passive transit signal priority can be implemented at a much lower cost than active transit signal priority.

In addition, unlike most forms of active transit signal priority, a policy of short cycle lengths does not penalize vehicles along the cross streets by using a portion of their green time to favor transit vehicles. Therefore, all vehicles within the arterial network stand to benefit from short cycle lengths during off-peak hours.

It is important to note, however, that intersections with short cycle lengths have less capacity than intersections with long cycle lengths. In addition, demand at an intersection varies from cycle to cycle. Therefore, a buffer (in the form of excess capacity) is needed at an intersection to allow it to withstand variations in traffic volumes along its approaches. Long cycle lengths offer the advantage of a large buffer, allowing the intersection to resist cycle failures even when variations in traffic volumes bring sharp demand increases to the intersection. Short cycle lengths have smaller buffers because they have less excess capacity than long cycle lengths. Therefore, variations in demand at an intersection with a short cycle length may cause demand to temporarily exceed capacity. If this occurs often, the intersection will perform poorly and vehicles will experience large delays. Therefore, when implementing a policy of short cycle lengths along an arterial, attention should be given to the 1 or 2 busiest intersections along the arterial to ensure that adequate buffer capacity exists.

Evaluation of Reduced Cycle Lengths as a Passive Priority Strategy

Test Methodology. The effectiveness of granting passive signal priority to transit vehicles with shortened cycle lengths was evaluated using TRAF-Netsim. TRAF-Netsim was used to simulate 60 minutes of off-peak traffic along the Guadalupe-N. Lamar case study arterial using both existing off-peak cycle lengths and shortened cycle lengths. The existing off-peak cycle lengths along the Guadalupe-N. Lamar arterial are 100 seconds. Passive priority was implemented by reducing these cycle lengths to 70 seconds.

To maintain an unbiased comparison between the base case and the passive priority case, Kell's Method [Ref 31] was used to determine offsets of the signals along the arterial for the base case and the passive priority case. Kell's Method maximizes progression in both directions of an arterial by using signal offsets equal to either 0, the arterial's common cycle length, or one half of the arterial's common cycle length. After determining signal offsets with Kell's method, the base case and passive priority case exhibited similar time-space diagrams.

To account for variability over simulation runs, 3 replicate runs of the base and passive priority case were simulated using 3 random number seeds within TRAF-Netsim.

Cumulative delay statistics along the cross streets and the arterial and average bus travel times along the arterial were generated by TRAF-Netsim for the base case and the passive priority case. The cumulative delay statistics were converted to level of service (LOS) measures ranging from A to F. The traffic conditions associated with each LOS measure are summarized as follows [Ref 20]:

Level of Service A: This service level corresponds to delays less than 5.0 seconds per vehicle. These conditions arise when favorable progression exists and most vehicles can traverse the intersection without stopping.

Level of Service B: This service level corresponds to delays ranging from 5.1 to 15.0 seconds per vehicle. Good progression still exists under these conditions, but more vehicles stop than with LOS A.

Level of Service C: This service level corresponds to delays ranging from 15.1 to 25.0 seconds per vehicle. More noticeable delays begin to surface under these conditions as many vehicles are forced to stop at the intersection.

Level of Service D: This service level corresponds to delays ranging from 25.1 to 40.0 seconds per vehicle. Traffic congestion becomes apparent under these conditions as the proportion of vehicles forced to stop at the intersection continues to grow.

Level of Service E: This service level corresponds to delays ranging from 40.1 to 60.0 seconds per vehicle. Under these conditions, traffic congestion is on the verge of becoming unacceptable. Most vehicles are forced to stop at the intersection and cycle failures frequently occur.

Level of Service F: This service level corresponds to delays above 60.0 seconds per vehicle. This is considered an unacceptable delay level and often results from oversaturated conditions, where the capacity of the intersection is exceeded by the vehicle arrival rates at the intersection.

Results. Table 4.1 indicates that a 70 second cycle length benefits buses by reducing the average bus travel time. Average bus travel times along the Northbound route decreased from 797 seconds with the use of 100 second cycles to 768 seconds with the use of 70 second cycles. Benefits to the Southbound bus route are even more impressive, as the average travel time dropped 11%, from 814 seconds to 725 seconds with the use of passive signal priority.

TABLE 4.1 EFFECT OF SHORTENED CYCLE LENGTHS UPON BUS TRAVEL TIMES AND AUTO DELAY

	Base Case (100 Second Cycle Length)					*Passive Priority (70 Second Cycle Length)*				
	Run 1	Run 2	Run 3	**Average**		Run 1	Run 2	Run 3	**Average**	
Ave. NB Bus Trip (sec)	800.8	789.4	800.1	**797**		780.6	765.6	759.0	**768**	
Ave. SB Bus Trip (sec)	823.9	805.8	810.9	**814**		739.6	697.2	739.2	**725**	
Cumulative Sidestreet Delay (sec/veh)					LOS					LOS
Koenig Lane (EB)	35.8	37.5	37.6	**37**	D	32.6	31.4	32.2	**32**	D
Koenig Lane (WB)	37.4	37.8	36.5	**37**	D	30.2	30.4	29.7	**30**	D
N. Loop (EB)	37.0	35.3	35.2	**36**	D	26.2	25.6	28.1	**27**	D
N. Loop (WB)	37.5	34.5	36.5	**36**	D	27.8	26.0	27.5	**27**	D
51st Street (WB)	25.7	25.9	28.9	**27**	D	18.9	21.4	20.7	**20**	C
45th Street (EB)	58.0	55.7	56.1	**57**	E	35.9	34.1	33.8	**35**	D
45th Street (WB)	32.4	31.5	31.6	**32**	D	24.7	24.2	23.1	**24**	C
38th Street (EB)	25.6	26.6	26.4	**26**	D	20.9	21.7	22.3	**22**	C
38th Street (WB)	30.8	32.4	35.3	**33**	D	25.2	26.0	27.5	**26**	D
30th Street (EB)	29.5	18.0	25.3	**24**	C	23.5	20.2	20.1	**21**	C
30th Street (WB)	41.2	41.2	39.4	**41**	E	28.9	29.0	29.5	**29**	D
Cumulative Arterial Delay (sec/veh)										
NB at 30th	26.1	27.2	27.4	**27**	D	19.2	19.6	19.4	**19**	C
NB at 38th	15.2	14.1	14.3	**15**	B	16.6	15.2	16.4	**16**	C
NB at 45th	30.3	26.7	26.1	**28**	D	14.4	15.7	14.1	**15**	B
NB at Lamar	41.2	36.3	38.8	**39**	D	31.3	32.1	31.5	**32**	D
NB at 51st	7.0	6.6	7.9	**7**	B	7.3	7.6	8.0	**8**	B
NB at N. Loop	21.4	19.7	24.2	**22**	C	19.6	19.8	20.4	**20**	C
NB at Koenig	15.2	16.9	15.6	**16**	C	15.1	16.1	13.7	**15**	B
SB at N. Loop	29.8	30.1	31.5	**30**	D	20.1	19.8	19.9	**20**	C
SB at 51st	8.7	8.3	8.1	**8**	B	6.3	6.3	6.2	**6**	B
SB at Lamar	29.6	32.5	32.2	**31**	D	23.2	23.7	22.7	**23**	C
SB at 45th	42.2	42.7	43.8	**43**	E	21.6	21.0	22.8	**22**	C
SB at 38th	30.9	31.6	29.4	**31**	D	11.6	11.3	12.5	**12**	B
SB at 30th	12.8	13.0	13.3	**13**	B	19.3	20.1	20.8	**20**	C

Table 4.1 shows that private automobiles on the arterial and cross streets also benefit from 70 second cycle lengths. Except for a few instances, a 70 second cycle length causes a

reduction in the delay per vehicle along these approaches. Figure 4.1 shows a histogram of the LOS along the arterial and cross street approaches for the base case, where a 100 second cycle length is used.

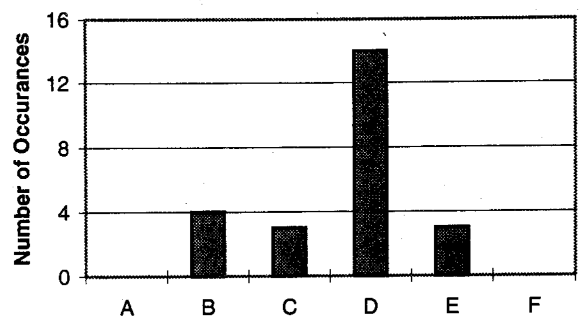


Figure 4.1 Histogram of the LOS at approaches in network (base case)

By contrast, Figure 4.2 shows this same histogram when a 70 second cycle length is used along the arterial.

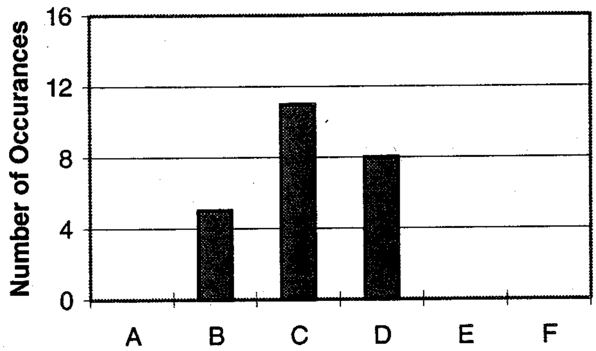


Figure 4.2 Histogram of the LOS at approaches in network (passive priority)

As shown in Figure 4.1, when a 100 second cycle length is used, many approaches experience delays corresponding to level of service D, with a few approaches even experiencing delays corresponding to level of service E. However, when passive signal priority is introduced by using a 70 second cycle length, the majority of the approaches experience delays corresponding to level of service C, while no approach experiences delays corresponding to level of service E.

An arterial's optimal off-peak cycle length, determined primarily by its off-peak volume, will most likely differ from its optimal peak period cycle length. This analysis shows both buses and private vehicles benefit when the cycle length along an arterial is pushed closer to its optimum value in response to its lower off-peak traffic volumes.

Split Phasing

Split phasing is another form of passive transit signal priority which may be useful during off-peak hours. The concept of split phasing is illustrated in Figure 4.3 [Ref 1]. Under normal phasing, if a bus arrives at the intersection on a red signal indication, it may have to wait the length of phases B and C before it receives a green indication with phase A. With split phasing, if a bus receives a red indication, it will only wait at most the length of phase B or phase C before receiving its green indication.

Split phasing essentially shortens a bus' cycle length, while maintaining the signal's original cycle length. As stated in the last section, short signal cycles benefit buses, but also reduce the capacity of the intersection. With split phasing, the bus receives the benefit of a shortened cycle, while not greatly sacrificing the intersection capacity.

Also, like shortened cycle lengths, split phasing is a passive form of transit signal priority. Therefore, split phasing can be implemented by simply changing the controls at intersections where split phasing is to be used. This makes it an inexpensive alternative to active transit signal priority.

The most apparent drawback to split phasing lies in the increased number of phases. As can be seen in Figure 4.3, the normal phasing plan requires only 3 phases, while the split phasing plan requires 4 phases. Therefore, additional start-up and amber times are introduced with split phasing, which lowers the intersection capacity slightly. Therefore, use of split phasing should be reserved for off-peak periods, when intersections typically operate with excess capacity.

In addition, split phasing can only be used when at least 2 non-bus phases exist within the timing plan for every bus phase, allowing a portion of bus' original phase to be inserted between the 2 non-bus phases.

Evaluation of Split Phasing as a Passive Priority Strategy

Test Methodology. Split phasing was evaluated using TRAF-Netsim by splitting bus phases at most intersections along the Guadalupe-N. Lamar case study arterial and comparing the resulting delays and bus travel times to those of the base case. Off-peak traffic volumes were used within the analysis.

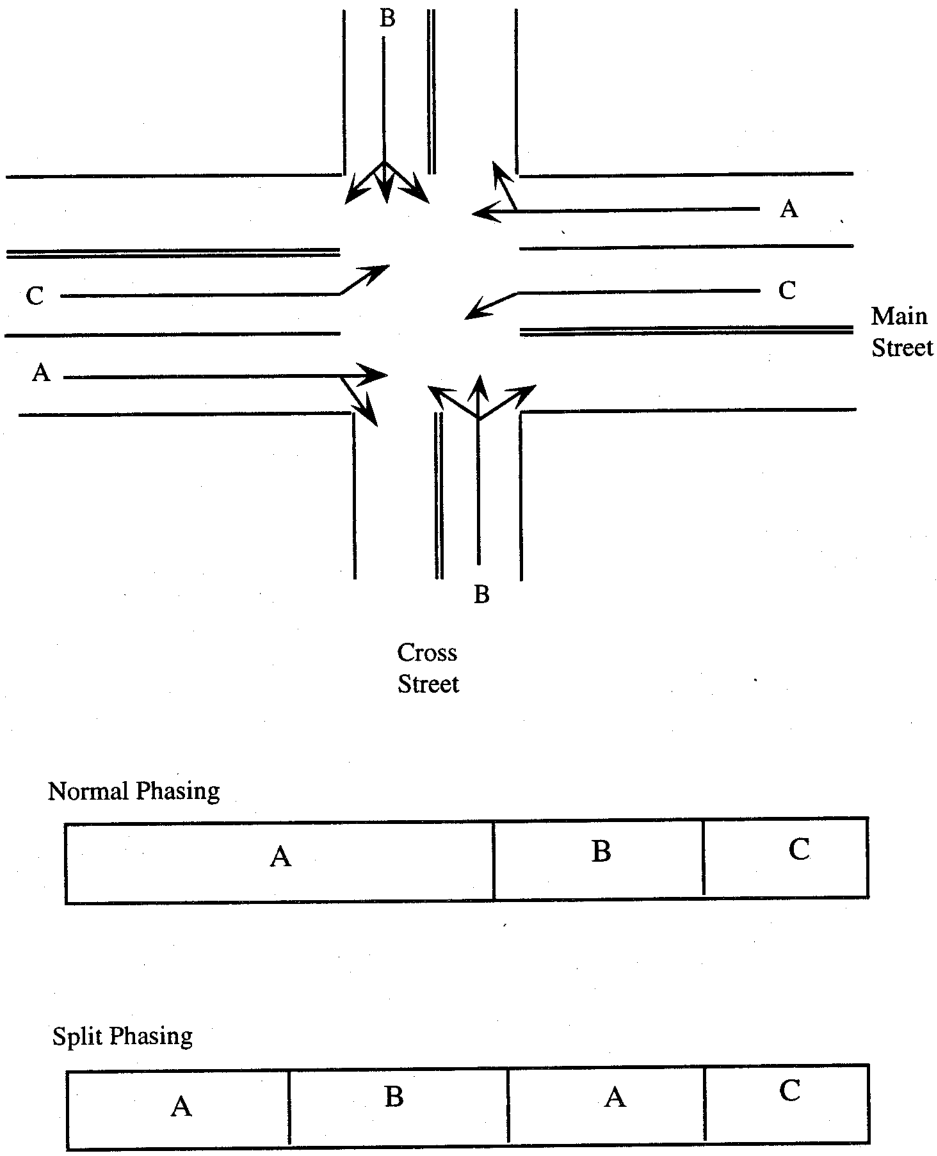


Figure 4.3 Passive transit signal priority with split phasing [Ref 1]

As mentioned previously, split phasing requires at least 2 non-bus phases for every bus phase. Several signal timings along the Guadalupe-N. Lamar case study arterial failed to meet this requirement. Therefore, split phasing could not be implemented at these intersections. These intersections include the junctions of Guadalupe Street with Lamar Boulevard (node 4), 41st Street (node 6) and 34th Street (node 8). However, split phasing was simulated at the remaining 8 arterial intersections.

As with the previous analysis involving reduced signal cycle lengths, the duration of each TRAF-Netsim simulation was 1 hour. Also, 3 random number seeds were used within TRAF-Netsim to create 3 replicate observations of the effects of split phasing, accompanied by 3 base cases where the bus phase was not split.

Results. As shown in Table 4.2, the impact of split phasing on bus performance is mixed. The Northbound bus benefits from split phasing, as its average travel time drops by nearly 10% from 841 seconds to 757 seconds. However, the Southbound bus does not benefit from split phasing. Its average travel time actually increases slightly from 751 seconds to 767 seconds.

Table 4.2 further shows that split phasing has a minimal impact upon delay along the cross streets. Only at the 45th Street Eastbound and 30th Street Eastbound approaches does the cumulative delay decrease significantly with the use of split phasing. Since split phasing does not impact the amount of cross street green time, this result is not surprising.

However, this analysis assumes that signal progression is not present along the cross streets. Although split phasing does not affect the amount of green time along the cross streets, Figure 4.3 shows that it does impact the offsets of the cross street green indications. If progression is provided along a cross street, the use of split phasing should be cautioned because split phasing may disrupt signal progression.

Finally, Table 4.2 shows that, with a few exceptions, split phasing has little significant impact upon delay experienced along the arterial approaches. The Southbound approaches of 45th Street, 30th Street, and Lamar Boulevard are the only arterial links which see significant delay changes with the use of split phasing. This also stands to reason since split phasing does not affect the overall green time allocated to the arterial approaches.

The offsets used within this analysis were not optimized to provide progression along the arterial. Rather, the offsets used in the base case were taken directly from the signal timing plans used by the City of Austin. However, if existing offsets provide signal progression along the arterial, the use of split phasing may disrupt this progression. Therefore, when using split phasing, consideration should be given to resetting the arterial offsets based on the split phasing timing. Although the resulting progression bandwidth would probably not be as wide as the original, due to the shorter green phases which the arterial receives with split phasing, stopped delay along the arterial would be reduced.

TABLE 4.2 EFFECT OF SPLIT PHASING UPON BUS TRAVEL TIMES AND AUTO DELAY

	Base Case (Off-Peak Local Bus)					Passive Priority (Split Phasing at Most Int'ns)				
	Run 1	Run 2	Run 3	Average		Run 1	Run 2	Run 3	Average	
Ave. NB Bus Trip (sec)	827.2	810.4	886.1	841		791.6	712.1	767.3	757	
Ave. SB Bus Trip (sec)	772.0	727.2	754.5	751		793.1	747.6	761.1	767	
Cumulative Sidestreet Delay (sec/veh)					LOS					LOS
Koenig Lane (EB)	38.6	38.4	36.9	38	D	36.1	38.1	35.0	36	D
Koenig Lane (WB)	36.7	36.5	36.1	36	D	37.6	36.2	37.4	37	D
N. Loop (EB)	35.0	34.0	37.5	35	D	33.1	34.9	35.8	35	D
N. Loop (WB)	34.4	34.8	35.9	35	D	36.0	33.7	37.1	36	D
51st Street (WB)	24.9	27.2	27.6	27	D	27.0	24.8	26.3	26	D
45th Street (EB)	19.2	20.4	17.7	19	C	10.3	11.9	8.4	10	B
45th Street (WB)	33.8	33.5	33.9	34	D	33.7	32.4	33.3	33	D
38th Street (EB)	24.3	26.3	25.4	25	D	24.4	25.8	24.7	25	C
38th Street (WB)	32.3	33.7	33.5	33	D	31.0	31.8	33.6	32	D
30th Street (EB)	24.3	23.9	24.0	24	C	22.2	21.8	15.5	20	C
30th Street (WB)	29.2	30.8	28.2	29	D	29.3	29.7	26.5	29	D
Cumulative Arterial Delay (sec/veh)										
NB at 30th	11.0	10.7	10.5	11	B	9.2	9.2	8.8	9	B
NB at 38th	19.9	18.7	19.6	19	C	18.7	17.7	18.6	18	C
NB at 45th	34.2	35.8	35.2	35	D	31.6	28.9	31.9	31	D
NB at Lamar	20.1	18.3	19.0	19	C	20.4	18.0	18.7	19	C
NB at 51st	8.2	7.6	10.2	9	B	12.5	11.4	13.6	12	B
NB at N. Loop	22.4	23.9	21.7	23	C	23.4	22.9	24.5	24	C
NB at Koenig	28.8	29.3	29.4	29	D	25.5	27.3	29.1	27	D
SB at N. Loop	21.7	21.8	22.4	22	C	21.8	21.8	20.3	21	C
SB at 51st	12.5	12.6	13.4	13	B	11.5	12.1	11.7	12	B
SB at Lamar	22.5	21.9	21.8	22	C	32.5	31.6	29.6	31	D
SB at 45th	43.4	43.7	43.4	43	E	16.6	19.0	15.7	17	C
SB at 38th	20.3	21.0	19.7	20	C	17.6	18.1	16.2	17	C
SB at 30th	27.0	25.3	26.9	26	D	8.5	10.1	7.9	9	B

EXPRESS TRANSIT SERVICE

Capital Metro provides express bus service using 30 to 60 minute headways during off-peak hours. A 30 minute bus headway has been assumed for the subsequent analysis involving express bus service during off-peak hours.

Unconditional Priority

Unconditional priority is an active transit signal priority strategy where transit vehicles receive signal priority at intersections upon request, regardless of the cross street queue lengths or the time since priority was last used [Ref 1]. Unconditional priority typically makes use of green extensions, where a transit vehicle's green phase is lengthened by a predetermined amount, or red truncations, where a transit vehicle's red phase is prematurely terminated in favor of a green phase. The extra green time allocated to the transit vehicle approach through the use of green extensions or red truncations is taken from the cross streets, allowing the intersection cycle length to remain fixed.

While unconditional priority offers significant potential for transit, vehicles traveling on cross streets may feel severe negative impacts from its usage. Therefore, the use of unconditional priority should be reserved for express bus service during off-peak hours. Express bus service uses longer headways than local bus service, resulting in fewer priority calls over time, while off-peak traffic volumes enable cross streets to recover from each priority call more quickly than during the peak period.

The cross street degree of saturation (also known as its saturation level) and the length of green extensions or red truncations made available to express buses, are critical parameters to the success of unconditional priority. If too much time is taken from highly saturated cross streets, the effect of one transit priority call may be felt along the cross street long after the bus has departed the intersection.

By definition, the degree of saturation, S, of an approach is defined as follows [Ref 31]:

$S = q/(l*s*n)$ where

q = volume along the approach (vehicles/hour)

l = g/c ratio (green and amber time of approach/cycle time)

s = saturation flow rate per lane (vehicles/hour)

n = number of lanes on approach

Cross streets with high saturation levels will be more severely impacted by unconditional priority than cross streets with low saturation levels. At low saturation levels, a cross street enjoys sufficient excess capacity to recover from its temporary green time loss. However, as a cross street's saturation level increases, its green time becomes more precious, and any loss of green time may result in a significant increase in delay which may not dissipate before the next bus arrival. This analysis will examine the effects of unconditional priority over cross streets with a range of saturation levels in order to develop guidelines for unconditional priority usage.

The length of green extensions or red truncations used with unconditional priority will also be analyzed. As more green time is taken from cross streets to benefit transit, delays along cross streets increase. The cross street's ability to recover from this delay will depend on its saturation level. Guidelines will be developed indicating the appropriate green extension or red truncation length to be used in conjunction with various cross street saturation levels.

Evaluation of Unconditional Priority

Test Methodology. The impact which unconditional priority has upon cross streets with various saturation levels was determined by performing several analyses. The first analysis used TRAF-Netsim to examine how often unconditional priority would likely be triggered at the intersections along the Guadalupe-N. Lamar case study arterial. Then, using the results from this analysis, a sensitivity analysis was performed using TRAF-Netsim to determine the effects of unconditional priority over a range of cross street saturation levels and green extension or red truncation lengths.

The first analysis was performed by implementing unconditional priority along the Guadalupe-N. Lamar case study arterial using TRAF-Netsim's multiple time periods, as well as its animation feature. The results of an initial simulation which did not use unconditional priority were observed using TRAF-Netsim's animation. The Northbound bus was tracked over its route and unconditional priority was given to the bus upon encountering an intersection where it needed signal priority. Unconditional priority was simulated using TRAF-Netsim by inserting a time period (the duration of 1 cycle length) into the simulation which provided the priority signal timing at the intersection in question as the bus arrived. After the bus departed from the intersection, its normal signal timing was restored. This procedure was repeated along the arterial until the Northbound bus exited the network. Then, unconditional priority was also granted to the Southbound bus using the same procedure.

Unconditional priority was implemented along the Northbound and Southbound bus routes in this fashion using 3 separate TRAF-Netsim simulations which used 3 different random number seeds. Therefore, a total of 6 buses (3 Northbound and 3 Southbound) approached most intersections along the arterial over the 3 simulations.

Results. Table 4.3 shows how unconditional priority affected the bus travel times along the Guadalupe-N. Lamar case study arterial.

TABLE 4.3 UNCONDITIONAL PRIORITY IMPACTS ON EXPRESS BUS TRAVEL TIMES (SECONDS)

	Base Case (Off-Peak Express Bus)				*Unconditional Priority for NB & SB Buses*			
	Run 1	Run 2	Run 3	Average	Run 1	Run 2	Run 3	Average
Northbound Bus	427.6	350	528.2	435	372.8	337.8	353.9	355
Southbound Bus	471.5	532.5	460.7	488	422.7	367.9	378.1	390

Table 4.3 clearly demonstrates that unconditional priority reduced express bus travel times. Unconditional priority reduced the average Northbound and Southbound bus travel times by 18% and 20%, respectively. For this analysis, however, the length of the green extensions and red truncations used was unbounded. Therefore, bus travel time savings shown in Table 4.3 reflect upper bounds on travel time savings which unconditional priority offers. Had limits been placed on the lengths of green extensions and red truncations that were used, bus travel time savings would not have been quite as significant.

Table 4.4 shows how often signal priority was used at selected intersections along the Guadalupe-N. Lamar case study arterial.

TABLE 4.4 PERCENT OF TIME PRIORITY USED AT INTERSECTIONS

Intersection	No. of Bus Arrivals	No. of Priority Calls	% Priority Needed
North Loop & Lamar	6	2	33%
51st Street & Lamar	6	1	17%
45th Street & Guad'lp	6	3	50%
38th Street & Guad'lp	6	6	100%
30th Street & Guad'lp	6	2	33%

These results indicate that unconditional priority will be used in varying amounts depending on the cross street volume present. Where the cross street volume is light, such as the intersection of 51st Street and Guadalupe Street, unconditional priority will rarely be triggered by the bus because the bus approach already owns a large fraction of intersection green time. In addition, this high proportion of green time tends to keep queue lengths and delays at low levels along the bus approach, which further reduces the bus' need for unconditional priority.

As the cross street volume grows, the bus' need for unconditional priority will likely grow also. This results because the bus approach enjoys a smaller fraction of intersection green time. Therefore, the bus will more likely encounter a red signal indication or a queue upon arriving at the intersection.

At the intersection of 45th Street and Guadalupe Street, for instance, moderate traffic levels along 45th Street result in the bus' need for priority 50% of the time. Further, at the intersection of 38th Street and Guadalupe Street, where significant cross street traffic levels are present, buses were in need of priority every time they approached the intersection over the 3 replicate simulation runs.

The intersections along the Guadalupe-N. Lamar study corridor may be grouped into several categories as follows:

1) Low to Moderate Cross Street Traffic: Signal priority often not needed along the bus approach because it already owns a large proportion of green time, due to light to moderate traffic along the cross street.
2) Moderate to Heavy Cross Street Traffic: Signal priority often needed along the bus approach, as its share of green time drops to accommodate moderate to heavy cross street traffic levels.

The next analysis will examine the effects of varying green extension and red truncation lengths and cross street saturation levels at intersections which fall under these 2 categories.

Test Methodology. To determine how sensitive various intersections are to changes in green extension and red truncation lengths as well as cross street saturation levels, 2 separate simulation analyses for the off-peak period were performed using the TRAF-Netsim model.

The first analysis examined the impact which unconditional priority had on the Eastbound approach of 38th Street, a cross street with heavy traffic. Within this analysis, unconditional priority with varying green extension and red truncation lengths was simulated. In particular, green extension or red truncation lengths available to the buses included 10 seconds of additional green, 20 seconds of additional green, and an unlimited amount of additional green as needed for the bus to traverse the intersection.

The existing off-peak saturation level along the Eastbound approach of 38th Street was estimated at 0.62, based on traffic counts for that approach and an assumed saturation flow rate of 1800 vehicles per hour [Ref 20]. Volumes along this approach were varied using TRAF-Netsim to simulate saturation levels of 0.70 and 0.50 respectively, in addition to the existing saturation level of 0.62.

Unconditional priority was simulated at the Eastbound approach of 38th Street by taking green time from 38th Street in favor of the bus approach at 600 and 800 seconds into the simulation. Results of the previous analysis indicated that the Northbound bus typically requested priority at 38th Street 600 seconds into the simulation, followed by a priority request from the Southbound bus 200 seconds later. The effects of these priority calls were simulated until the next Northbound express bus was scheduled to arrive, at 2400 seconds.

Finally, 3 random number seeds in TRAF-Netsim were used to provide 3 runs over all scenarios which were simulated, resulting in the factorial experiment design shown in Table 4.5.

TABLE 4.5 FACTORIAL EXPERIMENT DESIGN FOR THE ANALYSIS OF UNCONDITIONAL PRIORITY IMPACTS ON THE EASTBOUND APPROACH OF 38TH STREET

38th Street EB Saturation Level	Bus Receives 10 Seconds of Added Green	Bus Receives 20 Seconds of Added Green	Bus Receives Unlimited Amount of Added Green
0.50	3 Observations	3 Observations	3 Observations
0.62	3 Observations	3 Observations	3 Observations
0.70	3 Observations	3 Observations	3 Observations

The second analysis examined the impact which unconditional priority had on the Westbound approach of 45th Street, a cross street with only light to moderate traffic during off-peak hours. This proceeded in a similar fashion to the last analysis. The existing degree of saturation along the Westbound approach of 45th Street was estimated at 0.38, based on measured traffic volumes along this approach [Ref 20]. Therefore, the volume along this approach was varied using TRAF-Netsim to simulate saturation levels of 0.25 and 0.50 respectively, in addition to the existing 0.38 saturation level.

As seen in the previous section, buses requested signal priority at the 45th Street and Guadalupe Street intersection 50% of the time. Therefore, for this analysis, only 1 priority call takes place, at 600 seconds into the simulation. The effect of this priority call is examined until the next priority call is expected a half hour later, at 2400 seconds. The factorial experiment design showing the effect of unconditional priority upon the Westbound approach of 45th Street is summarized in Table 4.6.

TABLE 4.6 FACTORIAL EXPERIMENT DESIGN FOR THE ANALYSIS OF UNCONDITIONAL PRIORITY IMPACTS ON THE WESTBOUND APPROACH OF 45TH STREET

45th Street WB Saturation Level	Bus Receives 10 Seconds of Added Green	Bus Receives 20 Seconds of Added Green	Bus Receives Unlimited Amount of Added Green
0.25	3 Observations	3 Observations	3 Observations
0.38	3 Observations	3 Observations	3 Observations
0.50	3 Observations	3 Observations	3 Observations

Results. Unlike the previous analyses involving passive transit signal priority, unconditional priority (an active form of signal priority) will typically have dramatic short-term effects upon an intersection before it recovers from the unconditional priority call. Therefore, instead of using the cumulative delay per vehicle at the conclusion of the simulation to compare alternative priority strategies to the base case, a measure which evaluates the effect of unconditional priority from cycle to cycle should be used.

As stated in Chapter 3, TRAF-Netsim generates output at the conclusion of each time interval. The time interval used in TRAF-Netsim typically corresponds to the most common cycle length used along the arterial, or 100 seconds for the Guadalupe-N. Lamar case study arterial during off-peak hours. Therefore, TRAF-Netsim updates the cumulative delay and vehicle arrivals every 100 seconds, over the duration of each simulation. For example, TRAF-Netsim's output for a particular link over a 10 minute simulation may look like the following:

Elapsed Simulation Time (seconds)	Cumulative Delay (sec)	Cumulative Vehicle Count (vehicles)
100	34	5
200	56	11
300	97	16
400	120	24
500	145	38
600	178	56

To transform these cumulative statistics into statistics which reflect the traffic conditions along the link from cycle to cycle, the cumulative delay at time (n-1) should be subtracted from the cumulative delay at time n, and divided by the number of vehicles processed between times n and (n-1) to obtain the delay per vehicle over the simulation time from (n-1) to n. For example, the delay per vehicle along this hypothetical link from 300 to 400 seconds is found with the following calculation:

$$\text{Delay (seconds/vehicle)} = (120 - 97)/(24 - 16)$$

$$\text{Delay} = 2.88 \text{ seconds/vehicle}$$

This calculation was performed over all 100 second time intervals to produce cycle by cycle measures of delay per vehicle over the duration of each simulation in the results which follow.

Figures 4.4 to 4.9 all show results of a single simulation run comparing the effects of 10 seconds, 20 seconds, and unlimited priority to the base case. These results are most representative of the trends observed over the 3 simulation runs performed with each scenario. A complete list of the figures showing results over all the simulation runs is supplied in the Appendix.

Eastbound Approach of 38th Street. Figure 4.4 shows the delay per vehicle along the Eastbound approach of 38th Street when signal priority is requested by buses 600 and 800 seconds into the simulation. The saturation level of this approach is approximately 0.70.

As can be seen in the figure, placing a 10 second limit on the amount of added green which the bus approach receives from the cross street limits the impacts to the Eastbound approach of 38th Street. The delay per vehicle experienced along this approach when a 10 second ceiling is placed on each signal priority call is only slightly higher than the delay experienced during the base case, when no signal priority is used. Placing a 20 second limit on each signal priority call results in significant delay increases along the cross street, as delay levels hover in the range of 45 seconds per vehicle for roughly 500 seconds.

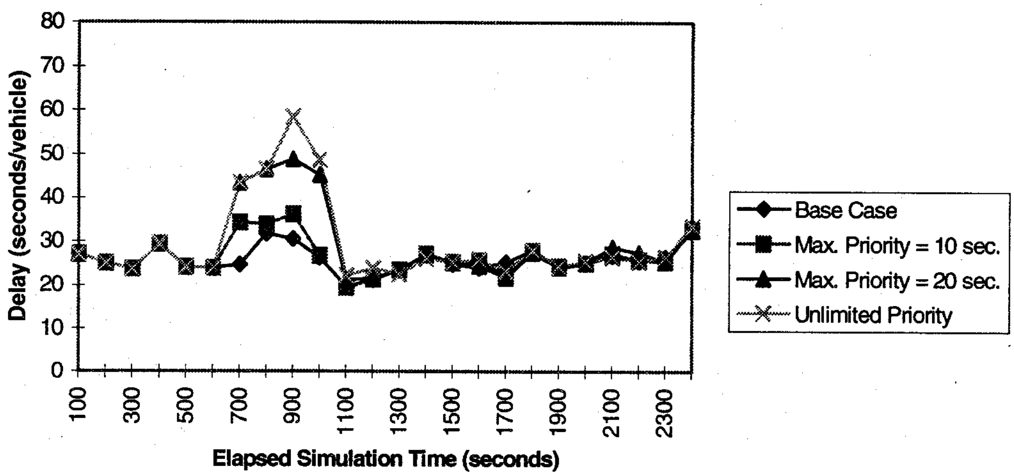


Figure 4.4 Delay at 38th Street Eastbound, saturation level = 0.70

Using unlimited priority hurts the cross street most severely, as the delay approaches 60 seconds per vehicle after the second priority call.

However, with a saturation level of 0.70, the Eastbound approach of 38th Street appears to have little trouble recovering from both signal priority calls before the next express bus is scheduled to arrive, at 2400 seconds. Figure 4.4 shows the delay returns to the base case delay level by about 1100 seconds, even when unlimited priority is used.

Figure 4.5 shows the impact which the various priority strategies has upon the Eastbound approach of 38th Street when its saturation level is 0.62. Figure 4.5 also indicates that placing a 10 second limit on each signal priority call limits the cross street impacts. Taking only 10 seconds of green away from the cross street produces slight increases in delay over the base case which is manifested shortly after each priority call.

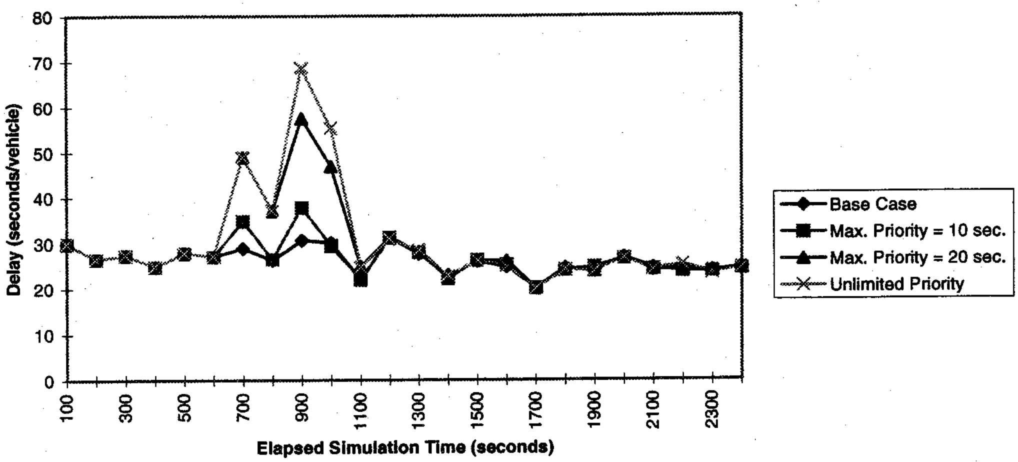


Figure 4.5 Delay at 38th Street Eastbound, saturation level = 0.62

Limiting the amount of signal priority to 20 seconds, however, has almost the same impact to the cross street as unlimited priority. Delay approaches 60 seconds per vehicle after the second priority call when 20 seconds of signal priority is used, while unlimited priority causes delay to approach 70 seconds per vehicle.

As expected, with a saturation level of 0.62, the Eastbound approach of 38th Street has little trouble recovering from the effects of signal priority before the next scheduled express bus arrival. As the saturation level along this approach drops, its excess capacity enables it to quickly recover from signal priority.

Figure 4.6 shows the effects of unconditional priority on the Eastbound approach of 38th Street when its saturation level is 0.50. Once again, placing a 10 second limit on the amount of signal priority protects the cross street from significant delay increases.

Each 10 second priority call results in increased delay to the cross street, but these increases are minor (delay increases by about 7 seconds/vehicle) and is short-lived.

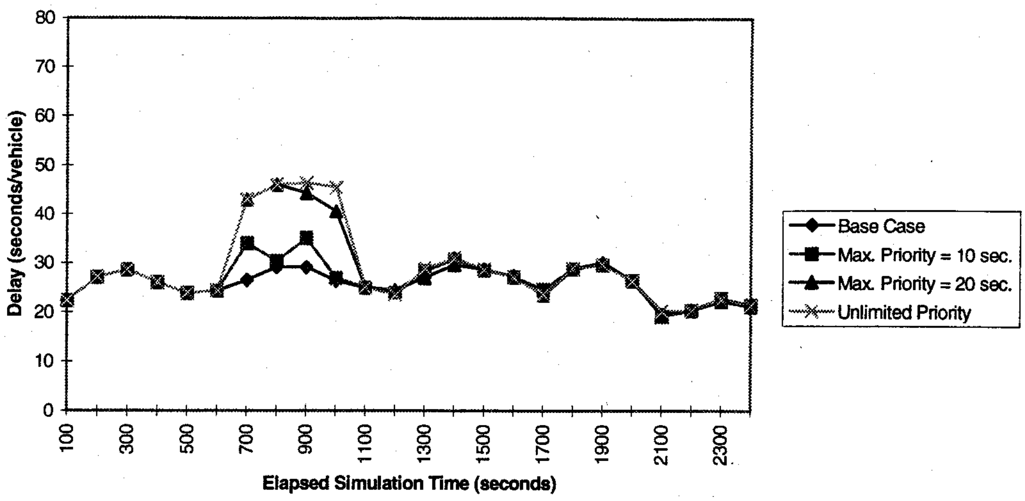


Figure 4.6 Delay at 38th Street Eastbound, saturation level = 0.50

Using a 20 second limit on priority and unlimited priority results in more significant increases in delay which impact the cross street for a longer time. Clearly, limiting the duration of green extensions or red truncations to 10 seconds is beneficial to cross streets with significant off-peak volume.

Westbound Approach of 45th Street. Figure 4.7 shows the effect on the Westbound approach of 45th Street from a signal priority call at 600 seconds. As stated previously, only 1 priority call is simulated for this analysis because the previous analysis showed that buses needed priority less frequently at the 45th Street intersection than at the 38th Street intersection.

As shown in Figure 4.7, unlimited priority continues to plague the cross street as a significant increase in delay lasting about 5 minutes results from its use. Both 10 second and 20 second priority calls, however, have little impact upon the delay along the Westbound approach of 45th Street when its saturation level is 0.50.

The previous analysis at the Eastbound approach of 38th Street indicated that the use of 20 seconds of priority has a significant impact upon that approach, even when its saturation level was only 0.50. Therefore, taking 20 seconds of green time away from cross streets with saturation levels of 0.50 remains questionable.

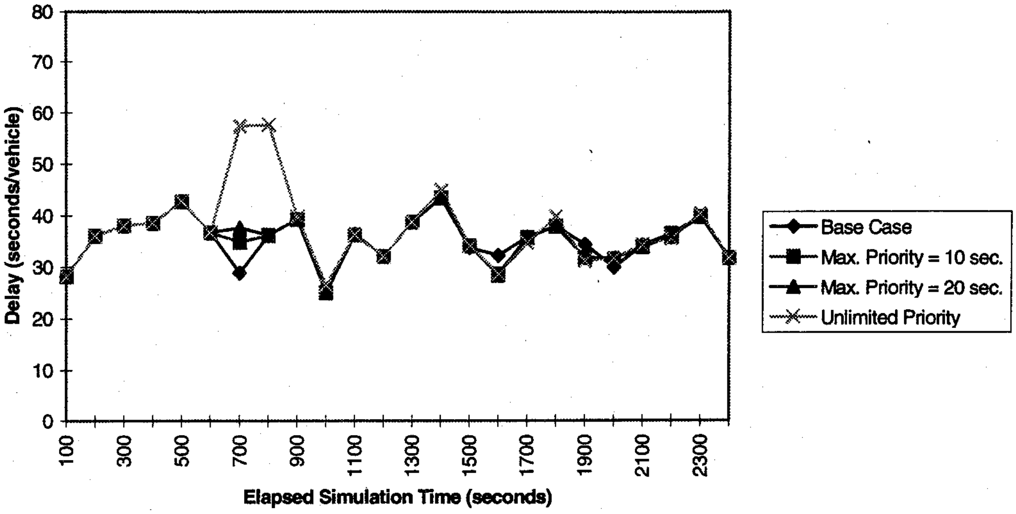


Figure 4.7 Delay at 45th Street Westbound, saturation level = 0.50

Figure 4.8 shows results similar to Figure 4.7, as the saturation level along the Westbound approach of 45th Street is 0.38. The use of an unlimited amount of green time from the cross street to benefit the bus results in a large increase in delay along Westbound approach of 45th Street.

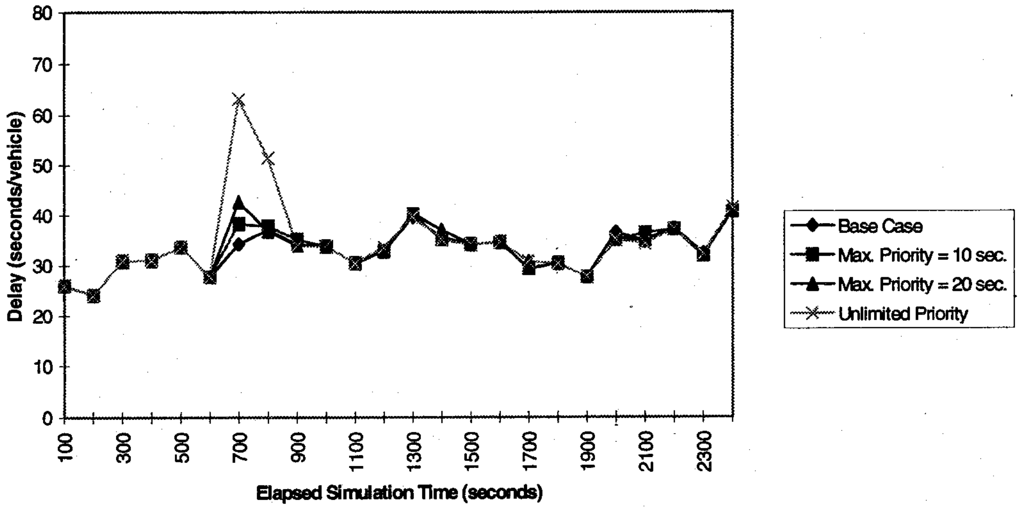


Figure 4.8 Delay at 45th Street Westbound, saturation level = 0.38

However, by placing a ceiling on the amount of green time which may be taken from the cross street, the negative effect of the priority call is reduced considerably. In fact, when the cross street saturation level is 0.38, taking 20 seconds of its green time to favor the bus approach does not appear to severely impact the cross street.

Figure 4.9 shows that when the cross street saturation level is reduced to 0.25, it enjoys enough excess capacity to quickly recover from even an unlimited priority call. Although the delay increase resulting from an unlimited priority call (which typically steals 30 to 40 seconds of green away from the cross street) was greater than the delay increases when limits were imposed on signal priority, the cross street was not severely impacted.

Therefore, when the cross street saturation levels at an intersection drop below 0.25, one might consider using an unlimited amount of signal priority at the intersection.

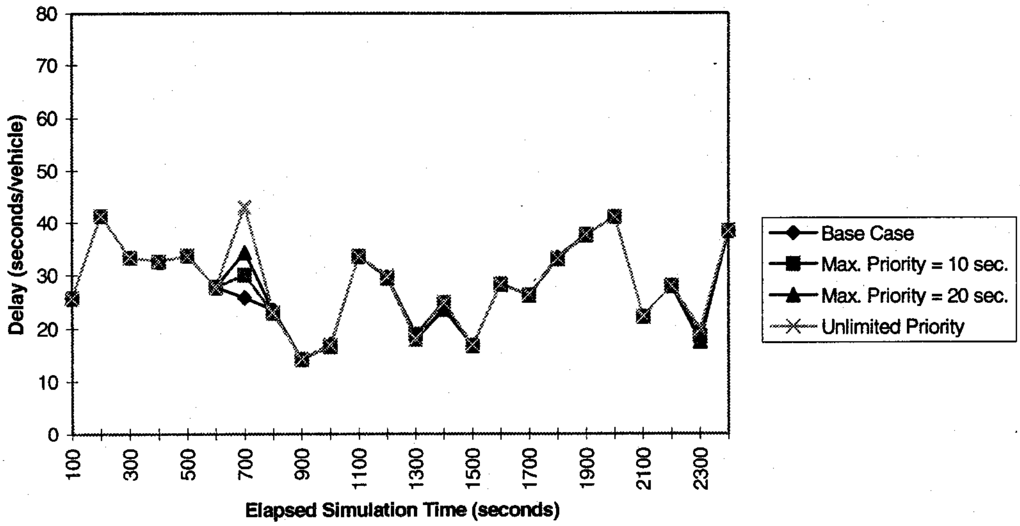


Figure 4.9 Delay at 45th Street Westbound, saturation level = 0.25

When the cross street saturation levels are lower than 0.25, the present signal timing should already heavily favor the bus approach. Therefore, the bus will often not need to use priority, and the amount of priority needed by the bus will typically be fairly small. These factors, combined with the cross street ability to quickly recover from its loss of green time, makes the use of unconditional priority feasible at cross streets with saturation levels below 0.25.

The results of the analysis of unconditional priority at the Eastbound approach of 38th Street and the Westbound approach of 45th Street are summarized in Table 4.7.

TABLE 4.7 GUIDELINES FOR THE USE OF UNCONDITIONAL PRIORITY DURING THE OFF-PEAK HOURS

Cross Street Saturation Level	Recommended Green Extension or Red Truncation Length
Below 0.25	Unbounded
0.25 to 0.35	20 Seconds
0.35 to 0.70	10 Seconds

As shown in the Table 4.7, increasing saturation levels along cross streets forces tighter restrictions on signal priority use. When the cross street saturation level grows, the frequency of signal priority use at intersections also grows because of increased competition for green time between the arterial and cross street. In addition, the ability of a cross street to recover from signal priority reduces as its saturation level increases. These two factors force greater control over unconditional signal priority at major intersections, even when used with express transit service during off-peak hours.

SUMMARY

Shortening cycle lengths is a passive form of transit signal priority which may be useful during off-peak hours. If the cycle length along an arterial has not been reduced too much from its peak period length, resulting in large amounts of excess capacity, reducing the arterial's common cycle length may help operate the arterial more efficiently. This benefits transit, as well as other vehicles along the arterial and cross streets, by reducing delay.

Split phasing is another form of passive transit signal priority which may be considered during off-peak hours. The overall effectiveness of split phasing remains somewhat uncertain. While split phasing reduced the Northbound bus travel time in the Guadalupe-N. Lamar network, it had little impact upon the Southbound bus performance. In addition, the use of split phasing is cautioned if signal progression currently exists along an arterial, or along its cross streets. However, split phasing offers an inexpensive alternative to active transit signal priority and does not take green time from cross streets.

Unconditional priority offers considerable potential for express transit during off-peak periods, especially when limits are not imposed on its green extension and red truncation lengths. However, unconditional priority also has considerable negative impacts upon major cross streets. Therefore, use of unconditional priority should be regulated at major cross streets by limiting green extension and red truncation lengths. At minor cross streets, limiting green extension and red truncation lengths becomes less important and unlimited priority may even be introduced, depending on the cross street saturation level. Unfortunately, transit vehicles will likely need signal priority most often at intersections with major cross streets, where signal priority should be regulated.

CHAPTER 5. PEAK TIME PERIOD TRANSIT SIGNAL PRIORITY

INTRODUCTION

Implementation of transit signal priority during peak time periods is more difficult than during off-peak time periods. Because both cross streets and arterials are likely to be operating at higher degrees of saturation than during off-peak times, less excess transportation network capacity is available to use for transit's benefit. Therefore, during peak time periods cross street traffic may feel the negative effects of a signal priority call, while transit vehicles are forced to compete with heavy arterial traffic to utilize the signal priority they have received. As a result, both positive and negative impacts resulting from the use of transit signal priority should be closely monitored in order to determine whether transit signal priority impacts the overall transportation network in a positive or negative fashion during the peak time period.

This analysis will answer the question of whether transit signal priority is a viable alternative during peak time periods for local bus operations within the case study arterial network under consideration. To do so, transit signal priority impacts upon cross streets will first be examined, followed by an investigation into the effectiveness of transit signal priority under varying degrees of arterial saturation and different bus stop locations. These analyses will provide general guidelines for determining the traffic conditions where transit signal priority is feasible, and will narrow the scope of the final two analyses which examine the overall effects of transit signal priority at an isolated intersection and an arterial network.

LOCAL TRANSIT SERVICE

All analyses in the remainder of this chapter are based on local bus operations during the peak time period. Because peak period travel patterns generally favor one direction (inbound direction during the morning peak and outbound direction during the evening peak), the assumption has been made that priority is used only by buses traveling in the peak direction. In addition, bus headways are assumed to be 10 minutes, based on the 1996 schedule from Capital Metro in Austin, Texas.

Impact of Transit Signal Priority Upon Cross Street Delay

This analysis will help quantify the effects which priority signal timings have upon the delay experienced along cross streets. Obviously one would expect cross street traffic delay to increase as a portion of its green time is used to provide priority to a bus traveling along an arterial. However, both the magnitude of this delay increase and the length of time this delay increase is sustained before the cross street fully recovers from a priority call are important considerations. Taking these considerations into account, this analysis will identify conditions favorable for transit signal priority usage.

Test Methodology. To observe the effects of transit signal priority on cross street delay during the peak time period, the delay calculated within TRAF-Netsim at several cross streets was monitored as green time was taken from these approaches and given to the bus approach in the form of a green extension. These delay statistics were compared to delay statistics collected along these cross street for the base case, where signal priority was not initiated. A factorial experiment design was developed where traffic and signal priority characteristics at several intersections were varied among simulation runs. In particular, the cross street degree of saturation and the length of the green time taken from the cross street to provide to the bus approach were varied over the different simulation runs. The resulting impacts were observed separately at two cross streets; the Eastbound approach at 38th Street and the Westbound approach at 45th Street. In order to account for the variability involved with each simulation, each particular scenario was simulated three separate times, resulting in the factorial experiment design shown in Table 5.1. A different random number seed was used for every run.

TABLE 5.1 FACTORIAL EXPERIMENT DESIGN FOR ANALYSIS OF TRANSIT SIGNAL PRIORITY EFFECTS UPON CROSS STREETS

Saturation Levels	Green Extension=10 Sec.	Green Extension=20 Sec.
38th Street Eastbound=0.8	3 Runs	3 Runs
38th Street Eastbound=0.9	3 Runs	3 Runs
38th Street Eastbound=1.0	3 Runs	3 Runs
45th Street Westbound=0.8	3 Runs	3 Runs
45th Street Westbound=0.9	3 Runs	3 Runs
45th Street Westbound=1.0	3 Runs	3 Runs

The total simulation time used for every run was 1 hour. Within each run, a transit signal priority timing was inserted in place of the normal signal timing at the particular intersection under examination once every 10 minutes. Since the cycle lengths at the intersections of 38th Street and Guadalupe and 45th Street and Guadalupe are 120 seconds, their normal timing plans were replaced by the signal priority timing every fifth cycle, during each 1 hour simulation.

This mimics the arrival of a bus requesting priority at the intersection under consideration once every 10 minutes (the assumed bus headway). However, in reality, most active signal priority systems are not triggered unless a transit vehicle requires priority to traverse an intersection without stopping. Therefore, when transit vehicles operate at 10 minute headways, signal priority should be triggered *at most* once every 10 minutes. Taking this into account, this analysis actually simulates the effects of priority occurring when used with a transit service providing headways slightly shorter than 10 minutes.

It is also important to note that only 5 seconds of green time are taken from 38th Street Eastbound or 45th Street Westbound during simulation runs involving 10 second green extensions for the bus approach. For instance, the 5 seconds of green time taken from the 38th Street Eastbound approach is complemented by 5 seconds of green time taken from the Westbound approach at 38th Street to provide a 10 second green extension for the bus approach. Similarly, during runs with 20 second green extensions, only 10 seconds of green time are taken from either the 38th Street Eastbound or 45th Street Westbound approaches.

The time interval specified within TRAF-Netsim for the reporting of cumulative delay and cumulative vehicle arrival statistics along the cross streets was 120 seconds. Therefore, TRAF-Netsim updated the cumulative delay and vehicle arrivals within its output at 120 second increments. As with the previous analysis involving unconditional priority, the cumulative delay which TRAF-Netsim generates as output at the end of every time interval was transformed into a cycle by cycle measure of delay by determining the delay per vehicle occurring within each 120 second time interval.

Results. A summary of the results of the simulation runs over the range of cross street traffic conditions and green extension lengths follows. Figures 5.1 to 5.12 all depict the results of the single simulation run (with its accompanying base case) which is most representative of the trends observed over the 3 simulation runs performed for the traffic and signal priority conditions which follow. A complete list of the figures showing results over all the simulation runs is supplied in the Appendix.

Green Extension=10 Seconds, Cross Street Degree of Saturation=0.8. According to the simulation results, cross street degrees of saturation of 0.8, accompanied by 10 second green extensions do not result in substantial increases in delay per vehicle along the cross street approaches.

As can be seen in Figures 5.1 and 5.2, the signal priority timing typically causes a slight increase in average delay per vehicle along the cross streets. In all simulations, the priority timing was initiated at the elapsed simulation times of 600, 1200, 1800, 2400, and 3000 seconds. Figure 5.1 clearly shows an increase in delay per vehicle occurring along the Eastbound approach of 38th Street following each initiation of signal priority. However, these increases in delay per vehicle are typically not too substantial. Figure 5.1 shows that the increase in delay per vehicle relative to the base case along the Eastbound approach of 38th Street only lasts one signal cycle (120 seconds) following the use of the priority timing. Clearly, the Eastbound approach of 38th Street has adequate excess capacity to recover from the signal priority call effects prior to the next initiation of signal priority.

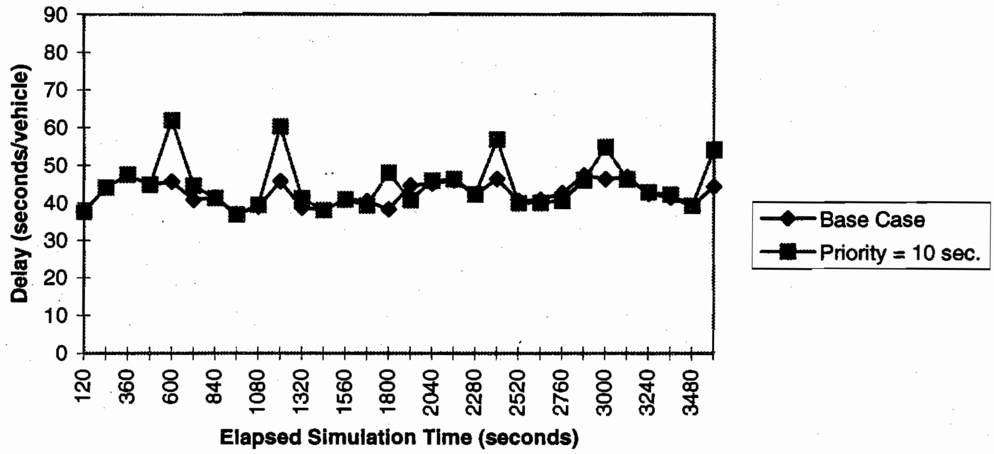


Figure 5.1 Delay at 38th Street Eastbound (green extension = 10 seconds, S = 0.8)

Figure 5.2 shows that the increase in delay per vehicle at the Westbound approach of 45th Street is almost nonexistent until approximately 3000 seconds into the simulation. However, a substantial increase in delay results from the final priority call of the simulation. The increase in delay per vehicle resulting from this final priority call barely returns to base case conditions prior to the next scheduled priority call. However, this instance appears to be relatively isolated, indicating that the Westbound approach of 45th Street is not substantially impacted by the priority signal timing.

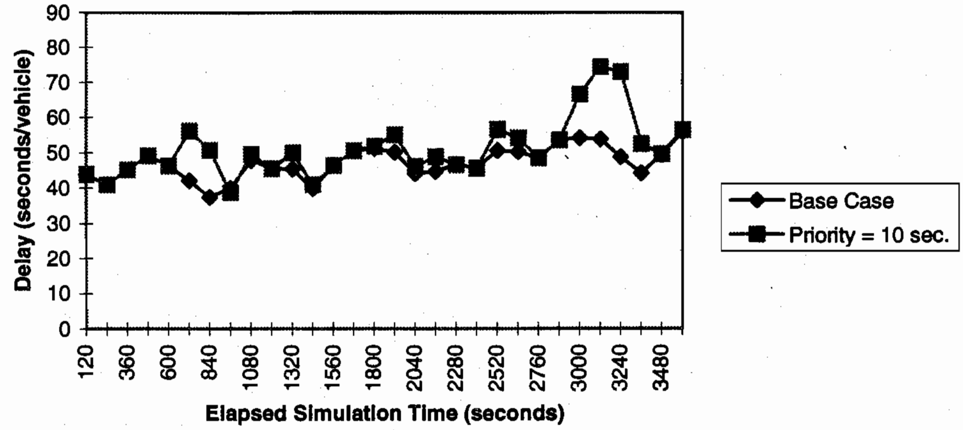


Figure 5.2 Delay at 45th Street Westbound (green extension = 10 seconds, S = 0.8)

Green Extension=10 Seconds, Cross Street Degree of Saturation=0.9. When the cross street saturation level was raised to 0.9 in conjunction with the use of 10 second green extensions, differences between the resulting increase in delay per vehicle at the Westbound approach at 45th Street and the Eastbound approach at 38th Street began to surface. As can be seen in Figure 5.3, the priority signal timing appears to cause only minor increases in the delay per vehicle at the Eastbound approach of 38th Street.

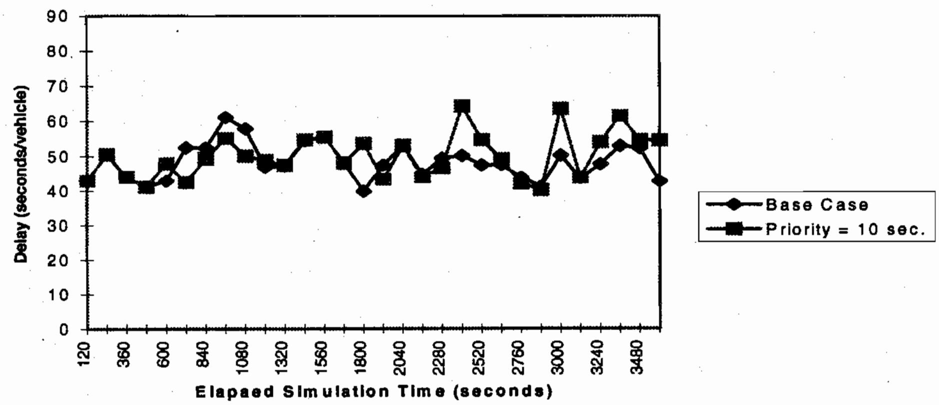


Figure 5.3 Delay at 38th Street Eastbound (green extension = 10 seconds, S = 0.9)

These increases in delay are manifested along this cross street for 1 or 2 cycle lengths following each priority signal timing initiation. Generally, Figure 5.3 indicates that the Eastbound approach of 38th Street can safely withstand the signal priority effects, even when the traffic saturation level along this approach is estimated at 0.9.

Figure 5.4 shows the increase in delay per vehicle occurring along the Westbound approach of 45th Street as signal priority is triggered.

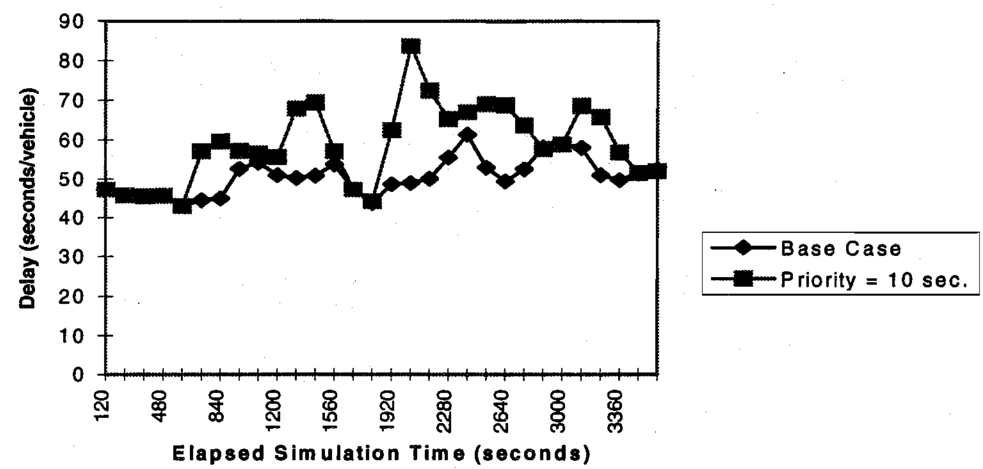


Figure 5.4 Delay at 45th Street Westbound (green extension = 10 seconds, S = 0.9)

Unlike Figure 5.3, Figure 5.4 indicates that the use of priority is very questionable when cross street saturation levels reach 0.9. As shown in Figure 5.4, the increase in delay felt by the cross street does not readily dissipate with time. In fact, the increase in delay felt by the cross street from signal priority triggered 600 seconds into the simulation does not completely dissipate before the next call for signal priority, occurring 1200 seconds into the simulation. Similar results can be observed when priority is triggered at 1800 seconds, causing the delay per vehicle along the cross street to remain above the delay experienced in the base case until 3000 seconds into the simulation. Because an increase in delay per vehicle is manifested at the Westbound approach of 45th Street for the majority of the simulation, one should question the use of 10 second green extensions at intersections where cross street saturation levels approach 0.9.

Green Extension=10 Seconds, Cross Street Degree of Saturation=1.0. By definition, a saturation level of 1.0 along an approach indicates that, on average, the approach receives just enough green time per hour to process the hourly volume of traffic which arrives. Therefore, signal priority timing plans which reduce the amount of green time originally allocated to a cross street with a saturation level of 1.0 may cause increases in delay which are nearly irreversible.

Since little excess capacity exists for the cross street to recover from the loss of green time, the gap between the delay per vehicle for the base case and the priority case could widen with each priority call.

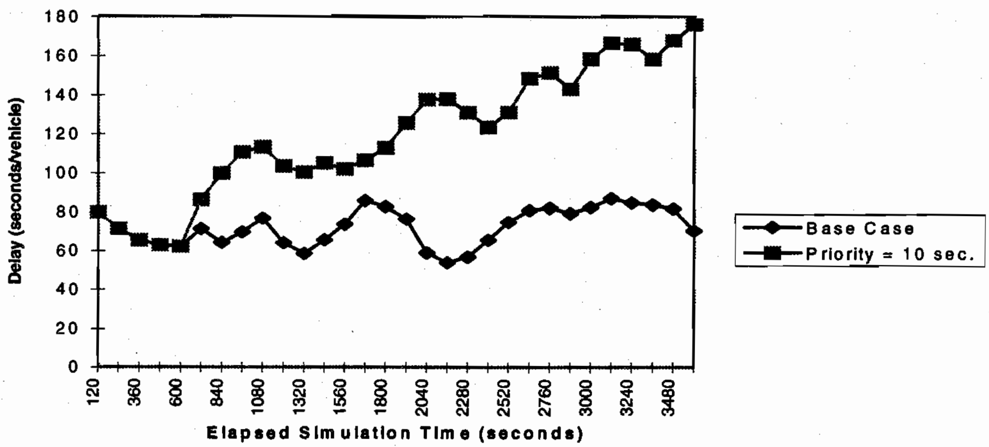


Figure 5.5 Delay at 45th Street Westbound (green extension = 10 seconds, S = 1.0)

This pattern is shown in Figure 5.5, where the delay per vehicle along the Westbound approach of 45th Street increases steadily with each priority call. Obviously, these results indicate that green time should never be taken from a cross street operating at a saturation level of 1.0 to benefit transit vehicles.

As shown in Figure 5.6, the results from the Eastbound approach at 38th Street are not as definitive. The increase in delay per vehicle along the cross street does not rise steadily with each priority call, as in Figure 5.5.

However, substantial increases in delay which do not dissipate prior to the next priority call are present. For instance, increases in delay resulting from a priority call 1800 seconds into the simulation do not dissipate before the next priority call, occurring 2400 seconds into the simulation. These results underscore the indication that green time should not be taken from cross streets operating at saturation levels of 1.0 in order to award priority to transit vehicles along an arterial.

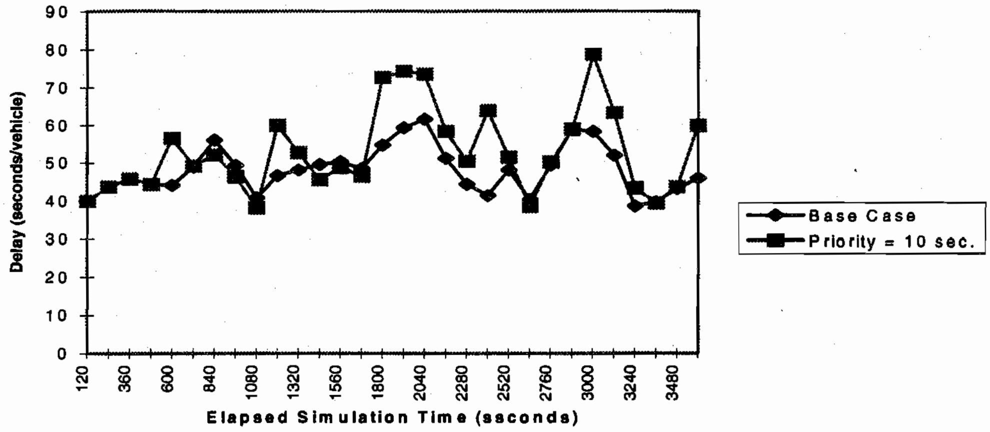


Figure 5.6 Delay at 38th Street Eastbound (green extension = 10 seconds, S = 1.0)

Green Extension=20 Seconds, Cross Street Degree of Saturation=0.8. When the green extensions awarded to the bus approach are increased from 10 seconds to 20 seconds per priority call, the resulting loss in green time along the cross streets per priority call increases from 5 seconds to 10 seconds. As shown in Figure 5.7, the 10 second loss in green time along the Eastbound approach at 38th Street causes a larger increase in delay per vehicle than was found when only 5 seconds of green was taken from this cross street.

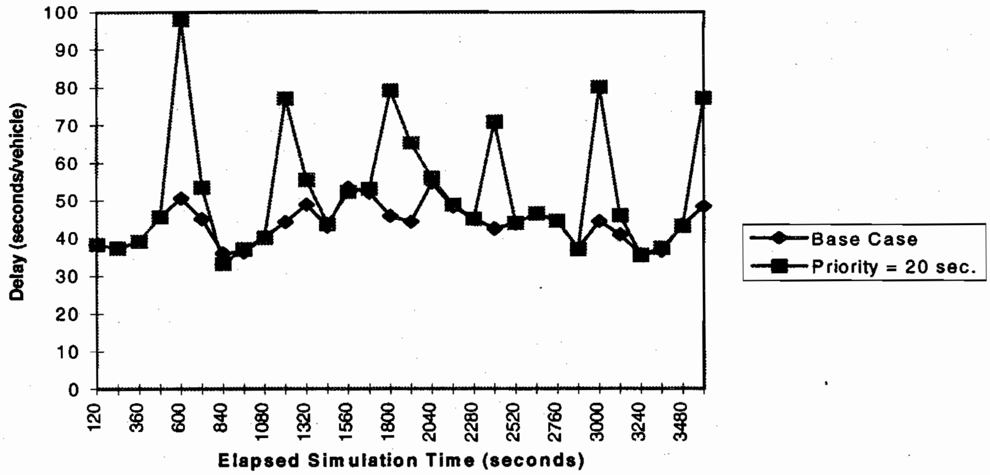


Figure 5.7 Delay at 38th Street Eastbound (green extension = 20 seconds, S = 0.8)

However, because the cross street is only operating at a saturation level of 0.8, enough excess capacity is available to allow it to recover from the impacts of the priority signal timing within 2 to 3 signal cycles following the priority call.

Figure 5.8 shows the effects of supplying the bus approach with 20 second green extensions, while the Westbound approach of 45th Street operates at a saturation level of 0.8. From the figure, one can see that the priority calls typically cause an increase in delay along the cross street which remains over the next 3 or 4 cycle lengths. Although the increase in delay along the cross street typically dissipates before the subsequent priority call, delay per vehicle is noticeably higher than the base case delay over the majority of the simulation.

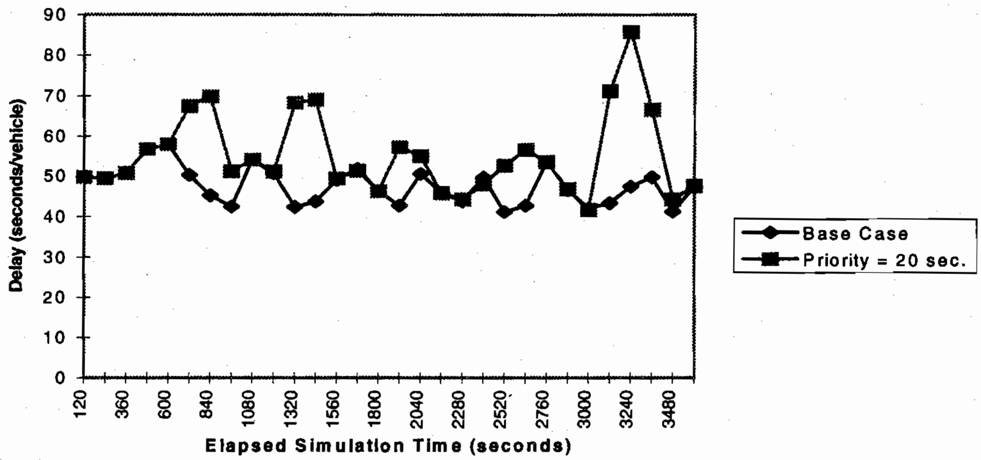


Figure 5.8 Delay at 45th Street Westbound (green extension = 20 seconds, S = 0.8)

When cross street saturation levels approach 0.8 and green extensions of 20 seconds are used, it is unclear whether the benefits to transit from signal priority outweigh the increases in delay incurred by vehicles along the side street. A more comprehensive analysis, similar to the analysis to be performed at the end of this chapter, is required.

Green Extension=20 Seconds, Cross Street Degree of Saturation=0.9. As the saturation level of the Eastbound approach at 38th Street is increased to 0.9, a more definitive decision regarding the choice to use signal priority can be made. As shown in Figure 5.9, substantial increases in cross street delay relative to the base case are felt over the majority of the simulation time.

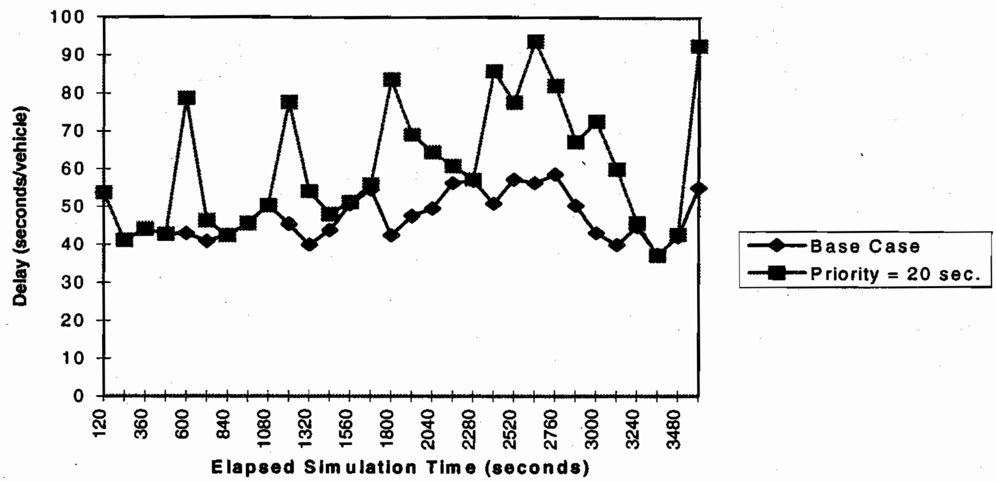


Figure 5.9 Delay at 38th Street Eastbound (green extension = 20 seconds, S = 0.9)

In particular, the increase in delay along the Eastbound approach of 38th Street initiated by the priority call at 2400 seconds does not completely dissipate until about 3360 seconds into the simulation. This sustained delay increase clearly causes an unacceptable level of service along this cross street, which probably cannot be justified by the potential gains along the bus approach.

As shown in Figure 5.10, similar results were encountered at the Westbound approach of 45th Street. A substantial increase in delay results along this cross street from a priority call initiated 600 seconds into the simulation. In addition, the increased delay never completely dissipates before the end of the simulation. Clearly, taking 10 seconds of green away from this cross street approach is not advisable.

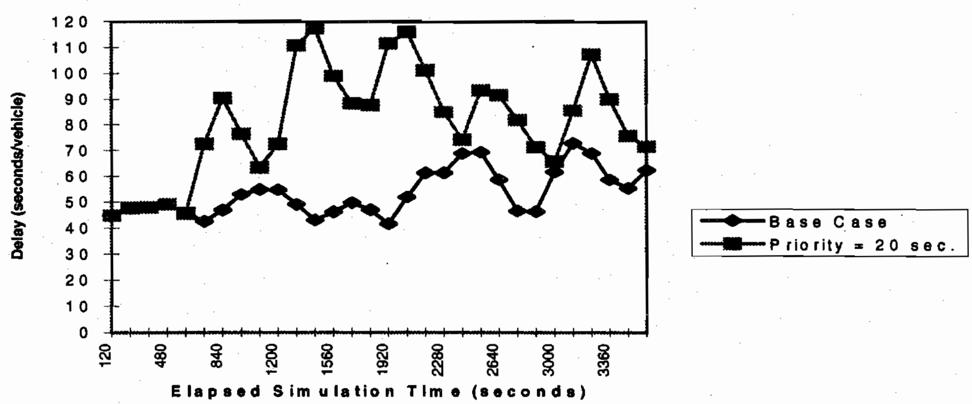


Figure 5.10 Delay at 45th Street Westbound (green extension = 20 seconds, S = 0.9)

Green Extension=20 Seconds, Cross Street Degree of Saturation=1.0. As shown in Figures 5.11 and 5.12, the increase in delay resulting from the use of 20 second green extensions at cross streets with saturation levels of 1.0 results in unacceptable delay levels.

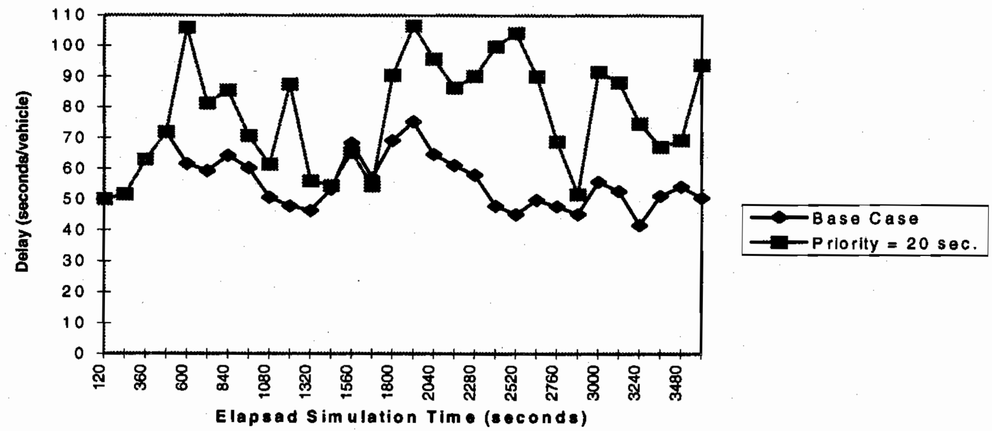


Figure 5.11 Delay at 38th Street Eastbound (green extension = 20 seconds, S = 1.0)

This is not surprising since a previous analysis indicated that taking only 5 seconds of green time from the cross street approaches with saturation levels of 1.0 produced unacceptable delay levels. By taking 10 seconds of green time from the cross streets, even more drastic delay increases result.

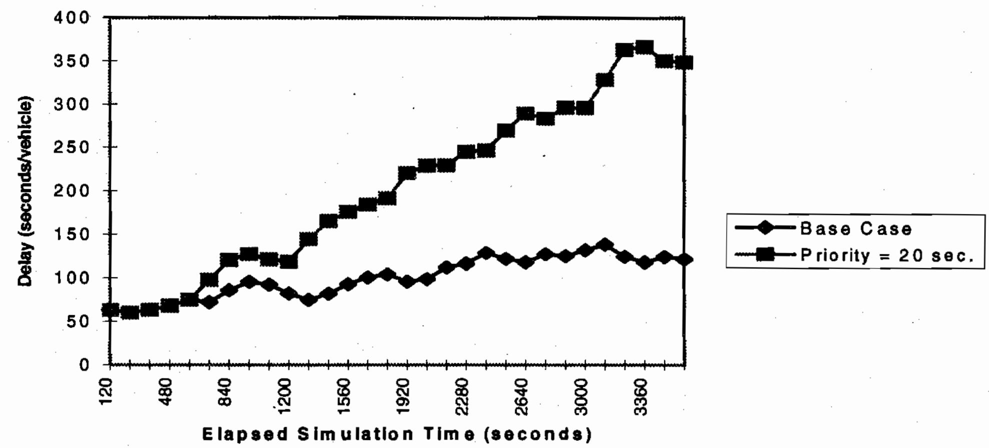


Figure 5.12 Delay at 45th Street Westbound (green extension = 20 seconds, S = 1.0)

The results of this analysis are summarized in Table 5.2. Under conditions where only minimal negative impacts are felt by cross streets due to signal priority, increases in delay along the cross streets from signal priority were almost always confined to the signal cycle following the priority signal cycle. The use of signal priority may be appropriate under these conditions as long as the benefits accrued by the transit vehicle and arterial traffic justify the minimal negative impacts to the cross streets.

Should transit signal priority be used under conditions which generate moderate negative impacts along the cross streets, the resulting increases in delay along the cross streets should be closely scrutinized. Simulation runs under these conditions often produced unpredictable results, with signal priority barely affecting the cross streets for one portion of the simulation and seriously increasing the delay along the cross streets during other portions of the simulation.

TABLE 5.2 NEGATIVE IMPACTS ACCRUING ON CROSS STREETS DUE TO SIGNAL PRIORITY (ASSUMED BUS HEADWAY = 10 MINUTES)

Cross Street Saturation	Green Extension=10 Sec.	Green Extension=20 Sec.
Saturation Level=0.8	Minimal	Moderate
Saturation Level=0.9	Moderate	Significant
Saturation Level=1.0	Significant	Significant

Transit signal priority should be avoided under conditions which generate significant negative impacts to the cross streets. Simulations run under these conditions produced extremely large increases in delay along the cross streets, which often did not dissipate before the end of the simulation.

Arterial Street Impacts Upon Signal Priority Effectiveness

This analysis examines how different characteristics of the bus arterial affect the success of active transit signal priority. In particular, two characteristics will be examined: 1) the location of bus stops along the arterial (near-side versus far-side) and 2) the saturation level of the bus approach.

Figure 5.13 shows the difference between near-side and far-side bus stop locations relative to the bus approach and its stop line. Intuitively, one would expect transit signal priority to perform better in conjunction with far-side bus stops. Long or variable dwell times at near-side bus stops would seem to pose a hazard for the success of transit signal priority, as the extra green time a bus receives may be wasted as the bus dwells at a bus stop prior to traversing the intersection.

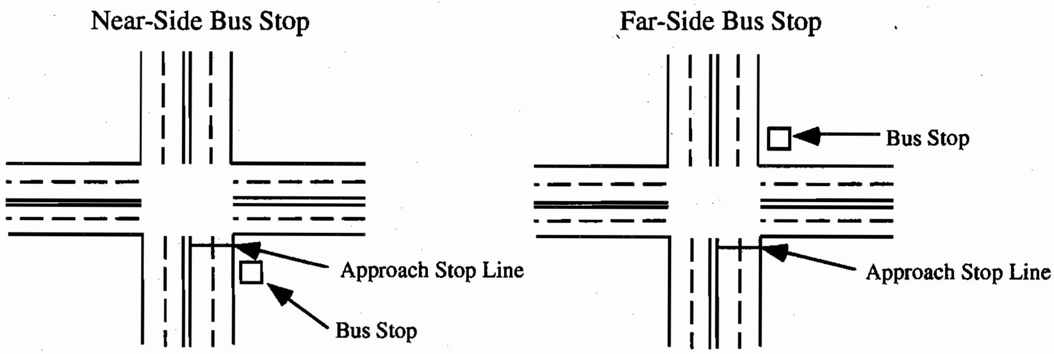


Figure 5.13 Near-side and far-side bus stop configurations

The success of transit signal priority also appears to depend on the bus approach saturation level. At lower saturation levels buses are not slowed as much by traffic along their approach, giving buses a greater chance of utilizing the added green they have requested.

Test Methodology. In order to assess the impact of bus stop location and the bus approach saturation level on the success of transit signal priority, an experiment using TRAF-Netsim was designed. First, the volume along the bus' approach was fixed to create a degree of saturation along the bus approach of 0.8. In order to accomplish this task, a hypothetical bus route was created which ran along the Koenig Lane cross street, traversing nodes in the following order: 8002, 12, 1, 13, 8003. The link-node diagram of the network created within TRAF-Netsim is shown in Figure 5.14 for reference.

The creation of this hypothetical bus route was necessary for this analysis in order to secure a certain volume (and saturation level) along the bus approach for each simulation run. Since link (8002, 12) is an entry link which transfers all of its vehicles directly onto link (12, 1), specifying an hourly volume entering link (8002, 12) automatically specifies this same fixed and known volume along link (12, 1). This enables one to vary the saturation level along link (12, 1) by simply changing the entry volume at link (8002, 12) within TRAF-Netsim.

Had one of the original bus routes been used for the analysis, the volume along any selected bus approach would have been much harder to control, and might have fluctuated greatly between different simulation runs. For instance, if link (10, 9) had been selected as the

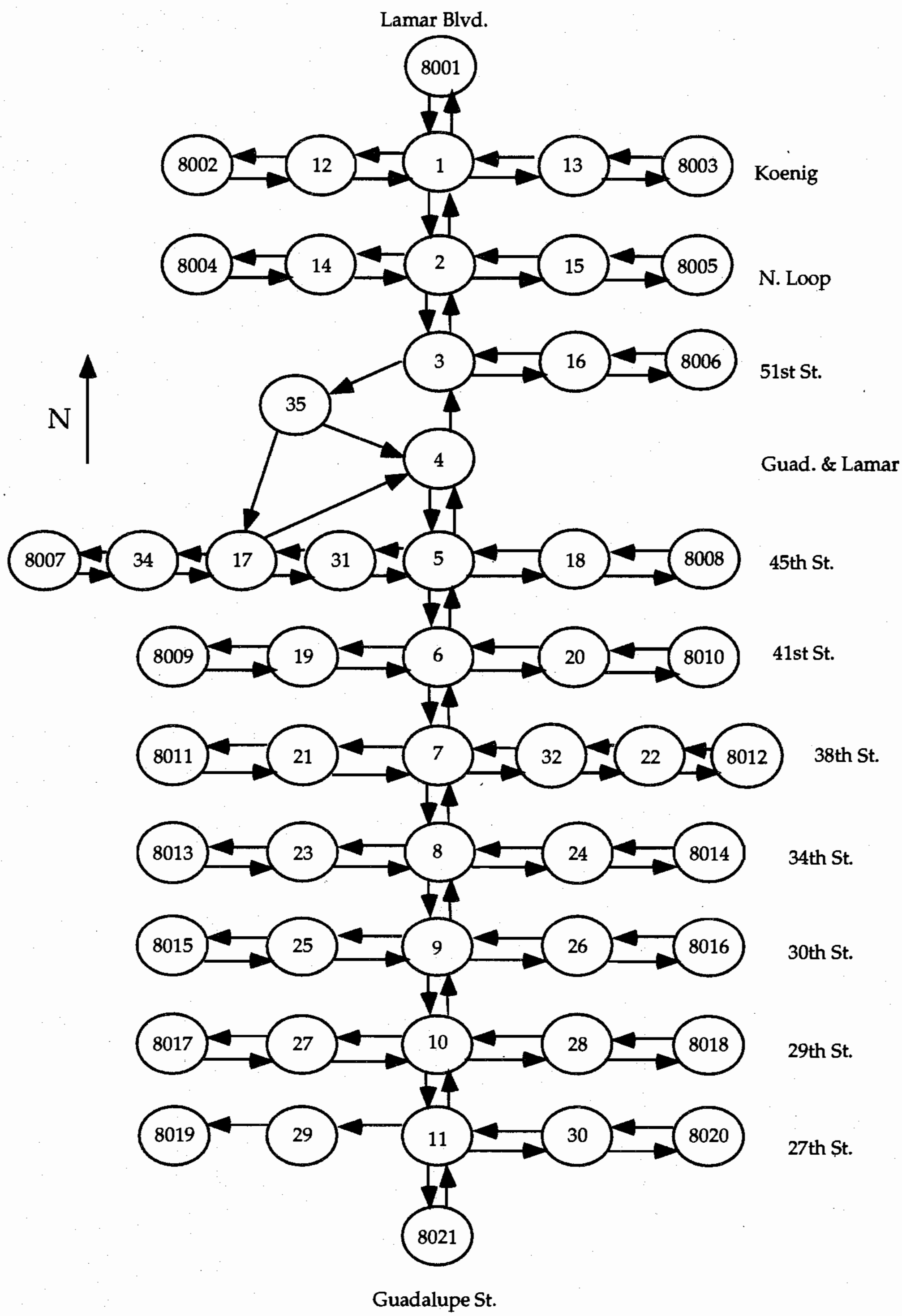


Figure 5.14 Link-node representation of Guadalupe-N. Lamar arterial

link to be used for this analysis, its volume from run to run would vary depending not only on the entry volume at link (8021, 11), but also on the turning percentages and volumes on links (30, 11), (28, 10), (27, 10), and (11, 10).

After the creation of the hypothetical bus route, the saturation level along link (12, 1) was set at 0.8. Then this link was observed using TRAF-Netsim's graphics display to identify a situation where the bus needed a green extension to traverse the intersection without being forced to stop by a red signal indication. Once this situation was encountered, the success of a green extension in allowing the bus to traverse the intersection without stopping was examined under a range of different scenarios. In particular, the bus stop location, bus approach saturation level, and green extension length were all varied within simulation runs using the same random number seed. Then, by changing the random number seed and performing the same analysis a second time, a second observation over all scenarios was created. At the conclusion of the analysis, 10 different random number seeds were used, resulting in the factorial experiment design shown in Table 5.3.

TABLE 5.3 FACTORIAL EXPERIMENT DESIGN FOR THE ANALYSIS OF ARTERIAL STREET IMPACTS UPON THE SUCCESS OF GREEN EXTENSIONS

Green Extension Length	Bus Approach Saturation Level	Near-Side Bus Stop	Far-Side Bus Stop
10 Seconds	Saturation Level=0.8	10 Observations	8 Observations
10 Seconds	Saturation Level=0.9	10 Observations	9 Observations
10 Seconds	Saturation Level=1.0	10 Observations	10 Observations
20 Seconds	Saturation Level=0.8	10 Observations	8 Observations
20 Seconds	Saturation Level=0.9	10 Observations	9 Observations
20 Seconds	Saturation Level=1.0	10 Observations	10 Observations

Not all cells within the factorial experiment design have 10 observations. This occurs because the need for a green extension for this analysis is determined with respect to a base case where the bus approach saturation level is 0.8 and a near-side bus stop is present at the end of link (12, 1). In a few instances, the bus' need for signal priority was eliminated as the bus stop configuration was changed from near-side to far-side. Since each observation identifies whether the green extension successfully allowed the bus passage through the intersection, *given that an extension was needed*, a few cells have less than 10 observations.

Results. Tables 5.4 and 5.5 summarize the results of this analysis for near-side and far-side bus stops, respectively. For each scenario, a success rate for the green extension used is given. Success in this context indicates that the green extension enabled the bus to avoid a red signal indication at the intersection, which it would have otherwise received.

TABLE 5.4 SUCCESS RATE OF GREEN EXTENSIONS (NEAR-SIDE BUS STOP)

Green Extension Length	Bus Approach Saturation Level	No. of Attempted Extensions	No. of Successful Extensions	Success Rate
10 Seconds	Saturation = 0.8	10	2	20%
10 Seconds	Saturation = 0.9	10	1	10%
10 Seconds	Saturation = 1.0	10	0	0%
20 Seconds	Saturation = 0.8	10	3	30%
20 Seconds	Saturation = 0.9	10	3	30%
20 Seconds	Saturation = 1.0	10	0	0%

As can be seen in Table 5.4, the presence of a near-side bus stop greatly hinders the effectiveness of green extensions. Even when 20 second green extensions are used when bus approach saturation levels are 0.8, only 30% of the extensions successfully enabled the bus to avoid a red signal indication. Success rates fall even lower as the bus approach saturation level increases and 10 second extensions are used. Near-side bus stops limit the success of green extensions because a significant portion, if not all, the green extension is wasted while passengers board and deboard at the near-side bus stop.

An unsuccessful signal priority call will typically have a negative overall impact upon an intersection because priority is intended to reduce the delays to a large number of people traveling on a transit vehicle at the expense of low occupancy vehicles along the cross streets. By failing to reduce the delay experienced by the bus, an unsuccessful priority call disrupts normal traffic operations without providing any benefit.

The average duration and variability of bus dwell times at a near-side bus stop have a significant impact upon the success of green extensions. Highly variable or long dwell times will limit the success of green extensions more than short dwell times, or dwell time distributions with little variability. For this analysis, the bus dwell time distribution is shown in Figure 5.15. This distribution is based on measured bus dwell times from the peak period at bus stops along the Guadalupe-N. Lamar bus route in Austin, Texas.

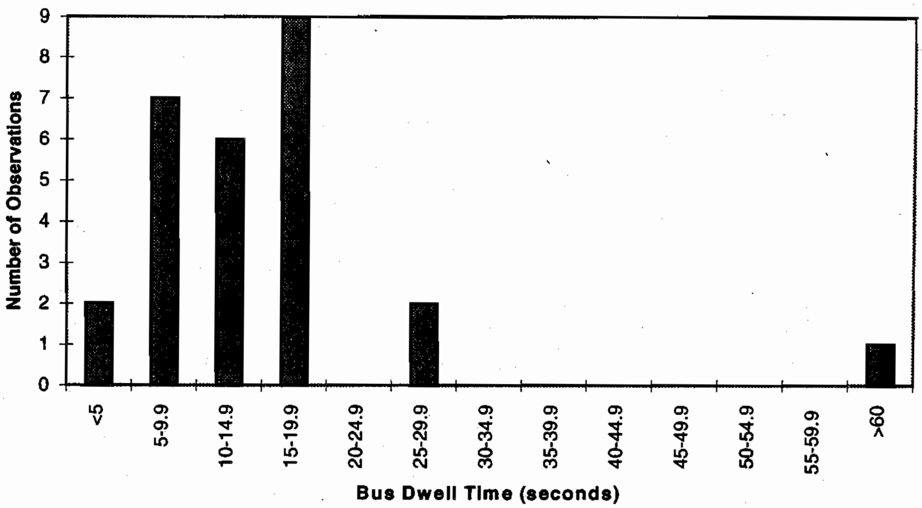


Figure 5.15 Bus dwell time distribution

Table 5.5 shows the success rate of green extensions when used with a far-side bus stop configuration.

TABLE 5.5 SUCCESS RATE OF GREEN EXTENSIONS (FAR-SIDE BUS STOP)

Green Extension Length	Bus Approach Saturation Level	No. of Attempted Extensions	No. of Successful Extensions	Success Rate
10 Seconds	Saturation = 0.8	8	5	63%
10 Seconds	Saturation = 0.9	9	6	67%
10 Seconds	Saturation = 1.0	10	5	50%
20 Seconds	Saturation = 0.8	8	7	88%
20 Seconds	Saturation = 0.9	9	8	89%
20 Seconds	Saturation = 1.0	10	6	60%

As shown in Table 5.5, transit signal priority is much more successful when used with far-side bus stops, rather than near-side bus stops. Figure 5.16 reiterates this point by graphically depicting the overall success rate of all green extensions which were attempted in conjunction with both near-side and far-side bus stop locations over all simulations within the analysis.

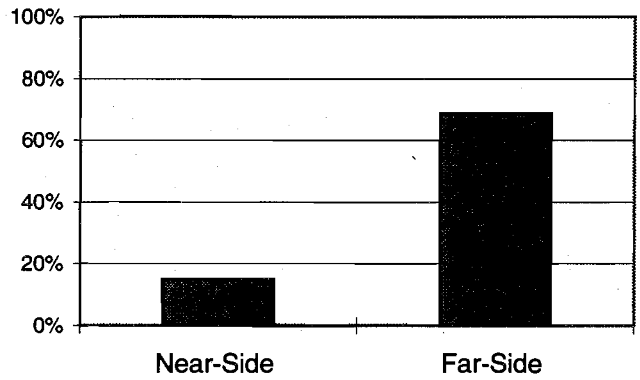


Figure 5.16 Overall success rate of green extensions with near-side and far-side bus stop locations

With far-side bus stop configurations, the success of signal priority is no longer a function of the bus dwell time. As a result, the success rates of the various green extensions increases drastically between Table 5.4 and Table 5.5.

Table 5.5 further shows that the success rates of both the 10 and 20 second green extensions remain relatively constant as the bus approach degree of saturation increases from 0.8 to 0.9. In particular, the success rate of the 20 second green extensions along bus approaches with saturation levels of 0.8 or 0.9 looks extremely promising from the bus' viewpoint. However as shown in the previous section, the use of 20 second green extensions causes moderate to significant increases in delay along cross streets operating at saturation levels above 0.8. The previous section also showed that 10 second green extensions have minimal negative impacts upon cross streets operating at saturation levels below 0.8. However, Table 5.5 shows that the success rate of 10 second green extensions is considerably lower than the success rate of 20 second green extensions.

These findings identify the direct conflict arising between the success of signal priority and the negative impacts along cross streets resulting from signal priority. In order to determine whether the use of signal priority is justified, a comprehensive analysis which examines the overall net effect of signal priority upon an intersection is needed.

As the bus approach degree of saturation reaches 1.0, a more drastic reduction in the success rate of the 10 and 20 second green extensions is encountered. This is shown in Figure 5.17.

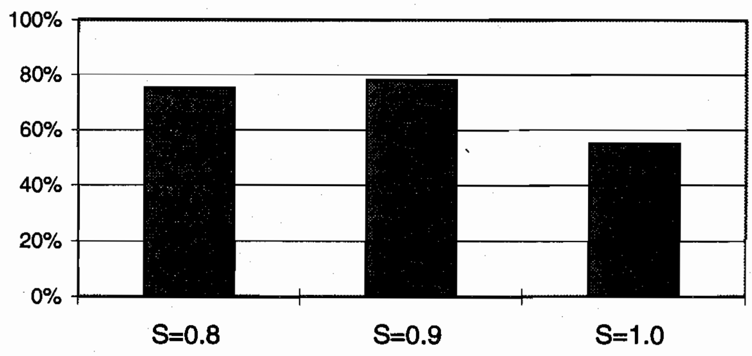


Figure 5.17 Overall success rate of green extensions used with far-side bus stops and bus approach saturation levels of 0.8, 0.9, and 1.0

As the bus approach saturation level reaches 1.0, the bus is forced to compete with a large number of vehicles for the use of its green extension. This increase in saturation also causes longer queues along the bus approach. As a result, the green extension aids in discharging these long queues, but often fails to usher the bus through the intersection before the red signal indication. This results in relatively low success rates of 50% and 60% for 10 second and 20 second green extensions, respectively.

Upon initial inspection, these lower success rates seem to indicate that the use of signal priority is questionable when the bus approach degree of saturation reaches 1.0. However when one recognizes that the arterial traffic sharing the bus approach also stands to benefit from signal priority, it remains unclear whether one can justify using signal priority under these conditions. Once again, the overall net impact of signal priority upon the intersection should be evaluated before a conclusion is reached. This analysis is conducted in the next section.

Effectiveness of Signal Priority at an Isolated Intersection

This analysis will address the questions which were raised in the previous two sections regarding the overall net impact of transit signal priority at a single intersection. The previous two analyses have identified the potential advantages of signal priority for traffic along the bus arterial and the potential disadvantages of signal priority for traffic along the cross streets. Because a conflict exists between the two groups of traffic, one must identify the overall impact of transit signal priority over all four approaches of an intersection before addressing overall transit signal priority effectiveness.

Test Methodology. This analysis utilizes TRAF-Netsim to determine the overall impact of a single priority call upon a single intersection. The intersection of 38th Street and Guadalupe Street is used for the analysis. This intersection was chosen because the cross street volume along 38th Street is significant and, therefore, a definite conflict exists between arterial traffic along Guadalupe Street which stands to benefit from signal priority and the cross street traffic which is negatively influenced by signal priority.

Before this analysis was conducted, several assumptions were made regarding the operations at the designated test intersection of 38th Street and Guadalupe Street. Based on the results of the last section, a far-side bus stop configuration is assumed. Near-side bus stop configurations were shown to seriously limit the effectiveness of transit signal priority as the green extension is often wasted during the bus' dwell time at the near-side bus stop. Also, a 10 minute bus headway is assumed and transit signal priority is assumed to only be used by buses traveling in the peak period direction (the Northbound intersection approach).

The criteria which is used to address the effectiveness of transit signal priority at a single intersection is the travel time *per person* over all individuals approaching the intersection, over a given time frame. By comparing the effectiveness of various signal priority strategies to the base case (no priority used) on a travel time per person basis, rather than per vehicle basis, the impact of favoring high occupancy vehicles at the intersection will be addressed.

The time frame used for this analysis begins 600 seconds into each TRAF-Netsim simulation and ends 10 minutes later, at 1200 seconds. A green extension is used at the intersection 600 seconds into the simulation and the effects of this green extension are examined over the following 10 minutes. The 10 minutes chosen for the analysis time frame coincides with the 10 minute bus headway, allowing the overall effect of a single signal priority call at the intersection to be observed.

The analysis of signal priority effects at a single intersection is broken into the following three components: 1) the analysis of signal priority effects on travel time per person along non-bus approaches, 2) the analysis of signal priority effects on travel time per person for non-bus traffic along the bus approach, and 3) the analysis of signal priority effects on travel time per person on-board the bus.

Traffic volumes consistent with peak period volumes from the Guadalupe-N. Lamar case study network were used for the non-bus approaches (Southbound, Eastbound and Westbound). The effects of signal priority along the non-bus approaches were monitored by acquiring cumulative travel time and vehicle counts along the three non-bus links 600 and 1200 seconds into each simulation. This data was collected in conjunction with both 10 second and 20 second green extensions, with each simulation accompanied by a base case where no signal priority was used. To account for variability within the simulations, both 10 and 20 second green extensions were simulated 3 times apiece with different random number seeds used across all 6 simulations. This factorial experiment design is summarized in Table 5.6.

TABLE 5.6 FACTORIAL EXPERIMENT DESIGN FOR NON-BUS TRAFFIC ALONG NON-BUS APPROACHES

Approach	10 Second Green Extension	Base Case (No 10 Second Ext'n)	20 Second Green Extension	Base Case (No 20 Second Ext'n)
Southbound	3 Observations	3 Observations	3 Observations	3 Observations
Eastbound	3 Observations	3 Observations	3 Observations	3 Observations
Westbound	3 Observations	3 Observations	3 Observations	3 Observations

After performing all the simulations runs according to the factorial experiment design shown in Table 5.6, the total travel time for each run over the analysis time frame along each non-bus approach was calculated as follows:

$$\text{Total Travel Time}_{\text{analysis period}} = \text{Total Travel Time}_{1200} - \text{Total Travel Time}_{600}$$

where: $\text{Total Travel Time}_{1200}$ = Cumulative travel time on the approach 1200 seconds after the beginning of the simulation

$\text{Total Travel Time}_{600}$ = Cumulative travel time on the approach 600 seconds after the beginning of the simulation

$\text{Total Travel Time}_{\text{analysis period}}$ = Travel time on the approach accruing during the analysis period

A similar calculation is performed in terms of the cumulative vehicle count along the three non-bus approaches over each run. This determines the number of vehicles processed along each non-bus approach during the analysis time frame.

Finally, at each of the 3 approaches, the results were averaged over the 3 runs, resulting in the following summary statistics for each of the 3 non-bus approaches:

1) Total travel time for all vehicles along approach during analysis period (minutes) (An average over 3 simulations)

2) Number of vehicles processed by approach during analysis period (An average over 3 simulations)

Whereas the volumes along the non-bus approaches were fixed at the volumes consistent with peak period volumes from the Guadalupe-N. Lamar case study network, the bus approach volume was varied to create approach saturation levels of 0.8, 0.9, and 1.0. As with the previous analysis, the bus actual approach (link (8, 7)) could not be used due to the complexities of determining the actual traffic volumes accruing along this interior link. Therefore, a hypothetical bus route running on link (12, 1) was once again used as a substitute for the bus approach, allowing for an easy determination of traffic volumes along this approach.

Following this adjustment, a factorial design similar to the design developed for the non-bus approaches was used. However, an additional parameter, the bus approach saturation level, was added to the factorial experiment design shown in Table 5.7.

TABLE 5.7 FACTORIAL EXPERIMENT DESIGN FOR NON-BUS TRAFFIC ALONG THE BUS APPROACH

Bus Approach Saturation Level	10 Second Green Extension	Base Case (No 10 Second Ext'n)	20 Second Green Extension	Base Case (No 20 Second Ext'n)
Saturation = 0.8	3 Observations	3 Observations	3 Observations	3 Observations
Saturation = 0.9	3 Observations	3 Observations	3 Observations	3 Observations
Saturation = 1.0	3 Observations	3 Observations	3 Observations	3 Observations

As with the analysis of traffic along the non-bus approaches, data within the analysis time frame from 600 to 1200 seconds was averaged over 3 observations. This resulted in the following statistics regarding signal priority effect upon non-bus traffic on the bus approach.

1) Total travel time for autos along approach with a saturation level of 0.8, 0.9 and 1.0 (minutes) (All averaged over 3 simulations)
2) Number of autos processed by approach (For saturation levels = 0.8, 0.9, and 1.0) during analysis period (All averaged over 3 simulations)

Finally, data concerning the effect which signal priority had on the bus travel time along its approach was obtained by collecting data on the bus travel time along link (12, 1) from TRAF-Netsim output. Travel times for the bus were collected for each simulation according to the factorial experiment design shown in Table 5.8.

TABLE 5.8 FACTORIAL EXPERIMENT DESIGN USED TO OBTAIN BUS TRAVEL TIMES

Bus Approach Saturation Level	10 Second Green Extension	20 Second Green Extension	Base Case (No Green Extension)
Saturation = 0.8	3 Observations	3 Observations	3 Observations
Saturation = 0.9	3 Observations	3 Observations	3 Observations
Saturation = 1.0	3 Observations	3 Observations	3 Observations

As with the previous two analyses, the bus travel times along its approach were averaged over the 3 simulation runs performed within each cell of Table 5.8. However, an additional calculation was necessary to account for the fact that the bus green extension is not always successful in ushering the bus through the intersection before the red indication, as seen in the last section.

To accomplish this, the success rates of green extensions used with far-side bus stop configurations found in the previous section (Table 5.5) were used to find an expected bus travel time. An example of the calculation used to determine the bus expected travel time follows:

E(Bus Travel Time) = P(Extension Successful) * (Priority Trvl Time)
+ (1-P(Extension Successful)) * (Base Case Trvl Time)

where: P(Extension Successful) = The success rate of the green extension

E(Bus Travel Time) = Expected Bus Travel Time considering not all green extensions are successful

This resulted in the following statistics regarding signal priority effect upon bus travel times.

1) Expected bus travel time along approach with a saturation level of 0.8 (minutes) (An average over 3 simulations)
2) Expected bus travel time along approach with a saturation level of 0.9 (minutes) (An average over 3 simulations)
3) Expected bus travel time along approach with a saturation level of 1.0 (minutes) (An average over 3 simulations)

Having collected statistics regarding the total travel times and number of vehicles processed along all 4 approaches of the 38th Street and Guadalupe Street intersection, the overall travel time per person at the intersection was calculated by assuming occupancy rates for the bus and the automobiles. A sample calculation is presented as follows (for the case where the bus approach saturation level is 0.8):

$$\text{Total Travel Time}_{0.8} = (\text{TrTmEB} + \text{TrTmWB} + \text{TrTmSB}) + (\text{TrTmNB}_{0.8}) + (\text{TrTmBus}_{0.8})$$

$$\text{Total Person-Trips}_{0.8} = [(\text{Auto Occ}) * (\text{VehEB} + \text{VehWB} + \text{VehSB})] + [(\text{Auto Occ}) * (\text{VehNB}_{0.8})] + [(\text{Bus Occ}) * (1)]$$

$$\text{Travel Time Per Person}_{0.8} = (\text{Total Travel Time}_{0.8} / \text{Total Person Trips}_{0.8})$$

where:

Auto Occ =	Assumed automobile occupancy (pax/vehicle)
Bus Occ =	Assumed bus occupancy (pax/vehicle)
TrTmEB =	Total travel time for all autos on Eastbound approach (minutes)
TrTmWB =	Total travel time for all autos on Westbound approach (minutes)
TrTmSB =	Total travel time for all autos on Southbound approach (minutes)
$\text{TrTmNB}_{0.8}$ =	Total travel time for all autos on Northbound approach with saturation level = 0.8 (minutes)
$\text{TrTmBus}_{0.8}$ =	Expected bus travel time on the Northbound approach with saturation level = 0.8 (minutes)
VehEB =	Number of vehicles processed by the Eastbound approach
VehWB =	Number of vehicles processed by the Westbound approach
VehSB =	Number of vehicles processed by the Southbound approach
$\text{VehNB}_{0.8}$ =	Number of vehicles processed by the Northbound approach with a saturation level of 0.8

A similar calculation is used for bus approach saturation levels of 0.9 and 1.0, respectively.

Results. Upon assuming an auto occupancy of 1.2 and a bus occupancy of 25, the measures of travel time per person shown in Table 5.9 were obtained.

TABLE 5.9 TRAVEL TIME PER PERSON (SECONDS/PERSON) AT 38TH STREET AND GUADALUPE (AUTO OCCUPANCY = 1.2, BUS OCCUPANCY = 25)

	Priority	Base Case	*% Change from Base Case*
10 Second Green Extension:			
Bus Approach Sat'n Level=0.8	47.5	47.6	-0.2
Bus Approach Sat'n Level=0.9	49.1	49.9	-1.7
Bus Approach Sat'n Level=1.0	53.0	55.0	-3.7
20 Second Green Extension:			
Bus Approach Sat'n Level=0.8	52.8	49.8	6.1
Bus Approach Sat'n Level=0.9	52.7	50.8	3.7
Bus Approach Sat'n Level=1.0	55.3	56.6	-2.3

As can be seen in Table 5.9, signal priority does not appear to significantly impact the overall travel time per person at the intersection. At most, a 6.1% difference between the base case where no priority is used and the signal priority case is found. This result stems from the small bus share of total person-trips at the intersection. The total number of automobile trips over all 4 approaches to the intersection during the analysis time frame was found to be roughly 700. By contrast, only 1 bus eligible for signal priority arrived at the intersection over the analysis time frame. Therefore, even considering that the bus' occupancy is 25, while assuming an average auto occupancy of 1.2, the bus still only carries roughly 2.9% of the total person-trips occurring at the intersection over the analysis time frame. As a result, reducing the travel time for the 25 individuals on the bus has a negligible overall impact upon the travel time per person over the entire intersection, during the 10 minute analysis time period.

Several other trends can be seen from Table 5.9. First, the success of transit signal priority relative to the base case improves as the bus approach saturation level increases. This answers a question which was raised in the previous section regarding the diminishing success rate of green extensions at higher bus approach saturation levels. Although high saturation levels along the bus approach reduce the probability of a successful green extension from the bus standpoint, the automobile traffic along the arterial benefits from the added green time. This stands to reason because the original signal timings were based on saturation levels of roughly

0.8 along the bus approach. Therefore, when one increases these saturation levels to 0.9 or 1.0, without re-timing the original signal to accommodate this increased volume, a reduction in the performance of the bus approach can be expected. Therefore, additional green time in the form of signal priority is needed along the bus approach. This indicates that the signal timing at this intersection (and any intersection) should accommodate the *users* of the intersection. Since roughly 97% of the users are traveling in autos, changing the signal timing for the bus' benefit seems inappropriate.

A second trend which is apparent when looking at Table 5.9 is the superior performance of the 10 second green extension over the 20 second green extension. Across all bus saturation levels (0.8, 0.9, and 1.0), the use of the 10 second green extension results in improvements (albeit extremely slight) over the base case. However, the use of 20 second green extensions tend to diminish the overall performance of the intersection, except when bus approach saturation levels are 1.0. This finding reinforces the previous finding that a signal should accommodate its users. Offering larger green extensions places the signal timing of an intersection farther away from the original timing intended for individuals in autos, the intersection's major group of users.

Table 5.10 shows the travel time per person at the selected intersection when the bus occupancy is assumed to be 50 passengers.

TABLE 5.10 TRAVEL TIME PER PERSON (SECONDS/PERSON) AT 38TH STREET AND GUADALUPE (AUTO OCCUPANCY = 1.2, BUS OCCUPANCY = 50)

	Priority	Base Case	*% Change from Base Case*
10 Second Green Extension:			
Bus Approach Sat'n Level=0.8	46.1	46.2	-0.2
Bus Approach Sat'n Level=0.9	47.7	48.6	-1.7
Bus Approach Sat'n Level=1.0	51.6	53.6	-3.7
20 Second Green Extension:			
Bus Approach Sat'n Level=0.8	51.3	48.4	6.1
Bus Approach Sat'n Level=0.9	51.3	49.4	3.7
Bus Approach Sat'n Level=1.0	53.9	55.1	-2.3

The results of Table 5.10 are very similar to the results in Table 5.9. The travel time per person is slightly lower with higher bus occupancies, due to the fact that more people traverse the intersection in the same amount of time when the bus occupancy is raised from 25 to 50. However, since the travel time per person for both the base case and the priority case is reduced, the percent difference between the base and priority cases are identical to those in Table 5.9. This shows that the bus still enjoys only an extremely small share of total person-trips at the intersection, even when its occupancy is 50, rather than 25. Therefore, improving the level of service of these 50 passengers by using priority fails to create significant overall improvements in the performance of the intersection, and often causes the performance of the intersection to diminish.

It is important to note that the findings from this analysis are based on 10 minute headways and heavy automobile volumes taken from traffic counts at the 38th Street and Guadalupe Street intersection. Under these conditions, transit's share of the total person trips at the intersection is extremely small, causing signal priority to be largely ineffective. Had the analysis been based on data at another intersection in a different part of the United States, where bus headways were shorter and transit's mode share was higher, then the effectiveness of signal priority would likely increase. This reiterates the point that signal timings should serve the principal users. If transit's mode split in a city is small, then the principal users of traffic signals are automobiles. Only when short headways and high occupancies enable transit to gain a significant mode split, should the traffic signals be altered to grant priority to transit vehicles.

Effectiveness of Signal Priority within an Arterial Street Network

The previous analysis showed transit signal priority to be largely ineffective at an isolated intersection with high cross street traffic volumes. However, in reality transit signal priority systems are not operated only at isolated intersections, but along transit corridors, such as the Guadalupe-N. Lamar arterial. Only by looking at the overall impact of transit signal priority upon the entire arterial and its cross streets can one clearly determine whether the use of transit signal priority can be justified along the corridor.

Test Methodology. The users of the Guadalupe-N. Lamar arterial network can be broken into three categories.

1) Non-bus users traveling along the cross streets
2) Non-bus users traveling along the arterial, and
3) Bus users traveling along the arterial

Previous analyses have clearly indicated that non-bus users traveling along the cross streets suffer increased delays with the use of transit signal priority.

However, the effect which transit signal priority has upon non-bus users traveling along the arterial remains somewhat unclear. This group of users stands to benefit from the effects of transit signal priority as their overall green time increases with the use of transit signal priority.

However, signal coordination along the arterial is also very important to the success of this user group. It is still unclear how transit signal priority affects signal coordination along an arterial.

Finally, bus users should realize improvements in service levels with the use of transit signal priority. However, as shown in the previous section, the benefits to this small group of users might not justify the negative impacts to cross street users or potential negative impacts to automobiles traveling along the arterial.

To determine the overall effect of transit signal priority upon the Guadalupe-N. Lamar arterial, this analysis will quantify the effects which transit signal priority has on the three user groups. Only if benefits to bus and automobile users along the arterial offset the negative impacts which transit signal priority causes to the cross streets, will transit signal priority be considered a viable arterial network option.

Previous analyses have demonstrated that transit signal priority has an increasingly negative impact upon cross streets as the cross street saturation level increases. In addition, the analysis performed in the last section indicated that shorter green extensions are more beneficial than longer green extensions at intersections with significant cross street volumes. Therefore, several transit signal priority implementation strategies will be tested within this analysis which limit the use of transit signal priority at intersections along the arterial with highly saturated cross streets. The four cases which will be compared through this section are as follows:

Case 0:	Transit signal priority not used at any of the intersections along the Guadalupe-N. Lamar arterial (base case)
Case 1:	Transit signal priority available in equal amounts (20 second green extensions) at all intersections along the arterial
Case 2:	Transit signal priority available in a limited fashion (10 second green extensions) at high volume cross street intersections (Koenig Lane, N. Loop, 45th Street, and 38th Street) with 20 second green extensions available at all other intersections
Case 3:	Transit signal priority unavailable at high volume cross street intersections, with 20 second green extensions available at all other intersections

As with the previous analysis, far-side bus stop configurations and a 10 minute bus headway are assumed. In addition, transit signal priority is only used by buses traveling in the peak period direction, the Northbound direction.

The time frame used for this analysis begins 6 minutes after the beginning of each TRAF-Netsim simulation and concludes 18 minutes after the beginning of each simulation. This analysis time frame has been chosen because the Northbound bus enters the network about 6 minutes after the beginning of each simulation and exits the network about 18 minutes after the beginning of each simulation. Therefore, by choosing the 12 minutes when the bus traverses the arterial as the analysis time frame, the overall impact from one bus usage of transit signal priority is isolated.

As stated previously, a bug within TRAF-Netsim causes all buses to stop at each bus stop along the route, regardless of the value of the bus-stop bypass parameter that has been specified within TRAF-Netsim for each bus stop. To account for this discrepancy, a random number between 0 and 1 was specified for each bus stop using Microsoft Excel. These random numbers were then compared to the probability of the bus stopping at each bus stop. If the random number was greater than the probability of the bus stopping, then the bus was assumed to bypass that particular stop. If, however, the random number was less than the probability of the bus stopping, then the bus was assumed to board or deboard passengers at the stop, rather than bypass the bus stop. An example for 3 bus stops is shown as follows:

TABLE 5.11 SAMPLE DETERMINATION OF BUS STOP BYPASS LOCATIONS

Bus Stop	Random Number	P(Stop at Bus Stop)	Determination
1	0.17	0.81	Stop
2	0.90	0.35	Bypass
3	0.22	0.57	Stop

Bus stop locations which were found to be bypassed by the bus were then deleted from the bus route in preparation for the base case simulation run.

The simulation runs over cases 0, 1, 2, and 3 all used the same random number seeds. The difference between the 4 simulations lies in the multiple time periods which were used within TRAF-Netsim for cases 1, 2, and 3. TRAF-Netsim's graphical animation was used to determine when the Northbound bus was in need of priority during the simulation of cases 1, 2, and 3. When priority was needed, a separate time period was inserted within the simulation, allowing for the signal priority timing to be used at the intersection where the bus was in need of priority.

Additional time periods were added as needed within the simulation until the bus exited the network.

To account for the variability which occurs over different simulation runs, a second random number seed was entered into TRAF-Netsim, and the simulation of cases 0, 1, 2, and 3 was repeated. These repeat runs also utilized a second determination of bus stops which were bypassed, using a second set of random numbers from Microsoft Excel. As a result, a total of 8 simulations were run, with the results of 2 simulations averaged for each of the 4 cases.

Unfortunately, since an unknown number of vehicles make turning movements from the arterial onto the cross streets and from the cross streets onto the arterial within each separate simulation, the number of trips along the arterial links cannot be determined. This makes it impossible to determine the overall travel time per person of vehicles traveling along the arterial. Therefore, the criteria which was used to compare the various transit signal priority strategies was the total travel time occurring along the cross street and arterial links during the analysis time frame.

Obviously, as the number of vehicles processed within a simulation increases, the total travel time of all vehicles in the simulation also increases. However, this analysis assumes that approximately the same numbers of vehicles are processed during the analysis time frame over the separate simulations. Therefore, a comparison of the total travel times along the cross street and arterial links will give a good indication of the relative effectiveness of the various transit signal priority strategies.

The following data was collected following each simulation run:

1) Cumulative travel time measured 18 minutes after the beginning of the simulation along arterial and cross street links (vehicle minutes)
2) Cumulative travel time measured 6 minutes after the beginning of the simulation along arterial and cross street links (vehicle minutes)
3) Bus travel time (vehicle minutes)

Upon the collection of this data, the travel times along each link during the analysis time period were determined by subtracting the cumulative travel time along the links measured 6 minutes after the beginning of the simulation from the cumulative travel time along the links measured 18 minutes after the beginning of the simulation. Measures of total travel time along the individual links were then summed to obtain the overall travel times along the arterial and cross streets links during the analysis time period.

Figure 5.18 shows the link-node representation of the Guadalupe-N. Lamar arterial. Nodes 1 through 11 represent the intersections along the arterial where the bus operates. Arterial links include all the links which connect nodes 1 through 11 to each other, in addition to links (3, 35) and (35, 4). Cross street links include all links entering nodes 1 through 11 from the Eastern or Western directions, such as links (12, 1) and (13, 1).

Finally, the occupancy of the bus and autos was taken into consideration by multiplying the travel times (in vehicle minutes) by the occupancy rates (passengers per vehicle) to obtain the travel time along each link in terms of total person-minutes.

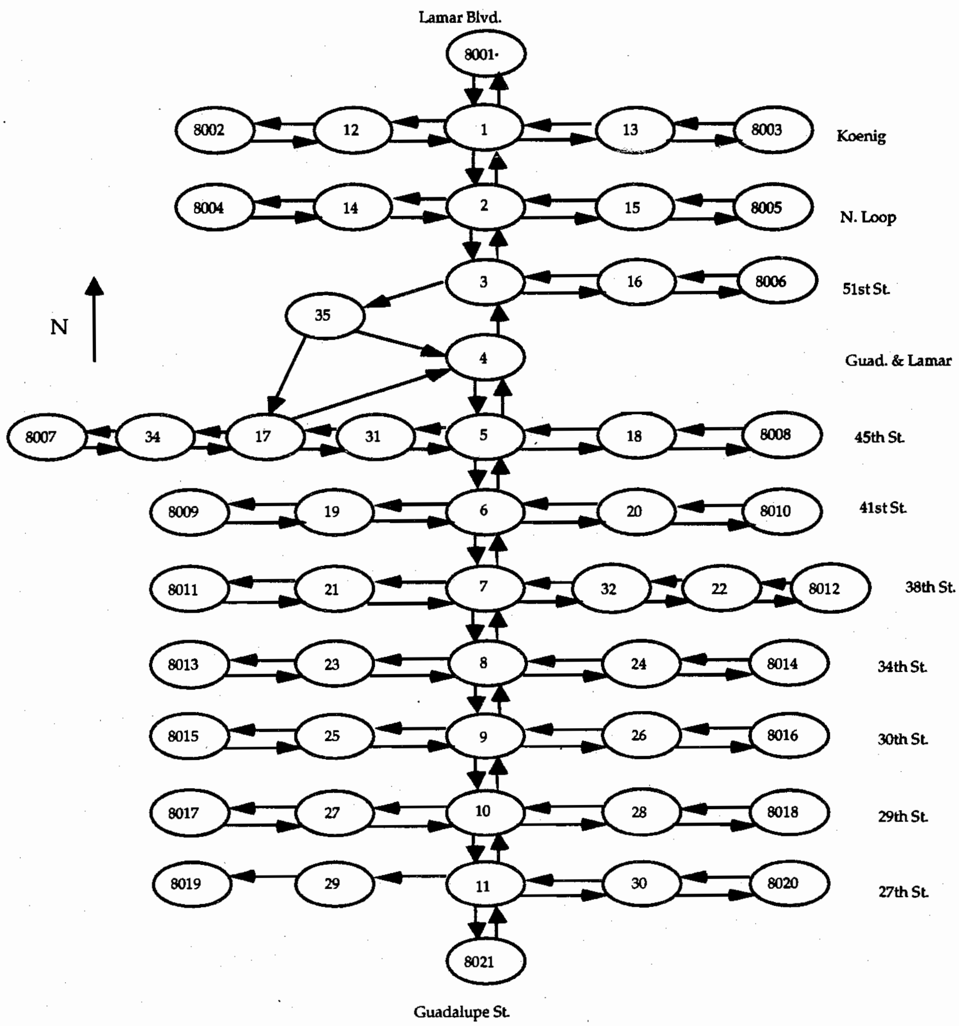


Figure 5.18 Link-node representation of Guadalupe-N. Lamar arterial

Results. Table 5.12 shows the results of this analysis when the bus occupancy is assumed to be 10 passengers per bus, accompanied by an average auto occupancy of 1.2 passengers.

TABLE 5.12 TOTAL TRAVEL TIME (PERSON-MINUTES) WITHIN ARTERIAL NETWORK
BUS OCCUPANCY = 10, AUTO OCCUPANCY = 1.2

	Case 0	Case 1	Case 2	Case 3
Auto Travel Time along Arterial	4405	4379	4376	4417
Auto Travel Time along Cross Streets	2899	3193	3023	2985
Bus Travel Time along Arterial	108	89	96	99
Total Travel Time within Arterial Network	***7412***	***7661***	***7494***	***7501***

As can be seen from Table 5.12, the base case (case 0) outperforms all the cases where transit signal priority was used. As expected, the cross streets suffer with the use of transit signal priority, with the greatest increase (10% increase) in cross street travel time occurring with case 1. When priority is limited and restricted at the high volume cross street locations (cases 2 and 3, respectively), the travel times along the cross streets are reduced relative to case 1, but are still greater than the base case.

The travel time which auto traffic experiences along the arterial fluctuates over the 4 cases with no apparent pattern. Auto travel times on the arterial are reduced in cases 1 and 2 relative to the base case, but increase in case 3 relative to the base case. However, it is important to note that none of the changes are very large with respect to the base case. In fact, over the 4 cases auto travel times along the arterial all fall within 1% of one another. This indicates that transit signal priority has little effect on the performance of automobile traffic traveling along the arterial which receives priority.

An explanation of this phenomenon was apparent when observing a simulation with TRAF-Netsim's graphical animation. The graphical animation showed that arterial traffic in the vicinity of the bus benefited from the bus' first priority call. However, after receiving priority, the bus typically stopped at a far-side bus stop, which caused it to lose coordination with the arterial traffic which benefited from the first priority call. As a result, the arterial traffic approached the downstream intersection sooner than it would have, had it not received a "free priority" from the bus. However, since the arterial signal timing offsets were not designed with signal priority in mind, the arterial traffic was typically delayed at the downstream intersection. The net result of this phenomenon is a minimal change in the overall travel time of arterial automobile traffic.

Finally, Table 5.12 shows that the bus travel time is reduced relative to the base case over all 3 signal priority strategies, with the shortest bus travel time occurring with case 1. However, although the bus travel time is reduced by significant percentages, the *absolute* travel time savings which the bus receives is minor compared with the absolute travel time increases imposed upon the cross streets when signal priority is initiated.

For instance, from case 0 to case 1, the bus travel time is reduced by almost 18%. However, this represents an absolute savings in travel time of only 19 person-minutes. The cross streets, meanwhile, must endure a 294 person-minute increase to their overall travel time. Clearly, making 20 second green extensions available to the bus at all intersections along the Guadalupe-N. Lamar arterial is not advisable.

The results shown in Table 5.12 reiterate a point which was made in the previous section. With 10 minute bus headways and significant automobile traffic volumes, the bus mode share is extremely small. When the bus occupancy is assumed to be 10 passengers, the bus' share of the total travel time within the network over the analysis period is only 1.5% (for the base case). Therefore, even improving the bus' performance significantly (on a percent basis) fails to provide the overall transportation network with significant *absolute* gains. In addition, the disruption caused to the network with the use of the signal priority timings overwhelms any small benefits realized by bus passengers.

Tables 5.13 and 5.14 are presented to show the effects of assuming bus occupancies of 25 and 50 passengers, respectively.

TABLE 5.13 TOTAL TRAVEL TIME (PERSON-MINUTES) WITHIN ARTERIAL NETWORK
BUS OCCUPANCY = 25, AUTO OCCUPANCY = 1.2

	Case 0	Case 1	Case 2	Case 3
Auto Travel Time along Arterial	4405	4379	4376	4417
Auto Travel Time along Cross Streets	2899	3193	3023	2985
Bus Travel Time along Arterial	269	223	239	248
Total Travel Time within Arterial Network	***7573***	***7795***	***7637***	***7649***

As can be seen in Table 5.13, assuming a bus occupancy of 25 passengers does not affect the overall results significantly. The base case still enjoys the lowest overall network travel time. However, the absolute travel time savings which bus travelers enjoy increases. For instance, the difference between the bus travel time in the base case and case 1 is 46 person-minutes when a bus occupancy of 25 passengers is assumed.

With an occupancy of 25 passengers, the bus now accounts for about 3.6% of the total person-minutes of travel time within the network over the analysis time period. This share of travel time is extremely small, causing the benefits of signal priority to be overshadowed by the resulting increased travel times along the cross streets.

TABLE 5.14 TOTAL TRAVEL TIME (PERSON-MINUTES) WITHIN ARTERIAL NETWORK
BUS OCCUPANCY = 50, AUTO OCCUPANCY = 1.2

	Case 0	Case 1	Case 2	Case 3
Auto Travel Time along Arterial	4405	4379	4376	4417
Auto Travel Time along Cross Streets	2899	3193	3023	2985
Bus Travel Time along Arterial	538	446	478	495
Total Travel Time within Arterial Network	***7842***	***8018***	***7876***	***7897***

Table 5.14 shows that even with a bus occupancy of 50 passengers, the base case remains the alternative with the lowest overall network travel time. With 50 passengers, the bus owns roughly 6.9% of the overall person-minutes of base case travel time. Therefore, transit signal priority has an increasing impact upon overall network travel time. However, this impact is still not large enough to offset the increased travel time occurring along the cross streets.

If the bus' mode split was increased further, the performance of case 2 would eventually surpass the base case, followed by case 3 and case 1. This leads to several conclusions. First, in areas where transit enjoys only a small mode share, transit signal priority is not recommended. However, in areas where transit enjoys a higher mode split, active signal priority may be feasible. It is important to note, however, that if transit enjoys a high mode split within a particular transportation network, the network signal timings will almost certainly reflect the needs of the transit vehicles to begin with (perhaps in the form of passive priority). Therefore, under these circumstances active signal priority may not provide significant incremental benefits to transit.

In general, the transportation network signal timings should accommodate the users. If the vast majority of the transportation network users travel within automobiles, then the use of signal priority cannot be justified. If, however, a large share of the trips within a transportation network are made with transit, signal priority might be justified if the present signal timings do not *already* adequately serve the transit vehicles.

SUMMARY

This chapter has reached several conclusions regarding the use of transit signal priority during the peak time period. First, the cross street saturation level and the amount of green time taken from the cross street are important considerations in determining whether signal priority should be used at any intersection.

Taking 5 and 10 seconds of green time from cross streets with saturation levels in excess of 0.9 and 0.8 respectively, can cause serious increased delay effects to cross streets which often do not dissipate before the initiation of the subsequent signal priority timing.

Far-side bus stop configurations were found to be much more favorable to the success of transit signal priority than near-side bus stop configurations. Typically, green extensions used in tandem with near-side bus stops were wasted while passengers boarded and deboarded the bus. Long or variable bus dwell time distributions at near-side bus stops are especially disruptive to the success of transit signal priority.

Transit signal priority does not impact the overall travel time per person at intersections with significant cross street saturation levels. With 10 minute bus headways and significant auto volumes, transit owns only a small share of the person-trips at an intersection, even if the bus occupancy is assumed to be 50 passengers. Therefore, reducing the travel time of the 50 bus passengers does not significantly influence the overall travel time per person at the intersection. Further, the intersection's overall travel time per person increases with longer green extensions, indicating that transit signal priority should be limited to only short green extensions if used at intersections with significant cross street saturation levels.

Finally, transit signal priority was also determined to be ineffective within an arterial street environment. With 10 minute bus headways and heavy traffic volumes, the benefits received by bus passengers with transit signal priority are overwhelmed by the negative impacts which accrue along the cross streets. Only when shorter bus headways and high bus occupancies cause significant increases in transit's mode split does transit signal priority begin to become a viable option.

CHAPTER 6. CONCLUSIONS

FINDINGS

This study has summarized past research on transit signal priority, as well as developed new findings regarding the potential of various transit signal priority strategies, during both peak and off-peak times.

As shown in the literature, transit signal priority has been used in many different contexts, with mixed results. Transit signal priority generally benefits areas with high transit usage, but often poses problems in transportation networks where the automobile is the primary transportation mode. Other factors which influence the success of transit signal priority include the time of day when used, and the characteristics of the transit service itself. Implementing transit signal priority is less challenging during off-peak times than peak times. Excess capacity available during off-peak times may be used to transit's advantage, but little or no excess capacity is available during peak times, making the use of transit signal priority more questionable. Also, signal priority is generally more successful in transportation networks featuring high transit usage. From a network perspective, as the transit mode share increases, impacts from transit signal priority will benefit an increasing percentage of travelers.

Reducing signal cycle lengths and split phasing are passive priority techniques which may be useful during off-peak times with local transit service. Reducing the cycle lengths along an arterial reduces transit delay, and delay to general traffic if the arterial is operated with a generous amount of excess capacity. However, when implementing a shortened cycle length, one should pay close attention to high volume intersections to ensure that their performance is not sacrificed. Split phasing is also potentially useful during off-peak times, but should not interfere with existing progression along an arterial or its cross streets. Also, consideration should be given to re-setting offsets along an arterial when initiating split phasing, to account for the new phase pattern.

Unconditional signal priority during off-peak times offers express transit service significant potential benefits. However, its use should be regulated by placing limits on green extension and red truncation lengths, especially at intersections with busy cross streets.

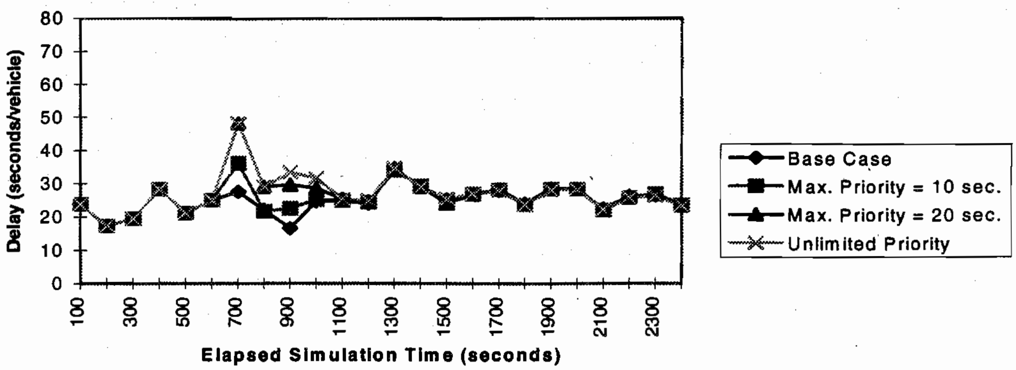
During peak times, active transit signal priority should be used with caution. Active signal priority may cause disruptions along highly saturated cross streets which do not dissipate before the next priority call. Far-side bus stops should be used with active signal priority to ensure that signal priority calls are not wasted as transit vehicles dwell at bus stops. Also, the success of transit signal priority during peak times is proportional to the transit mode share within the network. With only a small mode share, even large benefits to transit vehicles are overwhelmed by disruption to private vehicles through signal priority usage. Only when transit gains a significant share of trips within the network, will transit signal priority have an overall positive network impact. In general, since control settings within a transportation network should accommodate the network's primary users, use of transit signal priority cannot be justified if transit does not own a significant share of peak period trips.

RECOMMENDATIONS FOR FUTURE RESEARCH

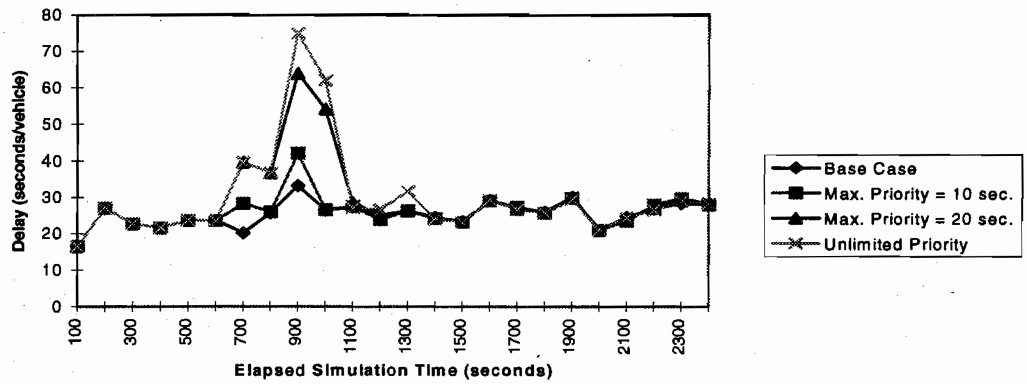
This report has concluded that transit signal priority is largely ineffective when used in a transportation network heavily skewed toward private automobile use. However, findings from this study also support the hypothesis that transit signal priority success will increase as transit's mode share increases. A follow up study similar to this one, which evaluates the effects of transit signal priority within a network skewed towards public transit, would provide an added perspective on the usefulness of transit signal priority over a range of environments.

In addition, due to time constraints, an evaluation of signal priority for express transit service during peak times was not performed. However, the potential benefits of this form of signal priority deserve additional consideration. Because trajectories of express transit vehicles are more predictable than those of local transit vehicles, more robust signal priority strategies may be developed to aid express transit. In addition, because express transit vehicles travel with general traffic more readily than local transit vehicles, priority strategies which benefit express transit may not come at such a high cost to general traffic.

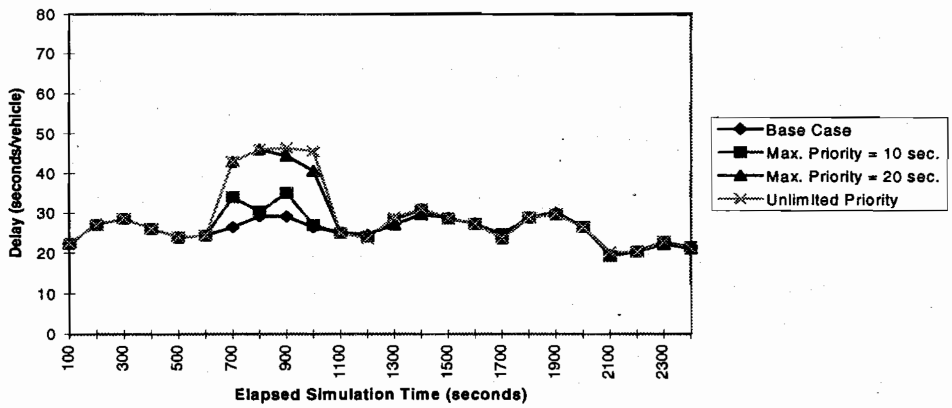
APPENDIX A. SIMULATION RESULTS OF UNCONDITIONAL PRIORITY DURING OFF-PEAK HOURS



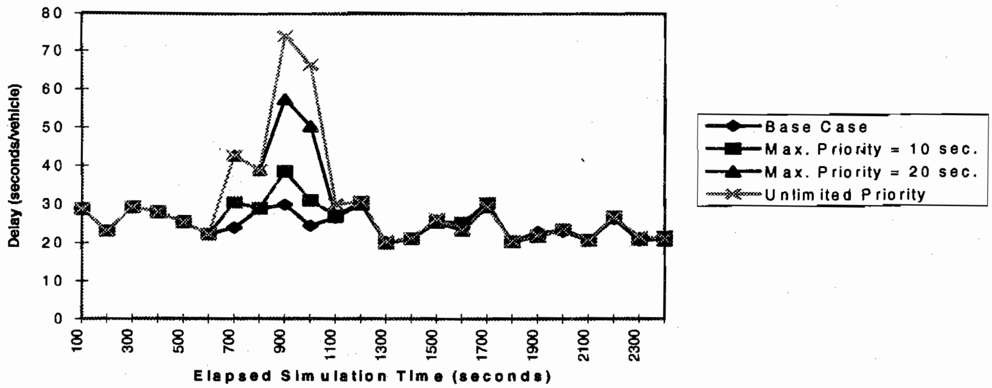
Delay at 38th Street Eastbound, saturation level = 0.50 (run 1)



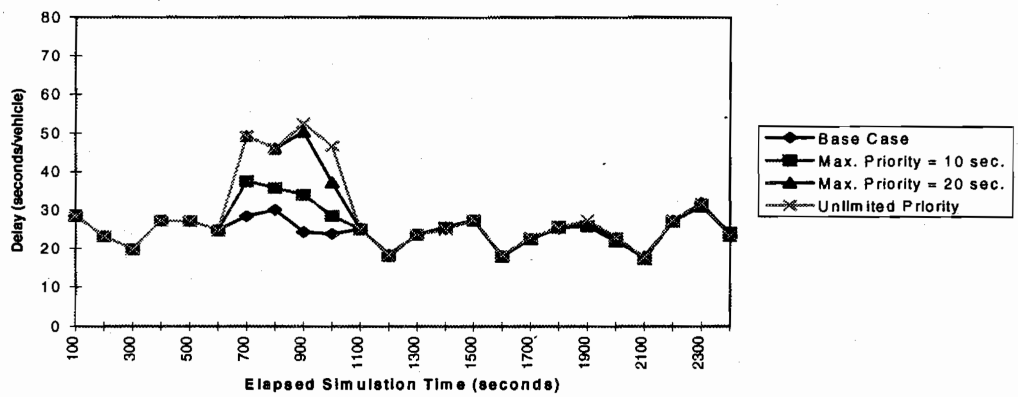
Delay at 38th Street Eastbound, saturation level = 0.50 (run 2)



Delay at 38th Street Eastbound, saturation level = 0.50 (run 3)



Delay at 38th Street Eastbound, saturation level = 0.62 (run 1)



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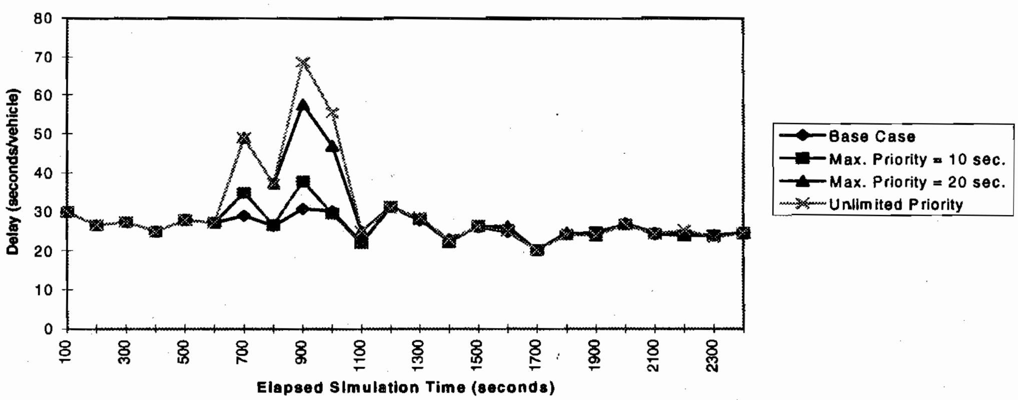

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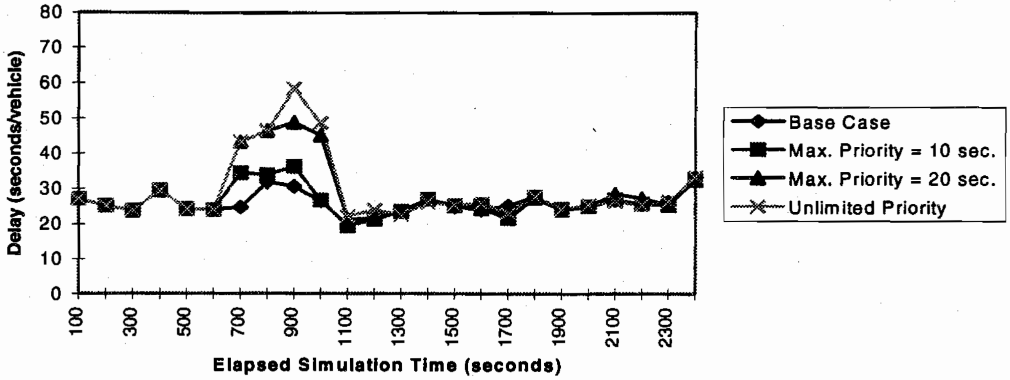

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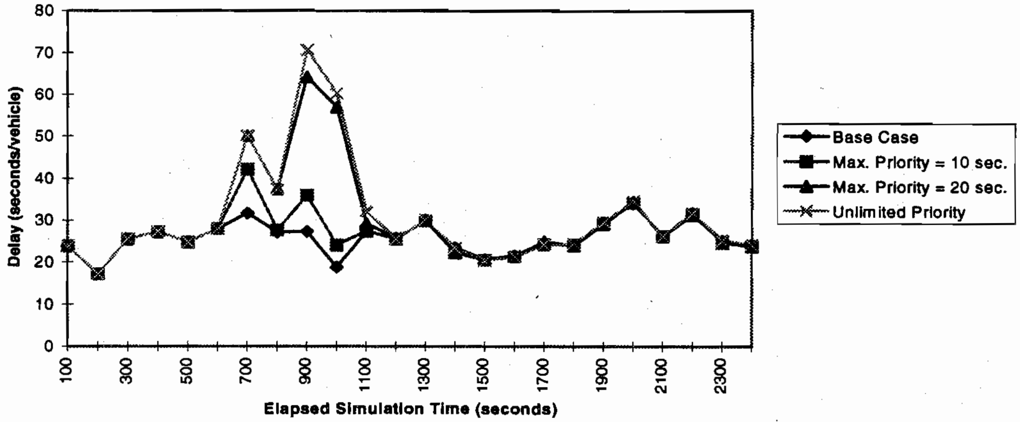

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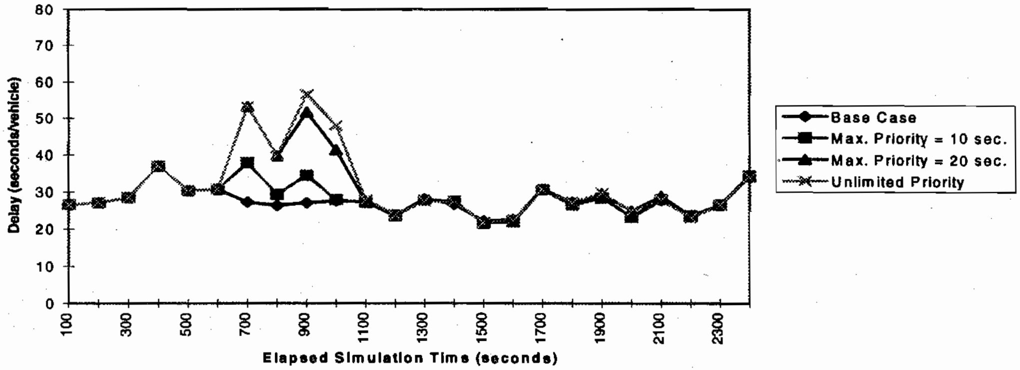

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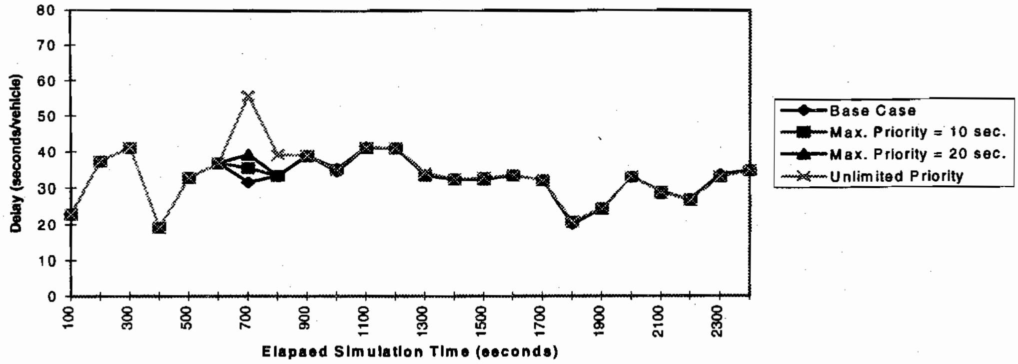

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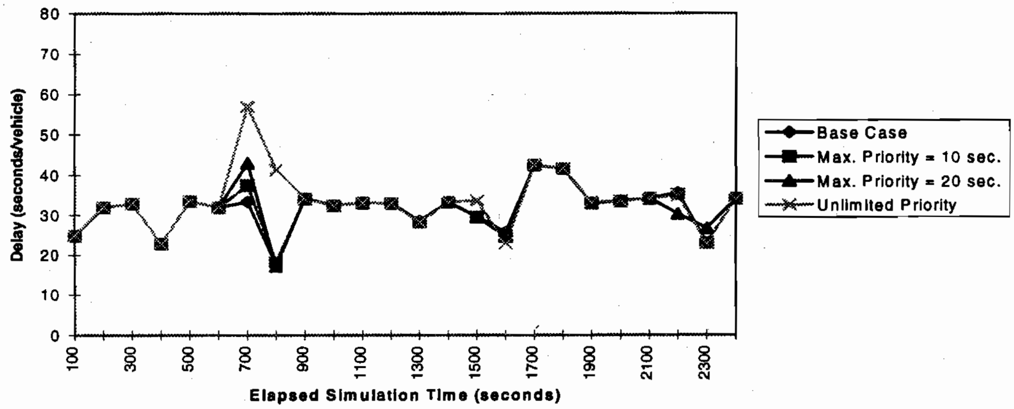

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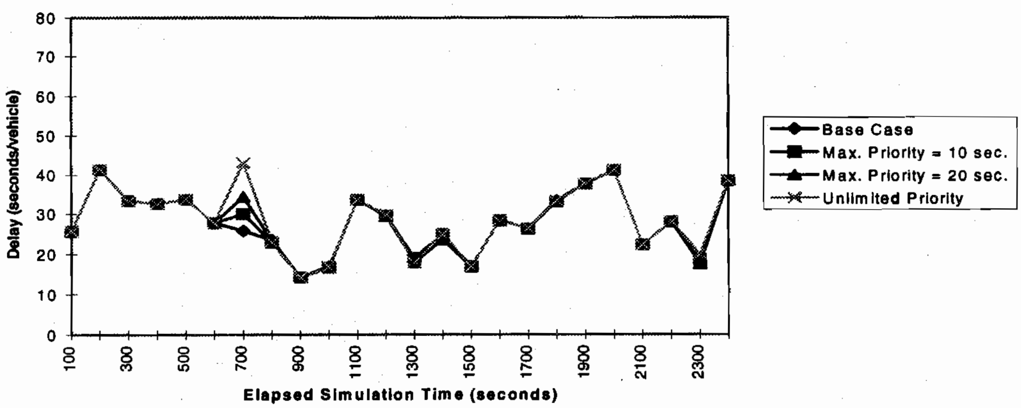

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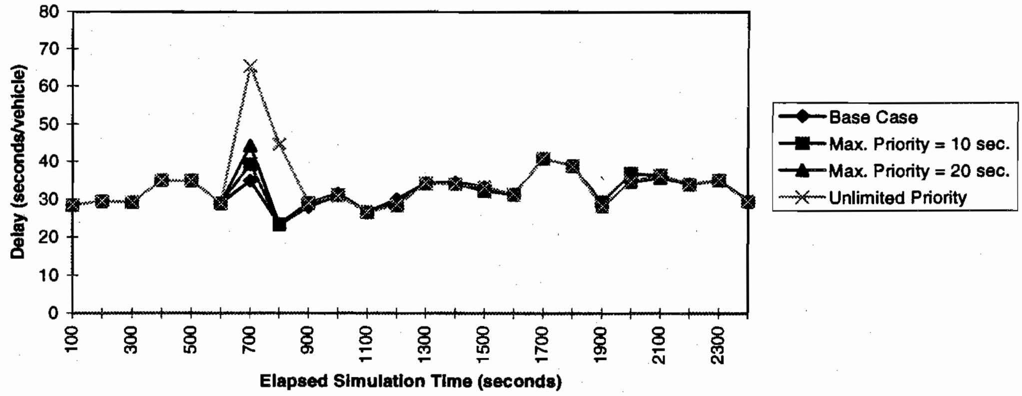

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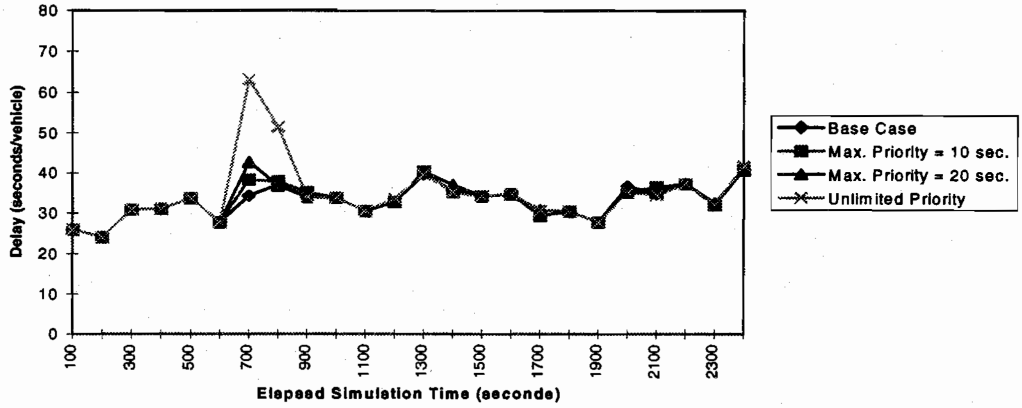

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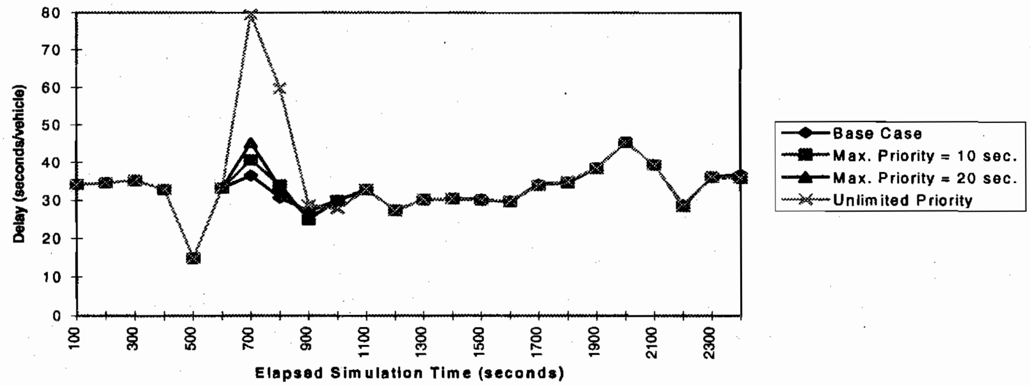

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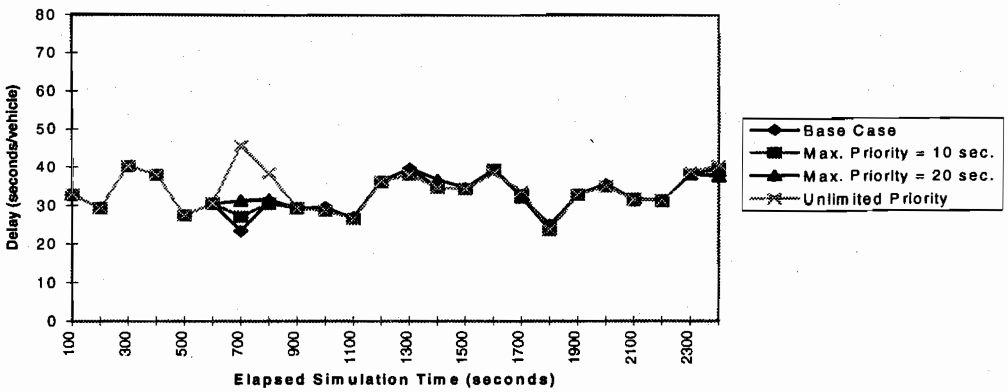

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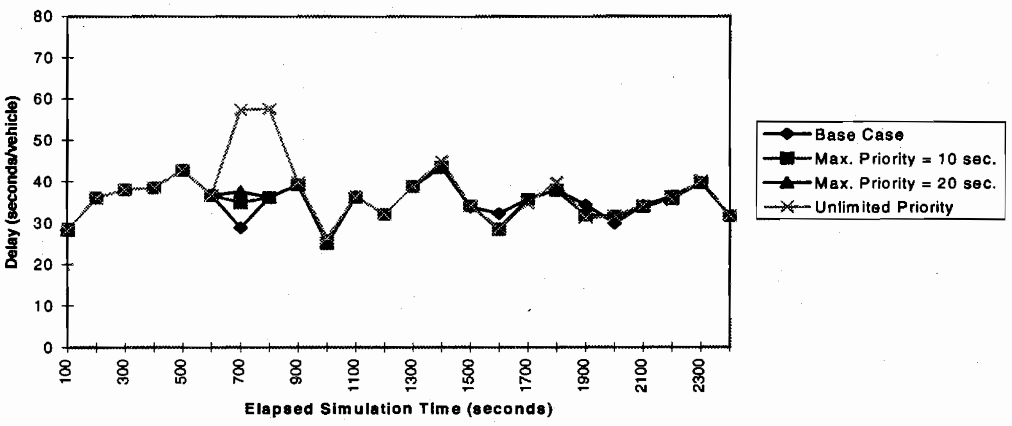

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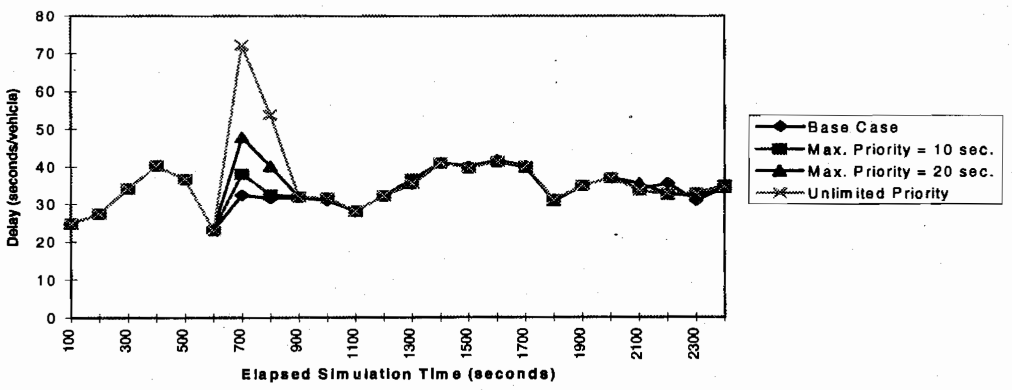

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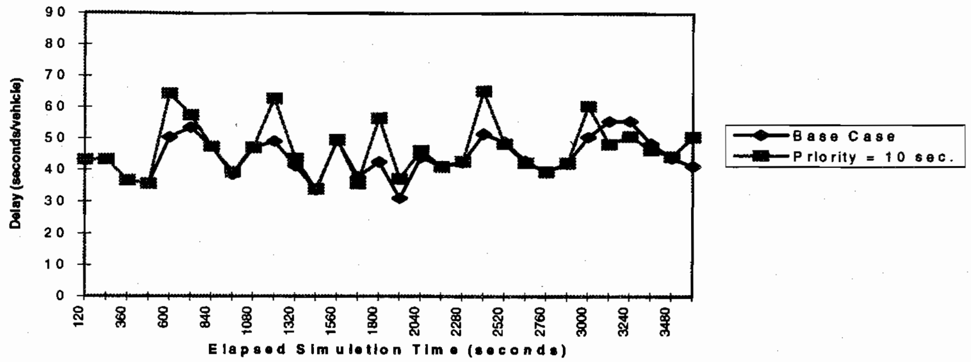
APPENDIX B. SIMULATION RESULTS OF PEAK PERIOD SIGNAL PRIORITY WITH 10 MINUTE BUS HEADWAYS



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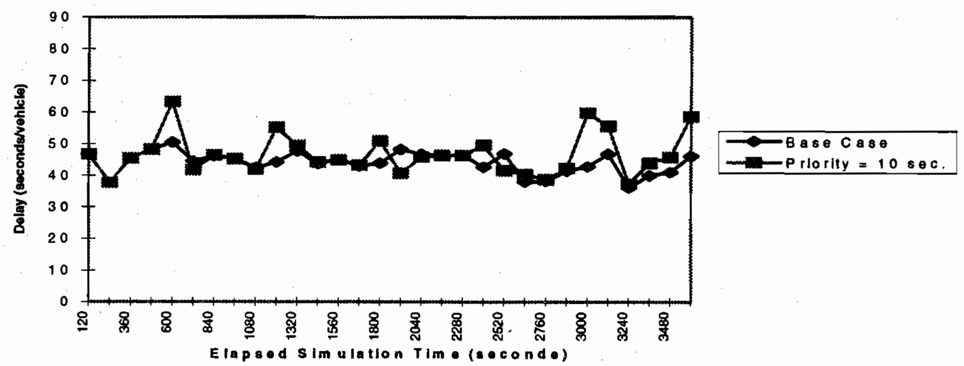

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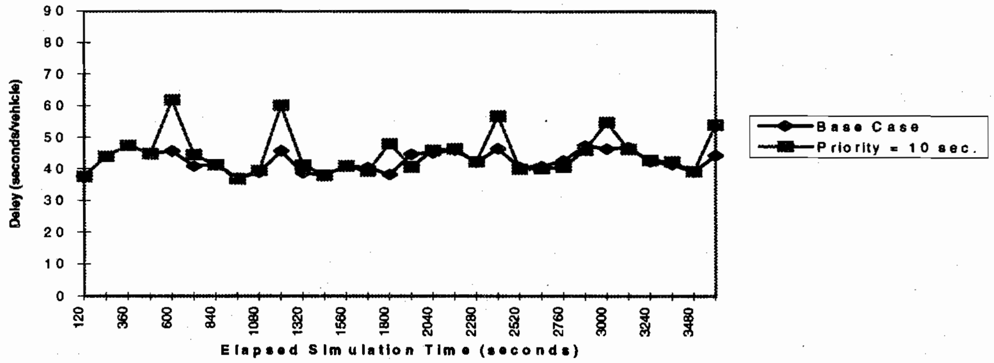

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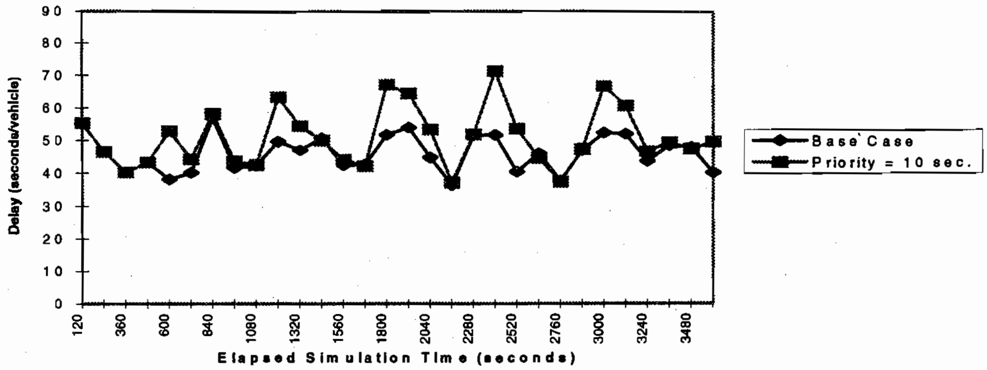

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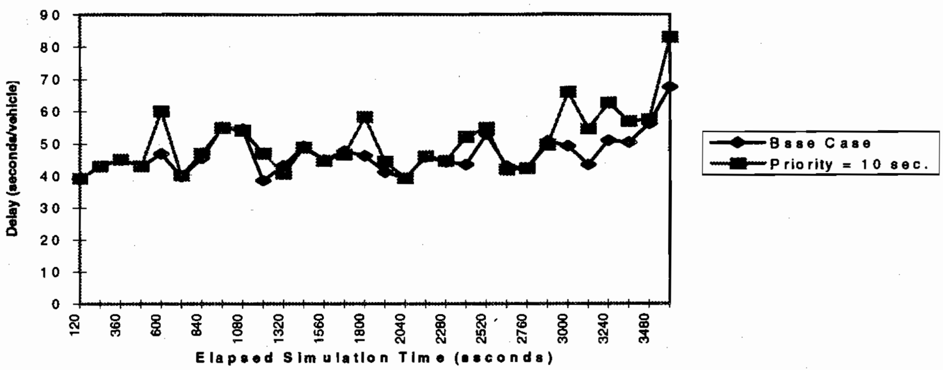

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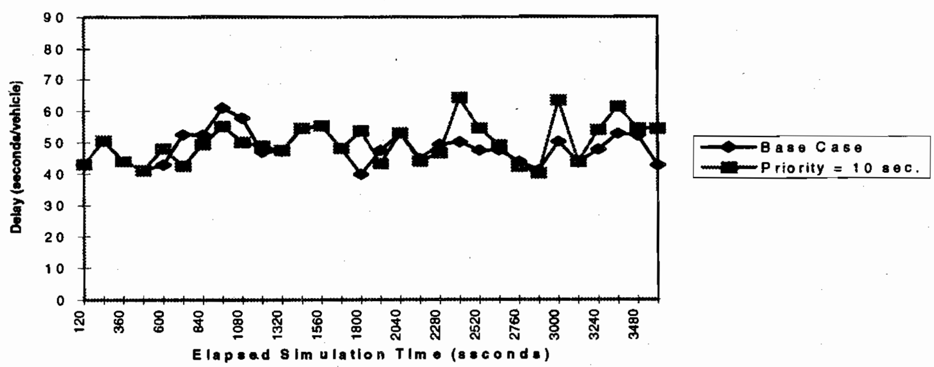

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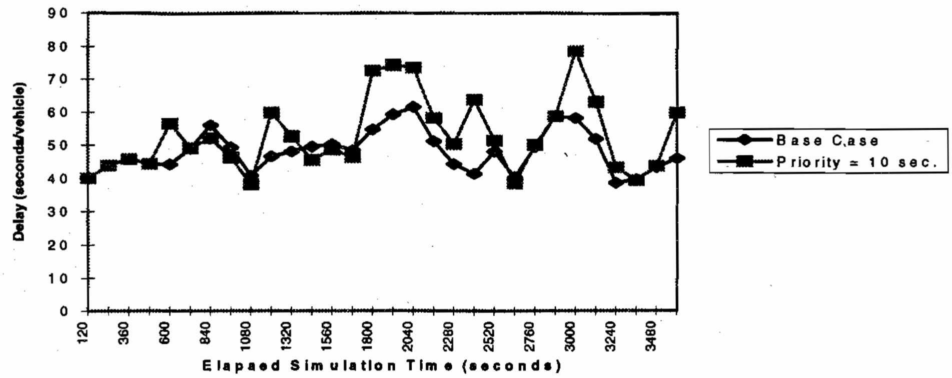

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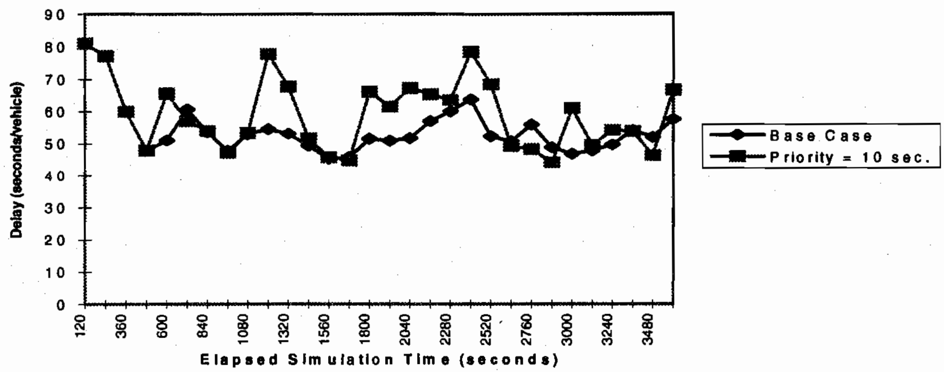

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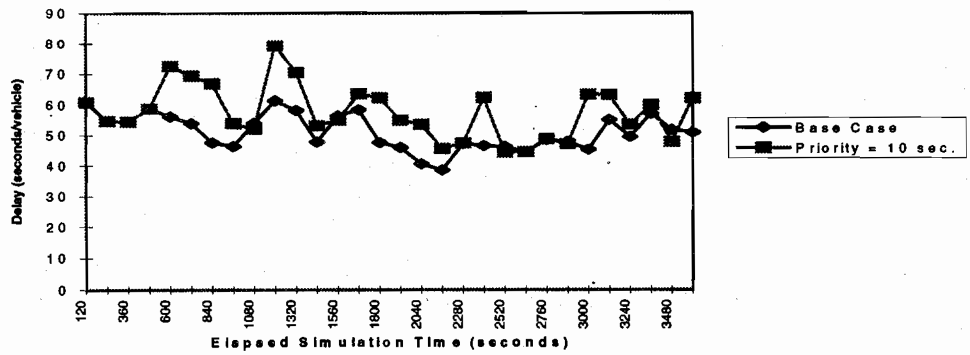

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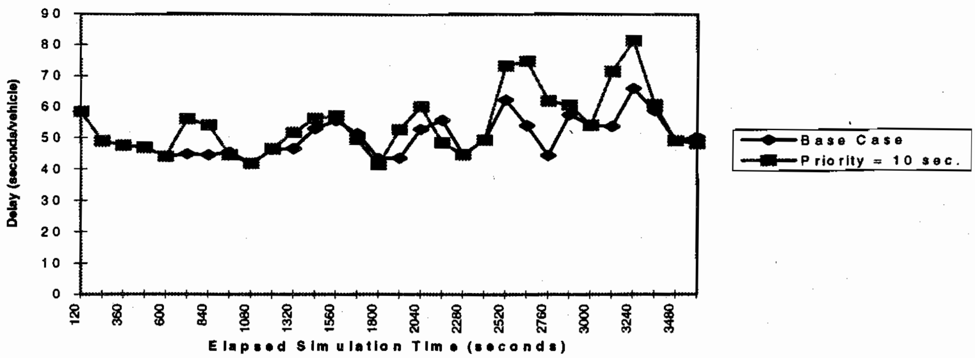

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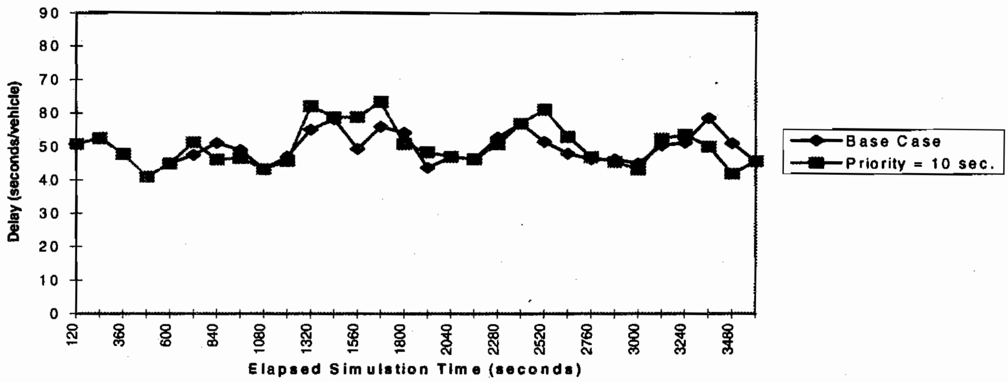

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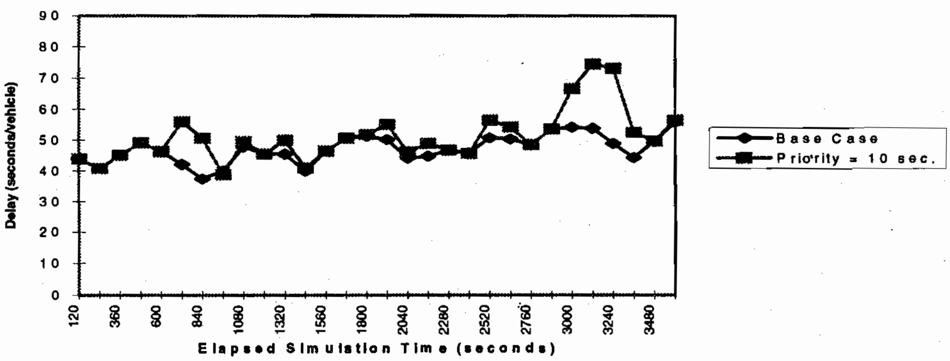

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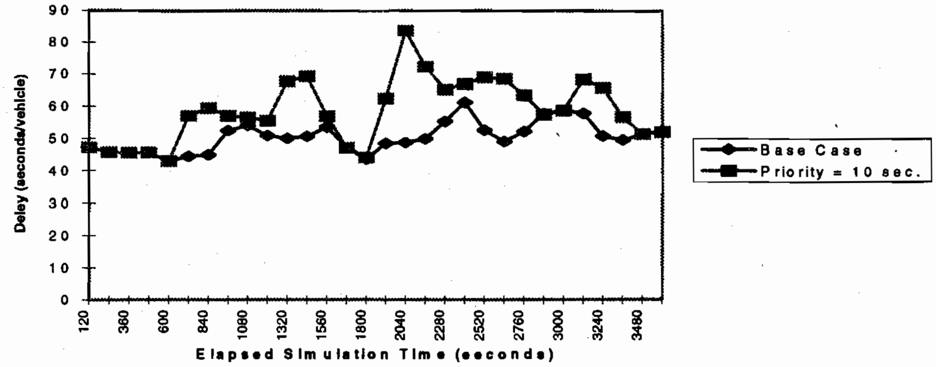

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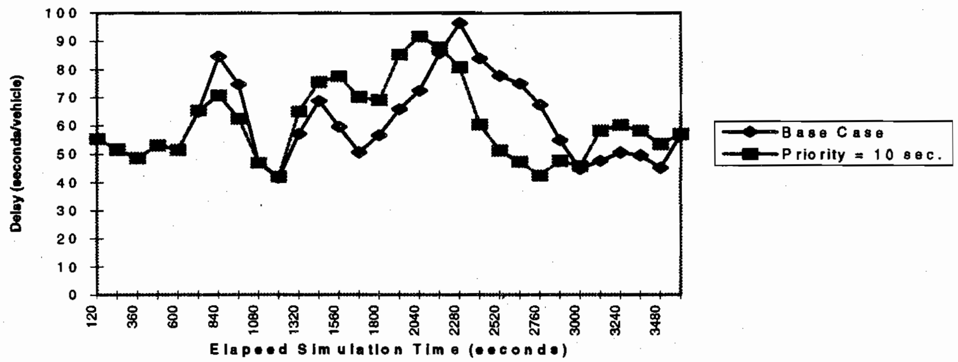

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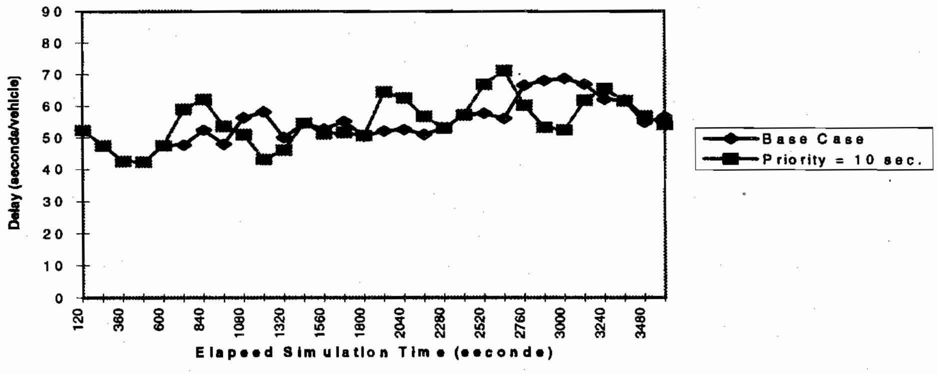

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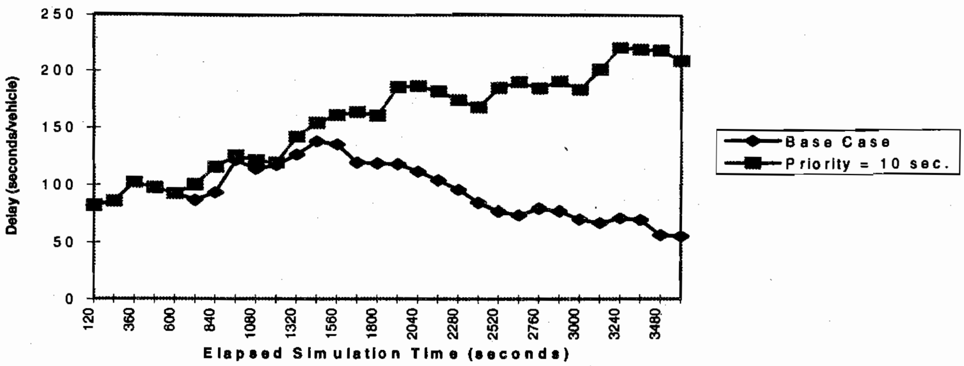

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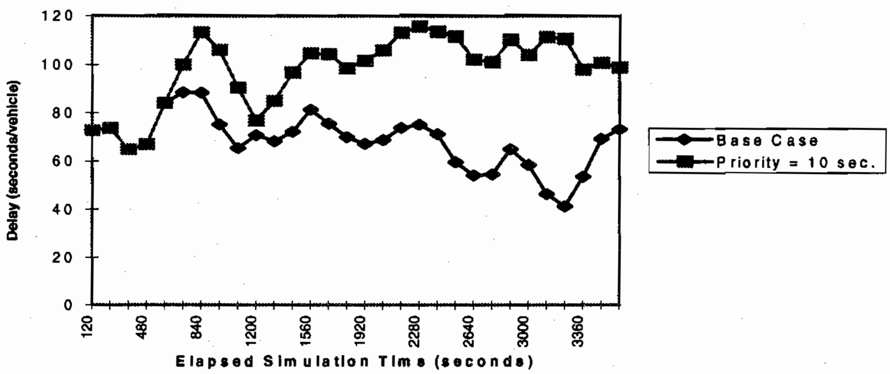

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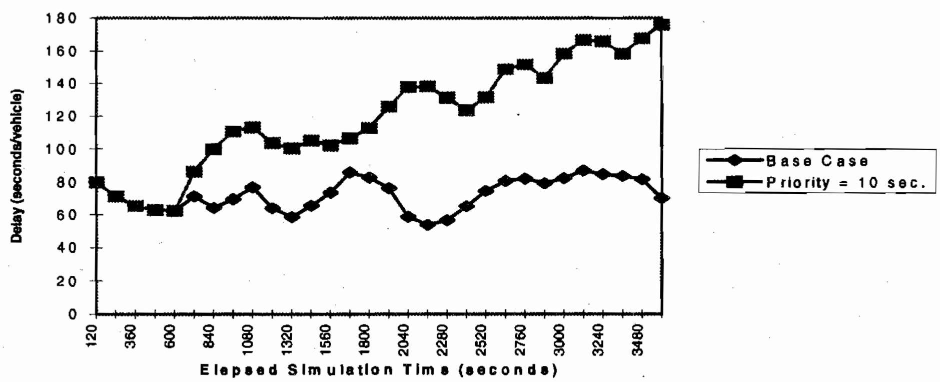

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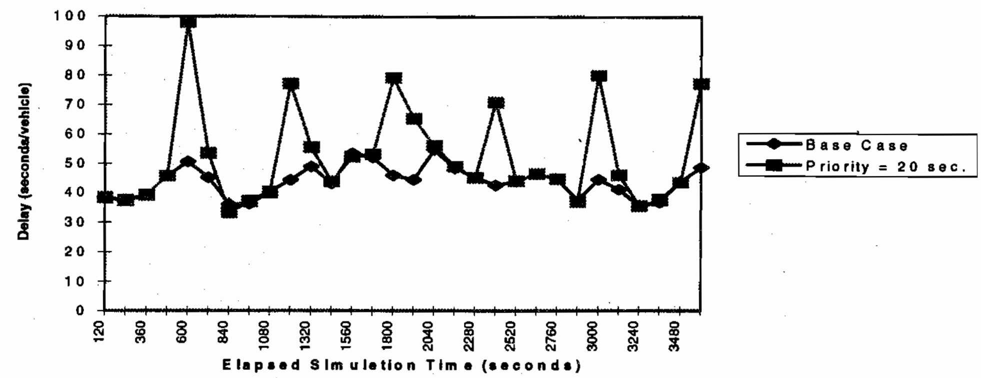

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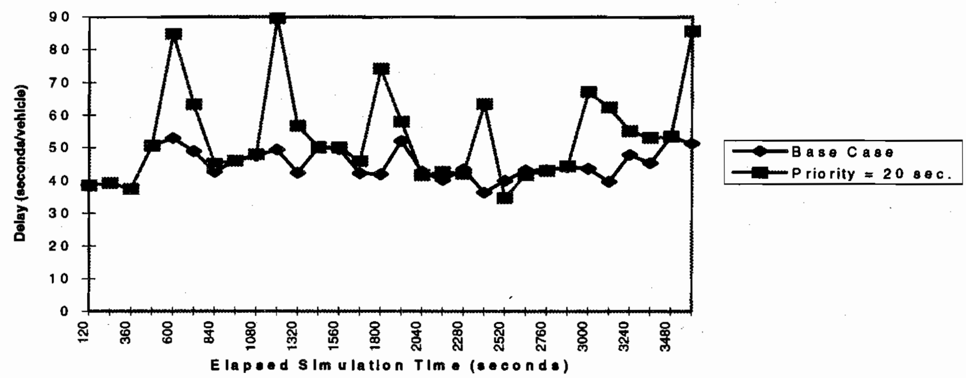

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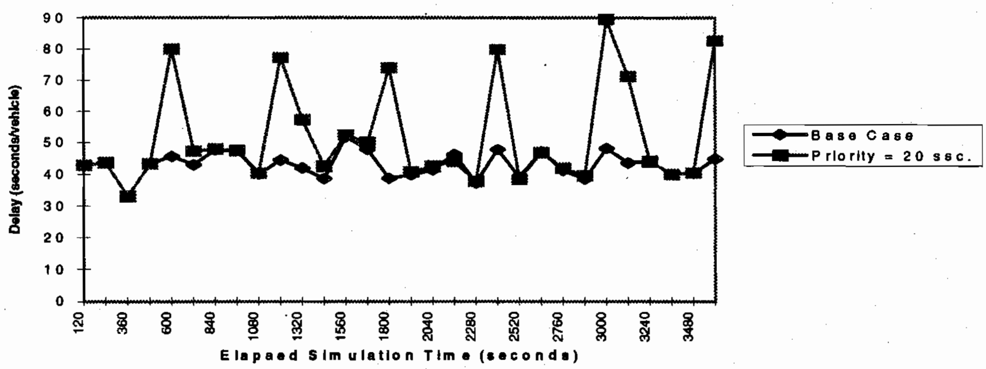

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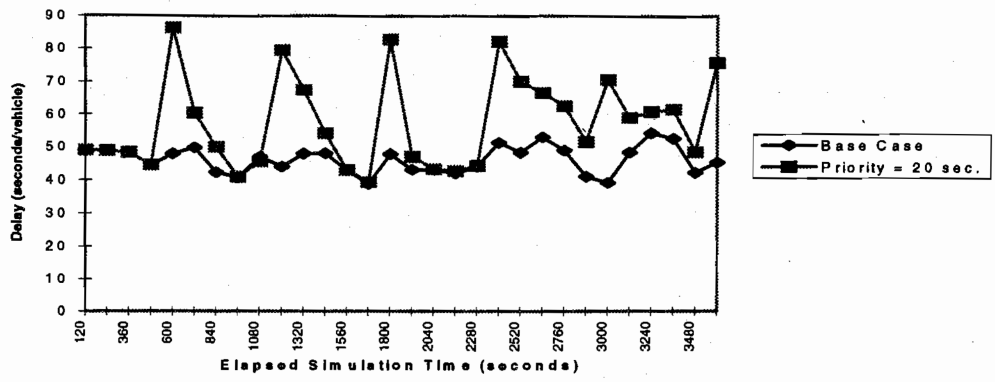

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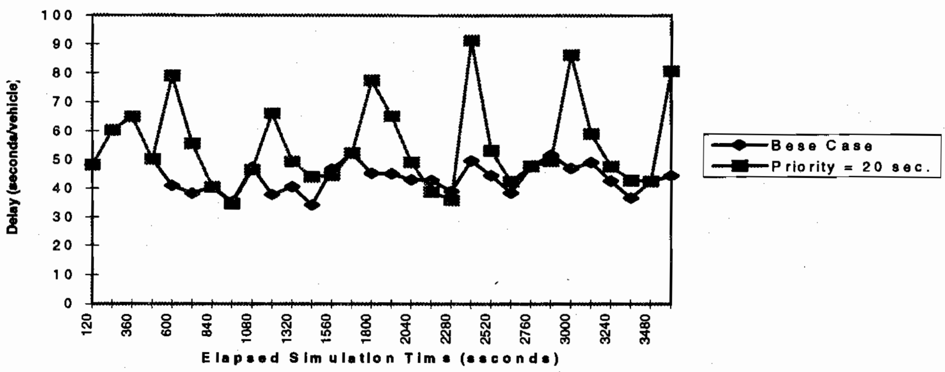

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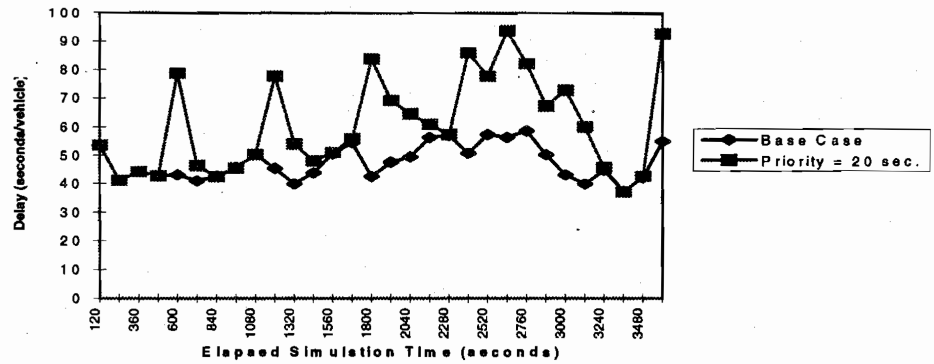

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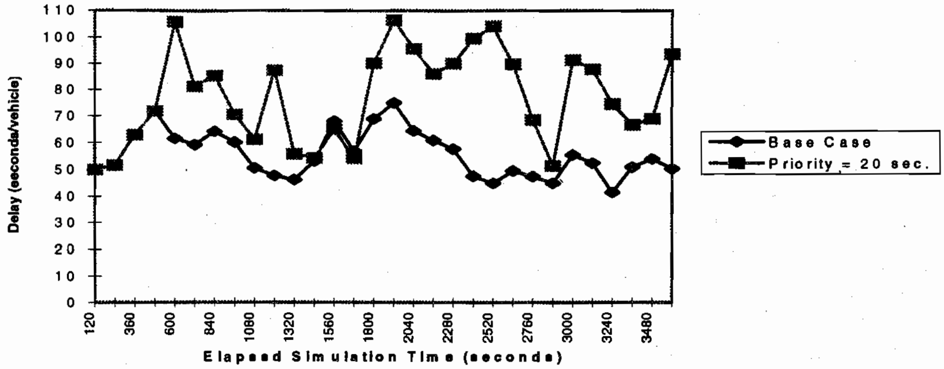

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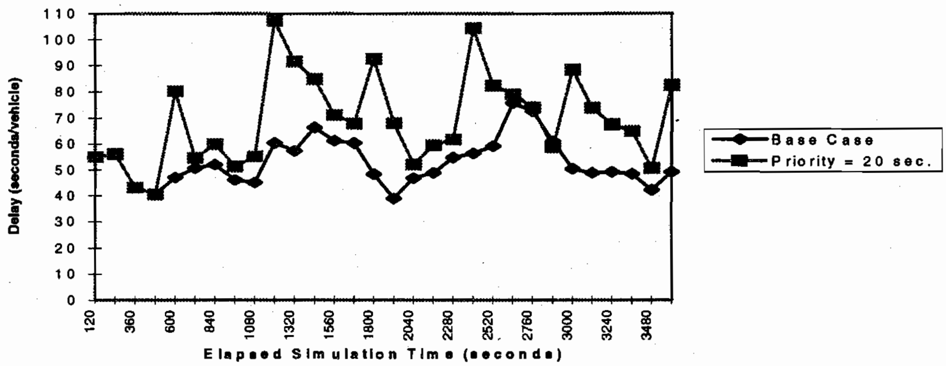

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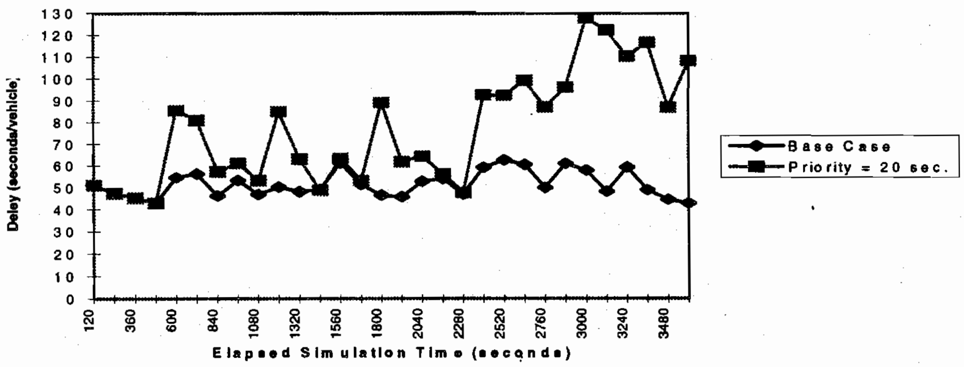

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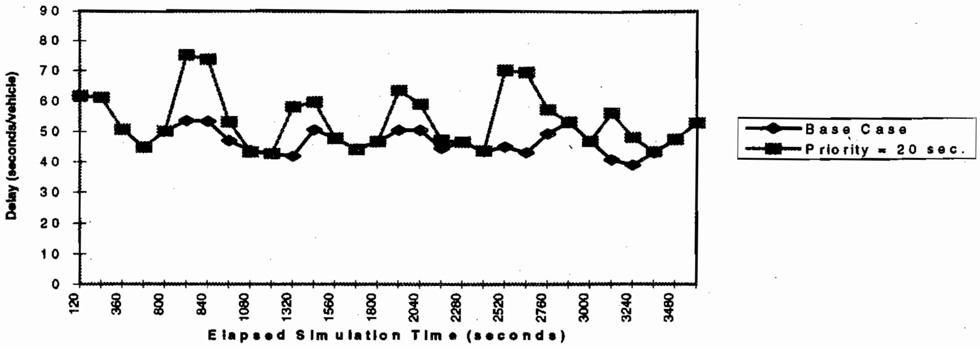

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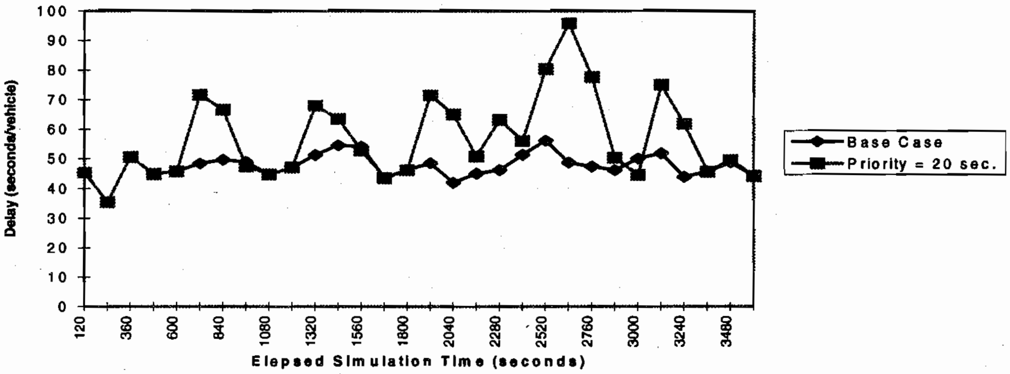

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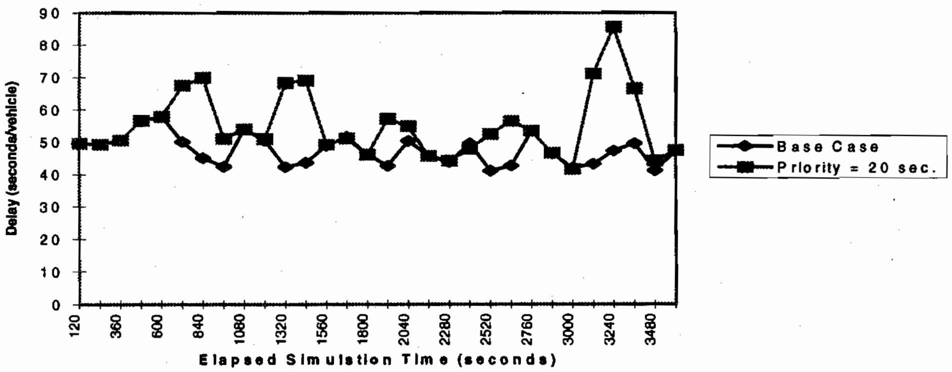

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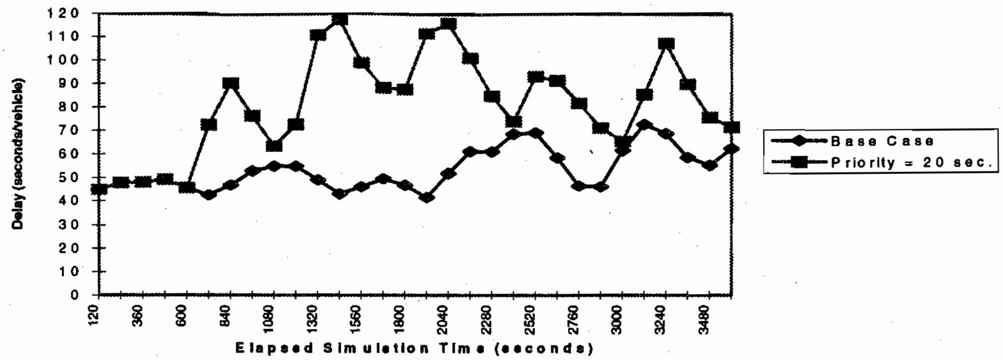

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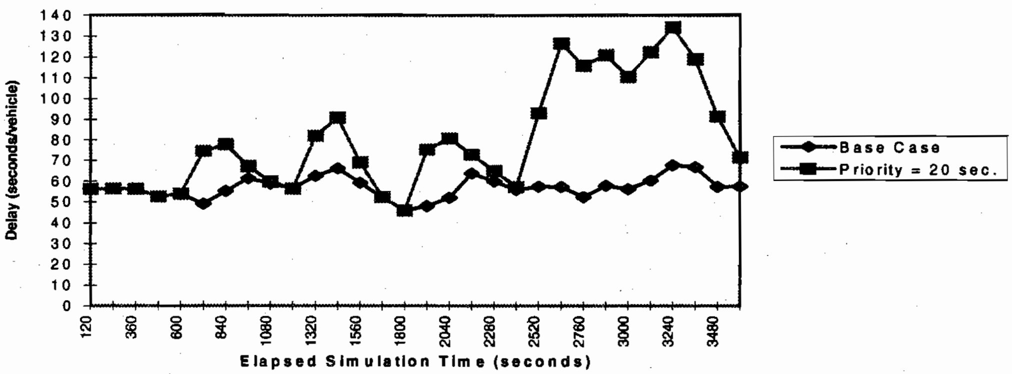

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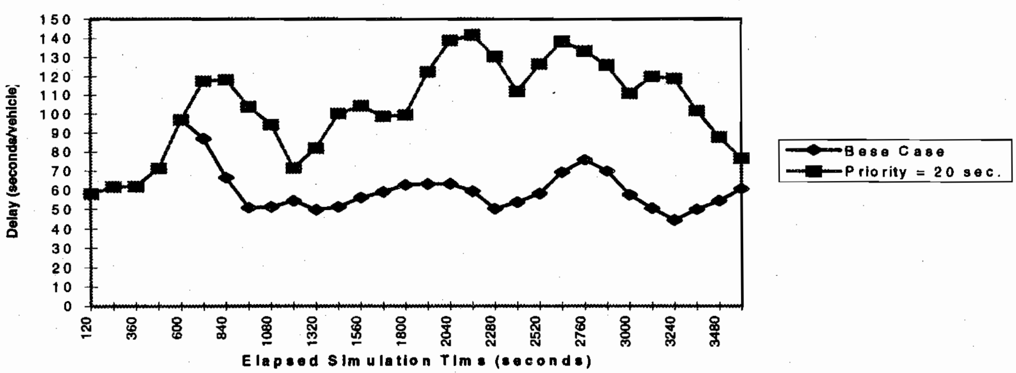

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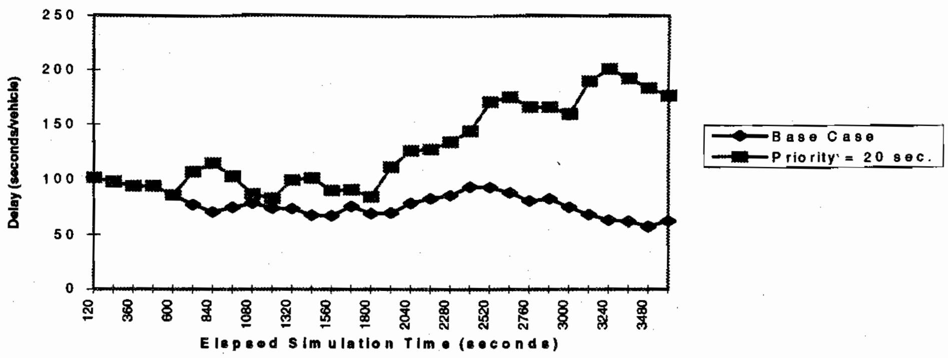

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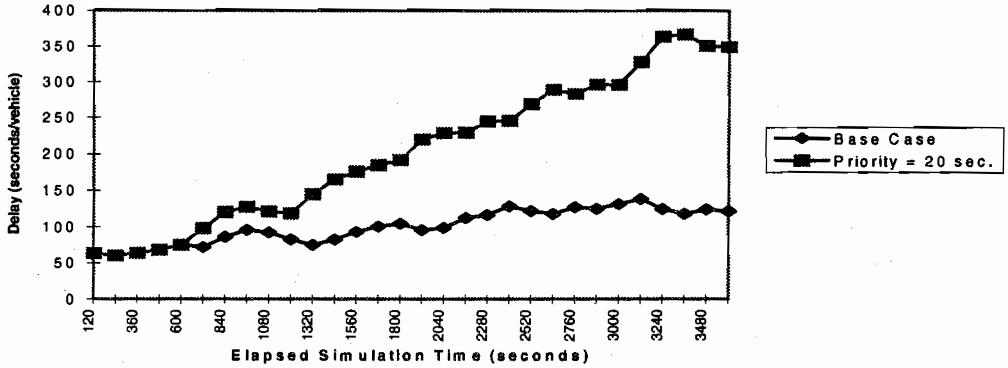

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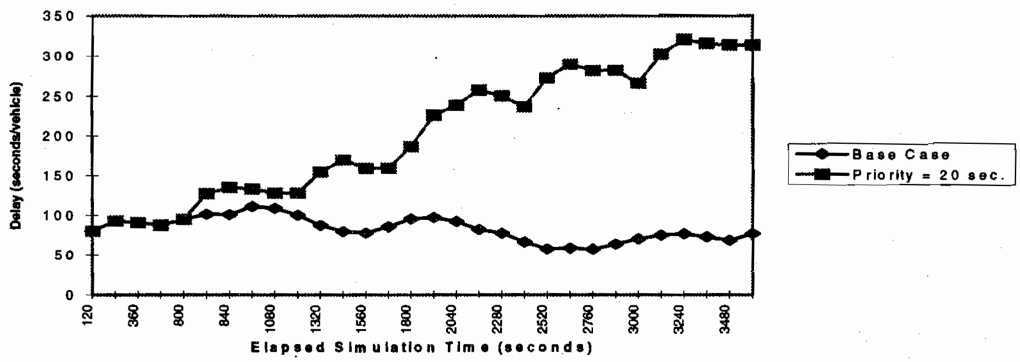

Delay at 45th Street Westbound, saturation level = 1.0,
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REFERENCES

1. Urbanik II, Thomas, and R. W. Holder, "Evaluation of Priority Techniques for High Occupancy Vehicles on Arterial Streets", Texas Transportation Institute, Texas A&M University, July, 1977.

2. Wattleworth, Joseph A., Kenneth G. Courage, and Charles E. Wallace, "Evaluation of Bus-Priority Strategies on Northwest Seventh Avenue in Miami", *Transportation Research Record 626*, pp. 32-35, 1977.

3. Yagar, Sam and Ben Heydecker, "Potential Benefits to Transit in Setting Traffic Signals", *Transportation Research Board Special Report 221; Light Rail Transit: New System Successes at Affordable Prices*, pp. 657-667, 1988.

4. Fehon, K. J., W. A. Tighe, and A. O. Albers, "Advanced Integration of LRT and Traffic Signals", *Third International Conference on Road Traffic Control*, pp. 209-214, May, 1990.

5. Khasnabis, Snehamay, Gangula V. Reddy, and Bharat B. Chaudry, "Signal Preemption as a Priority Treatment Tool for Transit Demand Management", *Vehicle Navigation and Information Systems*, pp. 1093-1104, 1991.

6. "Mainline Traffic Signal Priority Study. Phase 5-Demonstration Project. Final Report.", Municipality of Metropolitan Toronto, April, 1991.

7. Yagar, Sam, Bin Han, and John Greenough "Real-Time Signal Control for Mixed Traffic and Transit Based on Priority Rules", Proceedings of Conference on Traffic Management: Sponsored by Engineering Foundation, pp. 147-166, 1992.

8. Celniker, Stephen and E. Wayne Terry, "Trolley Priority on Signalized Arterials in Downtown San Diego", *Transportation Research Record 1361*, pp. 184-187, 1992.

9. Kuah, Geok K. and Jeffrey B. Allen, "Designing At-Grade LRT Progression: Proposed Baltimore Central Light Rail", *Transportation Research Record 1361*, pp. 207-216, 1992.

10. Daniel, Janice, "Signal Priority for Public Transit Vehicles Using Advanced Traffic Control Systems: A Comparative Evaluation of ATSAC, SCATS, and SCOOT", Southwest Region University Transportation Center, Texas Transportation Institute, August, 1992.

11. Jacobson, Kern L., "Transit Signal Priority Treatments in the Puget Sound Region", *Proceedings: Pacific Rim TransTech Conference*, Volume 1, pp. 272-278, July, 1993.

12. Nelson, J. D., D. W. Brookes, and M. G. H. Bell, "Approaches to the Provision of Priority for Public Transport at Traffic Signals: A European Perspective", *Traffic Engineering and Control*, pp. 426-428, September, 1993.

13. Duncan, Gary, "Maryland Bus Priority Control System", *IMSA Journal*, page 24, May, 1993.

14. Williams, Thomas, Mark Haselkorn, and Kathy Alalusi, "Impact of Second Priority Signal Preemption on Kitsap Transit and Bremerton Travelers, Final Report", University of Washington, October, 1993.

15. Bowen, G. T., R. D. Bretherton, J. R. Landles, and D. J. Cook, "Active Bus Priority in SCOOT", *7th International Conference on Road Traffic Monitoring and Control*, pp. 73-76, April, 1994.

16. Saffer, H. G. and T. Wright, "The Development of LRT Signal Control Techniques for the Sheffield Supertram System", *7th International Conference on Road Traffic Monitoring and Control*, pp. 89-92, April, 1994.

17. Hunter-Zaworski, Katharine, William C. Kloos, and Alan R. Danaher, "Bus Priority at Traffic Signals in Portland: The Powell Boulevard Pilot Project", Submitted for *ITE 1994 Compendium of Technical Papers*, July, 1994.

18. Evans, G., R. A. Withill, "Carmarthen Road, Swansea - Bus Priority within SCOOT", *7th International Conference on Road Traffic Monitoring and Control*, pp. 81-88, April, 1994.

19. Sunkari, Srinivasa R., Phillip S. Beasley, Thomas Urbanik II, and Daniel B. Fambro, "Model to Evaluate the Impacts of Bus Priority on Signalized Intersections", *Transportation Research Record 1494*, pp. 117-123, July, 1995.

20. Machemehl, Randy, "Signal Priority Evaluation Project, Final Report", The University of Texas at Austin, December, 1995.

21. Cisco, Bill Alan and Snehamay Khasnabis, "Techniques to Assess Delay and Queue Length Consequences of Bus Preemption", *Transportation Research Record 1494*, pp. 167-175, July, 1995.

22. Chang, Gang-Len, Meenakshy Vasudenvan, and Chih-Chiang Su, "Bus-Preemption Under Adaptive Signal Control Environments", *Transportation Research Record 1494*, pp. 146-154, July, 1995.

23. Al-Sahili, Khaled, and William C. Taylor, "Bus Preemption Signal (BPS) - An Application of an Advanced Public Transportation System (APTS)", Executive Summary, Michigan State University, September, 1995.

24. Bauer, Thomas, Mark P. Medema and Subbarao V. Jayanthi, "Testing of Light Rail Signal Control Strategies by Combining Transit and Traffic Simulation Models", *Transportation Research Record 1494*, pp. 155-160, July, 1995.

25. Hounsell, N. B., and J. P. Wu, "Public Transport Priority in Real-Time Traffic Control Systems", *Applications of Advanced Technologies in Transportation Engineering*, pp. 71-75, June, 1995.

26. Metzger, Daniel D. G., "Bus Gate, Pre-Signal and Queue Relocation: The Park View Road Bus Priority Scheme", *Applications of Advanced Technologies in Transportation Engineering*, pp. 81-86, June, 1995.

27. Colquhoun, Dave, John Morrall, and John Hubbell, "Calgary Light Rail Transit Surface Operations and Grade-Level Crossings", *Transportation Research Record 1503*, pp. 127-136, July, 1995.

28. Hounsell, N. B., F. N. McLeod, R. D. Bretherton, and G. T. Bowen, "PROMPT: Field Trial and Simulation Results of Bus Priority in SCOOT", *8th International Conference on Road Traffic Monitoring and Control*, pp. 90-94, April, 1996.

29. Ikeda, Hayao, "PTPS and MOCS Verification Test", 1996.

30. "TRAF User Reference Guide, Version 5.0", U.S. Department of Transportation, Federal Highway Administration, March 1995.

31. Machemehl, Randy, "Class Notes: CE 391L, Advanced Traffic Engineering", The University of Texas at Austin, Spring, 1996.