BUS PREEMPTION SIGNAL (BPS) - AN APPLICATION OF AN ADVANCED PUBLIC TRANSPORTATION SYSTEM (APTS)

Executive Summary

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Conducted for the

MICHIGAN DEPARTMENT OF TRANSPORTATION AND
BUREAU OF URBAN PUBLIC TRANSPORTATION
and the

GREAT LAKES CENTER FOR TRUCK
TRANSIT RESEARCH

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Chapter 1

Introduction

Due to the lack of resources, there is a growing interest in the maintenance and management of the existing transportation system. One consequence of this has been the emergence of transportation system management (TSM) as a planning philosophy. TSM is a process for planning and operating for which the key objective is the conservation of fiscal resources, energy, environmental quality, and the urban quality of life. TSM has been defined to include a large number of project types; however, one type of particular interest is the bus priority system. This is a system of traffic controls in which buses are given special treatment over general vehicular traffic (for example, bus priority lanes or preemption of traffic signals). Of particular interest in this research is the bus priority (preemption) signal, BPS. It is a method of providing preferential treatment to buses and other high-occupancy vehicles (HOV) by altering the signal timing plan to favor those vehicles.

The concept of bus priority treatment is not a newly introduced strategy. In fact, an early experiment was conducted in Washington, D.C. in 1962. In that study, the offsets of a signalized network were adjusted to better match the lower average speed of buses (Sunkari et al, 1995). One or more of the following factors (acting singly or in combination) have prevented the widespread use of bus preemption in the United States (U.S.): (a) the absence of a reliable technology to track the bus arrival and to initiate preemption; that is the lack of an automatic vehicle location and classification system, (b) the lack of standards to determine warrants for preemption, (c) the failure of these systems to strike a balance between adequately providing for the needs of general traffic while concurrently providing sufficient benefits to transit to make such systems cost effective (Jacobson 1993), and (d) the lack of sufficient commitment to the HOV philosophy on the operational level.

In general, providing preferential treatment for buses is expected to improve the performance of buses and possibly of the other traffic on the bus direction. However, delay is expected to increase for traffic on the cross street. In an attempt to reduce reliance on automobile travel, efforts have been made to make public transit more attractive by reducing transit delays, providing more reliable transit schedules, and providing a level of service that might make it competitive with private automobiles. When bus delay is reduced, buses run on a more reliable schedule and their trip time is shorter. This makes transit a more attractive mode of transportation and may increase bus ridership by diverting private automobile drivers. This, in turn, will result in congestion relief and a reduction in exhaust emissions.

The Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) provides the framework for federal funding for transportation facilities over the next six years. ISTEA stipulates that the U.S. transportation network will provide the foundation for the Nation to compete in the global economy, and will move people and goods in an energy-efficient manner. One of the stated purposes of this bill is to reduce the number of single occupancy vehicles, particularly in cities designated as nonattainment areas. The seven county Detroit Metropolitan area, which includes Ann Arbor, was one of these designated areas when this study was initiated.

One method of meeting this objective is to improve the quality of service to public transit and high occupancy vehicles to make them more competitive with the automobile. The Ann Arbor Transit Authority (AATA) has recognized this need, and has initiated a project to improve transit service by incorporating technologies being developed under the Intelligent Transportation System (ITS) program into its bus system operation. The AATA received a grant to develop and implement "smart card" technology in its bus fleet operation.

The smart card, which is commonly understood to be an integrated circuit-based, credit card-size portable data carrier, is fast becoming a preferred medium for ITS applications. While there are many applications for the smart cards, the one of particular interest to this project is the use of these cards to transmit a signal that can be used by a traffic signal controller to identify the location of the HOV and to change the signal timing at selected intersections to provide priority treatment.

1.1 Research Objectives

The objectives of this research are:

1. To determine the benefits of providing buses with an electronic signal preemption device and to predict the changes in traffic performance and bus services caused by implementing various bus priority schemes. The Washtenaw Avenue Corridor in Ann Arbor, Michigan is used as the study location.

2. To determine the traffic conditions (e.g. volume, signal timing, percentage of HOV) under which signal preemption will improve flow.

NETwork SIMulation (NETSIM) will be used to simulate different algorithms for implementing signal preemption and to assess various bus preemption policies.

1.2 Bus Priority (Preemption)

One of the preferential treatments for buses is providing priority at traffic signals. Bus characteristics are different from the general vehicular traffic. Unlike automobiles, buses can not continue platooning through signalized corridor due to the random occurrence of passenger loading and unloading volume and the resultant variable dwelling time. A bus may skip a stop if there is no passenger waiting to get on or off. On the other hand, a large number of passengers boarding and unboarding requires more time. These variations make the bus arrival time at a signalized intersection uncertain. In addition, slow bus acceleration and deceleration and the typical slower bus movement makes the bus unable to stay in the traffic stream. In this case, the bus may not enjoy the full benefits of a coordinated signal system.

There are two main techniques to provide priority treatment for HOVs at traffic signals. These are passive and active detection and granting priority. Passive priority systems are characterized by the fact that the flow of buses need not be recorded at a particular instant in order to grant priority. Instead, the intensity of bus (or HOV) movements is deduced from historical measurements of traffic flow. An active priority system is when the passage of an individual bus is detected and priority is awarded to the bus as a result of this detection.

1.2.1. Passive Priority

This system is based on signal coordination and improved signal timing for all arterial traffic to favor bus traffic. The following are methods for improving transit operation (Sunkari et al 1995, Allsop 1977, Nato 1976):

Adjustment of cycle time. If signal cycle times are generally long, buses may have to wait longer on a red signal. Reducing cycle lengths at intersections carrying appreciable bus traffic can provide benefits to transit vehicles by reducing delay. However, short cycle times result in a decrease in capacity and can become insufficient to pass all the traffic arriving at an intersection.

Splitting phases. Splitting a priority phase movement into multiple phases within a cycle can reduce transit delays without necessarily reducing cycle length. By repeating the priority phase within the same cycle, transit vehicle delay may be reduced at the intersection. However, there is a delay penalty imposed each time a phase is initiated.

Area-wide timing plans. These plans provide priority treatment for buses through preferential progression by designing the signal offsets in a coordinated signal system using bus travel times. This optimization method would have the objective of minimizing passenger delay rather than vehicle delay. In addition, it would take into consideration stopping at bus stops.

Gating (Metering Vehicles). The idea behind this method is to limit the number of vehicles gaining access to a particular facility. Metering regulates the flow of vehicles through a network by limiting the number of vehicles allowed into the system. Buses benefit from this by allowing them to bypass metered signals with special reserved bus lanes, special signal phases, or by rerouting buses to nonmetered signals.

Turning prohibition. Where left-turning vehicles at junctions cause congestion, it is not uncommon to prohibit such turning movements even though the vehicles affected may incur significant extra trip time. Exempting buses from such bans not only saves them from delays due to diversion, but keeps them on those routes that are best for passengers.

1.2.2. Active Priority

Active priority is, sometimes, referred to as priority by detection or bus-actuated signals or bus preemption signals. The benefit of active priority over the passive priority is that the treatment is provided only when the bus is present. The followings are methods of active priority treatment (Sunkari et al 1995, Allsop 1977, Nato 1976):

Green extension. This means extending the green phase beyond its normal setting to allow the bus to pass the intersection; it is usually limited to some maximum value. Phase extension is provided when the bus will arrive at the intersection just after the end of the normal green period.

Phase recall (early start or red truncation). This priority treatment advances the bus street green phase by prematurely terminating all other nonbus phases (and truncating the bus red phase). This treatment is used when the bus arrives at the intersection during the red signal phase. This may be constrained by providing a minimum green time for the phase to be prematurely terminated.

Phase skipping. To facilitate the provision of the bus priority phase, one or more nonpriority phases may be omitted from the normal phase sequence. In order to avoid disrupting operations on the nonbus phases, some restrictions may be applied to this treatment, such as no phases with heavy demand are skipped.

Compensation. One may choose to compensate for the time lost (skipped or cut) from the other nonbus phases in the next cycle to limit the adverse effects priority has caused to the nonpriority traffic. Compensation for the nonpriority phases involves allocating extra green time to these phase to make up for time lost during signal preemption.

Conditional versus unconditional priority. Unconditional priority is the provision of signal priority each time it is requested (the bus detector or signal transmitter places a call to the signal controller), after all other vehicular and pedestrian safety required intervals are satisfied. Some professionals argue that since (unconditional) preemption is disruptive to the cross-street traffic, it would be better to subject preemption to certain conditions. These selective conditions determine when or if the signal priority will be granted to the bus. There are several factors that can be used, such as, is the bus on schedule or behind schedule, bus occupancy, cross-street traffic conditions, and time between consecutive preemptions (other conditions may also be used).

The above treatments are the most widely used forms of active priority. In this research, the active priority system in detecting the bus and granting priority under certain criteria is adopted. Several combinations of these various treatment schemes are tested. The NETSIM computer model has been selected to simulate this process (details will be discussed later).

The following chapters present a review of the literature and past experience, data collection and requirements, research methodology, bus preemption signal algorithms, evaluation of different BPS plans, evaluation of BPS under different traffic conditions, and conclusions.

Chapter 2

Literature Review

One of the earliest known bus preemption experiments was performed in 1967 by Wilbur Smith & Associates and the Bureau of Traffic Research in the Los Angeles Department of Transportation (Benevelli et al, 1983). Two intersections in Los Angeles were studied: Broadway and First and Broadway and Second. In discussing this experiment, the authors indicated that traffic signal delay constituted 10 to 20 percent of the average bus trip time and that signal delay would be the easiest component of delay to reduce. The bus preemption was accomplished by having a person manually actuate the signal, so as to begin the green interval earlier if a bus approached on the red interval, or to extend the green interval if necessary to allow the bus to pass through the intersection. Bus portal-to-portal travel time was reduced by 5 to 7 percent.

Several simulation models and field experiments with signal preemption have been conducted in the U. S. and Europe since this early experiment. Most of these involved isolated intersections, and only limited information is available on network level experiments. Most of these projects were conducted in the 1970s, a few of them were in the early 1980s, with very few recent studies in the late 1980s or 1990s.

2.1 Isolated Intersections

During the late 1970s, many papers were written on bus preemption with various strategies. Vincent et al, 1978, used a microscopic Bus Priority Assessment Simulation

(BUSPAS) program to test five preemption control strategies. They examined (a) green extension only; (b) green extension, red truncation, no compensation; (c) green extension, red truncation, compensation; (d) red truncation, no compensation; and (e) red truncation, compensation. Their experiments considered several traffic volumes, saturation flow rates, and signal timings. Several bus detector spacings and placements were also considered. For the three main priority control methods (a), (b), and (c), it was found that method (a) gave limited benefits to buses (0-8 seconds), with little delay to other traffic (less than 1 vehicle-hour/hour (veh-h/h)). Method (b) gave larger benefits to buses (4-24 seconds) but also larger losses to nonbus traffic (1-24 veh-h/h). Method (c) produced smaller benefits for buses (0-14 seconds) than (b), but also less delay to other traffic (1-14 veh-h/h). The above approach is somewhat similar to what was done in this study for an arterial.

Richardson et al, 1979, developed and applied a new methodology for the evaluation of an active-bus priority signal system that was installed at traffic signals in Victoria, Australia. Two new measures, perceived delay and budgeted delay, were introduced in their study and were shown to have important implications in the evaluation of bus priority and other transportation system management schemes. Perceived delay is a measure of the psychological effect of time delay (i.e., the value of time savings is a function of the amount of time saved). In this study, budgeted delay was defined as being equal to the sum of the mean and the standard deviation of travel time (or delay). It corresponds to an upper percentile point (for a normal distribution it would represent the 84th percentile point) of the delay distribution. They found the consideration of changes in "budgeted delay" rather than the mean delay results in a greater probability of justifying bus priority schemes. They stated that it is possible to have better service even when mean delay increases, provided that the reduction in variability of delay is of sufficient magnitude. Richardson et al concluded that reevaluation of TSM schemes on the basis of perceived and budgeted time savings would probably result in many of them being feasible. This concept has not been observed in other research and, in this research, the classical delay measures will be used.

Jacobson and Sheffi 1980, developed an analytical model of delay at isolated signalized intersections with a bus preemption scheme. The analysis was presented for the simplest case, i.e., two intersecting one-way streets. The model treated the beginning time of the green period as a random variable, the density function of which was developed. The model also assumed a Poisson arrival process for the vehicles approaching the intersection. Four cases were analyzed: (A) no preemption, minimizing total person delay; (B) no preemption, minimizing total vehicle delay; (C) preemption, minimizing total person delay; and (D) preemption, minimizing total vehicle delay. The intersection performance indicators were total person delay measured in seconds per hour, queue length, and delay to both private vehicles and bus patrons. **They showed that the preemption benefits can be substantially increased by changing the underlying signal setting once preemption is installed.** It was found that the inclusion of phase durations in the design variables (case D) significantly increased the benefits associated with preemption (17. percent with respect to case A).

As a general conclusion (no numerical value was furnished), **the benefits associated with bus preemption were relatively small when the traffic flow in the preemption direction was much higher than the cross traffic flow and thus this direction already**

experienced green for most of the cycle. Preemption was more beneficial where the rate of arrival of buses was higher.

Twenty-seven priority treatment projects for HOVs were evaluated by Rothenberg and Smdahl, 1981. Out of those, three included signal preemption treatments for buses. Two were active preemption systems using on-bus emitters, and the other project utilized a pavement loop to detect bus presence. The active preemption treatment produced bus travel time savings in the range of 4 to 8 minutes, a 10 to 20 percent reduction. Bus reliability was also improved. The passive preemptions produced comparable travel time saving rates. In both cases, impacts on cross street traffic was not significant in most situations. None of the preemption systems was reported to exhibit much direct impact on bus ridership.

A macroscopic traffic delay model that applied a stochastic procedure was presented by Radwan and Hurley, in 1982, to evaluate different bus preemption signal strategies at isolated intersections. The model permitted the user to evaluate various operational strategies provided for bus traffic. The model proved cross street passenger delay savings to be sensitive to saturation headways between 1800 and 1980 vehicle / hour.

Roark, 1982 determined the effectiveness of bus signal preemption to be a function of the cross-street traffic, with the greatest potential on arterial roadways with little cross-street traffic. He reported two problems associated with bus preemption signals: (1) platoons of automobiles travelling around a bus to take advantage of priority operation and (2) bus drivers who anticipate a green signal and approach the intersection at a high rate of speed. Roark reported on several field studies that bus preemption reduced bus travel times and resulted in smoother traffic flow on arterial streets. He recommended four criteria for bus preemption: (a) when total person delay (a function of cross-street volumes) is reduced, (b) at least 10 to 15 buses are carried on the arterial during the peak hour, (c) a daily volume of at least 100 buses in both directions, and (d) the cross-street green phase can be reduced without conflicting with the minimum pedestrian clearance time.

A bus signal preemption algorithm was built by Smith 1985, for the New Jersey Department of Transportation to be incorporated into the NETSIM simulation model. While five bus preemption strategies were selected initially, due to budget limits, the evaluation was reduced to just an algorithm for advancing or extending green while still maintaining a minimum side street green. Smith reported that the algorithm was programmed into the NETSIM model by the Federal Highway Administration (FHWA) and was tested by comparing the results obtained from NETSIM simulation and the results obtained from a manual implementation of bus signal preemption at one intersection. The algorithm was considered to be a reliable estimator of the effects of using bus signal preemption at an intersection. A nearside bus stop and a farside bus stop condition were considered in the algorithm. The t-test showed no significant difference between the data sets of (measures of effectiveness (MOEs) (average delay per vehicle and percent of vehicles stopping) measured and estimated at the 95 percent level. The preemption process resulted in savings of 6.2 vehicle hours and 9.2 passenger hours over the one-hour peak period.

To study possible means of improving the movement of transit vehicles in Metropolitan Toronto, the Transit Priority Study was established by the Metropolitan Toronto Roads and Traffic Department as a three-phase program. Bishop et al, 1988, addressed phase III of the study, which was to permit a transit-based preemption system test on one or more intersections on the selected routes. Several strategies were discussed: (1) green extension, (2) red truncation, (3) window stretching, (4) red interruption, and (5) green truncation. The first two strategies were selected for testing. The evaluation criteria were capacity improvement, implementation capability, progression problems, safety problems, and reduction of transit delay. Two isolated intersections were tested for preemption, Queen (streetcar) at Sherbourne and Sheppard Avenue West (bus) at Jane. For streetcar operations, it was determined that the transit priority strategies of green extension or red truncation produced a reduction in signal delay to the transit vehicles. The cumulative reduction in signal delay per streetcar travelling in both directions was in the range of 8.7 to 10.7 sec/veh. The impact to cross street delay was an increase of 0.3 to 10.6 sec/veh.

Davis et al,1991, **indicated that, despite the fact that in ideal conditions a transit priority scheme would produce no reduction in network capacity, in reality, some loss of capacity is likely to occur as a result of transit priority schemes.** U.K. Department of Transport guidelines state that for a good scheme, capacity loss should be no more than one or two percent. Total vehicle journey times might then be expected to increase by three to ten percent. Poor priority schemes, which produce much greater disruption, need to be modified or withdrawn.

There are a number of factors that have prevented the widespread application of bus preemption in the United States according to Khasnabis et al, 1991. These include the absence of a reliable technology to monitor the arrival of buses and to trigger preemption, lack of standards to determine warrants, and inability of the system to prevent inordinate delays to motorists travelling on the cross streets. Where a bus stop is located immediately prior to the intersection the predictions of exact arrival times can be particularly difficult. No effort was made to assess the adverse effects of preemption on cross street traffic.

Casey et al, 1991 indicated that currently signal preemption for HOVs is relatively uncommon in the U. S. He reported that a few cities do have preemption equipment for light rail lines, including the Southeastern Pennsylvania Transportation Authority (SEPTA) in Philadelphia, the Santa Clara County Transit District in San Jose, California, and the Southern California Rapid Transit District (SCRTD) in the Los Angeles area. SCRTD also had equipment installed for signal preemption on two bus routes. The system was taken off-line fairly soon after implementation due to highway construction, but was to be reactivated as soon as the construction was completed. They reported that two other agencies, the Chicago Transit Authority and Broward County Division of Mass Transit in Fort Lauderdale, Florida were also discussing signal preemption as part of Automatic Vehicle Location (AVL) systems.

Ingalls et al, 1993 studied different alternatives for providing priority to HOV in the suburban arterial environment. Different evaluation criteria of financial viability, geometric feasibility, functional adequacy, and public acceptance for these alternatives were analyzed. Alternatives included signal priority treatments, continuous right-side HOV lanes, continuous left-side HOV lanes, lane control for reversible HOV lanes, signal queue jump, single occupancy vehicle (SOV) turn restriction, off-route alternatives, and special access for HOV. Of these various alternatives, signal priority treatments that used advanced technologies to minimize person delay at intersections showed the greatest potential to achieve the goal of bypassing congestion without unacceptable impacts to general purpose traffic. However, no numeric values were provided.

Alice et al, 1993 altered the Traffic Network Study Tool (TRANSYT-7F) model to represent the case of near-side transit stops in shared lanes. When used for optimization purposes the transit-enhanced TRANSYT model tends to coordinate the intersections in such a way as to make the transit load/unload operations occur mainly during the red phase. Despite some limitations, it was seen that delays and stops can be reduced considerably when signal timings reflect the transit loading operation.

Chang et al, 1995 formulated a model for an integrated adaptive control system with both bus preemption and signal control functions. In the proposed model, absolute priority was not given and minimum cross street green time was imposed. The model made use of real-time algorithms instead of prespecified strategies used by most conventional bus-preemption logic. The control decision for signal settings was based on a performance index that incorporated bus delay, as well as passenger and vehicle delay. TRAF-NETSIM's outputs for an isolated intersection under different traffic conditions were used to test the performance of the algorithm. They claimed that experimental results proved the superiority of the model over the actuated control logic by NETSIM. However, since only a simple myopic adaptive logic was employed in the model, they suggested that more enhancements that employ information from both neural network prediction models and AVL were needed.

Sunkari et al, 1995 developed a simple analytical model to evaluate priority strategies, which uses the delay equation found in the 1985 Highway Capacity Manual (HCM). They have tested no priority, phase extension, and early start schemes. Stopped delay was used as the field measure to validate the model. It was found that the model is reasonably accurate in estimating the effects of bus priority at an intersection. However, it overestimated delay for some phases.

2.2 Network and Arterials

In an early simulation study, Ludwick, 1976, reported that an unconditional preemption algorithm using the Urban Traffic Control System / Bus Preemption Signal (UTCS/BPS) model on a network of quarter-mile route segments was used. The study provided a 25 percent travel time benefit to buses. However, the cross-street traffic delay could be extreme, particularly at short bus headways. An algorithm limiting the preemption to a maximum of 10 seconds still provided a 20 percent bus travel time improvement with only a 7 percent cross-street travel time increase. It was found that far-side bus stops were far superior to near-side bus stops. Buses with frequent stops have greater potential for improvement than express buses, especially if existing signal coordination is good.

In a demonstration project of signal preemption for express buses in Sacramento County (Elias 1976), a bus preemption system was evaluated on a 3.8-mile section that included nine signalized intersections operated as isolated, full-traffic, actuated signals equipped with traffic signal preemptors. Two buses were equipped with transmitting units. Elias reported a reduction in bus trip time of an average of 23 percent. Passengers benefitted by a smoother and more comfortable ride with increased schedule reliability. There were no accidents caused by the bus preemption identified during a 3-month testing period. No adverse effects were observed for cross street traffic. (However, no data were presented on cross-street delay.) Several benefits were reported: operating cost, trip time and dependability were improved; fuel was saved due to elimination of starting, stopping, and waiting; and air pollution was reduced, as was the noise and wear-and-tear on tires and brakes.

Another bus preemption demonstration field experiment was conducted in Miami on the Northwest Seventh Avenue corridor that has a 10-mile length (Wattleworth et al, 1976). Five combinations of three bus priority treatments were evaluated: (a) a reversible, exclusive bus lane; (b) a traffic signal preemption system; and (c) a coordinated signal system designed to favor movement of express buses in the peak-period direction. They evaluated the bus priority treatments by their effects on bus operations, traffic signal performance, traffic stream, and transit operation. The provision of a preemption capability reduced the average bus travel time by 22.5 percent from a before condition of 28.0 minutes. Buses were able to clear the preempted intersection within the maximum allowable preemption time of 120 sec. Slightly longer phase lengths were observed during cycles in which buses arrived. The bus priority treatment increased the number of persons moved on Northwest Seventh Avenue by 20 to 30 percent although buses constituted less than 2 percent of the traffic stream.

Liberman et al, 1978 reported on a simulation study that used the Simulation of COrridor Traffic (SCOT) model. This study evaluated a network in the Central Business District (CBD) of Minneapolis under a fixed-time signal timing plan generated by SIGOP-II to minimize person delay using a bus preemption control strategy. On each of two adjoining parallel, one-way arterials, a contraflow bus lane has been implemented. The bus preemption control strategy could call for green extension, red truncation, the signal to cycle to reinstate the normal green phase, or the signal to cycle to reinstall the green phase after satisfying other phase duration minimums. They indicated that the buses along the major arterials benefitted significantly, while those along the cross streets experience sharp degradation in performance. The overall bus performance experienced improved service as measured by a 12 percent reduction in the total delay relative to the base system. In the peak hour a net reduction in delay of 26.3 passenger-hours per hour could be achieved. No base value (or before value) was provided.

Salter and Shahi, 1979 developed a microscopic model to predict the travel times of buses and other vehicles along a highway network that has different types of intersection controls, with or without bus priority schemes in operation. Their model has the capability of evaluating the effect of bus priority measures at priority and roundabout intersections. Salter and Shahi tested the following highway and traffic situations: (a) a priority intersection where the nearside lane of the minor road is allocated to buses for different traffic flow conditions and different lengths of priority lanes; (b) signalized intersections that have two or three approach lanes where the nearside lane of one approach is allocated to buses for different traffic flow conditions and different lengths of priority lane, and (c) a 2-km length of bus route, which included three signalized intersections and eight bus stops for differing traffic volumes and proportions of buses in the traffic flow. They reported that the observed and simulated data were quite close to each other and that the model was adequate to represent vehicle behavior according to the purpose of their study. When bus priority schemes were introduced, travel time for nonbus vehicles was increased proportional to the traffic volume. Salter and Shahi's model is a general model to predict traffic characteristics, but does not deal with specific strategies of bus signal preemption, such as green extension and red truncation.

Hubschneider, 1982 presented a simulation study of an active priority system based on a bus guidance and control system (BGCS). It is a computer supported system used in the surveillance and control of a public transport system. All vehicles are supervised by a central computer by means of wireless digital communication. A minimum green restriction necessary for clearance and safety was used before the bus green period could begin. A microscopic simulation package, MISSION, was used to investigate the impact of different systems of modules in a small network. He demonstrated that buses with higher needs for priority (running behind schedule) can be treated preferentially, while the restrictions on the nonpriority traffic can be reduced by refusing priority to buses that are too early.

Urban Traffic Control System / Bus Priority Signal (UTCS/BPS) is a microscopic traffic simulation model that was developed by the Federal Highway Administration (FHWA) and was used to simulate the bus preemption system operation for various bus flow rates and bus stop locations. Benevelli et al, 1983 conducted a study on bus signal preemption using the UTCS/BPS model. They concluded, based on a benefit-cost analysis, that bus preemption was justified for the 1.3-mile segment of Monument Avenue in Richmond, Virginia. The benefits of bus preemption were found to be limited by the preemption algorithm structure and the bus stop locations. It was found that multiphase signals minimize the benefits of preemption under the control algorithm, and as more signals on the arterial were preempted, the benefits of coordinated signals disappeared and the vehicle delay increased. A farside bus stop was found to minimize the negative effects of bus preemption on automobile travel delay. Benevelli et al utilized SOAP and TRANSYT models to determine the phasing pattern and cycle length. **It was found that the inability of the algorithm to reestablish offsets once a signal preemption occurred may also have adversely affected road user costs. The control algorithm also did not have the capability to skip phases.**

It has been argued by Casey et al, 1991, that signal preemption disrupts traffic flow. Many traffic professionals argue that signal coordination and progression are more effective tools on heavily travelled arterials than preemption. It is difficult to give preference to buses in the mixed flow traffic, especially under congested conditions. Casey and others could identify at least four field tests of signal preemption in the U. S. during the 1970s: Kent, Ohio; Louisville, Kentucky; Miami, Florida; and Washington, D. C. In Kent, Ohio, equipment was installed in three signals along a four-mile section of East Main Street. In this study, the buses experienced higher average speeds and shorter delays at intersections. The project eventually terminated for administrative reasons. Louisville, Kentucky implemented 3M equipment on express routes, and bus travel time decreased significantly. In Washington, D. C. the buses signalled their presence to the loop through an antenna mounted in the undercarriage of the buses. Then, preemption would be granted as an extended green if there would be a net decrease in the overall passenger delay at the intersection. This proved largely ineffective. The Miami experience was discussed previously.

Davis et al, 1991 reported the use of TRANSYT in the U. K. for bus priority in Glasgow. This experiment involved the modification of signal timing plans in the city to optimize the movement of people, rather than the more conventional passenger car units (PCUs). For the purpose of calculating signal timing, the average occupancy of buses was considered to be 28 passengers, with 1.4 occupants assumed for other traffic. This experiment resulted in an increase in bus speeds of 9 percent, 8 percent, and 7 percent during the morning peak, off-peak, and evening peak periods, respectively, with an overall reduction of 16 percent in the time spent delayed by signals. Cars travelling along the bus route experienced a 5 percent reduction in journey time, while those travelling off bus routes faced a 15 percent increase in journey time. Overall, however, journey times for cars on the network did not change significantly.

They reported two other experiments implemented in the U.K. for bus priority at traffic signals. They were BADGE and PUMMEL. BADGE provided only limited variation from a fixed time plan to give priority to individual buses. Tests on the BADGE system showed a reduction in bus delays of 15 percent, 10 percent, and 13 percent during the morning peak, off-peak, and evening peak, respectively. PUMMEL allowed greater variation from the fixed time plan, using TRANSYT to estimate resulting delay to nonbus traffic. PUMMEL was found to be less effective than BADGE at reducing bus delays, with savings of 11 percent, 2 percent, and 7 percent in the morning peak, off-peak, and evening peak, respectively. Delays to other traffic were too small to measure.

2.3 Signal Technology

For the BPS to be operational, hardware that is capable of vehicle identification and location is required. The lack of reliable technology is one of the reasons that has prevented the widespread use of bus preemption in the US. However, there were several types of technologies used in different experiments. The Opticum System was developed by 3M in the U.S. around 1976. It was used in the Sacramento County signal preemption project in

1976 (Elias 1976). The Opticum System was based on strobe light pulses at a specified rate being received by detectors at the intersection. However, both the academic research and the actual demonstrations found major shortcomings. About the same time, the Philips Corporation of the Netherlands developed a product called Vetag. This was based on the use of inductive (magnetically activated) detector loops in streets, which are activated by programmable transponders on moving vehicles (buses). In 1987-1988, Philips released a new product called Vecom, which was more sophisticated than Vetag. The on-board equipment has the ability to receive, as well as send, messages, and has computerized control with considerable storage capacity. Traffic engineers were reported as generally comfortable with the greater reliability provided by this equipment.

Davis et al, 1991 discussed bus priority at signalized intersections as one of three Advanced Traffic Management Systems (ATMS) technology applications to transit rideshare schemes. Transit vehicles can be identified by using automatic vehicle classification (AVC) techniques, making use of inductive loops or piezoelectric axle sensors (Casey et al, 1991, and Davis et al, 1991). An alternative to AVC for signal preemption involves the use of automatic vehicle identification (AVI) technology. Davis et al indicated that this technology enables vehicles to be uniquely identified through a communications link between an onboard transponder and a roadside reader unit. Several alternative AVI approaches have been developed including optical infrared and radio frequency systems. AVI can therefore be used to detect transit vehicles for signal preemption. Davis et al reported that by 1976, for example, research on AVI conducted at the U.K. Transport and Road Research Laboratory (TRRL) had led to the development of selective vehicle detection systems for bus and emergency vehicle priority at signalized intersections. In Delft, Holland in 1971, buses between the Hague and Delft were given local priority at signalized intersections using a simple form of inductive AVI known as VIPS. This was reportedly successful in reducing travel times and delays. Traffic signal preemption in the Netherlands was accompanied by the activation of an acoustic signal to warn pedestrians and cyclists.

The Philips Vetag AVI system was implemented in Holland during the 1970s for automatic tram control. The Hague commissioned an automatic interlocking system covering the city's tram network. In Hong Kong, the AVI technology has also been used to provide priority and identification functions for a light rail transit system. The equipment automatically identifies each light rail vehicle (LRV) approaching the intersection and establishes the intended direction of movement. This information enables the traffic signal controller to provide the correct clearance and a signal to proceed.

Davis et al suggested that it may be possible to implement a scheme for traffic signal preemption for other HOVs using AVI technology. AVI transponders would be distributed for installation on vehicles registered to participate in a rideshare scheme. On-board computers and/or individual smart cards could be used to prevent signal preemption by registered vehicles that were not carrying the required number of occupants. The AVI transponder would become active only after the insertion of the required number of smart cards into a reader unit. A vehicle smart card could be used as an AVI selective vehicle detector. The onboard computers (OBCs) would contain a record of the vehicle's schedule, including its correct arrival time at each intersection and boarding point. If it is preferred, as the vehicle approached a signalized intersection, the OBC would activate the signal in favor of the transit vehicle only when a deviation from the required schedule is detected.

Smart cards are essentially miniaturized computers. Davis et al reported that smart card technology has recently been applied to transit operations. Smart cards could provide much of the data regarding scheduling of transit services, which currently relies on historical trip data gathered by labor-intensive manual methods, leading to cost and time savings and providing a more reliable base on which to plan transit services. License plate scanners is another technology that could be used for selective detection. These are capable of automatically reading the characters on vehicle license plates. The Dulles Toll Road in Virginia in 1989 tested a 3M manufactured license plate reader. Since the character recognition software was optimized for Virginia, the system was less successful in reading plates from other states. Read accuracy for Virginia plates was around 65 percent, although 3M reported accuracy improvements due to a system modification since the time of these tests. However, it is unlikely that the technology will ever provide the performance levels available from AVI. The French Elsydel company recently claimed accuracy levels of 95 percent for its infrared license plate scanner. Yamamoto (1992) claimed that the Japanese licence plate readers have 80 percent accuracy with one second image processing and fuzzy logic and 70 percent accuracy during the night.

Davis et al identified infrared beacons or digital radio communication as other potential future ATMS developments. This could be used to provide the unique vehicle identification function required for priority signal control. These systems could have advantages over AVI and license plate scanners in providing increased scope for the integration of ATMS with ATIS (Advanced Traveler Information Systems). Another technology is video image processing. This technology could be used to identify transit vehicles for signal activation. An example of this is the DACimage system developed in France by Elsydel. Classification by this technology is based on the features of the vehicle, such as its number of axles and height. In the longer term, Davis et al reported that it may become possible for a video image processing system to estimate or calculate the number of occupants in a vehicle. Infrared heat-sensing technology is potentially applicable in this area.

2.4 Summary

From the literature, one can conclude that bus preemption signal projects at isolated intersections were relatively successful in reducing delays for the main traffic stream. Delays for cross-street traffic were not significant at low volumes, but became significant as the intersection approach capacity. The effectiveness varies with different preemption schemes (strategies): green extension, red truncation, compensation and, no compensation. **The benefits of preemption could be increased by changing the underlying signal setting once preemption is installed.**

For arterials, the effectiveness of bus preemption was also found to be a function of cross-street traffic. The greatest potential lies on arterials with little crosstraffic. Buses drive smoothly on the main street, experience delay savings and more reliable schedules, but the cross-street traffic may experience a delay that could outweigh the savings on the main street. Signal preemption could disrupt traffic flow, and it was found by some investigators that signal coordination and progression are more effective tools than preemption on heavily travelled arterials.

The benefits of bus preemption were found to be dependent on the algorithm and the location of the bus stop along the route. A nearside bus stop was found to be less desirable in reducing negative effects. Results of conditional preemption have been more sound than unconditional preemptions in terms of less disruption to nonbus traffic, providing safer operation (by maintaining minimum green time for cross street vehicles and pedestrians), and preventing the bus from receiving priority treatment when it is not needed (bus is on-schedule).

Integration of the BPS process and vehicle identification facility with adaptive traffic control is a step toward the concept of interactive traffic control. Preferential treatment of bus users is one of the promising strategies to accomplish this. The integration of preferential treatment and adaptive signal systems is promising. However, research in this area is still very scarce.

The technology is available to accommodate the bus preemption signal process efficiently. License plate scanners as an AVI system seem accurate enough, with an 80 and 95 percent accuracy for the Japanese products and French Elsydel company, respectively. Smart cards and onboard computers are even more advanced and accurate. Smart cards can be used as a source of information for transit's schedule time including its correct arrival time at each intersection. It also can provide information about the transit vehicle's occupancy. HOVs can use smart cards to emit signals to traffic controllers to provide them with preemption.

Despite the fact the technology is available, bus preemption is not popular in the U.S. One of the main reasons for its failure is the inability of the system to reestablish the original settings as preemption is called. The literature lacks information on an up-to-date model that could be used to evaluate the effects of bus preemption on the system rather than just the corridor that has the preemption facilities. There is no comprehensive model that has the capability of testing several bus preemption strategies (including skip-phase plan). The UTCS/BPS model presumably had the potential for evaluating the effects of bus preemption on the system. Although the user manual is available, the model is no longer in use and current information on the model is not available.

Tables 1, 2, 3, and 4 summarize previous bus preemption simulation and field experiments at isolated intersections, as well as for networks and arterials.

In this research, a network including Washtenaw Avenue and one intersection across on each side will be evaluated under the bus preemption signal strategies. These strategies will be comprehensive and selected in a way that minimizes disruption to progression and coordination. TRANSYT-7F is used to optimize the network settings. The BPS operation is simulated by the TRAF-NETSIM simulation model by using some features that are rarely used. It will utilize the graphic animation as a way of detection and the different (nineteen) time periods (time plans) to provide different BPS strategies. Since it is proposed to test the smart card technology in an effort to encourage multiple occupancy vehicle usage, it is proposed that carpooler, may subscribe to this service and their vehicles might be provided with smart cards, as a way of seeking priority. This plan will be tested and its effects will be assessed.

To evaluate the different BPS plans, links, individual intersections, traffic directions, and network-wide measures of effectiveness with and without preemption will be evaluated.

Table 1: Summary of Previous BPS Simulation Studies at Isolated Intersections.

Year	Author	Model Used	Priority Treatment tested	Results	Comments
1978	Vincent et al	BUS-PAS	1. G.E.* 2. G.E., R.T., NC. 3. G.E., R.T, C. 4. R.T., NC. 5. R.T., C.	- Method 1 gave limited benefits to buses with little disbenefits to other traffic. - Method 2 gave larger benefits to buses and larger loss to the other traffic. - Method 3 produced smaller benefits than 2 but less disbenefits to other traffic.	
1979	Richardson et al	Own model	Perceived Delay Budgeted Delay	Consideration of changes in budgeted delay resulted in a greater probability of justifying BPS.	This concept has not been implemented in other studies.
1980	Jacobson et al	Analytical and stochastic	Minimizing total person delay, total vehicle delay with and without preemption.	The benefits of BPS were relatively small when the traffic flow in the preemption direction was much higher than the cross traffic flow. BPS was more beneficial when bus arrival rate was higher.	No numerical data were provided.
1982	Radwan et al	Macroscopic and stochastic	G.E. R.T.	Cross street passenger delay saving was sensitive to saturation headways.	For two-phase signals only. Buses were in all directions.
1985	Smith	NETSIM	G.E. and R.T.	Saving of 6.2 vehicle-hours and 9.2 passenger hours over 1-hour peak period.	- Near-side and far-side bus stops were tested. - The model verified with a field study.

Table 1, Continued.

Year	Author	Model Used	Priority Treatment tested	Results	Comments
1993	Alice et al	TRANSYT-7F		Delay and stops can be reduced when signal timings reflect the transit loading operation.	TRANSYT-7F was enhanced to optimize based on bus schedule and stops.
1995	Chang et al	TRAF-NETSIM	G.E. and R.T.	The experimental results proved the superiority of the model over the actuated controller logic.	-Integrated adaptive control with BPS and signal control functions were utilized. -More enhancement is needed.

***Notes: G.E. - Green Extension R.T. - Red Truncation N.C: No Compensation C: Compensation**

Table 2: Summary of Previous BPS Field Studies at Isolated Intersections.

Year	Author	Model Used	Priority Treatment tested	Results	Comments
1967	Benevelli et al	Manual Pre-emption	G.E.* R.T.	- Bus travel time reduced by 5% to 7%	The earliest experiment Conducted in Los Angeles
1981	Rothenberg et al		G.E R.T.	-Travel time saved by 10% to 20% -Insignificant impact on cross street - No direct impact on bus ridership	
1985	Smith	NETSIM	G.E. and R.T.	NETSIM was considered a good estimator of the BPS field results.	- NETSIM was enhanced. - There is no current information available about this model.
1988	Bishop et al		G.E., R.T., W.S., R.I., and G.T.	The BPS of green extension and red truncation produced a reduction in transit delay (8.7 to 10.7 sec/veh). The cross street delay increased (0.3 to 10.6 sec/veh)	Signals were preempted for streetcars

***Notes: G.E. - Green Extension R.T. - Red Truncation W.S.- Window Stretching R.I. - Red Interruption G.T. - Green Truncation.**

Table 3: Summary of Previous BPS Simulation Studies for Networks and Arterials.

Year	Author	Model Used	Priority Treatment tested	Results	Comments
1976	Ludwick	UTCS/BPS	G.E* R.T.	- Reduction of bus travel time by 25% - Farside bus-stops are better - Frequent stops have great potentials for improvement.	Unconditional preemption algorithm was used.
1978	Liberman et al	SCOT and SIGOP-II	G.E R.T.	- Overall bus performance improved by 12%. - Reduction of 26.3 passenger-hours.	SCOT was used to simulate the optimum timing plan generated by SIGOP-II to minimize person delay.
1979	Salter and Shahi	Own microscopic predicting model		- The observed and the simulated data were relatively close. - nonbus travel time was increased proportional to traffic volume.	The model predicts traffic characteristics, but does not deal with specific preemption strategy.
1982	Hubschneider	BGCD and MISSION	G.E. R.T.	Preemption for buses running behind schedule is well justified.	MISSION is a simulation model while BGCD is for bus surveillance and control.
1983	Benevelli et al	UTCS/BPS, SOAP, and TRANSYT	G.E. R.T.	Based on B/C analysis BPS was justified. Nearside bus-stops, multi-phase signals, many preemptions along the arterial, and the inability of the model to reestablish offsets were adversely affecting traffic performance.	Lessons from this study were learned and their deficiencies were avoided in our research.

Table 3: Continued.

Year	Author	Model Used	Priority Treatment tested	Results	Comments
1991	Davis et al	TRANSYT		- Bus speed increased by 8% - 16% reduction in bus delay - Cross street traffic travel time increased by 15%.	People movements were optimized rather than vehicle's. The authors provided review of several British experiments.
1991	Davis et al	BADGE		Bus delay reduced by 13%.	
1991	Davis et al	PUMMEL		Less effective than BADGE Savings of 11%, 2%, and 7% in the a.m. peak, off-peak, and p.m. peak, respectively.	The model used TRANSYT to estimate resulting delay to non-buses.
1995	Sunkari et al	Analytical and simple	G.E. R.T.	The model is reasonably accurate in estimating the effects of BPS.	1985 HCM delay equation was used.

***Notes: G.E. - Green ExtensionR.T. - Red Truncation**

Table 4: Summary of Previous BPS Field Studies for Networks and Arterials.

Year	Author	Model Used	Priority Treatment tested	Results	Comments
1976	Elias	Controllers with signal preemptors	G.E* R.T	- Reduced bus trips by 23% - No adverse effects for cross streets were observed.	
1976	Wattleworth et al			-Reduced bus trips by 22.5% -Slightly longer cycles when the bused arrived. -Person-trips increased by 20-30% - Increased service calls	No particular BPS treatment was specified. Its effects on side streets are not mentioned.

***Notes: G.E. - Green ExtensionR.T. - Red Truncation**

In this study, preemption algorithms for a test site contains a six-mile arterial of thirteen intersections in Ann Arbor, Michigan were used. Far-side bus stops and two-phase intersections are common throughout the network. TRANSYT-7F was used to optimize the network signal settings. Offsets are reestablished in the cycle following preemption. The model possessed the skip phase capability. There were several conditions placed on preemption to limit excessive preemption calls.

Chapter 3

Research Approach And Data Collection

The previous research has established that the benefits of preemption are negated if the traffic signal system does not return to the underlying signal setting once preemption is initiated. The inability of an algorithm to reestablish offsets once signal preemption occurred may also adversely affect road user costs. The literature showed that there is no computer model available that can simulate the bus preemption signal (BPS) operation directly for several preemption strategies, including skip phases, and then return to the optimum signal setting. In this research, these shortcomings were overcome.

3.1 Alternative Plans

In the search for an appropriate computer model to study the BPS operation, several elements were considered. The model must be microscopic in nature so that it can track individual vehicles, including buses, through the network. There must be a method to identify buses in the traffic mix, and their characteristics should be distinguishable from other vehicles. The location of these buses with respect to the signal at any particular time must be known. Fixed time signal settings must be changeable to accommodate bus preemption. In addition, the model should be compatible with the traffic controller type that exists or is to be installed in the corridor. The researched alternatives are discussed below.

3.1.1. Automatic Signal / Eagle Signal Software-Hardware interface:

It was known that the EPAC controllers of Automatic Signal / Eagle Signal and the MONARC (Master Office Network Adaptive Real-time Control) system were to be installed in the Washtenaw Avenue corridor. MONARC is a comprehensive computer software package that provides centralized transportation management and control. Also, it offers distributed area-wide, on-street, traffic control. It is a fully operational digital electronic data management processor, receiving continuous real-time inputs from multiple communication links. It generates status reports, failure reports, and sensor reports, and it makes adjustments to system traffic parameters.

Contacts were established with the Automatic Signal / Eagle Signal company to understand the controller system and logic. The company's headquarters in Austin, Texas was visited to discuss the model to determine how to incorporate it into this study. The EPAC controllers have the capability of processing a BPS operation. In order for the controller to place the priority call, buses have to actuate the system's detectors. This requires an interface between the simulation model and the MONARC controller to simulate vehicle and bus arrivals (see Figure 1).

A microscopic simulation capable of generating traffic into the EPAC(s) was required. Traffic volume data, turning percentages, signal timing and phasing, bus schedules, bus stops, and geometric design would need to be coded into the simulation software. The simulation model would then generate traffic arrivals, which would be converted to impulse signals into the EPAC controller. The controllers would, in turn, alter the timing plans in response to the input. This process requires a hardware interface between the

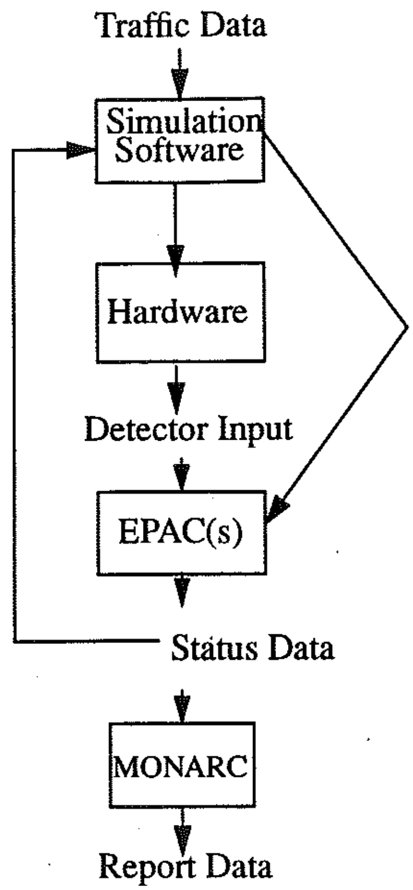


Figure 1: Automatic Signal / Eagle Signal BPS work plan

controller and the simulation model output from the computer equipment (personal computers, PC).

The NETSIM model was selected for the simulation. The NETSIM source code was provided by McTrans. Although the computer / controller interface was made available by Automatic Signal / Eagle Signal, after careful examination of the model, it was decided that the structure of the NETSIM model was not well suited to the design of the detector input interface required by the EPAC controllers.

3.1.2. THOREAU Model:

THOREAU is a recent Intelligent Transportation System (ITS) model developed by the MITRE Corporation in November 1992. It stands for the Traffic and Highway Objects for REsearch, Analysis, and Understanding. It is a microscopic and mesoscopic simulation package. Extensive testing was conducted to determine the suitability of the model for the bus preemption signal. Communication has been established with MITRE Corporation to assist in evaluating the model and to explore potential enhancement of the model.

As a result of this assessment, several modifications were added to the model by the MITRE Corporation. An understanding of what needs to be done to make the model capable of simulating the BPS process was reached. It was agreed that MITRE would enhance the model to accommodate the BPS, and that MSU would develop the BPS algorithms. The MITRE targeted date for implementing the enhancement extended beyond the MSU targeted project completion date. Thus, while this effort is being continued, it was not suitable for this project.

3.1.3. TRAF-NETSIM Graphics and Simulation:

A third option was to enhance TRAF-NETSIM to provide BPS operation. None of the other models researched was found to match the strengths and capabilities of TRAF-NETSIM. TRAF consists of an integrated set of simulation models each of which represents traffic on a particular environment (i.e., urban street, whether network or arterial, two lane rural roads and freeways). NETSIM, which stands for NETwork SIMulation, is one module of the TRAF family. It is a microscopic simulation model of urban traffic (TRAF User Reference Guide 1994).

The model generates vehicles into the network randomly (poisson distribution) according to a seed number coded in the data file. In this study, buses are introduced with uniform headway according to the bus frequency. NETSIM applies interval-based simulation to describe traffic operation. Every vehicle is a distinct object, which is moved every time period, and every variable control device (traffic signal) is also updated every time period. A vehicle's kinematic properties (speed and acceleration) are determined, as well as its free flow speed, queue discharge headways and other behavioral attributes. Each time a vehicle is moved, its position (both lateral and longitudinal) on the link and its relationship to other vehicles nearby are recalculated. Vehicles are moved according to car following logic and response to traffic control devices.

The current version of TRAF-NETSIM does not include the logic for bus preemption. There were previous efforts by the FHWA to include this operation, but the work was not completed and, therefore, was not embedded into the NETSIM model.

There are three issues involved in using NETSIM for simulating a BPS. First, the detection of bus arrivals at the intersection; second, interruption of the signal to respond to the bus preemption call; and, third, the ability to test different preemption strategies.

It was found that the current model keeps track of every vehicle throughout the network internally and does not provide this information as part of its output. However, by using the graphical animation feature of the model it was possible to visually track buses along the corridor (as buses are color labeled) and determine the signal status as the bus arrives at the intersection. Also, NETSIM has the option of utilizing up to nineteen time periods, each of which may describe changing conditions. These changing conditions are either indigenous changes (internal to the system) or exogenous (external inputs prepared by the user), such as changes in the signal timing, phasing, volume, or turning movement percentages. With the combination of both graphical animation and different time periods it is possible to simulate different BPS schemes.

The procedure is to (a) detect the bus arrival in the vicinity of the intersection, (b) determine the signal status as the bus arrives, (c) determine if preemption is to be awarded (based on certain criteria to be established), (d) select a plan (different signal timing or phasing) to be implemented, if any, and (e) select the exact implementation time. These decisions are then coded into the model and the system is simulated with these changes to secure bus passage through the green light. Buses are monitored along the corridor in both directions (east bound and west bound) and similar decisions are made at every intersection. Signal timing plans are reset to their normal settings (offset, phases, and phase intervals) after every preemption activation.

Some of the important characteristics of NETSIM's time periods (TRAF User Reference Guide 1992) are below.

a. Each set of exogenous input data applies to (and remains constant during) one time period.

b. Each time period is subdivided into a sequence of time intervals. Each simulation model requested for a given run is brought in and out of the central memory once each time interval. The time interval duration is typically set to the most common signal cycle length in a study network. (It is set to 60 seconds in this study.)

c. The duration of each time period must be an integer multiple of the time interval duration; 60 seconds.

In this study NETSIM's signal control cards: signal phases, offsets, and durations (cards 35 and 36) may have to be changed in each time period to correspond to the BPS operation. Due to different cycle offsets and constrained by the time interval requirement above (multiples of the cycle length) the beginning of a time period may occur in the middle of a signal phase. However, NETSIM does not interrupt the signal cycle to adopt the new change. Instead, the cycle is resumed as specified in the previous time period and the order is carried out in the next cycle. Thus, an order has to be placed one cycle length before the change is required. Also, it is worth mentioning that, in some cases, it may be necessary to change both cycle offset time and phase duration to advance the green phase according to the BPS.

3.2 Data Collection

3.2.1 Background

Washtenaw Avenue in Ann Arbor, Michigan was selected as the test site. Ann Arbor is located 43 miles west of Detroit and has a metropolitan area population of 250,000 (Ann Arbor Transport Plan, 1990). Its population, as the largest city in Washtenaw County, is estimated at 109,000. Approximately, 30,000 of the 35,000 students enrolled at the University of Michigan's Ann Arbor campus live in the city.

Public roads and streets are under the jurisdiction of the City of Ann Arbor and the Michigan Department of Transportation (MDOT). Public transportation is provided in the form of bus services by the Ann Arbor Transportation Authority (AATA) and the University of Michigan.

Growth and development of the city has led to increasing traffic congestion on major streets, diversion of traffic into residential neighborhoods, and increasing conflicts between University functions and non-University functions (Ann Arbor Transport Plan, 1990).

One of the recommended plans in the Ann Arbor Transportation Plan Update (Ann Arbor Transport Plan, 1990) is providing transit-related improvements to increase capacity and reduce congestion. In the field of transit, it was suggested that ridership should be enhanced by improving services. Although the study recommended different ways for enhancement, this research will be addressed to improving bus schedule reliability by signal preemption as a mean of encouraging automobile drivers to divert to transit.

The AATA operates twenty-two fixed-routes transit lines in Ann Arbor and the surrounding communities. Ninety-three percent of all Ann Arbor residents are within one-fourth mile of a route. Most routes operate with 30-minute service through the day, but the Washtenaw route is one of two that operates with a 15-minute headway during peak periods.

Ridership has increased during the last few years to a level of about 4 million riders in 1990. In total, transit trips make up about one percent of all trips made in the Ann Arbor-Ypsilanti Urbanized Area.

3.2.2 Network Selection

Washtenaw Avenue, east of the central business district has been identified as one of the roadways that exceeds its design capacity (Ann Arbor Transport Plan, 1990). It is one of the busiest corridors in the city. It runs from the west, crosses the CBD and continues to the east through the city of Ypsilanti, see Figure 2. A major Ann Arbor Transit Authority, east-west bus route runs through the corridor.

The eastern part of the corridor, between the Golfside / Washtenaw intersection on the east and South University / Washtenaw on the west, was selected for this study for the following reasons:

1. This particular corridor has been identified by the Ann Arbor Transportation Plan Update study (Ann Arbor Transport Plan, 1990) as one of the roadways with a major capacity deficiency.

2. Based on previous experience, it was decided that closely spaced and heavily congested intersections (e.g., downtown Ann Arbor) are not good choices for signal preemption. Furthermore, bus routes run in all directions (north, south, east, and west) in the CBD area, which makes it more difficult to improve overall service by implementing BPS.

3.2.3 Data Collected

The following data were collected to study the bus preemption operation along Washtenaw corridor:

A. Geometric Design: intersection geometry, including number of lanes and lane configurations and distances between intersections. Most of these data have been provided by

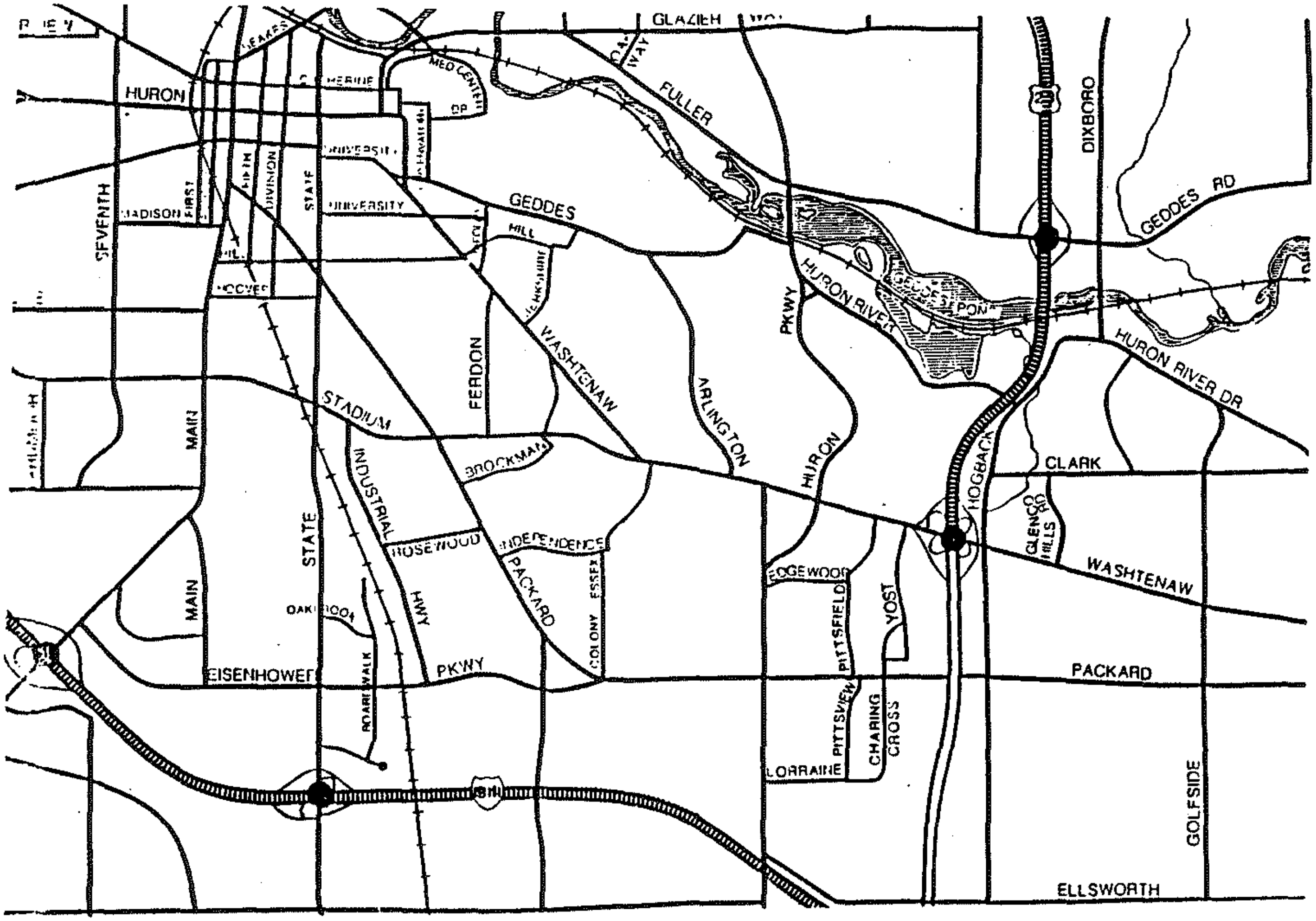


Figure 2: Map of Washtenaw Avenue - East, Ann Arbor

the Ann Arbor - Ypsilanti Urban Area Transportation Study Commission or determined from the city map.

B. Traffic Related Data: traffic volumes, including morning and evening peak hour and daily volumes and turning volumes (peak hourly volume are provided in Appendix A). Part of these data were provided by the Ann Arbor - Ypsilanti Urban Area Transportation Study Commission and MDOT. Students from Wayne State University collected data on the average and maximum queue length, and on pedestrian intensity. Videotaping of several intersections was conducted to calculate the stop time delay (these data were used for model calibration).

C. Signal Timing: signal phases and timing. The current timing plan for signals along the State trunkline in the City of Ann Arbor was provided by the City and MDOT. Signal timing was collected in the field, and it was determined that different intersections have different cycle lengths, which prevents progression along the corridor. Since the objective is to compare bus preemption against a "good" timing plan, it was decided to maintain the same signal phasing, but to optimize the cycle length, the green splits, and signal phase offsets along the Washtenaw Avenue Corridor. This has been achieved using the TRANSYT-7F computer model. The results of this optimization are utilized in the simulation model.

D. Bus Related Data: bus schedule, bus routes, bus headway, bus stop locations, bus ridership, and bus dwell time. Most of these data have been provided by AATA. However, bus stop locations were determined in the field.

The data were collected in the period of Fall 1993 to Spring 1994. From the data, it was determined that the morning peak hour was from 8:00 to 9:00 and the evening peak hour was from 5:00 to 6:00. Also, it was decided that the evening peak hour is the ultimate peak period. However, data were collected for both time periods.

Initial collection of queue data, speed limits, pedestrian intensity, and geometric features was conducted in the Fall 1993 (see example, Figure 3). It was decided to use video recording of traffic conditions at several intersections for model validation. This was conducted in the morning and evening peak periods in Spring 1994. The video recorded data were used to derive the stop time delay, the number of vehicles stopped, and to calculate the average stopped delay time.These were compared with model output results (Khasnabis et al, 1994).

3.3 Model Calibration

The data collected in the field and from MDOT, AATA, and the City of Ann Arbor for the study network were coded into NETSIM. NETSIM's link-node diagram for the study network is shown in Figure 4. Nodes numbered between 1 and 33 represent actual intersections, while nodes numbered between 8000 and 8023 are dummy entry / exit nodes.

The network contains thirteen intersections along Washtenaw Avenue and one intersection on each side along the cross street (if present). In this study, Washtenaw Avenue is considered the main street and all others are cross streets. The eastern part of the corridor (east of Stadium Road) has different characteristics than the western part. The main street is wider on the east. There are two lanes in each direction at Pittsfield, two lanes with turning pockets at Golfside, Carpenter, Huron Parkway, Yost, and Sheridan/Manchester, and three

INTERSECTION DATA COMPILED FROM SELECTED INTERCHANGES ALONG THE WASHTENAW CORRIDOR - ANN ARBOR

INTERSECTION:	WASHTENAW - GOLFSIDE
DATE:	SEPTEMBER 13, 1993
TIME:	7:30-8:30 AM
WEATHER:	PARTLY SUNNY

QUEUE DATA:

WASHTENAW WB:	LEFT TURN LANE:	0,1,1,1,0,0,1,0,0,1	AVE=0.5
	CENTER LANE:	2,10,3,4,3,3,5,5,3,6	AVE=4.4
	RIGHT LANE:	2,5,7,4,3,8,3,3,2,5	AVE=4.2
WASHTENAW EB:	LEFT TURN LANE:	3,2,4,1,3,2,6,3,1,3	AVE=2.8
	CENTER LANE.	7,11,1,3,8,3,8,0,2,9	AVE=5.2
	RIGHT LANE:	6,5,2,5,8,3,8,1,6,10	AVE=5.4
GOLFSIDE SB:	LEFT TURN LANE:	2,4,1,1,3,4,8,3,5,3	AVE=3 4
	CENTER LANE:	3,3,3,5,0,1,2,0,3,3	AVE=2.3
	RIGHT LANE:	6,2,7,2,5,4,3,3,4,5	AVE=4.1
GOLFSIDE NB:	LEFT TURN LANE:	1,1,2,0,1,2,1,3,1,2	AVE=1.4
	CENTER LANE:	2,2,1,2,1,1,1,4,1,2	AVE=1.7
	RIGHT LANE.	2,3,3,1,0,0,2,3,0,2	AVE=1.6

SPEED LIMITS. WASHTENAW = 40 MPH
GOLFSIDE = 35 MPH

RIGHT TURN INFORMATION NO TURN ON RED - ALL APPROACHES

PEDESTRIAN INTENSITY MEDIUM

LEFT TURN INFORMATION LEFT LEAD (LIGHT) - ALL APROACHES

CROSS STREET INTERSECTIONS.
GOLFSIDE SB LIGHT AT PACKARD
GOLFSIDE NB LIGHT AT CLARK

Figure 3: Example of The Wayne State's Field Data Collection. (Source: Khasnabis 1994).

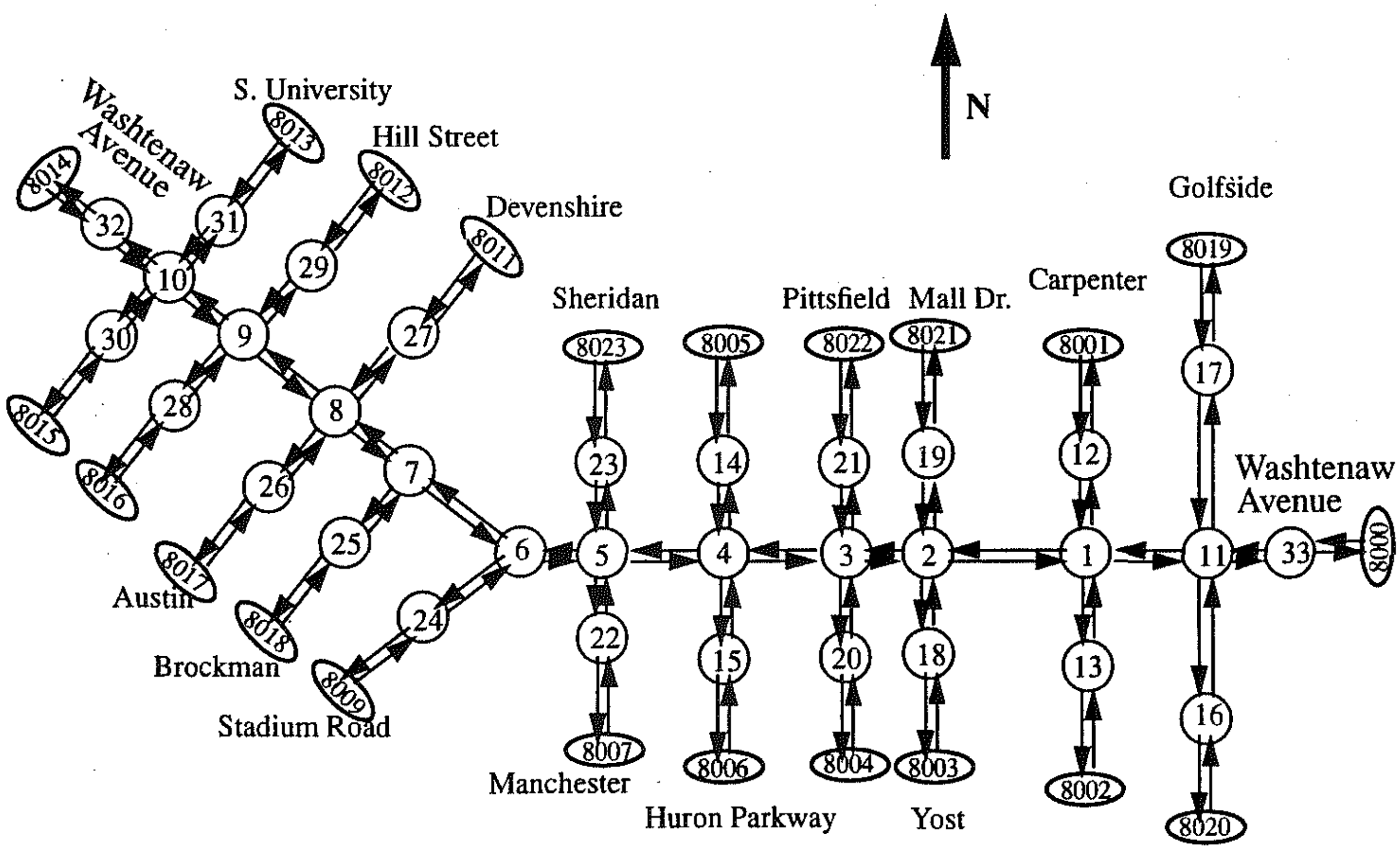


Figure 4: Simulation Network, Nodes and Links

lanes at Stadium Road. The western part, from Stadium to South University, has two lanes with no turning pockets.

Cross street traffic is relatively high at Golfside Street, Carpenter Road, Huron Parkway, and Stadium Road. Arborland Mall lies on the north side of Washtenaw between Pittsfield and Yost. Carpenter Road and Huron Parkway are controlled by actuated signals. Golfside, Carpenter Road, and Huron Parkway are four-phase, signal-control intersections--two protective left turn phases and two right and through phases. The rest of the intersections have two-phase signals.

The model was calibrated against the average and maximum queue length measures collected in the field, both manually and by video-camera recording. The simulation output and field data were compared for several parameter values. Both evening and morning peak hour conditions were studied. The model was calibrated until it reached a fair level of conformity with field data (Khasnabis et al, 1994).

3.4 Sensitivity Analysis

The sensitivity of the model to several variables was tested. In the BPS process signal green time is to be either extended (for the main street) or cut (for the cross street) in different time periods, as demanded by the bus preemption call.

Several intersections were selected to receive either a green extension or a termination of cross street green. Fourteen time periods were utilized to analyze the sensitivity of the model to the change. In the fourth and the ninth time period, main street green time was increased by ten seconds, and cross street green time was cut by ten seconds. One upstream link and two downstream links statistics were observed. These measures include vehicle-link-trips, total vehicle delay time, and average vehicle delay.

The model reacted logically to these changes. Generally, in the period where the signal timing was changed and one period after, main stream vehicle-trips increased and average delay decreased on Washtenaw Avenue, while the opposite occurred on the cross streets. However, it is worth mentioning that these results were not uniform due to the random vehicle arrival pattern, and the fact that the green time extension was selected independent of the traffic demand or the location of vehicles approaching the intersection. The intent of this calibration was to determine if the model behaves as expected. It was determined that NETSIM is fairly sensitive to a change in signal timing. Tables 5A, 5B, and 5C are provided as an example of this analysis.

The WSU group conducted a more extensive sensitivity analysis on several other variables (Khasnabis et al, 1994). These variables include a change in the green time, percentage of trucks on the main street, and presence of buses on the network. The study concluded that NETSIM is sensitive to these variables. A slight change in the input variable leads to logical changes in the output.

Table 5A: West Bound MOEs as a Result of 10-Seconds Preemption at Intersection #8 (10-Seconds Green Extension).

	MOEs	Period #1 1-hr	Period #2 70-sec	Period #3 70-sec	**Period #4 70-sec**	Period #5 70-sec	Period #6 70-sec	Period #7 70-sec	Period #8 280-sec	**Period #9 70-sec**	Period #10 70-sec	Period #11 70-sec	Period #12 70-sec
	Veh-Trip		5	3	4	10	6	2	18	9	5	11	6
7-8	Veh-Min	118.2	0.3	0.1	0.3	1.7	0.7	0.8	2.3	1.1	0.2	2.8	1.0
	Sec/Veh	12.8	3.0	1.0	4.3	10.2	6.5	22.5	7.7	7.4	2.6	15.2	9.9
	Veh-Trip		6	6	3	5	10	8	18	3	11	5.0	10
8-9	Veh-Min	191.6	2.5	0.8	0.7	1.4	2.3	1.8	4.9	1.0	3.7	0.5	5.9
	Sec/Veh	20.6	25.0	8.2	13.7	16.4	14.0	13.5	16.3	19.4	20.2	6.0	35.6
	Veh-Trip		6	10	6	7	9	12	30	7	6	10	7
9-10	Veh-Min	178.7	1.6	2.1	1.3	1.9	2.0	4.1	6.0	2.5	1.6	1.0	1.9
	Sec/Veh	16.8	16.5	12.4	13.0	16.1	13.4	20.4	12.1	21.5	16.2	6.0	16.4

*** Periods 4 and 9 are preempted.**
*** 70-Seconds is the original most common cycle length along the Washtenaw corridor.**

Table 5B: East Bound MOEs as a Result of 10-Seconds Preemption at Intersection #8 (10-Seconds Green Extension).

	MOEs	Period #1 1-hr	Period #2 70-sec	Period #3 70-sec	**Period #4 70-sec**	Period #5 70-sec	Period #6 70-sec	Period #7 70-sec	Period #8 280-sec	**Period #9 70-sec**	Period #10 70-sec	Period #11 70-sec	Period #12 70-sec
	Veh-Trip		18	9	16	7	18	14	45	9	15	13	15
9-8	Veh-Min	331.2	5.8	2.0	6.1	3.7	9.7	5.1	14.8	3.3	8.6	5.3	5.3
	Sec/Veh	28.7	19.4	13.6	23.0	31.8	32.5	21.8	19.7	22.1	34.6	24.5	21.2
	Veh-Trip		11	16	14	12	11	13	52	12	9	14	15
8-7	Veh-Min	602.3	21.5	12.6	11.3	7.9	9.4	7.4	60.5	9.5	2.4	4.4	4.5
	Sec/Veh	53.9	117.0	47.3	48.4	39.5	51.1	34.1	69.9	47.7	16.2	18.8	18.0
	Veh-Trip		16	16	8	16	11	7	51	14	15	10	8
7-6	Veh-Min	355.2	11.1	9.5	4.8	9.7	4.5	5.7	27.9	7.2	9.2	5.0	4.9
	Sec/Veh	34.0	41.7	35.7	35.9	36.3	24.3	48.5	32.9	30.7	36.9	29.8	36.5

Table 5C: North & South Bound MOEs as a Result of 10-Seconds Preemption at Intersection #8 (10-Seconds Green Cut).

	MOEs	Period #1 1-hr	Period #2 70-sec	Period #3 70-sec	**Period #4 70-sec**	Period #5 70-sec	Period #6 70-sec	Period #7 70-sec	Period #8 280-sec	**Period #9 70-sec**	Period #10 70-sec	Period #11 70-sec	Period #12 70-sec
	Veh-Trip		1	2	1	1	1	1	5	1	2	1	1
27-8	Veh-Min	19.5	0.3	0.8	0.1	0.2	0.4	0.6	0.9	0.3	0.9	0.0	0.2
	Sec/Veh	19.2	17.4	23.9	8.4	12.4	21.4	37.4	11.4	16.4	26.9	1.4	13.4
	Veh-Trip		1	1	1	1	1	1	4	1	1	1	1
26-8	Veh-Min	18.2	0.1	0.2	0.1	0.1	0.2	0.2	0.5	0.2	0.2	0.2	0.1
	Sec/Veh	21.1	3.4	12.4	6.4	7.4	12.4	11.4	7.4	14.4	10.4	11.4	5.4

Chapter 4

BPS Schemes and Algorithms

4.1 Bus Detectors

BPS operation requires a means of communication between the bus and a traffic controller. Historically, this communication has been conducted by placing detectors in the pavement that form an electromagnetic field. These detectors identify the bus presence within the vicinity of the intersection and communicate with the traffic controller, placing a call for preemption. The controller then awards the preemption according to its built-in logic.

In this study, detection of bus arrivals and signal status were visually observed utilizing NETSIM's graphical animation. In the implementation stage, it is proposed to use smart card technology to communicate between vehicles and traffic controllers. Although buried detectors are not used in this study, schematic intersection configurations with detectors were designed to develop the algorithms used in the research. The location of a bus-stop relative to the intersection plays a major role in the BPS algorithm. The intersection configurations for far-side and near-side bus stops are presented in Figures 5 and 6, respectively.

Three to four detectors are needed at every intersection. Each of the detectors monitors the bus arrival and progression at the intersection. The first detector is located at 400-500 feet

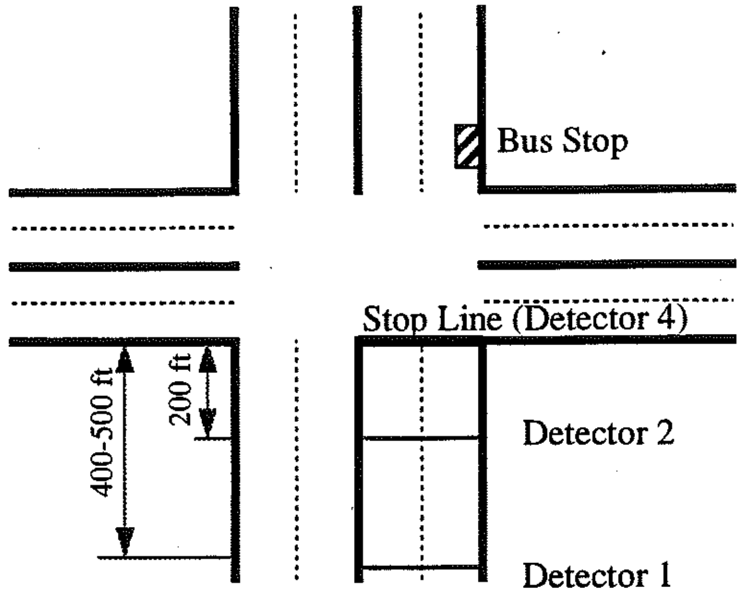


Figure 5: Far-Side Bus-Stop Intersection / Detector Configuration.

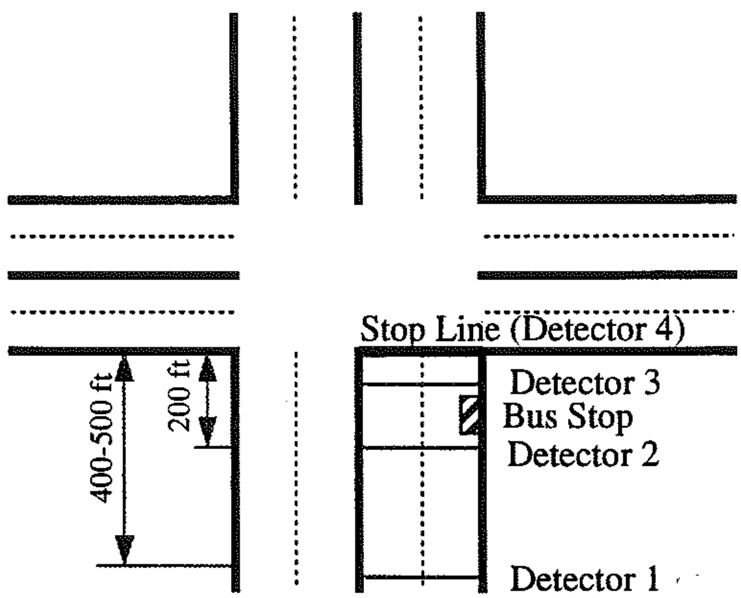


Figure 6: Near-Side Bus-Stop Intersection / Detector Configuration.

(ft) upstream from the stop bar. Its purpose is to detect the bus arrival in the vicinity of the intersection and to assist in checking the traffic status. The second detector is located at 200 ft upstream and its purpose is to detect the bus progression toward the intersection and to predict the signal status at the time the bus reaches the stop bar. The third detector is used only in the near-side bus-stop case. It is placed just after the bus-stop station and its purpose is to indicate the bus departure from the bus stop. The fourth detector is at the stop bar. Its function is to verify that the signal preemption scheme has been successful (the bus has left the intersection).

4.2 BPS Schemes

As mentioned earlier, several combinations of the existing BPS schemes are possible. The following are the schemes tested in this study:

(a) green extension, red truncation, no substitution (inhibit),

(b) green extension, red truncation, substitution (if necessary),

(c) skip phase, inhibit, and

(d) skip phase, substitution (if necessary).

Some of these plans work better than others at different intersections and under different traffic conditions. Sensitivity tests were conducted, and the most suitable plan(s) for each intersection were determined. In addition, a signal preemption plan conditioned on the bus running behind schedule was tested.

4.3 BPS Logic

The following constraints were used in testing the effect of different BPS strategies:

(1) no preemption is allowed during two consecutive cycles,

(2) the minimum green time for any signal phase is ten seconds, and

(3) the maximum extension or advance of the green signal phase is ten seconds.

BPS algorithms and flow charts for different strategies were constructed to be implemented as routines into the main computer program. This was initially developed to be used with the THOREAU model enhancement alternative plan that was examined earlier (refer to Chapter 4). As the bus arrival is detected in the vicinity of an intersection the following algorithmic steps are employed:

- The first check is to assess whether preemption has occurred in the last cycle. If yes, then preemption is not permitted. If no, then proceed.

- If this is conditional preemption, is the bus on schedule? If yes, then preemption is not allowed. If the bus is behind schedule or this is not conditional, then proceed.

- Does the bus arrive on red? If no, there is no need for preemption. If yes, then preemption might be possible.

- Is time available for preemption? (i.e., how many seconds are needed to secure the bus passage on a green light?) If more than 10 seconds are needed then preemption is not allowed (unless this is a skip phase plan). If 10 seconds or fewer are needed, is the cross street minimum green condition satisfied? If yes, then preemption is provided. In case of the skip-phase(s) option, one may choose to skip a phase(s) if it provides the bus passage successfully; minimum cross street green is to be completed before preemption.

- Select the suitable plan; advance green or green extension. Action is to be taken accordingly.

- After preemption is granted a compensation or no substitution alternative is selected.

Flow charts that describe the detailed programming steps for both far-side and near-side bus-stops are shown in Appendix B.

Chapter 5

BPS Simulation Results and Analysis

5.1 Study Cases:

There were six bus signal preemption cases studied in this research. These are:

1. **Base case**: No Preemption. The optimal existing conditions were simulated and no special treatment was given to the bus. This is the reference case against which all other cases are compared to assess the impact of BPS.

2. **Case 1:** Green Extension, Red Truncation, No Compensation. The green signal phase was either extended or advanced. There was no compensation given for the cross street or the phases that had been reduced.

3. **Case 2**: Green Extension, Red Truncation, With Compensation: Compensation was given only for phases that were reduced and were in high need to make up for capacity loss during preemption. The need for compensation was determined based on average vehicle delay, queue length, and number of vehicle-trips subsequent to preemption. Compensation was provided only when cross street delay increased to a degree that the queue resulting from preemption could not clear in the cycle immediately following preemption.

4. **Case 3:** Skip Phase, No Compensation. When the green extension or red truncation policy were not sufficient to let the bus pass through a green signal, phase(s) was (were)

completely skipped for one entire cycle, i.e., green phase was extended for one full cycle length. No compensation was provided in this case.

5. **Case 4:** Skip with compensation. As in case 2, compensation was given based on need. A few intersections that have low cross-street volume did not experience high delay due to preemption, and the queue was completely cleared in the next cycle. Therefore, there was no need to compensate at these locations.

6. **Case 5:** Selective plans. Based on the results obtained from the first four BPS plans, the most suitable plan for each intersection was selected. It was anticipated that the BPS process could result in higher delays than the original signal settings, since preemption causes the signal to deviate from its optimal timing. Thus, the most suitable plan(s) for each intersection were determined to be the plan(s) that did not cause excessive delays.

7. **Case 6:** Conditional Preemption. In this case, the bus progression against its scheduled arrival time at different stations was compared and the selective preemption plan, i.e, case 5, was awarded only when the bus was late.

These seven cases were simulated, and signals were changed at specific times to accommodate the BPS operation. Most signals have two phases and 60 second cycle length, except for three signals; at Golfside (120 second, four phases), and at Huron Parkway and Carpenter (Actuated, four phases). Preemption was not provided at the two actuated signal intersections. Most locations have a typical two-phase signal with permissive left turns. Golfside, Yost, and Stadium have different phasing movements and configurations. These phasing configurations are shown in Figure 7.

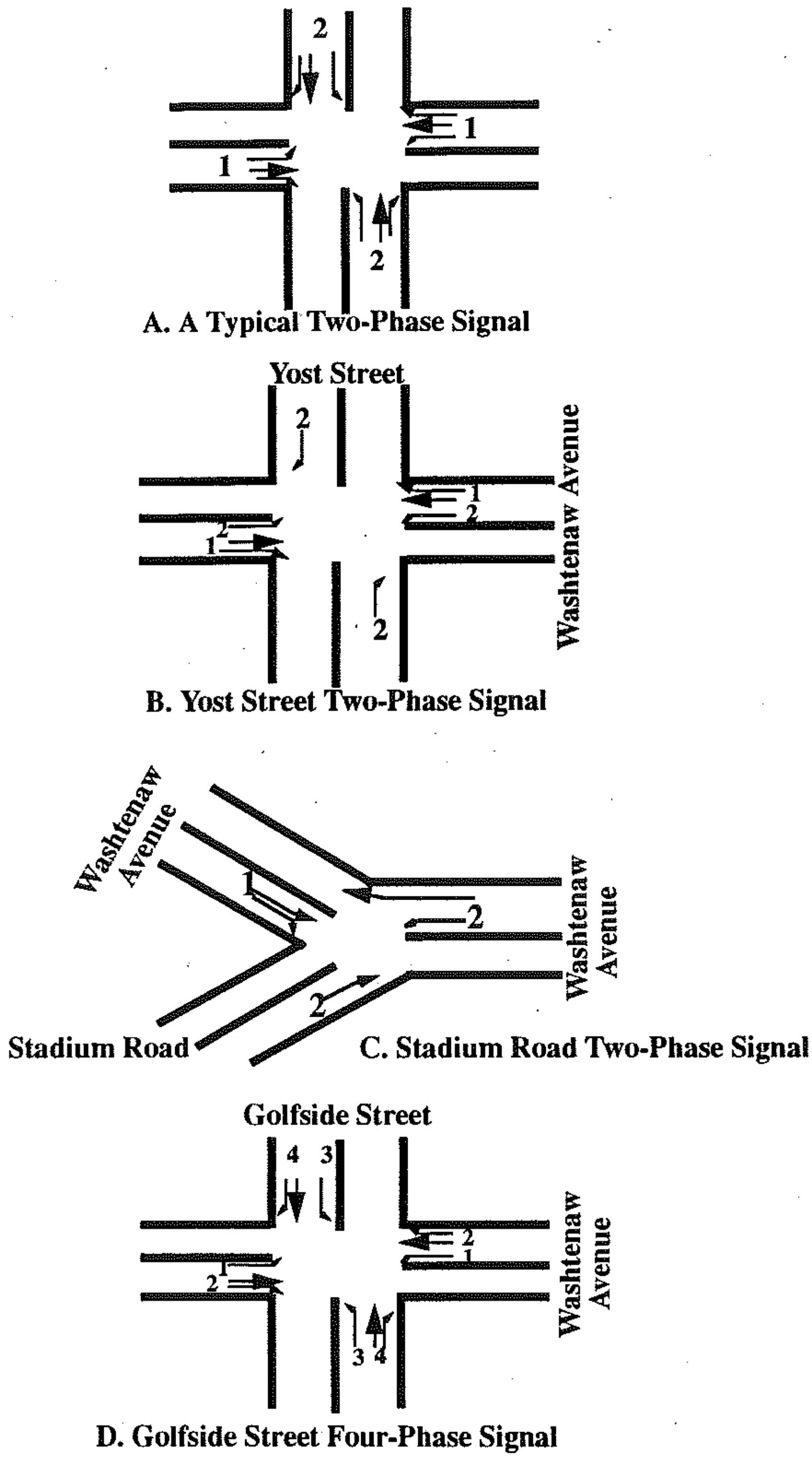


Figure 7: Phasing Configurations Along Washtenaw Avenue.

5.2 Analysis of BPS Time Period Specific Statistics

To understand the overall vehicle behavior resulting from preemption, each of the preemption strategies was simulated, and measures of effectiveness (MOEs) were collected every minute. NETSIM generates cumulative network statistics, as well as link and movement specific statistics. Cycle (or time period) specific statistics were derived from the cumulative statistics. The type of statistics (link or movement specifics) that fit each intersection depends on the particular signal phasing of that intersection. For example, movement specific statistics were collected for intersections with protected turn movements, and overall link statistics were collected for typical two-phase intersections. The total number of vehicle trips, the total delay in vehicle-minutes, and the average delay in seconds per vehicle were collected for each cycle. NETSIM also provides network-wide bus statistics and bus link statistics as part of its standard output.

Statistics for two cycles before and two cycles after preemption plus the preemption cycle (a total of five cycles) were collected. The first two cycles show the normal traffic behavior without preemption, and the last two show the traffic behavior immediately following preemption. Statistics were collected at the end of every sixtieth (60th) second. However, since the cycle length is either 60 or 120 seconds and many cycles have an offset larger than zero (the cycle does not begin and end at the beginning of an analysis period), preemption may take place and its effect may be partially observed during the preemption time period (third time period) and partially in the following time period statistics. Depending on intersection conditions, the effect of preemption may be observed for several cycles.

The three primary MOEs used are Vehicle-Trips, Total Delay, and Average Delay. NETSIM defines these terms as follows: **Vehicle-Trips** are the number of vehicles that have exited the link during a specific period of time, **Total Delay** is the difference between the free flow travel time and the actual travel time for all vehicles that exited the link during a specific period of time. Vehicles that are in the link at the end of the analysis period are counted in the time period as they depart the link. **Average Delay** (Seconds / Vehicle) is a derived formula computed as = Total Delay (Veh-Min) * 60 / Veh-Trips.

5.2.1. Case 1 Preemption:

During the 45-minute simulation period, there were a total of eight preemptions involving green extension or red truncation. Preemption time ranged from 3 seconds to full preemption (10 seconds). Each preemption was analyzed by studying the above mentioned MOEs for two cycles before and after preemption. The full results of case 1 preemptions are presented in Appendix C. Tables 6, 7, and 8 present examples of case 1 preemption results for three different intersections with different signal phasing.

Table 6 shows the results of preemption at a typical two-phase intersection (South University and Washtenaw). The first two time cycles represent the average vehicle-trips and delay before preemption. Preemption took place in the third time period. The east-west direction green time was extended and north-south direction green time was prematurely cut.

As a result of preemption, an increase in the number of vehicle trips and a decrease in delay along the main street, accompanied by a decrease in vehicle-trips and an increase in delay for cross street traffic, would be expected. However, since the main street green time

Table 6: Time Period Specific Statistics as a Result of Preemption For Intersection Number 10. Main Street (E-W) Green is Extended for 3-Seconds, Cross Street (N-S) is Cut by 3-Seconds. Third Time Period is Preempted. Bus Direction is East Bound.

Link	Direction	Measures of Effectiveness	1st Time Period 60-Seconds T=5:22	2nd Time Period 60-Seconds T=5:23	3rd Time Period 60-Seconds T=5:24	4th Time Period 60-Seconds T=5:25	5th Time Period 60-Seconds T=5:26
9-10	West Bound	Veh-Trips	10	11	10	14	10
		Delay (Veh-Min)	2.4	1.0	1.2	2.7	1.5
		Delay (Sec/Veh)	14.4	5.4	7.3	11.6	9.0
32-10	East Bound	Veh-Trips	9	8	11	8	9
		Delay (Veh-Min)	1.1	0.3	0.9	0.5	0.9
		Delay (Sec/Veh)	7.3	2.4	4.7	3.8	6.0
31-10	South Bound	Veh-Trips	1	1	2	1	1
		Delay (Veh-Min)	0.4	0.6	1.0	0.3	0.5
		Delay (Sec/Veh)	24.0	34.4	28.9	18.0	30.0
30-10	North Bound	Veh-Trips	2	2	2	3	2
		Delay (Veh-Min)	0.2	0.1	0.8	0.9	0.7
		Delay (Sec/Veh)	6.0	4.2	25.2	18.0	21.0

Table 7: Time Period Specific Statistics as a Result of Preemption For Intersection Number 6. 10-Seconds of Advance Green For Main Street EB, 10-Seconds Cut From Cross Street NB and Main Street WB left. Third Time Period is Preempted. Bus Direction is East Bound.

Link	Direction	Measures of Effectiveness	1st Time Period 60 -Seconds T = 5:13		2nd Time Period 60-Seconds T = 5:14		3rd Time Period 60-Seconds T = 5:15		4th Time Period 60-Seconds T = 5:16		5th Time Period 60-Seconds T = 5:17	
			L	R	L	R	L	R	L	R	L	R
5-6	West Bound	Veh-Trips	13	15	15	5	11	15	16	9	15	6
		Delay (Veh-Min)	1.7	2.2	3.6	0.8	1.4	1.8	4.9	1.3	1.5	0.6
		Delay (Sec/Veh)	7.8	8.6	14.2	10.0	7.7	7.2	18.3	8.3	5.8	6.3
			Total		Total		Total		Total		Total	
7-6	East Bound	Veh-Trips	7		11		14		5		15	
		Delay (Veh-Min)	2.0		6.1		9.3		2.0		14.1	
		Delay (Sec/Veh)	17.1		33.0		39.9		24.0		56.4	
24-6	North Bound	Veh-Trips	12		13		12		16		11	
		Delay (Veh-Min)	1.6		2.4		2.6		2.2		1.9	
		Delay (Sec/Veh)	8.0		11.1		13.2		8.3		10.4	

Table 8: Time Period Movement Specific Statistics as a Result of Preemption For Intersection Number 11. Main Street (E-W) R & T are Advanced for 10-Seconds, Cross Street (S-N) Left Turns are Cut by 10-Seconds. Third Time Period is Preempted. Bus Direction is East Bound.

Link	Direction	Measures of Effectiveness	First Time Period 120-Seconds T=5:23			Second Time Period 120-Seconds T=5:25			Third Time Period 120-Seconds T=5:27			Fourth Time Period 120-Seconds T=5:29			Fifth Time Period 120-Seconds T=5:31		
			L	T	R	L	T	R	L	T	R	L	T	R	L	T	R
33-11	West Bound	Veh-Trips	2	32	4	1	37	5	3	39	11	3	33	8	0	38	4
		Delay (Veh-Min)	1.1	71.0	10.8	1.7	84.7	10.6	3.1	74.7	21.4	3.1	54.4	14.4	0.0	59.7	10.3
		Delay (Sec/Veh)	33.3	133.1	162.6	103.2	137.3	127.6	62.8	115.0	116.5	61.4	98.9	107.6	0.0	94.2	153.9
1-11	East Bound	Veh-Trips	14	29	6	12	22	2	7	27	5	14	24	4	13	29	5
		Delay (Veh-Min)	57.6	23.6	6.6	45.5	15.4	1.7	29.9	19.6	3.0	71.1	21.2	1.85	67.2	24.1	3.5
		Delay (Sec/Veh)	246.8	48.9	65.7	227.3	42.1	49.5	256.4	43.6	36.2	304.8	53.1	27.8	310.3	49.8	41.5
17-11	South Bound.	Veh-Trips	12	12	7	2	13	6	14	14	9	9	10	9	11	6	10
		Delay (Veh-Min)	11.2	11.9	16.3	3.1	20.5	13.8	14.1	22.6	25.2	7.0	7.8	22.3	12.2	6.0	27.4
		Delay (Sec/Veh)	55.8	59.6	139.9	93.0	94.6	138.0	60.5	96.9	168.3	46.7	46.6	148.9	66.6	59.5	164.4
16-11	North Bound.	Veh-Trips	5	8	5	5	14	0	4	11	1	3	11	2	10	10	1
		Delay (Veh-Min)	3.1	4.4	2.7	4.1	10.7	0.0	4.1	9.3	0.7	3.0	10.2	0.9	9.9	7.7	1.3
		Delay (Sec/Veh)	37.0	33.2	32.2	49.3	45.7	0.0	62.0	50.9	43.2	60.8	55.7	27.0	59.3	46.0	79.2

was extended for only three seconds and traffic flow fluctuates randomly, the effect of preemption was not very significant for any direction. For example, there was no increase in west-bound vehicle-trips and no decrease in cross street vehicle trips as a result of preemption. The later may also be attributed to the right-turn on red movement allowed. While delay decreased during preemption (period #3) for the west bound direction, it did not decrease for east bound direction, since its delay is already low and fluctuates significantly. Northbound delay was significantly higher as a result of preemption. Traffic returns to its normal conditions during the fifth time period (two cycles after preemption).

Table 7 shows statistics at Stadium Road, which also has a two-phase signal. During preemption (3rd time period), the east bound green signal was advanced for 10 seconds, cross street (north bound) and east bound left turn green signals were terminated 10 seconds early, while the west bound right turn has a continuous green arrow.

Although more vehicles exited the east bound link during preemption (14 compared to 7 and 11), delay did not decrease. However, vehicles experienced a reduction in delay in the following cycle (4th period) as a result of fewer vehicles being stopped. Since vehicle arrival is fixed, and since more vehicles completed their trip during the preemption cycle, there were not as many vehicles in the link in the following cycle (only 5). Westbound left turning vehicles experienced a decrease in vehicle trips during preemption (11 compared to 13 and 15). As a result, vehicles that were stopped during preemption, in addition to vehicles arriving in the fourth period, left the link in the following cycle and experienced a higher average delay (18.3 compared to 7.8 and 14.2). Traffic returned to normal status after the first cycle following preemption.

Table 8 shows statistics at Golfside Street, which has a four-phase signal. During preemption, main street (east-west) right and through traffic green signals were advanced by 10 seconds, main street left turns were terminated 10 seconds early, and cross street (north-south) signals remained normal. As a result, east bound left turning traffic experienced a significant reduction in number of vehicle trips (7 compared to 12 and 14) with a significant increase in delay that was carried on for several cycles, because the left turn lane was already at saturation flow. However, west bound left turning traffic was not affected by preemption since its vehicle arrival and discharge rate is very low (2 to 3 vehicles per cycle). Therefore, all vehicles could exit the link before their green time was prematurely cut. Furthermore, main street (east-west) right and through traffic experienced a slight increase in their vehicle trips with a slight reduction in west bound average delay during preemption and the following two cycles (3rd, 4th, and 5th period). However, only east bound right turning traffic experienced a reduction in delay.

5.2.2. Case 2 Preemption:

By analyzing case 1 preemption results, it was determined that compensation should be awarded only at Golfside Street under the green extension / red truncation preemption plan. Thus, case 2 preemptions were exactly the same as case 1 preemptions, except that compensation was provided at Golfside Street. The results are shown in Table 9. Green time was extended for 10 seconds for main street right and through and cut from main street left turns (3rd time period). To compensate, in the following cycle (4th time period), 10 seconds were taken from main street right and through and were added to main street left turns. A total of six cycles-- two cycles before preemption, a cycle during which preemption occurs (third time period), a cycle during which compensation occurs (fourth

Table 9: Time Period Movement Specific Statistics as a Result of Preemption and Compensation For Intersection Number 11. Main Street (E-W) R & T are Advanced for 10-Seconds and Then Cut in The 3rd and 4th Periods, Respectively / Main Street (E-W) Left Turns are Cut by 10-Seconds and Compensated in the 3rd and 4th period, Respectively. Bus Direction is East Bound.

Link	Direction	Measures of Effectiveness	First Time Period 120-Seconds T=5:23			Second Time Period 120-Seconds T=5:25			Third Time Period 120-Seconds T=5:27			Fourth Time Period 120-Seconds T=5:29			Fifth Time Period 120-Seconds T=5:31			Sixth Time Period 120-Seconds T=5:32		
			L	T	R	L	T	R	L	T	R	L	T	R	L	T	R	L	T	R
33-11	W. Bound	Veh-Trips	2	32	4	1	37	5	3	39	11	3	27	5	0	35	7	4	36	1
		Delay (Veh-Min)	1.1	71.0	10.8	1.7	84.7	10.6	3.1	74.7	21.4	3.0	53.0	11.0	0	86.6	17.1	2.7	78.1	1.7
		Delay (Sec/Veh)	33.3	133.1	162.6	103.2	137.3	127.6	62.8	115.0	116.5	59.0	117.7	131.9	0	117.5	146.9	41.0	130.2	103.8
1-11	E. Bound	Veh-Trips	14	29	6	12	22	2	7	27	5	18	24	4	12	29	5	10	31	3
		Delay (Veh-Min)	57.6	23.6	6.6	45.5	15.4	1.7	29.9	19.6	3.0	88.4	25.0	2.3	56.0	14.0	3.4	51.7	20.9	3.2
		Delay (Sec/Veh)	246.8	48.9	65.7	227.3	42.1	49.5	256.4	43.6	36.2	294.7	62.5	33.8	280.2	49.6	41.4	310.4	40.5	63.8
17-11	S. Bound.	Veh-Trips	12	12	7	2	13	6	14	14	9	9	10	9	12	6	10	12	4	11
		Delay (Veh-Min)	11.2	11.9	16.3	3.1	20.5	13.8	14.1	22.6	25.2	7.0	7.8	22.3	12.2	6.0	27.4	14.5	4.2	24.9
		Delay (Sec/Veh)	55.8	59.6	139.9	93.0	94.6	138.0	60.5	96.9	168.3	46.7	46.6	148.9	66.6	59.5	164.4	72.6	63.6	135.6
16-11	N. Bound.	Veh-Trips	5	8	5	5	14	0	4	11	1	3	11	2	9	10	1	7	11	2
		Delay (Veh-Min)	3.1	4.4	2.7	4.1	10.7	0.0	4.1	9.3	0.7	3	11	2	9	10	1	4.5	10.0	2.6
		Delay (Sec/Veh)	37.0	33.2	32.2	49.3	45.7	0.0	62.0	50.9	43.2	60.8	55.7	27.0	64.7	46.0	79.2	38.2	54.4	77.1

time period), and two following cycles -- are presented in Table 9.

Although west bound left turn green time was cut by 10 seconds, traffic did not experience any decrease in the number of vehicle trips or any extra delay, because of its low traffic volume. However, east bound left turn vehicles experienced a decrease in vehicle trips (7 compared to 14 and 12) and a slight increase in average delay (256.4 compared to 246.8 and 227.3) due to preemption. During the compensation period (fourth time period), more vehicles exited the link (18 compared to 14 and 12) as a result of the 10 extra seconds added to the green time. Despite compensation to the main street left turn phase, east bound left turn delay continued to increase in the following cycles because the left turn lane was at saturation before preemption occurred.

Main street right and through traffic experienced an increase in vehicle trips and a slight decrease in average delay time during preemption. Vehicle-trips decreased and the average delay increased during the compensation period (fourth time period), since 10 seconds were cut from the green time. This direction returned to normal conditions in the following cycles (fifth and sixth).

North and south bound signal phases were not changed, and any changes in their statistics were merely due to random traffic variations.

5.2.3. Case 3 Preemption

Some of the bus preemption calls in case 1 and 2 were not awarded because of the 10-second maximum preemption time constraint. Since a skip phase option was used in this case (case 3), there were more opportunities for bus preemptions to be awarded. There were a total of ten preemptions; five skips and 5 green extensions / red truncations. The time period specific statistics for all preemptions are shown in Appendix D.

Under case 3 preemptions, traffic followed the same behavior as found in the first two cases, in terms of increase / decrease in vehicle-trips and decrease / increase in average delay. However, the effect on traffic behavior of the phase skipping preemption was more significant than the previous preemption plans. A phase (or more) was completely skipped, and thus, no vehicles could exit that link (except for right turn on red). At most locations, stopped vehicles for which green phases were skipped could exit their link in the cycle following preemption. Vehicles at Golfside Street had to wait more than one cycle to clear, due to traffic volume close to the saturation level.

5.2.4. Case 4 Preemption

By observing case 3 preemption statistics, it was determined that skipping a phase at Golfside Street is the only case that warrants compensation. All other stopped vehicles clear the intersection in the cycle following preemption without compensation. As a result, there were a total of ten preemptions; six green extension / red truncation and four skip phases, three of which included compensation. The time period specific statistics for all preemption occurrences are shown in Appendix E.

Although compensation was provided for the skipped phases, traffic could not recover from the adverse effect during preemption. Golfside Street's east bound left turn statistics remained disadvantaged for a very long period. By the time it started to recover another preemption took place, and thus the delay continued to increase towards the end of simulation time; from 110.9 seconds/vehicle at time equals 5:07 (Table E.1) to 407.7 seconds/vehicle at time equals 5:37 (Table E.10). However, when the phases were skipped from

Golfside Street, the adverse effect lasted no more than two cycles after preemption. This is because cross street traffic volume to capacity ratio is less than that of the main street east bound left turn.

5.2.5. Case 5 Preemption

For each previous preemption case, before and after statistics were collected. The overall intersection statistics for the three periods before preemption and the three periods after preemption are summarized below each table shown in Appendices C, D, and E. Five periods before and after preemption were considered for Golfside (with compensation) to capture the effect of compensation.

Vehicle-trips, total delay, and average delay were calculated for each preemption strategy. Strategies with minimum adverse effects were selected as the preemption choices for strategy 5. Traffic behavior (queues and delays) were visually observed using NETSIM's graphic animation to further assess preemption impacts on intersection MOEs. As a result, the following strategies were selected as the most suitable plan for each intersection:

Intersection 11 (Golfside): Cases 1 preemption.

Intersection 2 (Yost): Cases 1 and 3 preemptions.

Intersection 3 (Pittsfield): Cases 1, and 4 preemptions.

Intersection 5 (Sheridan): Case 3 preemption.

Intersection 6 (Stadium): Case 1 preemptions.

Intersection 7 (Brockman): Cases 1 and 3 preemptions.

Intersection 8 (Austin): Cases 1 and 3 preemptions.

Intersection 9 (Hill): Cases 1 and 3 preemptions.

Intersection 10 (South University): Cases 1 and 3 preemptions.

As a result of these selective plans, there were ten preemptions; seven case 1 preemptions, two case 3 preemptions, and one case 4 preemption. The results of this preemption plan (and the case 6 preemption plan) are discussed in the next section of the paper.

5.2.6. Case 6 Preemption:

When the bus schedule was compared with bus progress through the network, there were eight preemption occurrences; four case 1 preemptions, three case 3 preemptions, and one case 4 preemption.

5.3 Intersection and Link Overall Statistics

Since the maximum number of time periods allowed by NETSIM is nineteen, it was possible to simulate up to 45 minutes. Overall traffic performance at every link, in all directions, and for every intersection over the simulation time was summarized. Statistics over the simulation period with and without preemption were compared for the first four cases of preemption. Intersection statistics were obtained by adding all intersection inbound link vehicle trips and total delay. The average delay was then calculated as before (Tables 10, 11, 12 and 13).

Over a period of 45 minutes, the number of vehicles exiting the network (vehicle-trips) under preemption should not be much different from that under no preemption. The only difference might be due to the difference in the last cycle or two.

Table 10: Case 1 Total Link Statistics With and Without Preemption.

	W/Out.	With	W/Out	With	W/Out	With	W/Out	With	W/Out	With	W/Out.	With
West Bound	33 - 11		11 - 1		1 - 2		2 - 3		3 - 4		4 - 5	
Veh-Trips	1214	1242	1357	1361	1729	1726	1520	1527	1654	1647	1419	1402
Delay (Veh-Min)	2539.4	2232.7	1878.1	2112.1	615.6	619.6	392.3	385.6	2442.2	2685.7	565.6	549.4
Delay (Sec/Veh)	115.7	107.9	83.6	80.9	21.7	21.6	15.8	14.5	85.5	97.8	23.2	25.3
East Bound	1 - 11		2 - 1		3 - 2		4 - 3		5 - 4		6 - 5	
Veh-Trips	1278	1275	1566	1562	2229	2234	1671	1680	1353	1354	1405	1405
Delay (Veh-Min)	2155.4	2432.9	1306.2	1361.3	1102.4	1100.0	857.4	875.0	1573.0	1543.7	228.9	221.2
Delay (Sec/Veh)	101.2	114.5	50.0	52.3	29.7	29.5	30.8	31.2	69.8	68.4	9.8	9.4
North Bound	16 - 11		13 - 1		18 - 2		20 - 3		15 - 4		22 - 5	
Veh-Trips	549	549	836	837	131	130	468	463	686	686	164	164
Delay (Veh-Min)	449.6	450.4	486.8	482.5	26.0	25.8	425.5	434.1	760.5	759.6	50.8	52.2
Delay (Sec/Veh)	49.1	49.2	34.9	34.6	11.9	11.9	54.6	56.3	66.5	66.4	18.6	19.1
South Bound	17 - 11		12 - 1		19 - 2		21 - 3		14 - 4		23 - 5	
Veh-Trips	885	885	675	675	212	212	473	473	899	900	93	93
Delay (Veh-Min)	1174.2	1214.7	2154.3	2153.0	43.9	42.4	166.1	170.6	1668.8	1668.5	29.8	29.6
Delay (Sec/Veh)	79.6	82.3	191.4	191.4	12.4	12.0	21.1	21.6	111.4	111.2	19.1	19.2
Over-all	Intersection 11		Intersection 1		Intersection 2		Intersection 3		Intersection 4		Intersection 5	
Veh-Trips	3926	3951	4434	4435	4301	4302	4132	4143	4592	4587	3081	3064
Delay (Veh-Min)	6318.6	6330.7	5825.4	6108.9	1787.9	1787.8	1841.3	1865.3	6444.5	6657.5	866.0	852.4
Delay (Sec/Veh)	96.6	96.1	78.8	82.6	24.9	24.9	26.7	27.0	84.2	87.1	16.9	16.7

Table 10, Continued.

	W/Out	With	W/Out	With	W/Out	With	W/Out	With	W/Out	With	W/Out	With
West Bound	5 - 6		6 - 7		7 - 8		8 - 9		9 - 10		Total	
Veh-Trips	1324	1329	634	629	657	652	640	633	704	702		
Delay (Veh-Min)	200.0	207.7	233.2	239.9	160.4	158.8	215.4	198.9	162.5	138.9		
Delay (Sec/Veh)	9.1	9.4	22.1	22.9	14.6	14.6	20.2	18.9	13.8	11.9	418.5	409.0
East Bound	7 - 6		8 - 7		9 - 8		10 - 9		32 - 10			
Veh-Trips	641	641	685	685	714	715	592	592	526	526		
Delay (Veh-Min)	429.8	410.8	103.6	102.1	190.0	194.0	107.2	109.1	50.6	49.6		
Delay (Sec/Veh)	40.2	38.5	9.1	8.9	16.0	16.3	10.9	11.1	5.8	5.7	305.0	306.3
North Bound	24 - 6		25 - 7		26 - 8		28 - 9		30 - 10			
Veh-Trips	786	786	69	69	52	52	435	435	152	152		
Delay (Veh-Min)	141.8	143.3	19.0	19.3	15.6	16.4	139.9	144.7	32.9	32.8		
Delay (Sec/Veh)	10.8	10.9	16.6	16.8	18.0	18.9	19.3	20.0	13.0	13.0		
South Bound	-		-		27 - 8		29 - 9		31 - 10			
Veh-Trips					62	62	138	138	78	78		
Delay (Veh-Min)					22.2	22.0	43.3	43.8	27.8	28.3		
Delay (Sec/Veh)					21.5	21.3	18.8	19.0	21.4	21.8		
Over-All	Intersection 6		Intersection 7		Intersection 8		Intersection 9		Intersection 10		Network-Wide	
Veh-Trips	2751	2756	1388	1383	1485	1481	1805	1798	1460	1458	33355	33360
Delay (Veh-Min)	771.6	761.8	355.8	361.3	388.2	391.2	505.8	496.5	273.8	249.6	25379.	25863.
Delay (Sec/Veh)	16.8	16.6	15.4	15.8	15.7	15.8	16.8	16.6	11.3	10.3	45.7	46.5

Table 11: Case 2 Total Link Statistics With and Without Preemption.

	W/Out.	With	W/Out	With	W/Out	With	W/Out	With	W/Out	With	W/Out.	With
West Bound	33 - 11		11 - 1		1 - 2		2 - 3		3 - 4		4 - 5	
Veh-Trips	1214	1222	1357	1364	1729	1741	1520	1540	1654	1657	1419	1403
Delay (Veh-Min)	2539.4	2533.7	1878.1	1758.2	615.6	607.3	392.3	426.2	2442.2	2712.3	565.6	568.9
Delay (Sec/Veh)	115.7	124.4	83.6	77.2	21.7	20.9	15.8	16.6	88.6	98.2	23.2	24.3
East Bound	1 - 11		2 - 1		3 - 2		4 - 3		5 - 4		6 - 5	
Veh-Trips	1278	1273	1566	1578	2229	2239	1671	1684	1353	1358	1405	1403
Delay (Veh-Min)	2155.4	2366.1	1306.2	1416.5	1102.4	1040.9	857.4	871.8	1573.0	1586.4	228.9	219.9
Delay (Sec/Veh)	101.2	111.5	50.0	53.9	29.7	27.9	30.8	31.1	69.8	70.1	9.8	9.4
North Bound	16 - 11		13 - 1		18 - 2		20 - 3		15 - 4		22 - 5	
Veh-Trips	549	549	836	836	131	130	468	470	686	686	164	164
Delay (Veh-Min)	449.6	449.0	486.8	478.5	26.0	27.8	425.5	393.2	760.5	760.3	50.8	51.3
Delay (Sec/Veh)	49.1	49.1	34.9	34.3	11.9	12.8	54.6	50.2	66.5	66.5	18.6	18.8
South Bound	17 - 11		12 - 1		19 - 2		21 - 3		14 - 4		23 - 5	
Veh-Trips	885	885	675	675	212	212	473	472	899	899	93	93
Delay (Veh-Min)	1174.2	1188.6	2154.3	2155.0	43.9	42.3	166.1	169.8	1668.8	1671.8	29.8	27.0
Delay (Sec/Veh)	79.6	80.6	191.4	191.6	12.0	12.0	21.6	21.6	111.2	111.6	19.1	17.4
Over-all	Intersection 11		Intersection 1		Intersection 2		Intersection 3		Intersection 4		Intersection 5	
Veh-Trips	3926	3929	4434	4453	4301	4322	4132	4166	4592	4600	3081	3063
Delay (Veh-Min)	6318.6	6537.4	5825.4	5808.2	1787.9	1718.3	1841.3	1861.0	6444.5	6730.8	866.0	867.1
Delay (Sec/Veh)	96.6	99.8	78.8	78.3	24.9	23.9	26.7	26.8	84.2	87.8	16.9	17.0

Table 11, Continued.

	W/Out	With	W/Out	With	W/Out	With	W/Out	With	W/Out	With	W/Out	With
West Bound	5 - 6		6 - 7		7 - 8		8 - 9		9 - 10		Total	
Veh-Trips	1324	1329	634	623	657	641	640	626	704	690		
Delay (Veh-Min)	200.0	207.8	233.2	222.3	160.4	157.7	215.4	201.3	162.5	139.9		
Delay (Sec/Veh)	9.1	9.4	22.1	21.4	14.6	14.8	20.2	19.3	13.8	12.2	418.5	416.6
East Bound	7 - 6		8 - 7		9 - 8		10 - 9		32 - 10			
Veh-Trips	641	641	685	685	714	715	592	592	526	526		
Delay (Veh-Min)	429.8	411.6	103.6	104.3	190.0	192.5	107.2	109.1	50.6	49.6		
Delay (Sec/Veh)	40.2	38.5	9.1	9.1	16.0	16.2	10.9	11.1	5.8	5.7	305.0	310.8
North Bound	24 - 6		25 - 7		26 - 8		28 - 9		30 - 10			
Veh-Trips	786	786	69	69	52	52	435	435	152	152		
Delay (Veh-Min)	141.8	145.7	19.0	19.1	15.6	16.4	139.9	140.5	32.9	32.4		
Delay (Sec/Veh)	10.8	11.1	16.6	16.6	18.0	18.9	19.3	19.4	13.0	12.8		
South Bound	-		-		27 - 8		29 - 9		31 - 10			
Veh-Trips					62	62	138	138	78	78		
Delay (Veh-Min)					22.2	22.1	43.3	43.5	27.8	28.4		
Delay (Sec/Veh)					21.5	21.4	18.8	18.9	21.4	21.8		
Over-All	Intersection 6		Intersection 7		Intersection 8		Intersection 9		Intersection 10		Network-Wide	
Veh-Trips	2751	2756	1388	1377	1485	1470	1805	1791	1460	1446	33355	33373
Delay (Veh-Min)	771.6	765.1	355.8	345.7	388.2	388.7	505.8	494.4	273.8	250.3	25379.	25767.
Delay (Sec/Veh)	16.8	16.7	15.4	15.1	15.7	15.9	16.8	16.6	11.3	10.4	45.7	46.3

Table 12: Case 3 Total Link Statistics With and Without Preemption.

	W/Out.	With	W/Out	With	W/Out	With	W/Out	With	W/Out	With	W/Out.	With
West Bound	33 - 11		11 - 1		1 - 2		2 - 3		3 - 4		4 - 5	
Veh-Trips	931	963	1039	1052	1295	1302	1140	1153	1223	1228	1022	1021
Delay (Veh-Min)	1795.4	1075.0	1448.3	1528.8	468.2	468.8	299.7	296.8	1743.4	2012.2	395.3	387.7
Delay (Sec/Veh)	115.7	67.0	83.6	87.2	21.7	21.6	15.8	15.4	85.5	98.3	23.2	22.8
East Bound	1 - 11		2 - 1		3 - 2		4 - 3		5 - 4		6 - 5	
Veh-Trips	957	911	1181	1189	1656	1646	1243	1238	1010	1015	1032	1034
Delay (Veh-Min)	1625.4	2224.4	815.0	883.7	780.5	787.8	620.9	654.0	1142.7	1120.2	167.1	159.5
Delay (Sec/Veh)	101.9	146.5	41.4	44.6	28.3	28.7	30.0	31.7	67.9	66.2	9.7	9.3
North Bound	16 - 11		13 - 1		18 - 2		20 - 3		15 - 4		22 - 5	
Veh-Trips	404	402	626	626	99	99	352	342	515	515	123	123
Delay (Veh-Min)	325.7	399.7	376.8	372.8	19.1	19.2	342.8	318.5	597.6	597.3	36.7	36.9
Delay (Sec/Veh)	48.4	59.7	36.1	35.7	11.6	11.7	55.4	55.9	69.6	69.6	17.9	18.0
South Bound	17 - 11		12 - 1		19 - 2		21 - 3		14 - 4		23 - 5	
Veh-Trips	648	632	502	502	159	158	355	355	671	671	69	69
Delay (Veh-Min)	898.7	1119.2	1490.1	1489.7	31.8	31.7	125.5	131.2	1150.0	1147.9	21.1	21.1
Delay (Sec/Veh)	83.2	145.1	178.1	178.1	12.0	12.0	21.2	22.2	102.8	102.6	18.3	18.3
Over-all	Intersection 11		Intersection 1		Intersection 2		Intersection 3		Intersection 4		Intersection 5	
Veh-Trips	2940	2908	3348	3369	3209	3205	3090	3088	3419	3429	2246	2247
Delay (Veh-Min)	4645.2	4818.3	4130.2	4275.0	1299.6	1307.5	1388.9	1400.5	4633.7	4877.6	620.2	605.2
Delay (Sec/Veh)	94.8	99.4	74.0	76.1	24.3	24.5	27.0	27.2	81.3	85.3	16.6	16.2

Table 12, Continued.

	W/Out	With	W/Out	With	W/Out	With	W/Out	With	W/Out	With	W/Out	With
West Bound	5 - 6		6 - 7		7 - 8		8 - 9		9 - 10		Total	
Veh-Trips	957	960	435	456	460	477	451	468	497	519		
Delay (Veh-Min)	143.5	144.6	159.5	147.5	111.2	110.9	144.3	136.8	112.9	108.9		
Delay (Sec/Veh)	9.0	9.0	22.0	19.4	14.5	13.9	19.2	17.5	13.6	12.6	418.5	380.2
East Bound	7 - 6		8 - 7		9 - 8		10 - 9		32 - 10			
Veh-Trips	463	466	504	505	530	530	444	443	395	393		
Delay (Veh-Min)	306.8	293.6	77.2	73.6	142.4	141.2	82.4	80.5	37.3	35.1		
Delay (Sec/Veh)	39.8	37.8	9.2	8.7	16.1	16.0	11.1	10.9	5.7	5.4	305.0	330.5
North Bound	24 - 6		25 - 7		26 - 8		28 - 9		30 - 10			
Veh-Trips	589	589	52	52	39	39	326	321	114	114		
Delay (Veh-Min)	106.7	107.8	14.8	14.7	12.0	12.0	106.5	111.8	23.7	23.8		
Delay (Sec/Veh)	10.9	11.0	17.1	17.0	18.4	18.4	19.6	20.9	12.5	12.5		
South Bound	-		-		27 - 8		29 - 9		31 - 10			
Veh-Trips					46	46	103	103	58	58		
Delay (Veh-Min)					17.8	17.6	32.1	33.8	19.9	19.5		
Delay (Sec/Veh)					23.2	23.0	18.7	19.7	20.6	20.2		
Over-All	Intersection 6		Intersection 7		Intersection 8		Intersection 9		Intersection 10		Network-Wide	
Veh-Trips	2009	2015	991	1013	1075	1092	1324	1335	1062	1084	24713	24785
Delay (Veh-Min)	557.0	546.0	251.5	235.8	283.4	281.6	365.3	362.9	193.8	187.3	18368.	18898.
Delay (Sec/Veh)	16.6	16.3	15.2	14.0	15.8	15.5	16.6	16.3	10.9	10.4	44.6	45.7

Table 13: Case 4 Total Link Statistics With and Without Preemption.

	W/Out.	With	W/Out	With	W/Out	With	W/Out	With	W/Out	With	W/Out.	With
West Bound	33 - 11		11 - 1		1 - 2		2 - 3		3 - 4		4 - 5	
Veh-Trips	931	916	1039	1025	1295	1283	1140	1130	1223	1214	1022	1016
Delay (Veh-Min)	1795.4	2062	1448.3	1382.2	468.2	461.7	299.7	272.9	1743.4	1675.4	395.3	429.0
Delay (Sec/Veh)	115.7	135.1	83.6	80.9	21.7	21.6	15.8	14.5	85.5	82.8	23.2	25.3
East Bound	1 - 11		2 - 1		3 - 2		4 - 3		5 - 4		6 - 5	
Veh-Trips	957	903	1181	1185	1656	1656	1243	1237	1010	1009	1032	1029
Delay (Veh-Min)	1625.4	2205.3	815.0	997.1	780.5	796.4	620.9	597.2	1142.7	1129.3	167.1	160.1
Delay (Sec/Veh)	101.9	146.5	41.4	50.5	28.3	28.9	30.0	29.0	67.9	67.2	9.7	9.3
North Bound	16 - 11		13 - 1		18 - 2		20 - 3		15 - 4		22 - 5	
Veh-Trips	404	403	626	627	99	98	352	352	515	515	123	123
Delay (Veh-Min)	325.7	406.4	376.8	372.6	19.1	19.3	324.8	287.5	597.6	597.5	36.7	36.9
Delay (Sec/Veh)	48.4	60.5	36.1	35.7	11.6	11.8	55.4	49.0	69.6	69.6	17.9	18.0
South Bound	17 - 11		12 - 1		19 - 2		21 - 3		14 - 4		23 - 5	
Veh-Trips	648	651	502	502	159	159	355	356	671	671	69	69
Delay (Veh-Min)	898.7	1090.2	1490.1	1489.2	31.8	34.1	125.5	124.4	1150.0	1149	21.1	22.1
Delay (Sec/Veh)	83.2	100.5	178.1	178.0	12.0	12.9	21.2	21.0	102.8	102.8	18.3	19.2
Over-all	Intersection 11		Intersection 1		Intersection 2		Intersection 3		Intersection 4		Intersection 5	
Veh-Trips	2940	2873	3348	3339	3209	3196	3090	3075	3419	3409	2246	2237
Delay (Veh-Min)	4645.2	5763.4	4130.2	4240.7	1299.6	1311.5	1370.9	1282.0	4633.7	4550.0	620.2	648.1
Delay (Sec/Veh)	94.8	120.4	74.0	76.2	24.3	24.6	26.6	25.0	81.3	80.1	16.6	17.4

Table 13, Continued.

	W/Out	With	W/Out	With	W/Out	With	W/Out	With	W/Out	With	W/Out	With
West Bound	5 - 6		6 - 7		7 - 8		8 - 9		9 - 10		Total	
Veh-Trips	957	961	435	448	460	469	451	459	497	508		
Delay (Veh-Min)	143.5	148.8	159.5	151.6	111.2	109.1	144.3	148.3	112.9	108.5		
Delay (Sec/Veh)	9.0	9.3	22.0	20.3	14.5	14.0	19.2	19.4	13.6	12.8	418.5	421.7
East Bound	7 - 6		8 - 7		9 - 8		10 - 9		32 - 10			
Veh-Trips	463	461	504	503	530	530	444	393	395	393		
Delay (Veh-Min)	306.8	293.1	77.2	74.0	142.4	141.5	82.4	81.7	37.3	36.1		
Delay (Sec/Veh)	39.8	38.1	9.2	8.8	16.1	16.0	11.1	11.0	5.7	5.5	305.0	343.3
North Bound	24 - 6		25 - 7		26 - 8		28 - 9		30 - 10			
Veh-Trips	589	589	52	52	39	39	326	326	114	114		
Delay (Veh-Min)	106.7	108.2	14.8	14.9	12.0	12.7	106.5	107.1	23.7	23.6		
Delay (Sec/Veh)	10.9	11.0	17.1	17.2	18.4	19.6	19.6	19.7	12.5	12.4		
South Bound	-		-		27 - 8		29 - 9		31 - 10			
Veh-Trips					46	46	103	103	58	58		
Delay (Veh-Min)					17.8	16.6	32.1	31.8	19.9	19.9		
Delay (Sec/Veh)					23.2	23.0	18.7	18.5	20.6	20.6		
Over-All	Intersection 6		Intersection 7		Intersection 8		Intersection 9		Intersection 10		Network-Wide	
Veh-Trips	2009	2011	991	1003	1075	1084	1324	1332	1062	1073	24713	24632
Delay (Veh-Min)	557.0	550.1	251.5	240.5	283.4	280.9	365.3	368.9	193.8	188.1	18350.	19425.
Delay (Sec/Veh)	16.6	16.4	15.2	14.4	15.8	15.5	16.6	16.6	10.9	10.5	44.6	47.3

As far as average delay is concerned, most intersections experienced only minor differences over the 45-minute period. However, there are three key intersections that contributed significantly to the overall network statistics, because of their high volume and delay. These intersections were Golfside (intersection 11), Carpenter (intersection 1), and Huron Parkway (intersection 4). Although, no preemption was provided at Carpenter and Huron Parkway because their signals are actuated, their statistics vary significantly between no preemption and preemption cases.

Signal preemption had, in general, an adverse effect on both the Huron Parkway and Carpenter intersections. This might be due to preemption at an upstream node, when more vehicles were released into the link from the main street than the intersection could handle. Due to this flux of vehicles, progression was disrupted by the extra vehicle arrival time and volume. As a result, some of these vehicles could not clear the intersection in the green time, thus causing extra delay. Since these locations were already near saturation and the cycle length runs longer than two minutes, delay was significant at these locations. Compensation and skip phase preemption plans proved to be poor alternatives for traffic at Golfside Street, while the green extension / red truncation plan had no adverse effect in the long run. Network-wide overall statistics under preemption were slightly worse than under no preemption, and case 4 was the least favorable plan as shown in Table 14.

The average total delay experienced by only those vehicles travelling along the corridor in an east-west direction was also examined. For every preemption case, the average delay (in seconds per vehicle) at each link for east-bound and west-bound traffic was added and compared with average delay without preemption, as shown Table 14. These figures indicate the total average delay that vehicles travelling from the first entrance in the corridor to the last exit (east or west) would experience.

Table 14: Average Delay Over The 45-Minute Simulation Period

	Base Case	Case 1	Case 2	Case 3	Case4
W. Bound	418.5	409.0	416.6	380.2	421.1
E. Bound	305.0	306.3	310.8	330.5	343.3
Total Delay	44.6	46.5	46.3	45.7	47.3

Note: The W. Bound and E. Bound delay represent delay along the entry route, while total delay is delay per intersection.

The delay was higher in the off-peak direction (west bound) for both the base case and the preemption cases because progression on Washtenaw Avenue in the evening rush hour favors east bound traffic. Vehicles travelling west bound benefitted from preemption, since the green time was extended or advanced, and thus their travel delay was reduced, as in cases 1 and 3. However, compensation for phases prematurely cut or skipped increased travel time in both direction (case 4). Since main street traffic volume is relatively heavy, this increase in delay outweighed the delay reduction gained during preemption (case 4).

East bound through vehicles were always disadvantaged by preemption regardless of the plan used. The traffic volume in that direction is higher than west bound volume (Appendix A), and as a result each time preemption was awarded their progression was disturbed and delay was increased at the downstream node. It appears that for the heavy traffic direction progression is crucial and preemption increases travel time. The east bound through traffic experienced the highest delay under the skip phase preemption plans, since this plan involves the greatest signal disturbance.

The total network delay presented in Tables 10, 11, 12, and 13 includes vehicles travelling in the east, west, north, and south directions. The network-wide delay under preemption was higher than without preemption for all cases, because the network without preemption was optimized and preemption deviates the optimum.

5.4 Cumulative Network Measures of Effectiveness (MOEs)

The microscopic traffic behavior for every link and at every cycle has been presented and discussed in the previous sections. In this section, the network cumulative MOEs, overall vehicle statistics, person MOEs, bus route MOEs, and total bus link MOEs, for all six preemption cases are discussed and compared with the basic no preemption case, for the total simulation time.

The first bus enters the network (from both directions) approximately 8 minutes after the start of the simulation. Therefore, a significant portion of simulation time (8/45) has been processed before the first opportunity for bus preemption. Also, it was observed that network delay increases at the beginning of simulation as the network becomes loaded with vehicles. Therefore, it was decided that it is more reasonable to collect statistics after the network reaches steady state condition. It was determined that at time 5:23 the network reaches steady state with two buses from each direction in the network and constant delays.

Table 15 shows the cumulative network statistics for the steady state period (between time 5:23 and 5:45). As defined earlier, vehicle trips are the number of vehicles that have

Table 15: Cumulative Network Statistics; With and Without Preemption.

	Veh-Trips	Delay Veh-Hours	Delay Min/Veh-Trips
No Preemption	3469	163.43	2.83
Preemption Case 1	3426	165.8	2.90
Preemption Case 2	3435	165.7	2.89
Preemption Case 3	3408	170.57	3.00
Preemption Case 4	3398	178.45	3.15
Preemption Case 5	3424	167.83	2.94
Preemption Case 6	3449	170.65	2.97

completed their trips and exited the network from any entry point to any exit point (not including vehicles that are still in the network). It is clear that the no preemption option is the best plan (minimum delay) for overall system delay. This is no surprise, since the signal timing has been optimized and any signal preemption causes the signal timing to deviate from this optimum. Preemption cases 1 and 2 (green extension / red truncation, with and without compensation) are the options that produce the lowest increase in delay to the system (2.89 and 2.90 min / veh-trip), since they involve the minimum disturbance to the system. The skip phase plans create the highest system delay (3.00 to 3.15 min/veh-trip). NETSIM assumes an average occupancy of 1.3 persons per automobile and 25 persons per bus. The bus occupancy figures were compared with actual bus ridership provided by the Ann Arbor Transit Authority, and the number was close. Therefore, the NETSIM occupancy default values were used to assess the impact of BPS on person MOEs, in terms of number of trips, miles travelled, travel time, and total delay time, as shown in Table 16.

Table 16: Cumulative NETSIM Person Measures of Effectiveness; Before and After Preemption.

	Person Trips	Person Mile	Travel Time (Person-Min)	Delay (Person-Min)	Avge. Delay Sec /trip
No Preemption	14921	5255	20264	12042	48.4
Preemption Case 1	14911	5227	20350	12174	49.0
Preemption Case 2	14918	5232	20409	12221	49.2
Preemption Case 3	16662	5659	22758	13769	49.6
Preemption Case 4	16506	5557	23230	14398	52.3
Preemption Case 5	14974	5267	20624	12383	49.6
Preemption Case 6	14897	5239	20757	12561	50.6

NETSIM provides person statistics on a link-by-link basis (no network statistics). To assess the cumulative network person MOEs, the link statistics were summed for the steady state period (between time 5:23 and 5:45). The average person delay was calculated as the total person delay divided by the number of person trips. Although the average vehicle delay is indicative of the average person delay, the way each one was measured is different. The average network vehicle delay is measured for only vehicles that have exited the network, while the average person delay is calculated based on summing the delay at each link, and thus includes the delay to persons still in the network at 5:45. The average person delay ranges from 48.4 sec/trip (for the no preemption case) to 52.3 sec/trip for case 4 preemption. Person delay measures followed the same trend as the vehicle delay measures; the no preemption case had the lowest delay and the skip phase with compensation case had the highest delay. Bus headways were not small enough to have a major influence on the network person statistics.

Table 17: Cumulative Network-Wide Bus Statistics; With and Without Preemption.

	Route	Bus Trips	Total Travel-Time (Bus-Min)	Mean Travel-Time (Sec/Bus)	Person Trips	Person Travel-Time (Min)
Original Conditions	1	2	68.1	1361.6	50	1702.9
	2	3	60.7	1214.2	75	1518.3
Preemption Case 1	1	2	64.4	1361.8	50	1609.2
	2	3	60.5	1208.1	75	1511.3
Preemption Case 2	1	3	66.4	1326.3	75	1659.2
	2	3	60.4	1208.0	75	1510.8
Preemption Case 3	1	3	69.8	1296.1	75	1746.3
	2	3	60.6	1210.9	75	1515.0
Preemption Case 4	1	3	64.4	1288.0	75	1610.8
	2	3	60.7	1213.5	75	1517.9
Preemption Case 5	1	3	69.9	1301.4	75	1747.1
	2	3	59.3	1184.0	75	1481.3
Preemption Case 6	1	2	68.7	1342.3	50	1716.3
	2	3	61.8	1234.6	75	1544.6

Both route based and link based bus statistics were collected. NETSIM provides cumulative network-wide bus statistics per route. There were two bus routes in the network, both using Washtenaw Avenue; route 1 (west bound) and route 2 (east bound). NETSIM statistics are provided only for buses that exited the network (no consideration for buses in the system); therefore, it was necessary to collect bus statistics on a link basis to monitor the bus progression within the network.

As expected, skip phase preemption produces lower bus delays than the other plans, since having the bus pass through a green signal is almost guaranteed. However, when a signal phase is skipped, extra vehicles along the main street also take advantage of the extra green time. These vehicles accumulate at the next downstream link. As a result, these vehicles may form a long queue at the next down stream intersection and may not be able to clear the link within the fixed green time. Therefore, a bus arriving at that link, which might have originally faced a green light, may not be able to pass within the fixed green signal, especially when preemption is not allowed at the particular time or location. This phenomenon was observed on the graphical display, with the result that despite the provision of BPS, bus mean travel time was only slightly lower than without preemption. In some cases, travel time was equal to the no preemption case (route 1 of case 1, and route 2 of case 4) or even slightly longer (route 2 of case 6).

The total bus link statistics (bus trips, travel time, and delay time) were summed to form Table 18. The average bus delay was then calculated as: average delay (seconds per bus-trips) = total delay * 60 / bus-trips. The total bus-link-trips shows how far the bus has travelled along the network. In the 45-minute simulation time, buses travelled the greatest

Table 18: Total NETSIM Bus LINK Statistics; With and Without Preemption.

	Total Links Bus-Trips	Travel Time (Min)	Delay Time (Min)	Average Delay (sec/B-Trip)
No Preemption	65	127.4	86.2	79.6
Preemption Case 1	64	124.9	84.9	79.6
Preemption Case 2	65	126.7	85.5	78.9
Preemption Case 3	67	130.4	88.3	79.1
Preemption Case 4	66	123.0	83.7	76.1
Preemption Case 5	67	129.3	86.6	77.6
Preemption Case 6	65	130.7	89.8	82.9

distance (67 bus-link trips) during preemption cases 3 and 5, and travelled the least during preemption case 2 (64 bus-link trips). However, the lowest bus delay occurred during preemption cases 4 and 5.

Preemption case 5 (selective plans) has reasonably good MOEs for buses, persons, and overall vehicles. That is expected since these selective plans (case 5) were chosen so that the adverse effects of preemption (in terms of excessive delays and long queues) were minimized. Although case 5 puts a limit on certain kinds of preemptions at certain locations, the bus gained more benefits than in any other plan (except case 4). That is because when excessive delays and long queues were permitted to occur, as a result of BPS, the whole network was disadvantaged including the buses. If a second bus arrived at the same intersection from the other direction the bus would have a high chance of experiencing extra delays and a lesser chance of passing the green light, without a need to stop.

Chapter 6

The Dynamics of BPS

The impact of different preemption strategies on Washtenaw Avenue under the existing traffic conditions was discussed in the previous chapter. In this chapter, the effectiveness of BPS under changing traffic conditions is analyzed. The sensitivity of BPS to traffic volume, main street to cross street volume ratio, traffic mix (percentage of carpools), and randomness of vehicle generation was tested.

6.1 BPS Sensitivity to Volume

Traffic volume throughout the network was varied from 20 percent less than the original volume to 20 percent more, with a 10 percent incremental change. These different volume cases were tested with and without preemption, for a simulation period of 45 minutes. The case 5 preemption plan (selective preemptions) was applied. The results are shown in Tables 19, 20, 21, and 22. Also, the overall vehicle statistics and the total bus-trip-links statistics are shown in Figures 8 and 9, respectively.

Table 19 and Figure 8 show the network cumulative statistics with and without preemption. The overall traffic was better off without preemption because, as discussed earlier, preemption results in a deviation from the optimum signal settings. The adverse effects of preemption on overall vehicles MOEs at low traffic volume were less than the adverse effects at high traffic volume, because progression is very crucial at higher traffic volumes (as discussed in Chapter 6).

Table19: Cumulative Network Statistics; With and Without Preemption.

	Veh-Trips	Delay Veh-Hours	Delay Min/Veh-Trips
+20% Volume	3753	327.25	5.23
With Preemption	3750	327.06	5.23
+10% Volume	3619	243.17	4.03
With Preemption	3584	254.08	4.25
Base Volume	3469	163.43	2.83
With Preemption	3424	167.83	2.94
-10% Volume	3212	104.62	1.95
With Preemption	3194	106.15	1.98
-20% Volume	2800	82.03	1.76
With Preemption	2815	82.74	1.76

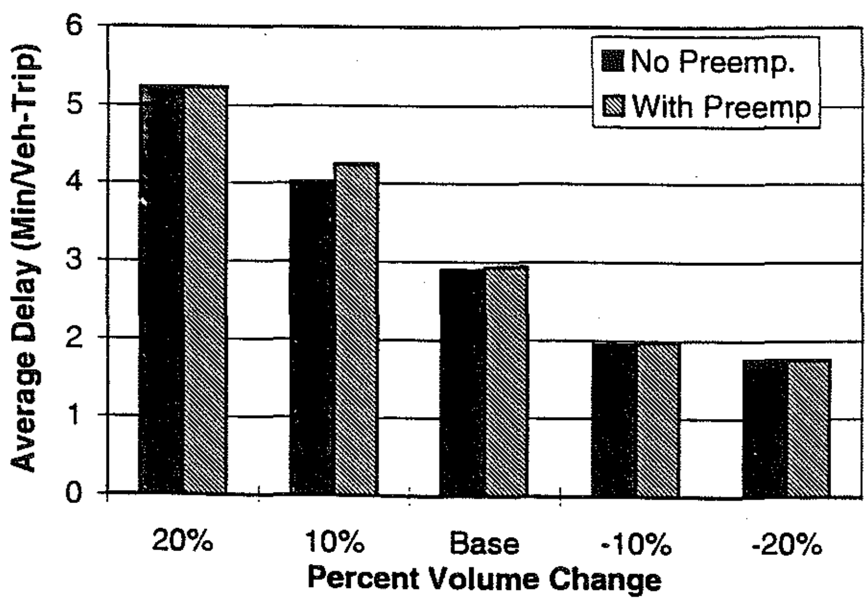


Figure 8: Network Average Delay Due to Volume Change

Table 20: Cumulative NETSIM Person Measures of Effectiveness; Before and After Preemption.

	Person Trips	Person Mile	Travel Time (Person-Min)	Delay (Person-Min)	Avge. Delay Sec / Person
+ 20% Volume	15877	5513	32519	23883	90.3
With Preemption	15793	5479	32309	23729	90.2
+ 10% Volume	17316	5813	28676	19430	67.3
With Preemption	19078	6199	31595	21605	67.9
Base Volume	14921	5255	20264	12042	48.4
With Preemption	14974	5267	20624	12383	49.6
- 10% Volume	13614	4809	15167	7629	33.6
With Preemption	13563	4787	15219	7733	34.2
- 20% Volume	12058	4243	12621	5975	29.7
With Preemption	12779	4274	12719	6021	28.3

At a very low traffic volume, deviation from the optimum was not as critical since the disadvantaged traffic (cross street traffic) is low. Furthermore, the main street traffic may gain some benefit during preemptions even though it may loose these benefits due to the loss of progression at the downstream intersection.

Under very high traffic volume, many intersections either reached saturation or became oversaturated. Although preemption might have provided some benefits for the main street through traffic, the same traffic would most likely be stopped at the downstream node since the links were already overloaded. Thus, any gains for through traffic during preemptions were most likely lost at the downstream intersection. The increased level of congestion is apparent in the recorded number of vehicle trips as the volume is increased in increments of 10 percent. When going from 20 to 10 percent below the base volume, the vehicle trips increased by 13 percent. The respective numbers for the remaining volume increases were 7, 5, and 5 percent, respectively.

As far as person measures are concerned (Table 20), preemption had little effect. However, at a very low volume rate (-20 percent) person delay under preemption was lower than no preemption. This is due to both the priority given to buses and to the fact that at low volume the bus passenger percentage in the traffic mix increases.

Bus statistics show that, generally, bus travel time was shorter and delay was less under preemption (Tables 21 and 22). The bus mean travel time was shorter under lighter traffic volume and buses travelled longer distances within the 45 minutes simulation period. Under heavier traffic volumes bus route 2 (east bound) benefitted from preemption, while this route did not benefit from lighter traffic volume. However, route 1 (west bound) generally benefitted from preemption. Except for a 10 percent increase in volume, the average total bus-link-trip delay time (Table 22 and Figure 9) was less under preemption. At low volumes, using preemption, buses could travel longer distances than at high volumes. Bus travel time and delay decreased with the decrease in traffic volumes. However, at very low volumes (-20%) the delay and travel time leveled off.

Table 21: Cumulative Network-Wide Bus Statistics; With and Without Preemption.

	Route	Bus Trips	Total Travel-Time (Bus-Min)	Mean Travel-Time (Sec/Bus)	Person Trips	Person Travel-Time (Min)
+ 20% Volume	1	2	66.4	1811.9	50	1660.8
	2	2	65.5	1396.2	50	1637.9
With Preemption	1	2	63.9	1753.3	50	1598.3
	2	2	62.8	1353.7	50	1570.8
+ 10% Volume	1	2	61.8	1529.2	50	1545.8
	2	2	59.3	1282.6	50	1481.3
With Preemption	1	2	62.2	1577.6	50	1555.4
	2	3	61.5	1231.1	75	1537.9
Base Case Volume	1	2	68.1	1384.3	50	1701.7
	2	3	59.2	1184.0	75	1480.4
With Preemption	1	3	69.9	1301.4	75	1747.1
	2	3	59.3	1184.0	75	1481.3
- 10% Volume	1	3	65.5	1308.6	75	1637.5
	2	3	57.0	1138.8	75	1423.8
With Preemption	1	3	62.4	1247.4	75	1560.8
	2	3	56.9	1137.6	75	1422.1
- 20% Volume	1	2	64.6	1315.8	50	1615.8
	2	3	56.9	1138.3	75	1422.5
With Preemption	1	3	63.3	1264.2	75	1581.3
	2	3	58.9	1264.2	75	1473.3

Table 22: Cumulative NETSIM Bus Statistics; With and Without Preemption.

	Total Bus-Link-Trips	Travel Time (Min)	Delay Time (Min)	Avge. Delay Sec / B-Trip
+ 20% Volume	57	131.9	97.8	102.9
With Preemption	57	126.8	92.7	97.6
+ 10% Volume	61	121.2	84.5	83.1
With Preemption	61	124.0	86.3	84.9
Base Case Volume	65	127.4	86.2	79.6
With Preemption	67	129.3	86.6	77.6
- 10% Volume	66	122.4	81.3	73.9
With Preemption	66	119.3	78.0	70.9
- 20% Volume	65	121.6	80.8	74.6
With Preemption	66	122.3	81.0	73.6

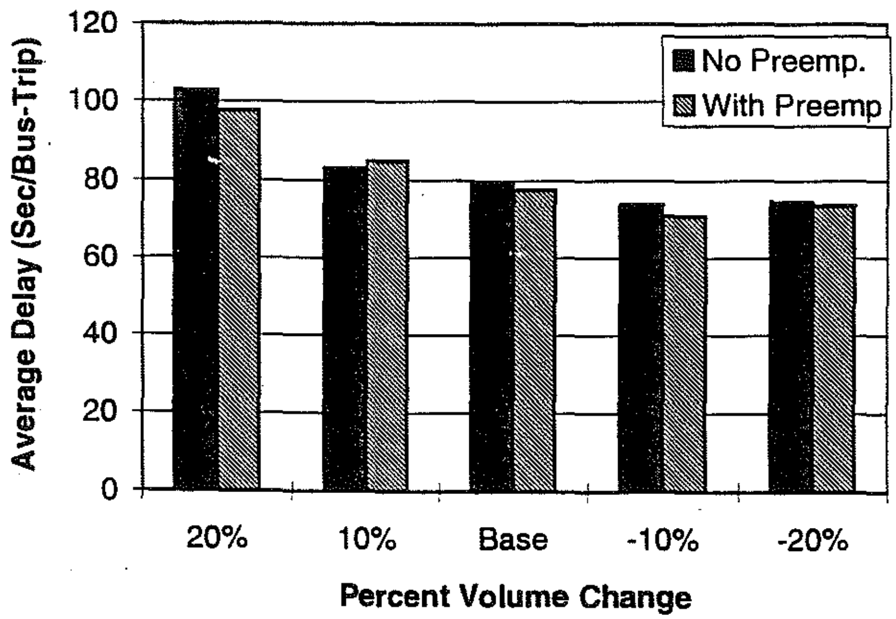


Figure 9: Total Link Bus Delay Due to Volume Change

6.2 BPS Sensitivity to Volume Ratio

In this test the volume and the main street to cross street volume ratios were varied to determine the sensitivity of BPS to these changes. In NETSIM, traffic volume is coded only at the entry nodes and not at each individual intersection. Thus, it was not possible to change link volumes by a constant increment for the whole network. However, changing main street and cross street volumes is feasible for a single intersection. In this test, BPS was simulated under different volume ratios for a typical two-phase signal at a two-lane (in each direction) isolated intersection. All preemption plans of green extension / red truncation, skip phase, and skip phase with compensation were tested.

Traffic volume ratios were selected to be 2:1, 3:1, and 5:1. It was determined (using common sense) that BPS for volume ratios less than 2:1 is not reasonable and for ratios higher than 5:1 will, most likely, reduce delay. Main street volume was chosen to range from 1000 vehicle per hour (VPH) to 2000 VPH, and the corresponding cross street traffic volume was calculated. The average turning percentage was set at 20 percent from the cross street and 7.5 percent from main the street. A five-minute bus headway was chosen for both directions, so that the effect of bus presence, and thus preemption, on the network overall statistics is not negligible.

The following volumes and ratios were used in this study:

Ratio	Symbol	Main / Cross Street Volume (VPH)
Upper 2:1	U2:1	1750 / 875
Middle 2:1	M2:1	1500 / 750
Lower 2:1	L2:1	1000 / 500

Upper 3:1	U3:1	2000 / 667
Middle 3:1	M3:1	1500 / 500
Lower 3:1	L3:1	1000 / 333
Upper 5:1	U5:1	2000 / 400
Middle 5:1	M5:1	1500 / 300
Lower 5:1	L5:1	1000 / 200

The reason that the main street volume for the upper 2:1 ratio was 1750 VPH instead of 2000 (as suggested earlier), is because under a two-phase signal and a 2:1 volume ratio the intersection was over saturated, and the queue continued to accumulate on both the main and cross street directions throughout the simulation. Thus, it was determined to reduce volumes to 1750 VPH: 875 VPH (2:1 ratio).

All nine volume cases were tested under no preemption, preemption (green extension / red truncation and skip phase) without compensation, and preemption with (skip phase) compensation, a total of twenty seven cases. For all 5:1 ratio cases, because their cross street green signal time was already at its minimum (10 seconds), the only preemption strategies were skip phases with and without compensation. A maximum simulation period of 55 minutes was achieved. Overall vehicle, person, and bus MOEs were evaluated. Also, overall intersection vehicle statistics for four cycles before and four cycles after preemption (including the preemption cycle) for different preemption plans were studied. The results are shown in Appendix F. Summary of these results are shown in Figures 10, 11, 12, 13, and 14.

6.2.1 BPS Overall Statistics

Figures 10 and 11 show the overall vehicle delay and the average person delay for high volume (main street volume of 1750 VPH or 2000 VPH), medium volume (main street volume of 1500 VPH), and low volume (main street volume of 1000 VPH) ratios. Vehicle delay generally increased with preemption. The adverse effects of preemption (in terms of delay) were very significant at the lower volume ratios (2:1), becoming insignificant at the upper volume ratio (5:1) and for low cross street volume.

The preemption with compensation plan was better for very low main to cross street volume ratios (2:1). Because of the high percentage of the cross street traffic, losing green time during preemption had a significant impact on delay. Compensating for this time loss is beneficial. However, compensation (for skipped phases) at very high volume ratios (5:1) added more delay to the intersection. In general, the 3:1 ratio is the border line, above which person and vehicle statistics favor preemption with no compensation, and below which preemption might not be favorable and, if it is provided, compensation would be warranted.

As far as bus statistics are concerned, they generally followed the same trends, as shown in Figures 12, 13, and 14. Bus travel time and delay reductions were relatively more significant at low volume ratios (2:1 and 3:1) and less significant at the higher volume ratio (5:1). At the high volume ratio, main street green time is naturally much longer than the cross street green time, and the bus has a better chance of facing a green light as it arrives at the intersection. Thus, the number of bus preemptions needed would be less than with lower volume ratios. Unlike the vehicle and person statistics, the cross street volume rate

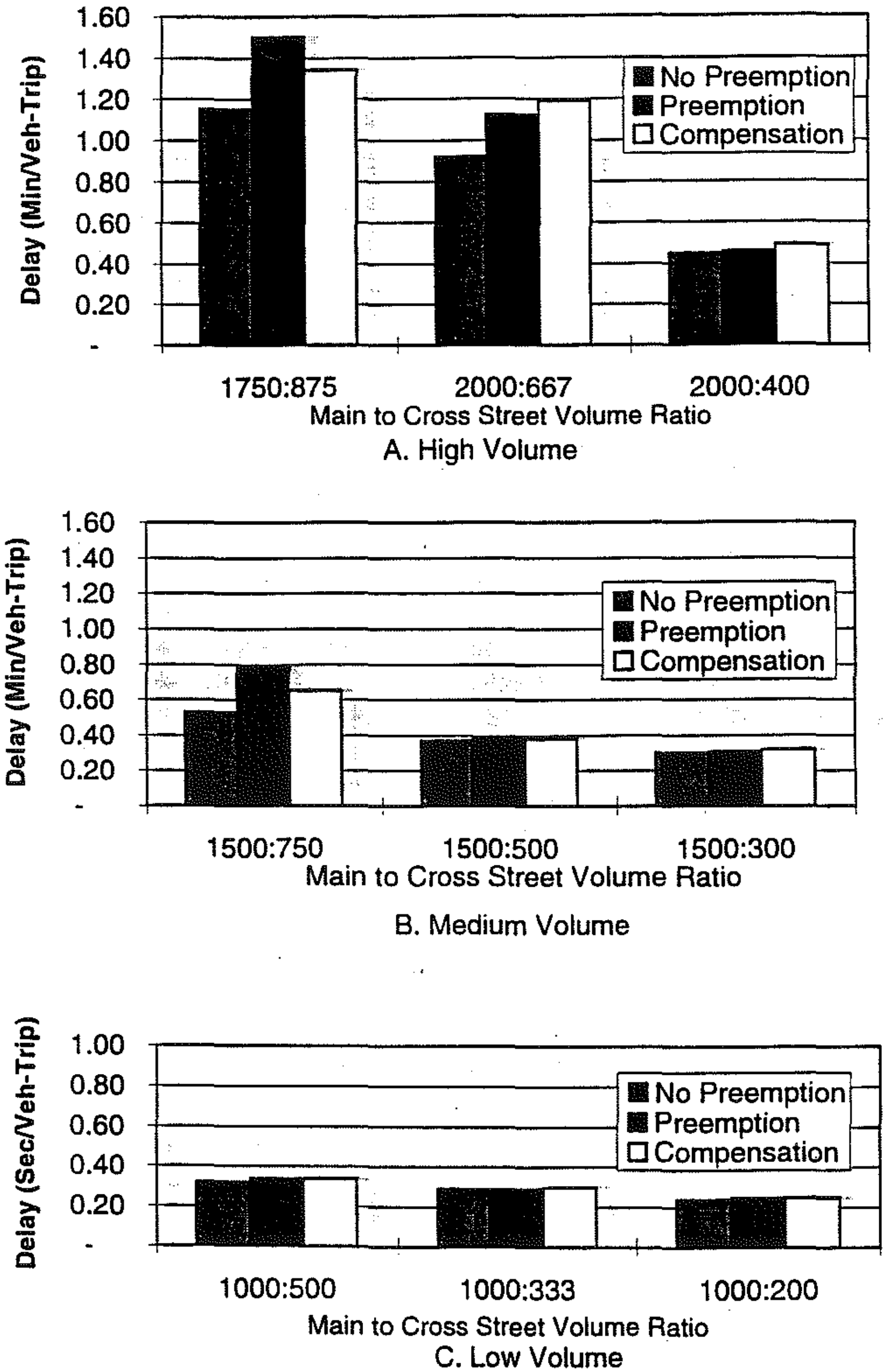
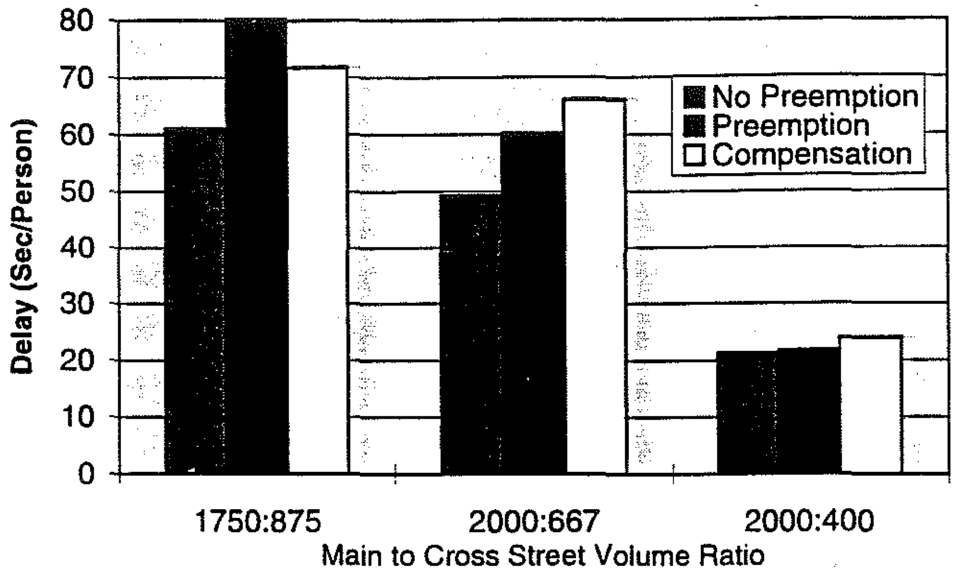
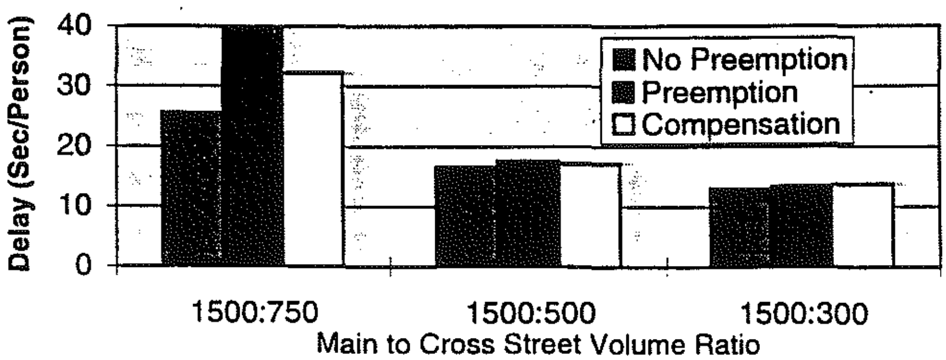


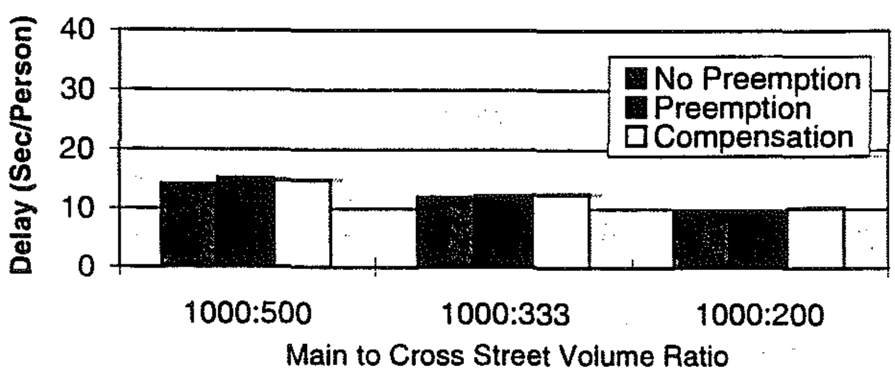
Figure 10: Network Average Vehicle Delay



A. High Volume

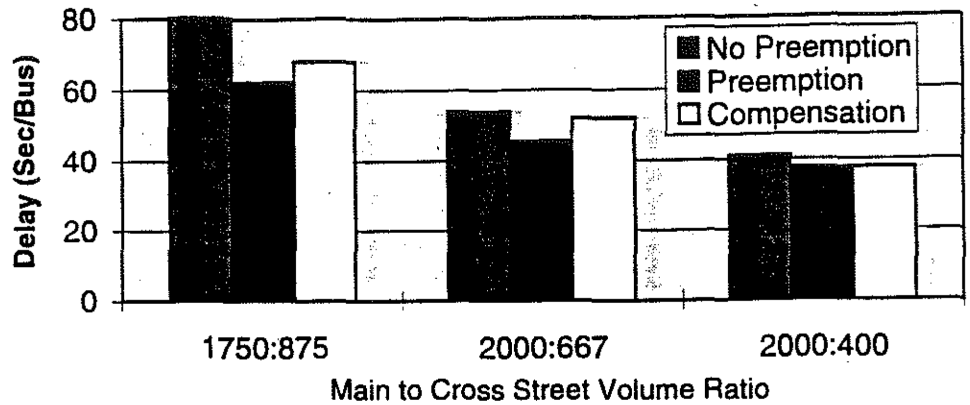


B. Medium Volume

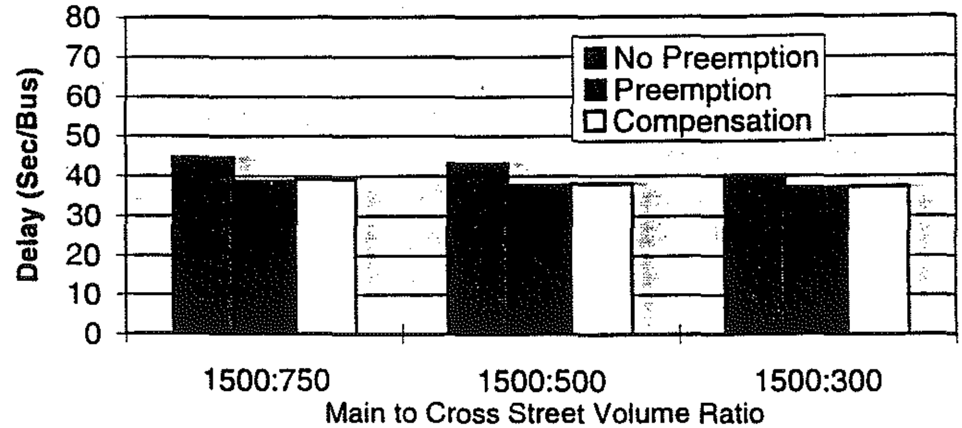


C. Low Volume

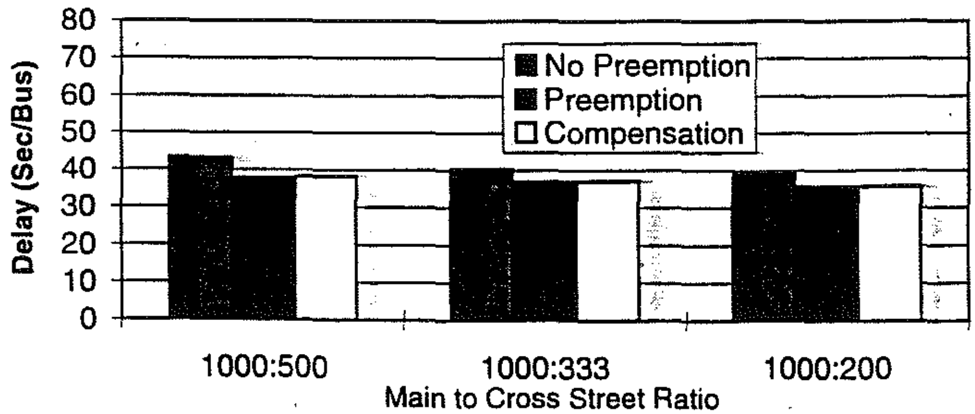
Figure 11: Person Average Link-Trip Delay



A. High Volume

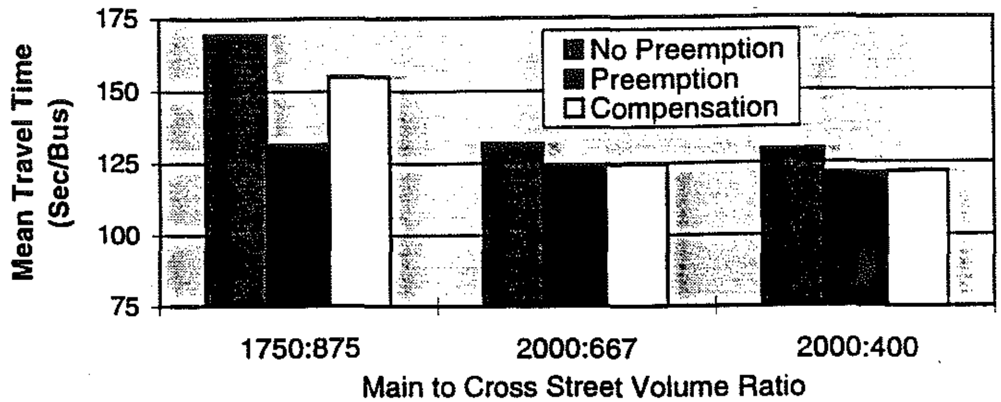


B. Medium Volume

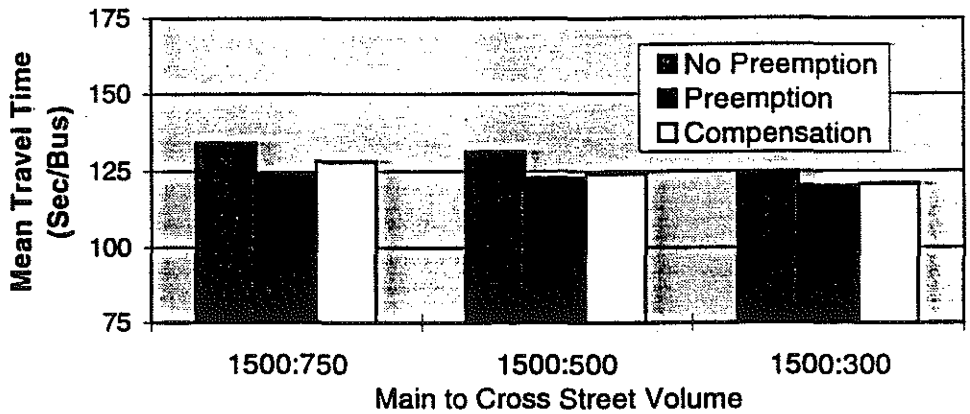


C. Low Volume

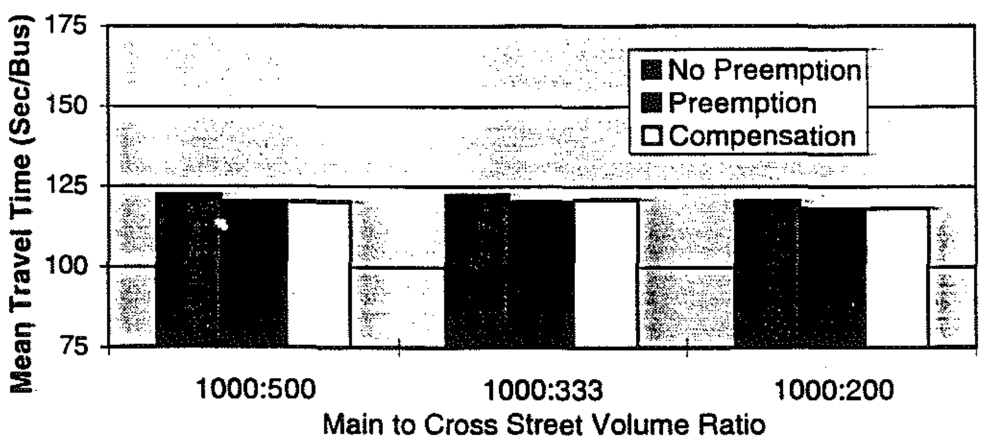
Figure 12: Average Total Bus-Link-Trip



A. High Volume

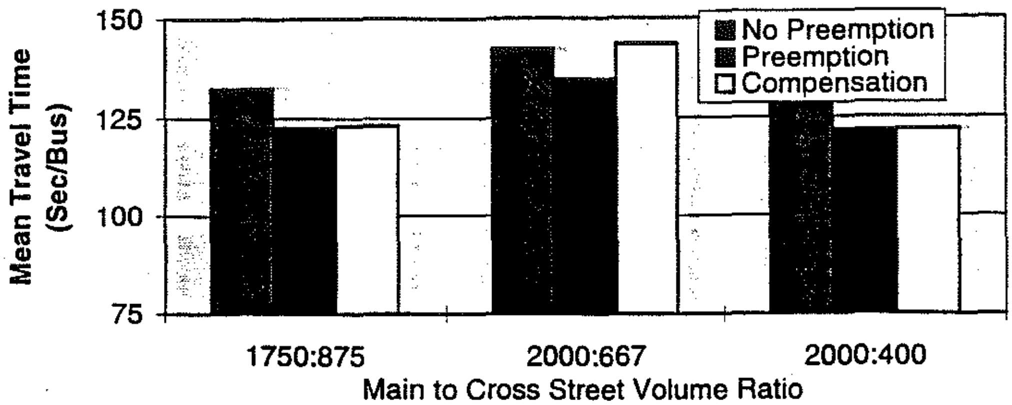


B. Medium Volume

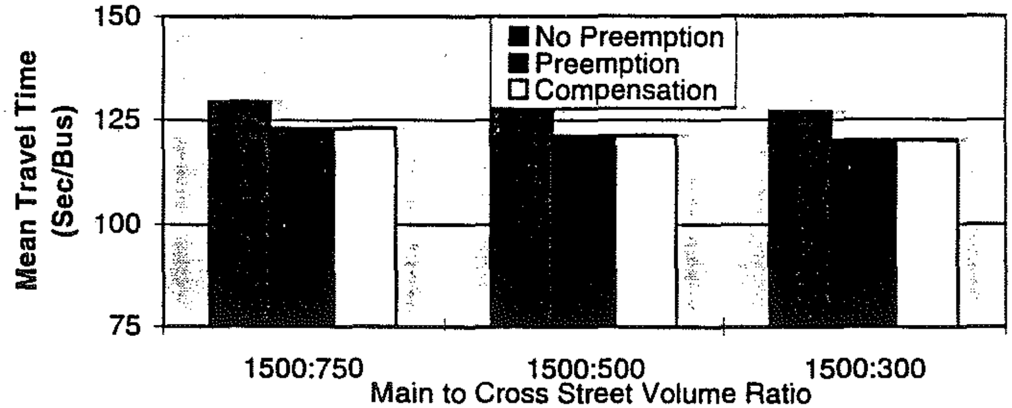


C. Low Volume

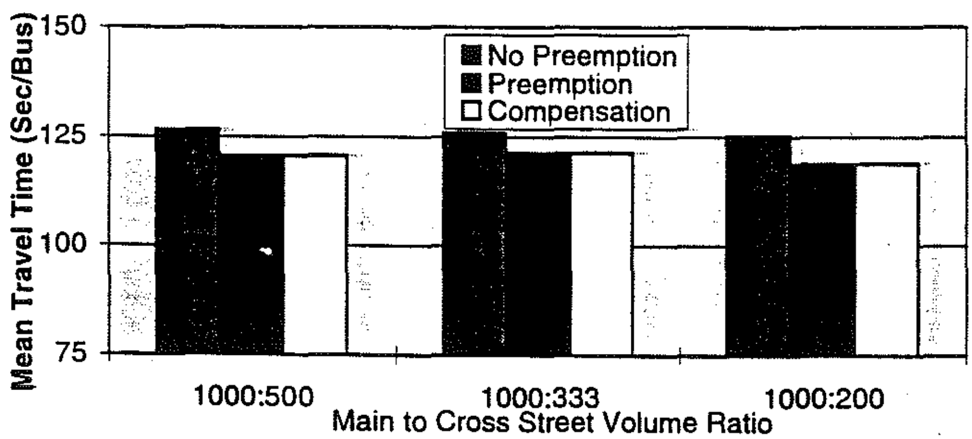
Figure 13: Bus Route 1 Mean Travel Time



A. High Volume



B. Medium Volume



C. Low Volume

Figure 14: Bus Route 2 Mean Travel Time

has no impact on bus statistics.

The bus average travel time and the average total bus-link delays under the compensating plan were higher than with no compensation for high traffic volume (main street volume larger than 1500) and low volume ratio (2:1 and 3:1). Using the compensation plan cuts some of the main street green time (the direction where the bus runs). As a result, main street high volume traffic became congested and long queues formed. As the next bus arrived at the intersection, it would experience a delay due to the delayed traffic and may have had to join the queue that was made longer by compensation. Since green phase timing is proportional to volume, low volume ratio would have a considerable cross street green time. When compensating, the main street green signal may be cut as much as the cross street green phase (if the phase was skipped). Compensation for the low volume ratio cases may increase delay for the main street traffic, and thus for the bus.

6.2.2 Before and After Analysis

For every preemption that took place, four cycles before preemption and four cycles after (including the preemption cycle) were considered. However, since bus headway is five minutes (random) and the cycle length is one minute, there was a good possibility of overlapping between two successive preemption before and after statistics. Therefore, to separate the effect of every preemption, only preemptions with no overlap were studied. As a result, four preemptions were selected for the analysis; two green extension / red truncation at around 5:13 and 5:24, and two skip phases at around 5:35 and 5:45. Overall vehicle statistics were calculated for the periods before and after preemption for each of the above four cases. For cases of 5:1 volume ratios the only possible preemption plan was skip phase, since cross street green time was already at the minimum (10 seconds).

Figures 15, 16, and 17 show a comparison between before and after overall intersection delay for the two preemption cases of each of the green extension / red truncation, the skip phase with no compensation, and the skip phase with compensation preemptions, respectively. Preemption #1 and preemption #2 in the graphs refer to the first and the second preemption of each. The detailed data is provided in Table F.6, Appendix F.

Figure 15 shows conflicting results between preemption #1 and #2. While the first shows that under the green extension / red truncation preemption policy, overall intersection delay increases with preemption, the second shows the opposite. Low traffic volume cases (L2:1 and L3:1) were exceptions to the first preemption, since cross street volume is also low and, thus, preemption might not increase delay. Low main street traffic volume would have a greater chance of clearing the intersection within the predetermined green signal, and thus extending the green time to facilitate the bus passage through the intersection may not benefit vehicles other than the bus. At low volumes, cross street right turning traffic may have enough gaps to turn on red and thus reduce excessive cross street delays. Therefore, preemption might be beneficial when employed at low volume intersections. Also, the upper 3:1 case was an exception to the second preemption. This might have been purely due to random traffic fluctuation. However, the impact was small.

Since two preemption cases of the same type gave two completely conflicting results, the effect of green extension / red truncation on overall intersection delay was inconclusive. The explanation might be that it is a function of traffic arrival randomness. The first green extension / red truncation preemption took place at the beginning of the simulation (at 5:13) where there was minimum disturbance due to any other preemption, while the

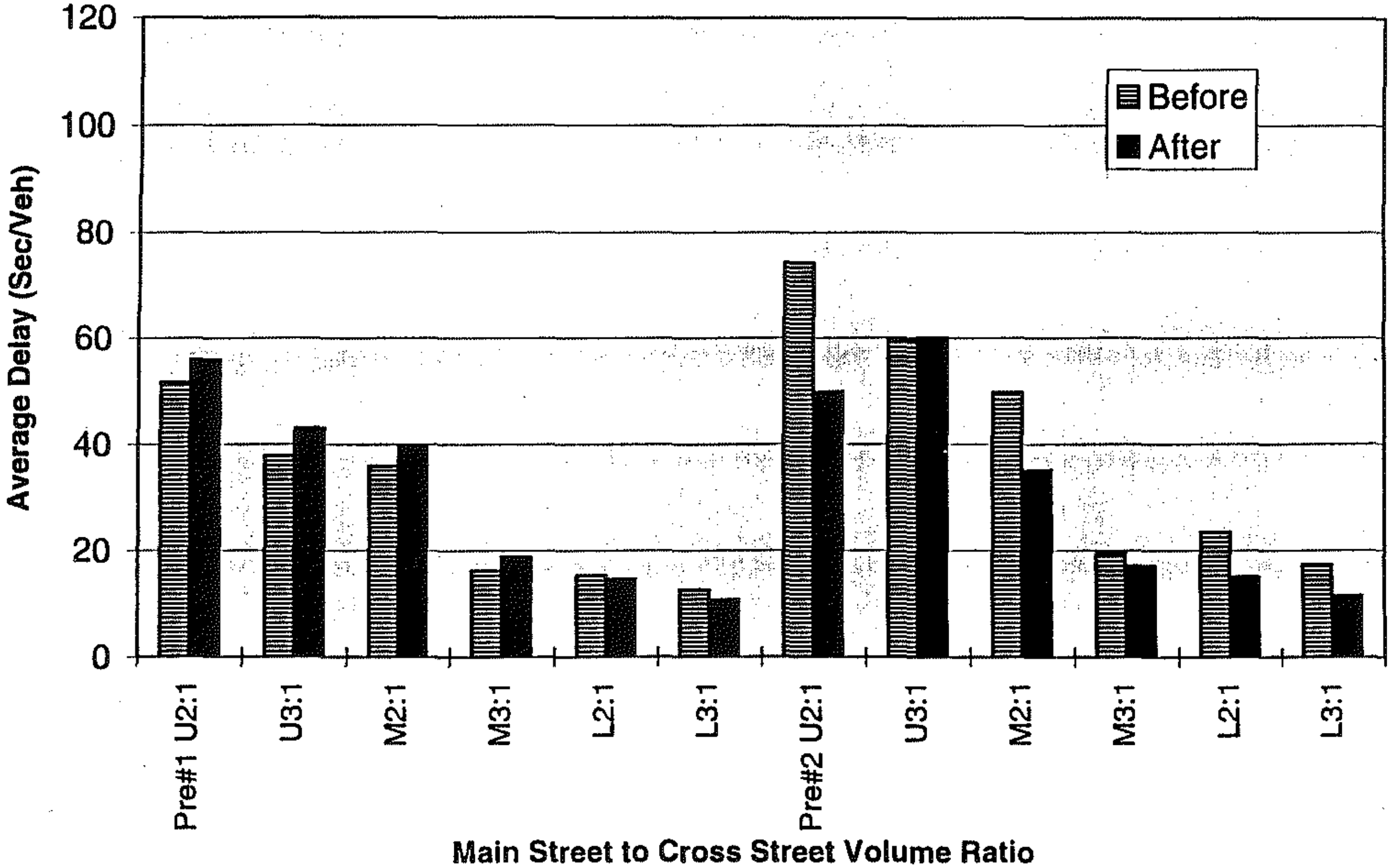


Figure 15: Average Delay For Advance Green / Green Extension Preemption.

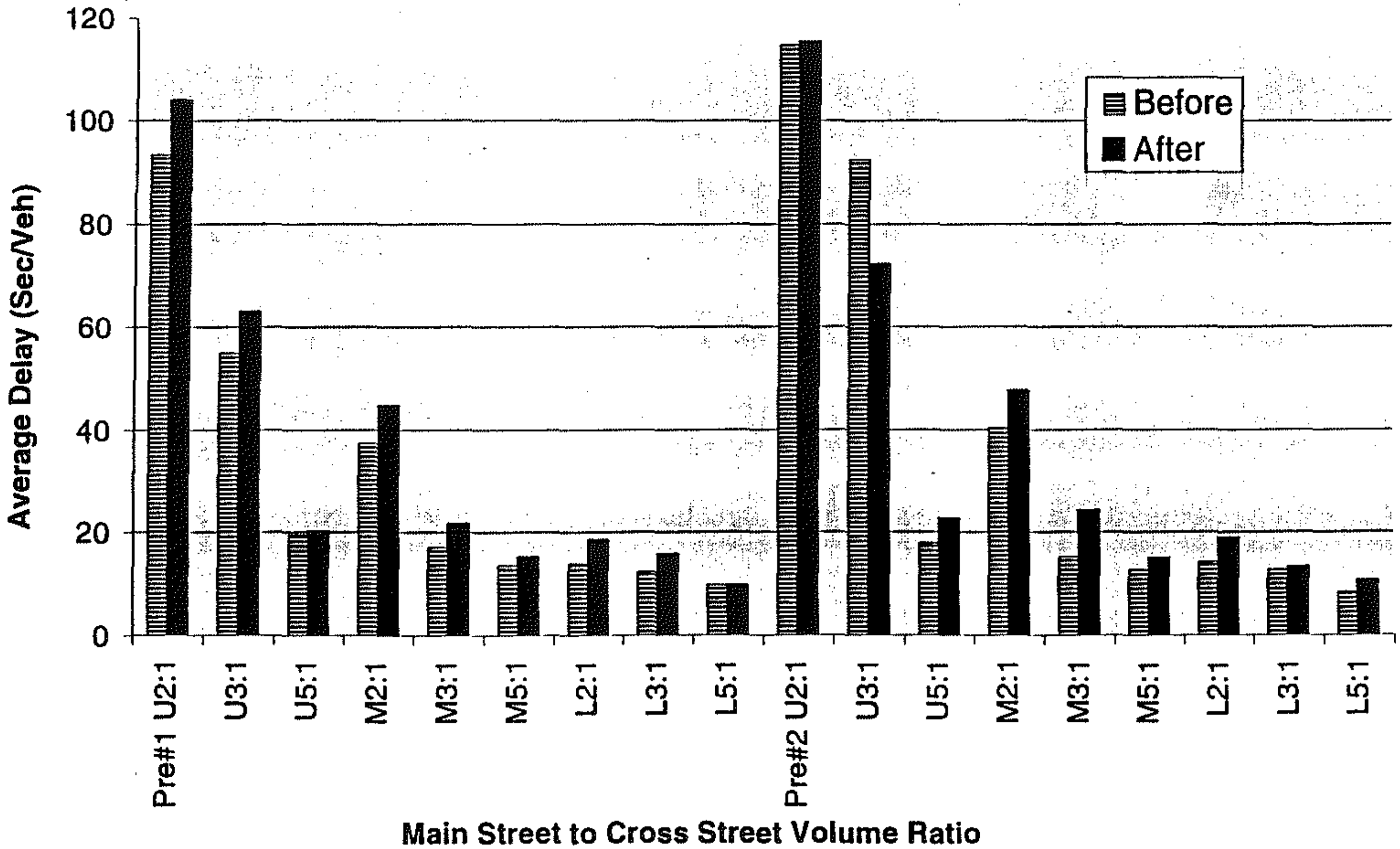


Figure 16: Average Delay For Skip Phase and No Compensation

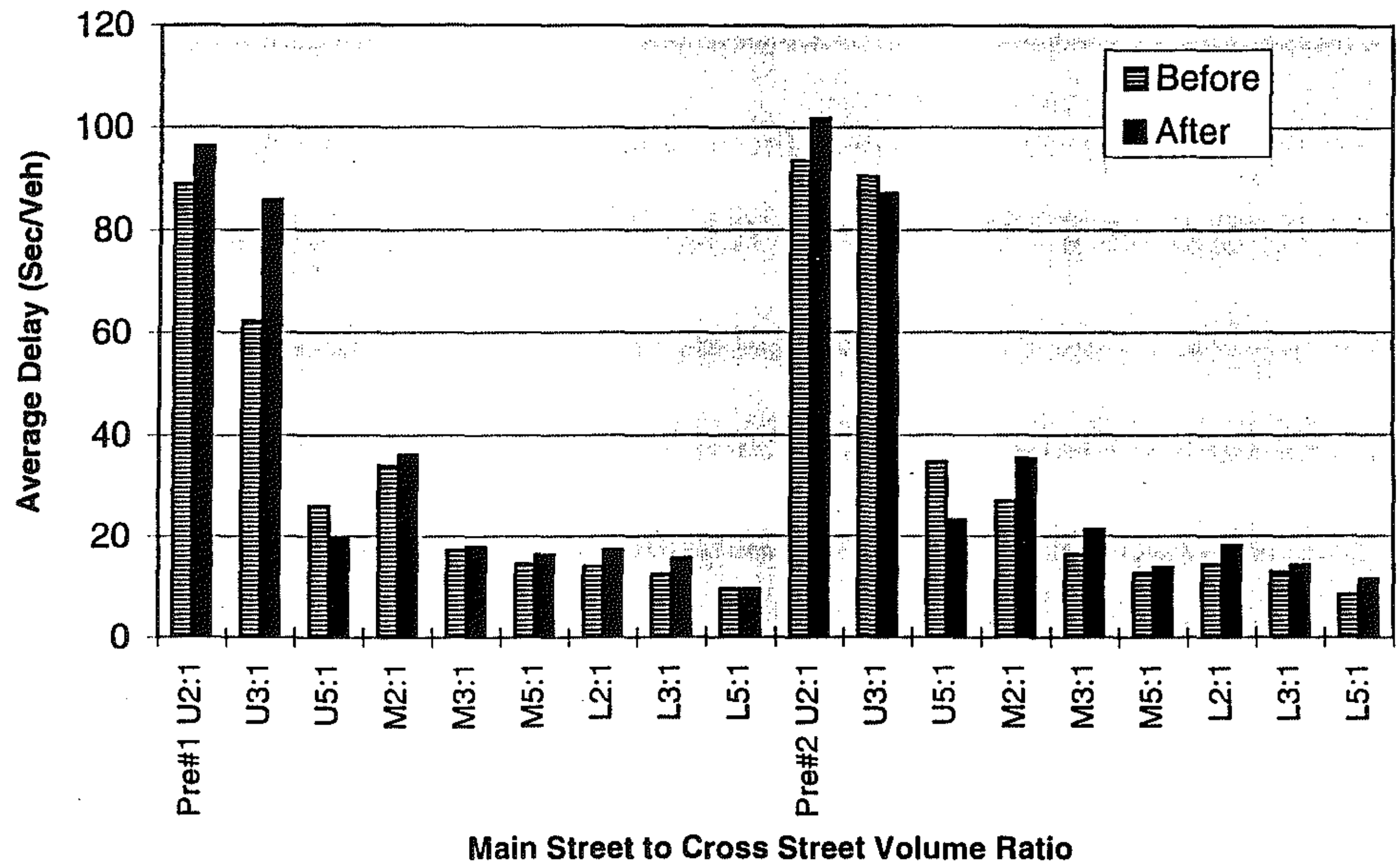


Figure 17: Average Delays For Skip Phase Preemption With Compensation

second one happened later in the simulation (at 5:24) after other disturbances may have occurred.

Figures 16 and 17 show that skip phase preemption, with and without compensation, was not beneficial to the overall intersection statistics. Delay generally increased with that type of preemption. However, skip phase preemption was more successful for high volume ratio cases (5:1 ratios). Compensation was not a decisive factor for low volume cases; however, it influenced intersection delays negatively at high volume, low ratio cases (U2:1 and U3:1). Compensation either increased the average delay or reduced the benefits.

6.3 BPS and Carpools

In an effort to reduce the usage of single occupancy automobiles and to encourage drivers to switch to multiple occupancy vehicles, a unique idea was proposed for use in the implementation stage of this project -- providing signal preemption service to carpools. The carpool choice could be more attractive for people than buses, if the necessary incentives were provided. One of these incentives is carpool signal preemption. However, loading the network with so many carpools that signal preemption would be called every cycle would be a great disturbance to traffic flow. Therefore, the effects of carpool preemption as a function of the percentage of carpool users in the network was tested, using the case 5 preemption plan (selective preemptions).

Cases of no carpool, 5 percent, and 10 percent carpools with and without preemption were simulated. The effects of the presence of carpools in the network and carpool signal preemption on bus trip delay were also tested. Carpools were introduced only at the east and west ends of the corridor. NETSIM assumes an average private vehicle occupancy of 1.3 persons per vehicle and an average carpool occupancy of 3.5 persons per vehicle. In order to maintain the same number of users along the main corridor, the appropriate conversion factors were used and the main corridor traffic volume was adjusted accordingly. Thus, the higher the carpool percentage the lower the network traffic volume.

Figures 18 and 19 show the effect of 5% and 10% carpools on the system, respectively. As the percentage of carpoolers in the system increased the average vehicle and person delays decreased (without preemption), because network traffic volume was reduced. A maximum of only 20 minutes of simulation time was achieved, since there was a preemption call at almost every minute and the maximum number of time periods allowed by NETSIM is nineteen. When 5% of the main street traffic were carpoolers using preemption, there was an insignificant effect on vehicle and person delays, although absolute network delays were significantly reduced. However, adding more carpools with preemption into the network (10%) increased the overall vehicle and person delay rapidly, because there was a carpool calling for preemption almost every cycle at every intersection, and thus traffic optimization and progression were greatly disrupted. Despite that, buses generally continued to gain benefits from the frequent preemption calls by buses and carpools, since they almost always found either a green signal or an already placed preemption call before they arrived at the intersection. These results are shown in Figures 20, 21, and 22. Detailed results are shown in Appendix G.

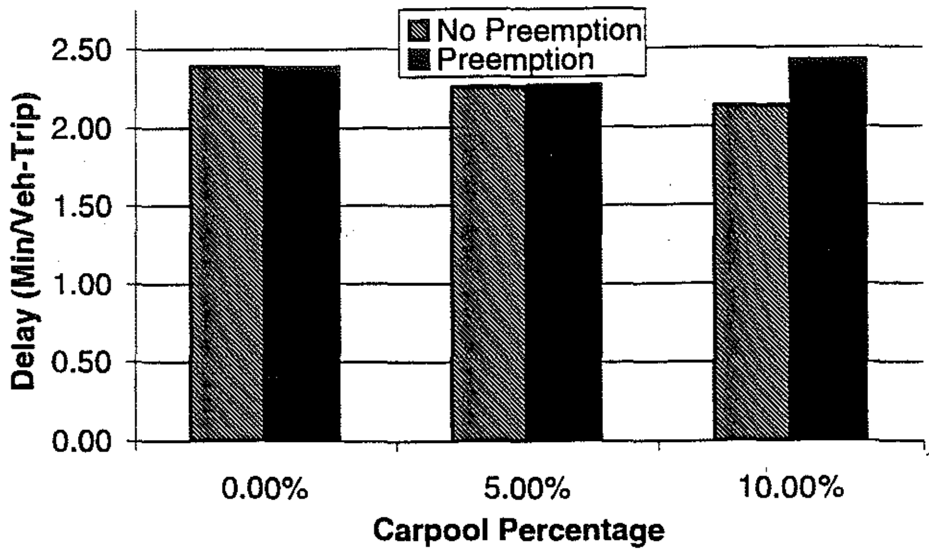


Figure 18: Cumulative Network Delay

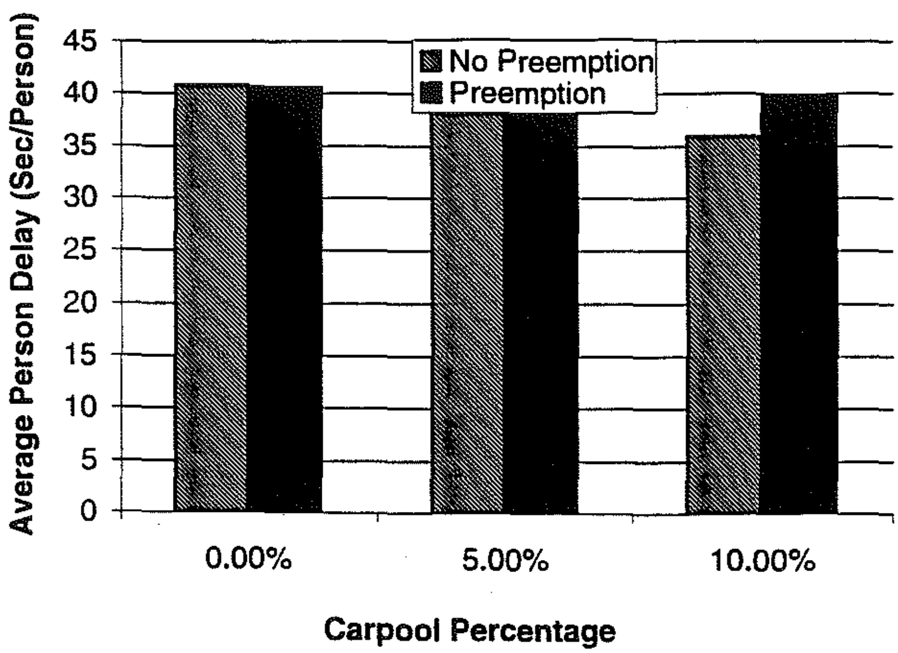


Figure 19: Average Person Statistics

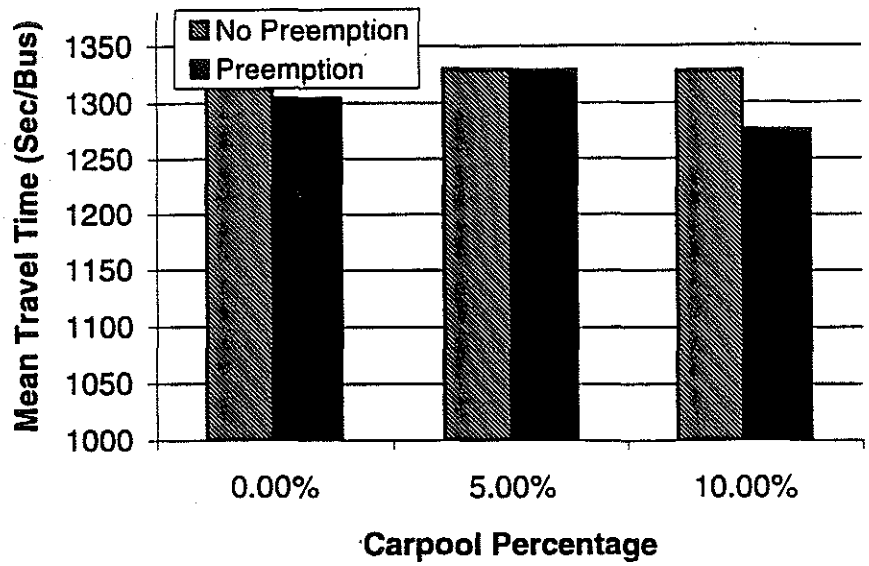


Figure 20: Bus Route 1 Mean Travel Time

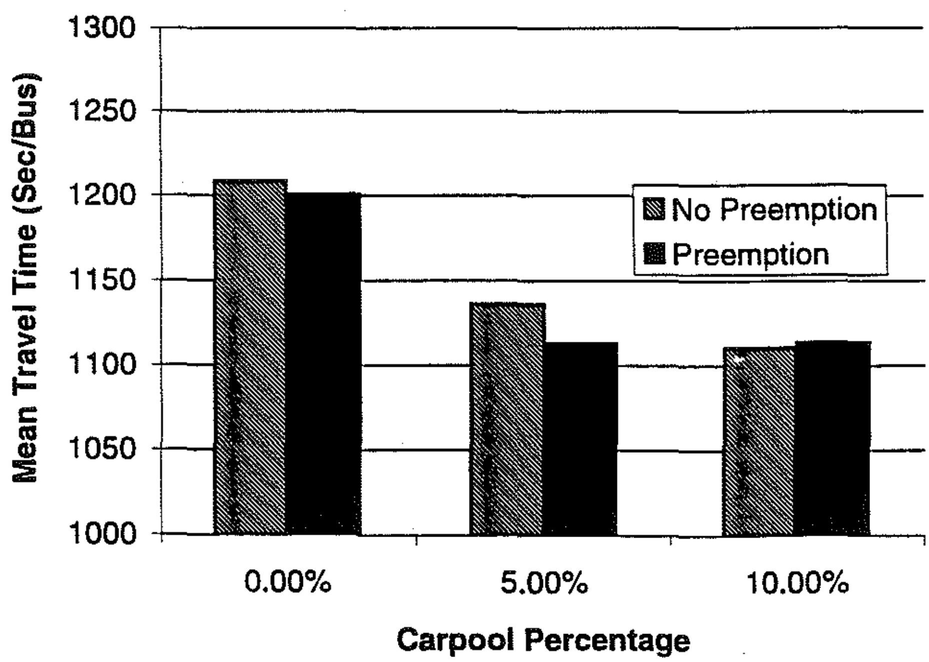


Figure 21: Bus Route 2 Mean Travel Time

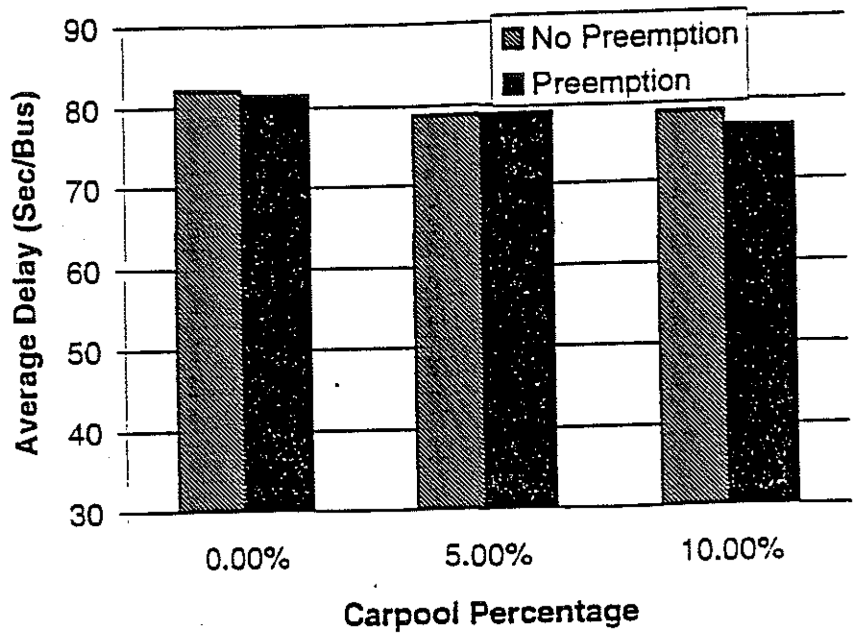


Figure 22: Total Links Bus Delay

Thus, a certain percentage of carpoolers in the system might be beneficial, since it reduces the number of vehicles on the streets and reduces network delay. However, a high percentage of carpools, such that a preemption call is made every cycle, is detrimental.

6.4 Test of Random Vehicle Generation

It was clear that in many instances vehicle generation at the entry nodes, vehicle arrivals, driver's behavior (cautious, normal, reckless), and turning movements, which were all randomly assigned by NETSIM, played a significant role in the network measures of effectiveness. The network characteristics are randomly selected based on a random number seed coded into NETSIM. The model's default number seed was used in the previous simulation runs. However, to test the effect of randomness on network MOEs, with and without preemption, a different number seed was selected. The network was first simulated without preemption and then the case 5 preemption plan was used. The results of these simulation runs are presented in Tables 23, 24, 25, and 26. A 45-minute simulation period was reached.

Table 23: Cumulative Network Statistics; With and Without Preemption for a Different Random Number Seed.

		Veh-Trips	Delay Veh-Hours	Delay Min/Veh-Trips
Default Seed No.	No Preemption	3469	163.43	2.83
	Preemption	3424	167.83	2.94
Second Seed No.	No Preemption	3446	147.69	2.57
	Preemption	3431	149.38	2.61

Table 24: Cumulative NETSIM Person Measures of Effectiveness; Before and After Preemption for a Different Random Number Seed.

		Person Trips	Person Mile	Travel Time (Person-Min)	Delay (Person-Min)	Avge. Delay Sec / Person
Default Seed No.	No Preemption	14921	5255	20264	12042	48.4
	Preemption	14974	5267	20624	12383	49.6
Second Seed No.	No Preemption	14131	4988	18698	10892	46.2
	Preemption	14248	5055	18857	10953	46.1

Table 25: Cumulative Network-Wide Bus Statistics; With and Without Preemption for a Different Random Number Seed.

		Route	Bus Trips	Total Travel-Time (Bus-Min)	Mean Travel-Time (Sec/Bus)	Person Trips	Person Travel-Time (Min)
Default Seed Number	No Preemption	1	2	68.1	1361.6	50	1702.9
		2	3	60.7	1214.2	75	1518.3
	With Preemption	1	2	69.9	1301.4	75	1610.8
		2	3	59.3	1184.0	75	1481.3
Second Seed Number	No Preemption	1	2	64.6	1481.0	50	1613.8
		2	3	62.4	1191.0	75	1559.6
	With Preemption	1	2	62.1	1429.5	50	1553.3
		2	3	61.1	1164.5	75	1527.1

Table 26: Cumulative NETSIM Bus Statistics; With and Without Preemption for a Different Random Number Seed.

		Total Bus Link-Trips	Travel Time (Min)	Delay Time (Min)	Avge. Delay Sec / B-Trip
Default Seed No.	No Preemption	65	127.4	86.2	79.6
	Preemption	67	129.3	86.6	77.6
Second Seed No.	No Preemption	64	127.0	87.2	81.8
	Preemption	64	123.3	83.3	78.1

As shown in the tables, different random numbers generated a difference in statistics for the reference case (no preemption) that ranged from 2% to 10%. However, the change resulted from preemption was less than 5%. Furthermore, in comparing the effect of randomness on the change from no preemption to preemption, Table 23 shows that vehicle delay was 3.9% worse using the default random number and 1.6% worse using another random number, a difference of 2.3%. Person MOEs (Table 24) show that preemption made a difference averaging from a 2.5% increase using the first random number to a 0.2% decrease using the second random number, a difference of 2.7%. These results indicate that the effect of preemption on the vehicle and person delays found in this study may fall within the normal traffic fluctuation.

As far as bus statistics are concerned, bus route 1 travel time was reduced by 4.4% using the default random number, and by 3.5% using another random number, a difference of 0.9%. Also, bus route 2 travel time dropped by 3.5% and 2.2% for the first and the second random number, respectively, a difference of 1.3%. Total bus link trips varied from 2.5% to 4.5% reduction in delay for the default random number and the second random number, respectively, a difference of 2.0%. Although, the second case reduced delay more than the first case, the bus did not travel a greater distance (in terms of total bus link-trips) within the simulation period. Even considering random variations, the bus still gains some benefits from preemption, although it might not be very significant.

The preemption tests studied in this research under different traffic conditions and using different preemption plans resulted in small changes in the network statistics (in terms of vehicle delay, person delay, bus delay, and bus travel time). Most did not exceed 5%. The randomness test showed that some of the network statistics varied more between two simulation runs using a different random number seed than they did between preemption and nonpreemption. Although randomness influenced these results, not all the changes described were the result of randomness. The changes in delays and vehicle trips associated with different preemption plans and under different traffic conditions (discussed in this research, chapters 6 and 7) were the result of the selected preemption strategies.

Chapter 7

Conclusions

The literature reviewed failed to identify an up-to-date model that can simulate various BPS strategies, that is comprehensive, and that is capable of restoring the original signal settings. These shortcomings are cited as reasons for the lack of implementation of BPS in the U.S. However, the use of NETSIM's graphical animation capability provided the flexibility to test several BPS plans and to restore the optimal signal settings after preemption is granted.

Based on the results of this study, it is clear that BPS provides little benefit to a corridor with the volume and bus frequency (15 minutes) characteristics of Washtenaw Avenue. Optimization of the network traffic signals and progression provide the least delay in the network. Preemption, which deviates from the optimum setting, created an increase in vehicle and person travel time and delay. As the frequency of preemptions increased, delay increased in the network. The green extension / red truncation plan resulted in less vehicular delay than the skip phase plan, since the later provides more disturbance to progression.

The maximum benefit that a bus gained under any tested condition averaged 80 seconds out of a 1380-second travel time (6%). This benefit (80 seconds) for any single bus trip could be lost or gained if a bus randomly missed or caught a green light at a signalized intersection that has more than a 60-second cycle length; e.g. Golfside, Huron Parkway, or Carpenter Streets. The overall benefits gained by buses from preemption were not sufficient to counter the delay to other vehicles in the traffic stream. Therefore, when considering the costs as a result of preemption, the BPS process was not beneficial overall. To justify the provision of BPS, bus headways would have to be less than 15 minutes.

The best BPS is the one that combines various treatments for different intersection (case 5), see Table 27. The green extension / red truncation plan results in the least increase in delay. The skip phase plan results in a significant increase in delay at intersections with high cross street volume and low main to cross street volume ratios. Compensation was generally inappropriate since the main street volume in the study corridor was relatively high. The success or failure of a specific BPS plan is, primarily, a function of signal phasing and traffic volume. Thus, the most suitable plan for each intersection in a corridor should be selected so that the benefits of BPS are maximized. For the study corridor, this means using green extension / red truncation and skip phase plans at Yost, Sheridan, Brockman, Austin, Hill, and South University; green extension / red truncation and skip phase with compensation plans at Pittsfield; and green extension / red truncation plan at Golfside intersection.

It was noted that when preemption took place at a highly congested intersection (at saturation), preemption effects continued for several cycles. Sometimes, the effect (delay) accumulated to the end of simulation (link reached over saturation).The presence of a single heavy volume intersection in the network can skew the overall network statistics. The weight of these intersection MOEs was very significant in the overall network MOEs.

Table 27: Summary of Statistics For Several Preemption Plans.

Cases	Avge. Veh. Delay Min/Veh-Trip	Avge. Person Delay Sec / Person-Trip	Avge. Bus Travel Time Sec / Bus	Avge. Bus Delay Sec / Bus-Trip
No Preemption	2.83	48.4	1361.6	79.6
Case 1	2.90	49.0	1361.8	79.6
Case 2	2.89	49.2	1326.3	78.9
Case 3	3.00	49.6	1296.1	79.1
Case 4	3.15	52.3	1288.0	76.1
Case 5	2.94	49.6	1301.4	77.6
Case 6	2.97	50.6	1342.6	82.9

By testing the sensitivity of BPS to volume change, it was found that the effects of BPS on delay to the general vehicular traffic were not significant at very high and very low volumes. Bus travel time and delay decreased with a decrease in volume up to a certain low point and then leveled off. In general, the 3:1 main to cross street volume ratio is the border line, above which person and vehicle statistics favor preemption with no compensation, and below which preemption might not be favorable and if it is provided, compensation is warranted. Providing preemption for intersections with 3:1 or higher ratios, and cross street volume of 500 VPH or less did not generally result in an increase in delay to the general traffic. Preemption increased delay for volume ratios less than 3:1 (see Table 28).

Testing the before and after MOEs at an isolated intersection showed that the green extension / red truncation preemption plan was inconclusive; beneficial at one time and causes

Table 28: Summary of The Overall Statistics For The Volume Sensitivity Test

Volume Ratio	With / Out Preemption	Avge. Veh. Delay Min/Veh-Trip	Avge. Person Delay Sec / Person-Trip	Avge. Bus Delay Sec / Bus-Trip
1500: 750	No Preemption	0.53	25.5	44.5
(2:1)	Preemp, No Comp.	0.79	40.0	38.8
	Preemp. W / Comp.	0.65	32.3	39.2
1500: 500	No Preemption	0.37	16.6	43.1
(3:1)	Preemp., No Comp.	0.39	17.6	37.8
	Preemp. W / Comp.	0.38	17.1	38.1
1500: 300	No Preemption	0.30	13.0	40.2
(5:1)	Preemp., No Comp.	0.31	13.5	37.1
	Preemp. W / Comp.	0.32	13.7	37.4

extra delay at another. The results were dependent on the vehicle arrival pattern. However, skip phase preemptions (with and without compensation) were beneficial at a high volume ratio (main street volume: cross street volume = 5:1). Compensation was not a decisive factor at low volumes, but resulted in a higher delay at high volume.

There appear to be advantages for providing carpools with preemption capability up to between 5 and 10 percent of the main street traffic volume. Carpool services provide benefit to the network, if they replace some of the private automobiles and, thus, reduce main street volume. When 5% of the main street traffic was replaced with carpoolers with preemption capability, network vehicular traffic delay was not increased, people's travel time and delay were slightly reduced, and bus statistics were generally improved. However, when increasing the number of carpools into the system, the bus travel time and delay continued to benefit, but the network vehicular delay and person delay were significantly increased, due to the frequent interruption of the optimum signal settings by preemption calls (Table 29).

Table 29: Summary of The Impact of Preemption on Carpools.

Case	Avge. Veh. Delay Min/Veh-Trip	Avge. Person Delay Sec / Person-Trip	Avge. Bus Travel Time Sec / Bus	Avge. Bus Delay Sec / Bus-Trip
Base Case	2.39	40.8	12.08.4	82.1
W/ Preemption	2.39	40.6	1200.9	81.6
5% Carpools	2.26	38.1	1136.0	78.8
W/ Preemption	2.27	38.0	1113.0	78.9
10% Carpool	2.13	35.9	1110.7	78.6
W/ Preemption	2.42	39.8	1114.0	76.8

In any corridor there is likely to be random fluctuation in the traffic demand, and this variation may be as large as the measured effect of BPS. Although NETSIM's time period specific statistics provided a microscopic picture of what happened before, during, and after preemption, the effect of vehicle arrival pattern was significant and may mask some of the preemption effects. Testing a different random number seed showed that most of the changes in network statistics and the effects of BPS found in this study corridor were within the range of variations that resulted from merely changing the random number seed (Table 30).

The primary recommendation for the Ann Arbor Transit Authority is that the provision of BPS for buses only under the current conditions is not worth the costs. However, providing limited carpools with preemption capabilities should be tested this may provide lower overall delay.

Table 30: Comparison Between The Results of a Different Random Seed Number and Case 5 Preemption

Random Number	Case	Avge. Veh. Delay Min/Veh-Trip	Avge. Person Delay Sec / Person-Trip	Avge. Bus Travel Time Sec / Bus	Avge. Bus Delay Sec / Bus-Trip
Default Number Seed	No Preemption	2.83	48.4	1361.6	79.6
	Preemption	2.94	49.6	1301.4	77.6
Second Number Seed	No preemption	2.57	46.2	1481.0	81.8
	Preemption	2.61	46.1	1429.5	78.1

For further research, it is recommend that a model be developed that has the capability of automatic bus detection and the flexibility of changing signals automatically, according to the preemption plan, instead of the visual detection using graphical animation. The NETSIM and THOREAU models have good potential for such an enhancement. The algorithm for both models has been developed in this research, see Appendix B. The application of these algorithms will be of greater benefit if the model possesses the capability to select the most appropriate preemption plan for every intersection and to optimize the network signal timing plan after each preemption.

Appendix A

Network Peak Hourly Traffic Volume

Table A1: P.M. Peak Hourly Volume Along Washtenaw Avenue

Intersection	Direction	Left	Through	Right
Intersection 11	East Bound	359	1445	129
	West Bound	107	947	196
	North Bound	151	100	314
	South Bound	344	341	227
Intersection 1	East Bound	299	1577	596
	West Bound	193	1217	56
	North Bound	380	331	226
	South Bound	130	331	374
Intersection 2	East Bound	228	2337	34
	West Bound	194	1511	266
	North Bound	0	0	135
	South Bound	0	0	210
Intersection 3	East Bound	0	2092	49
	West Bound	92	1419	0
	North Bound	106	0	117
	South Bound	390	22	76
Intersection 4	East Bound	147	1645	52
	West Bound	266	1167	168
	North Bound	134	371	248
	South Bound	248	552	197
Intersection 5	East Bound	38	1709	102
	West Bound	104	1370	24
	North Bound	42	32	95
	South Bound	40	23	33
Intersection 6	East Bound	0	1025	34
	West Bound	774	0	665
	North Bound	0	0	810

Intersection	Direction	Left	Through	Right
Intersection 7	East Bound	0	1031	97
	West Bound	19	646	0
	North Bound	44	0	26
Intersection 8	East Bound	42	1102	37
	West Bound	16	651	23
	North Bound	18	25	12
	South Bound	14	41	11
Intersection 9	East Bound	0	1250	70
	West Bound	0	660	27
	North Bound	107	137	136
	South Bound	28	94	27
Intersection 10	East Bound	12	537	21
	West Bound	130	406	11
	North Bound	26	66	76
	South Bound	22	53	11

Appendix B

BPS Algorithm

(Flow-Charts)

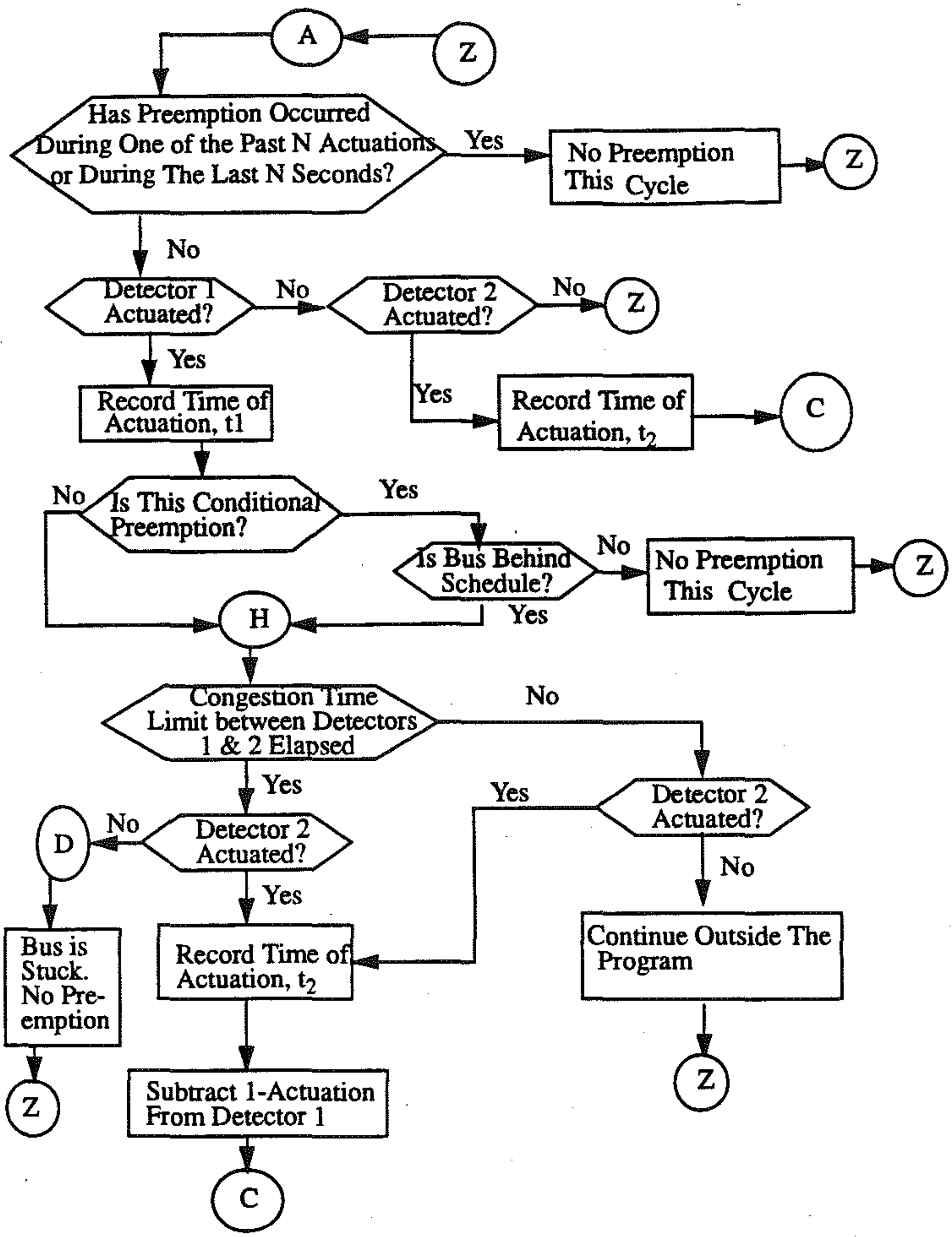


Figure B-1: Far-Side Bus-Stop BPS Algorithm

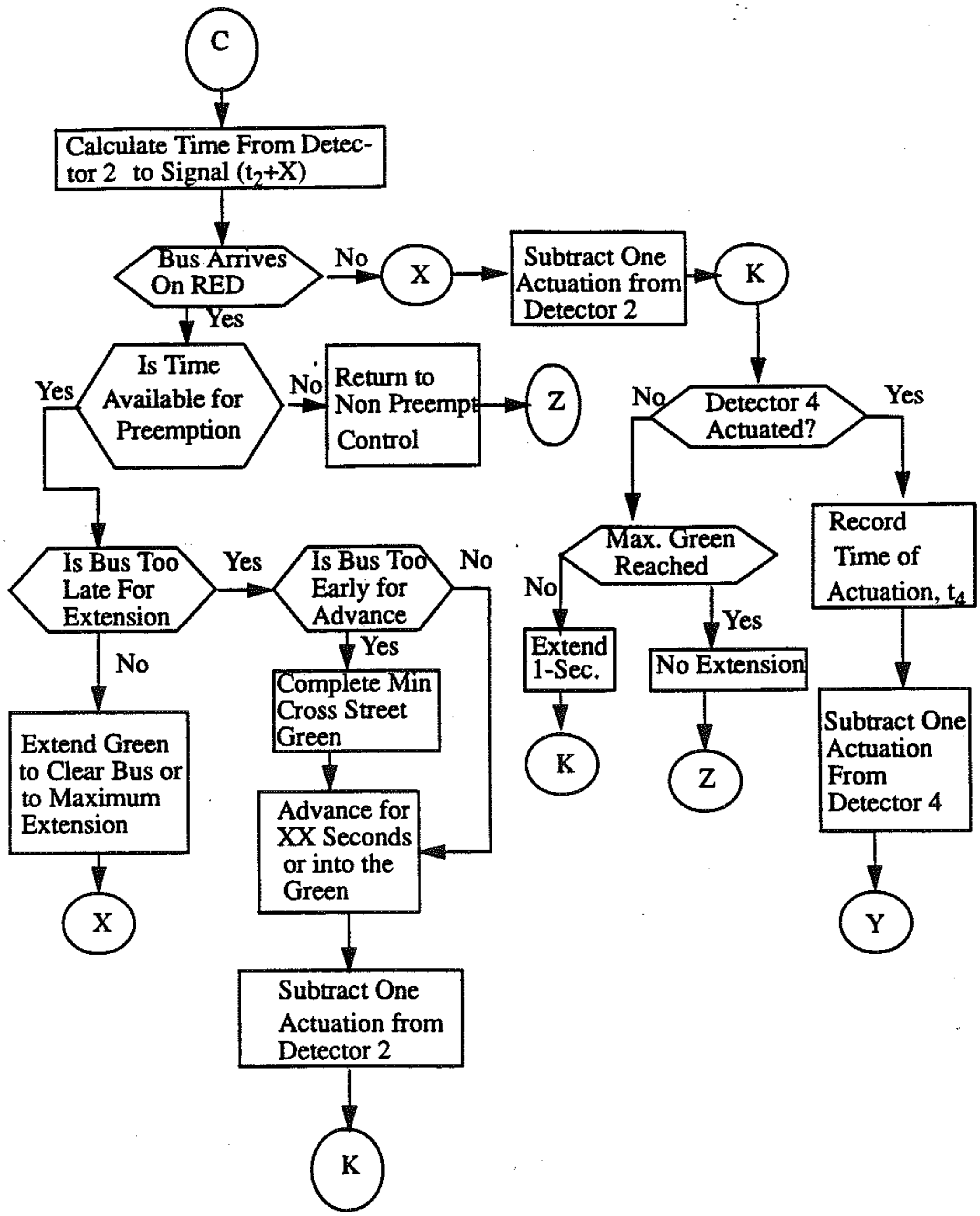


Figure B-1: Continued.

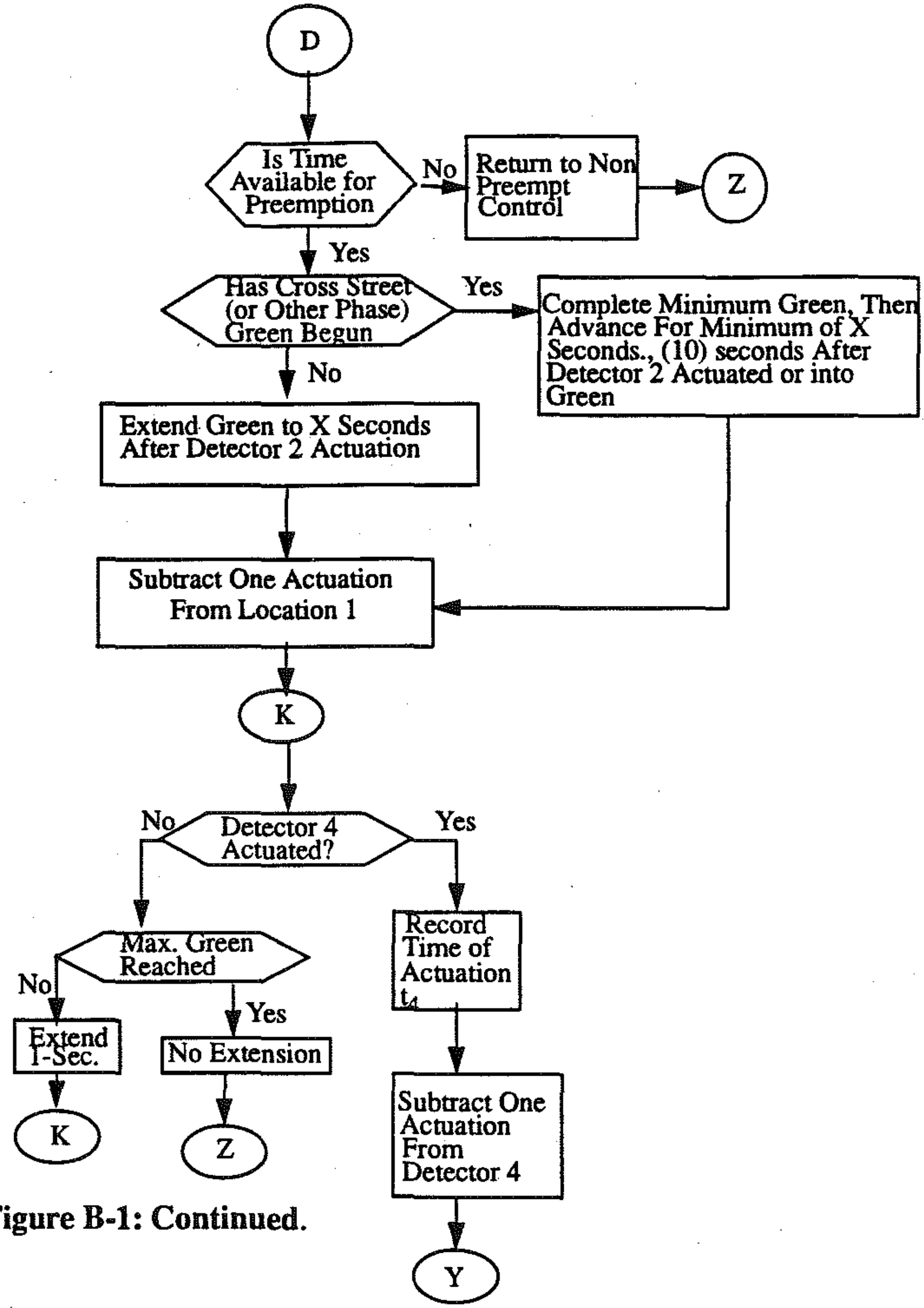


Figure B-1: Continued.

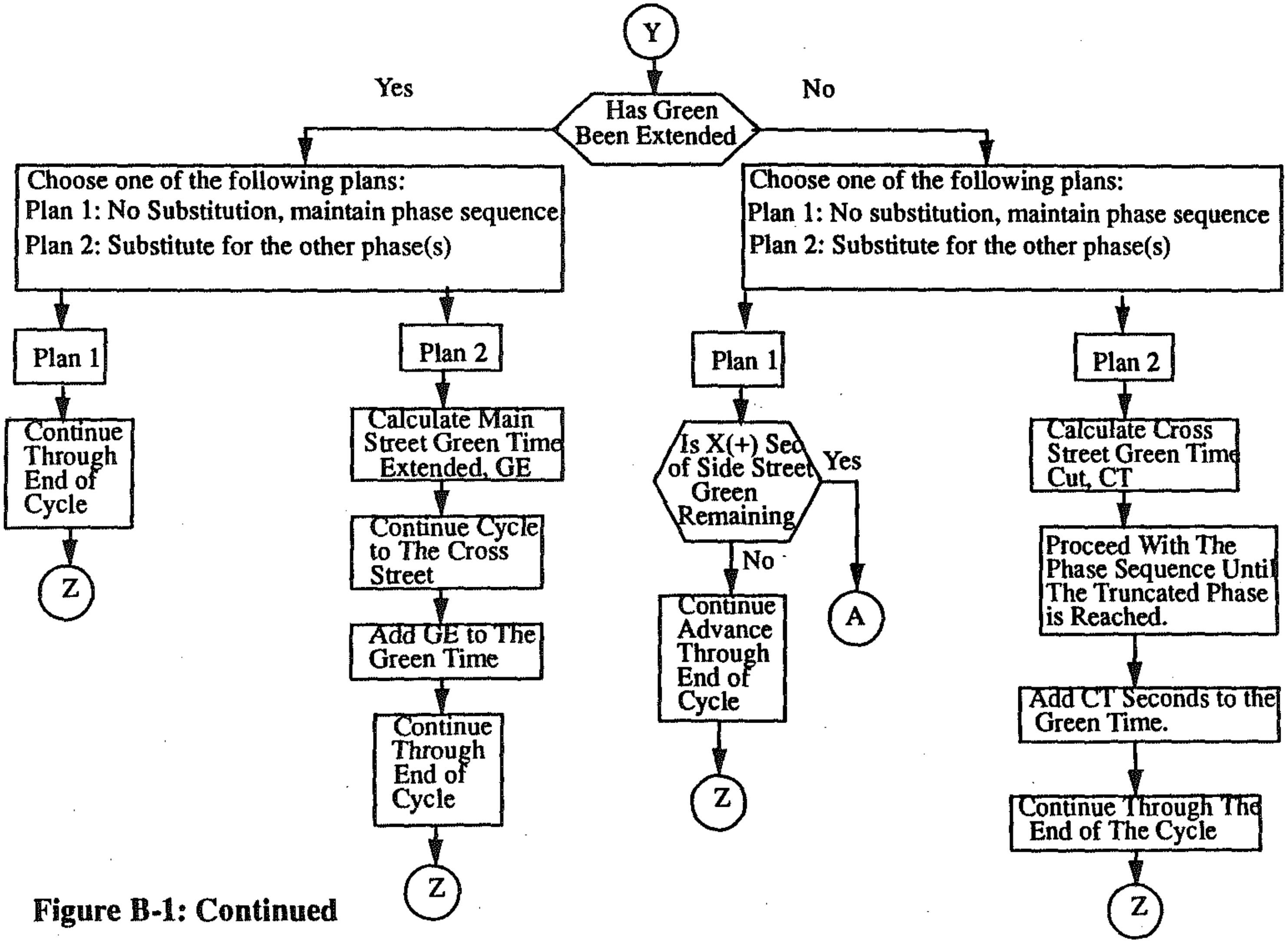


Figure B-1: Continued

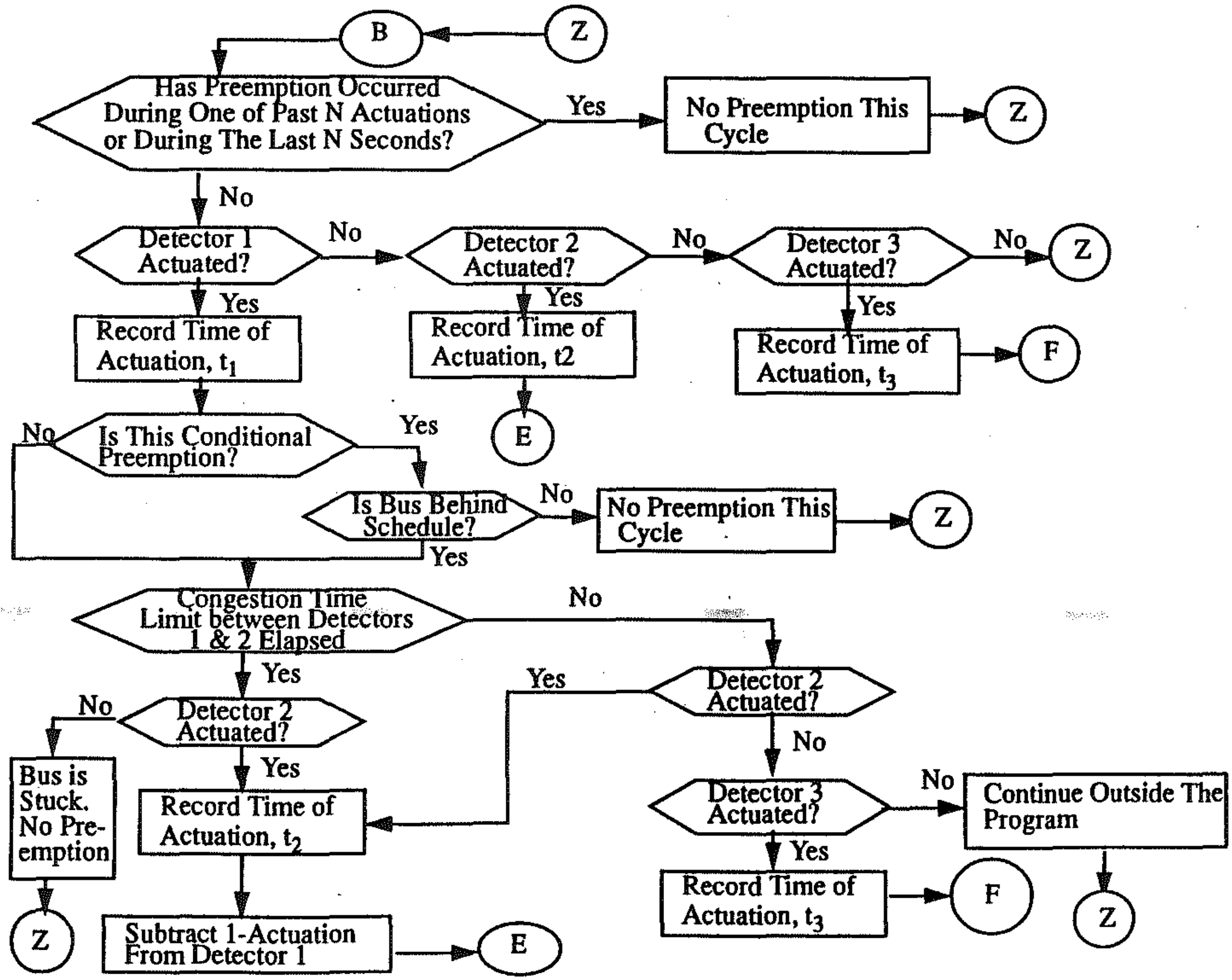


Figure B-2: Near-Side Bus Stop BPS Algorithm

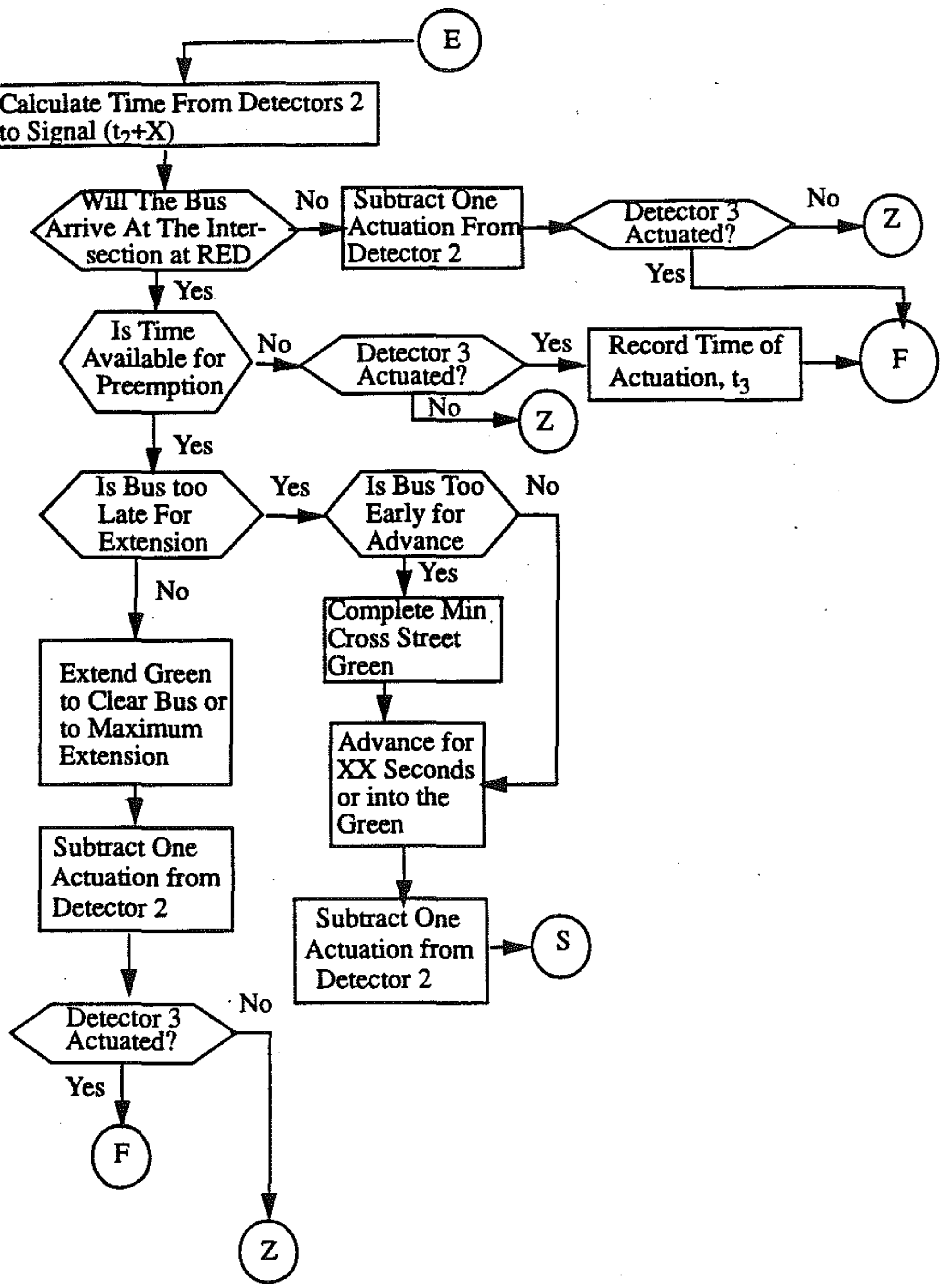


Figure B-2: Continued.

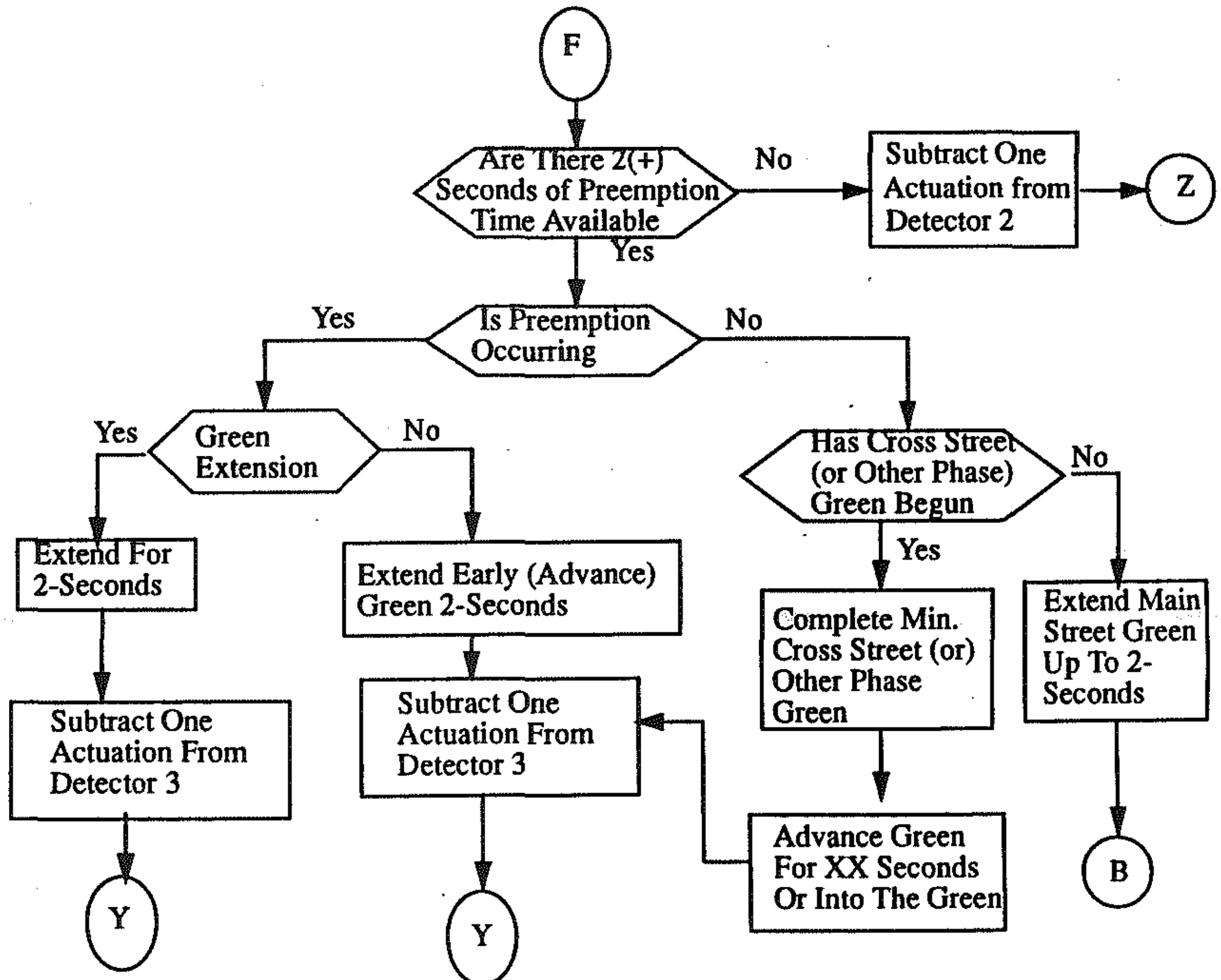


Figure B-2: Continued.

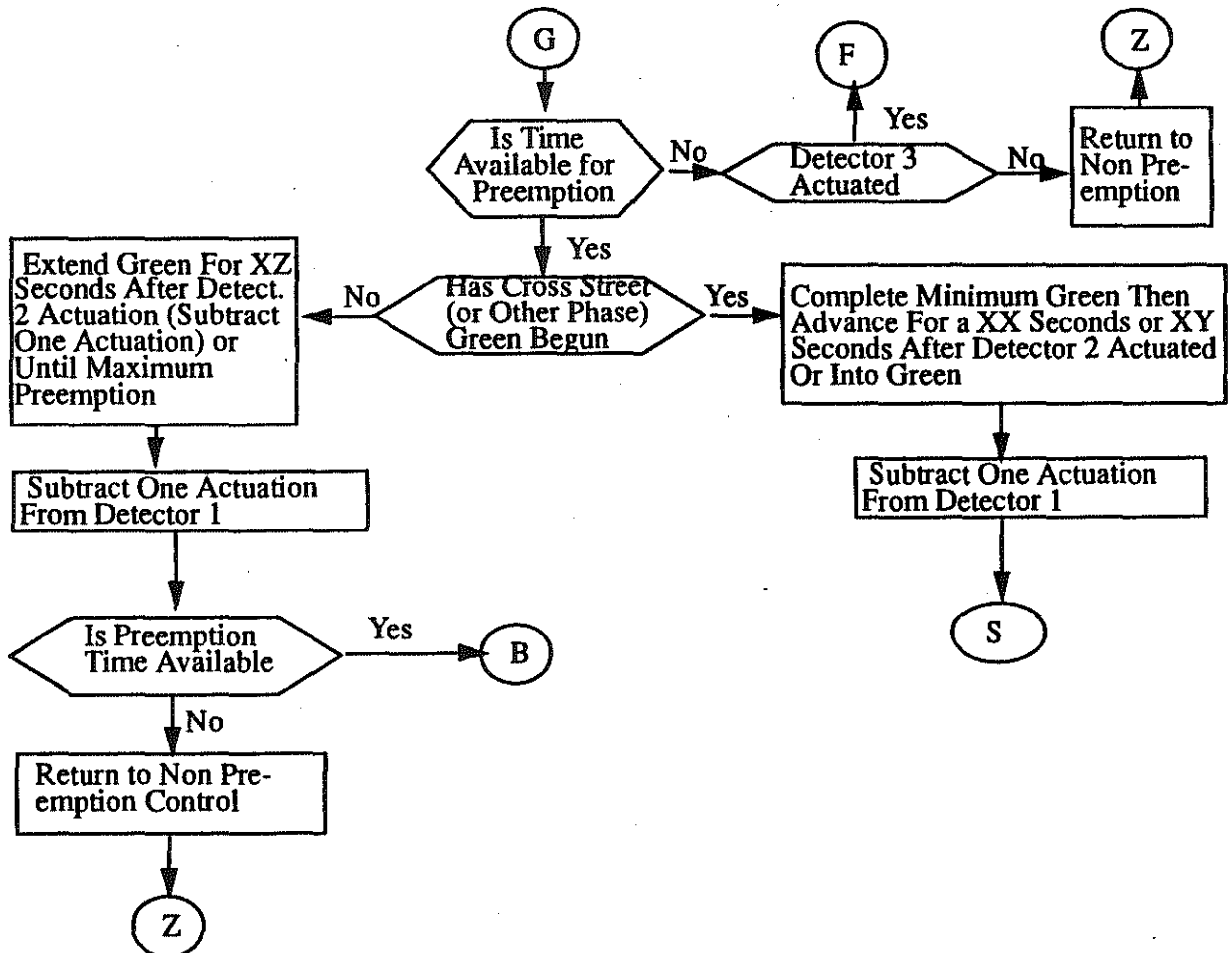


Figure B-2: Continued.

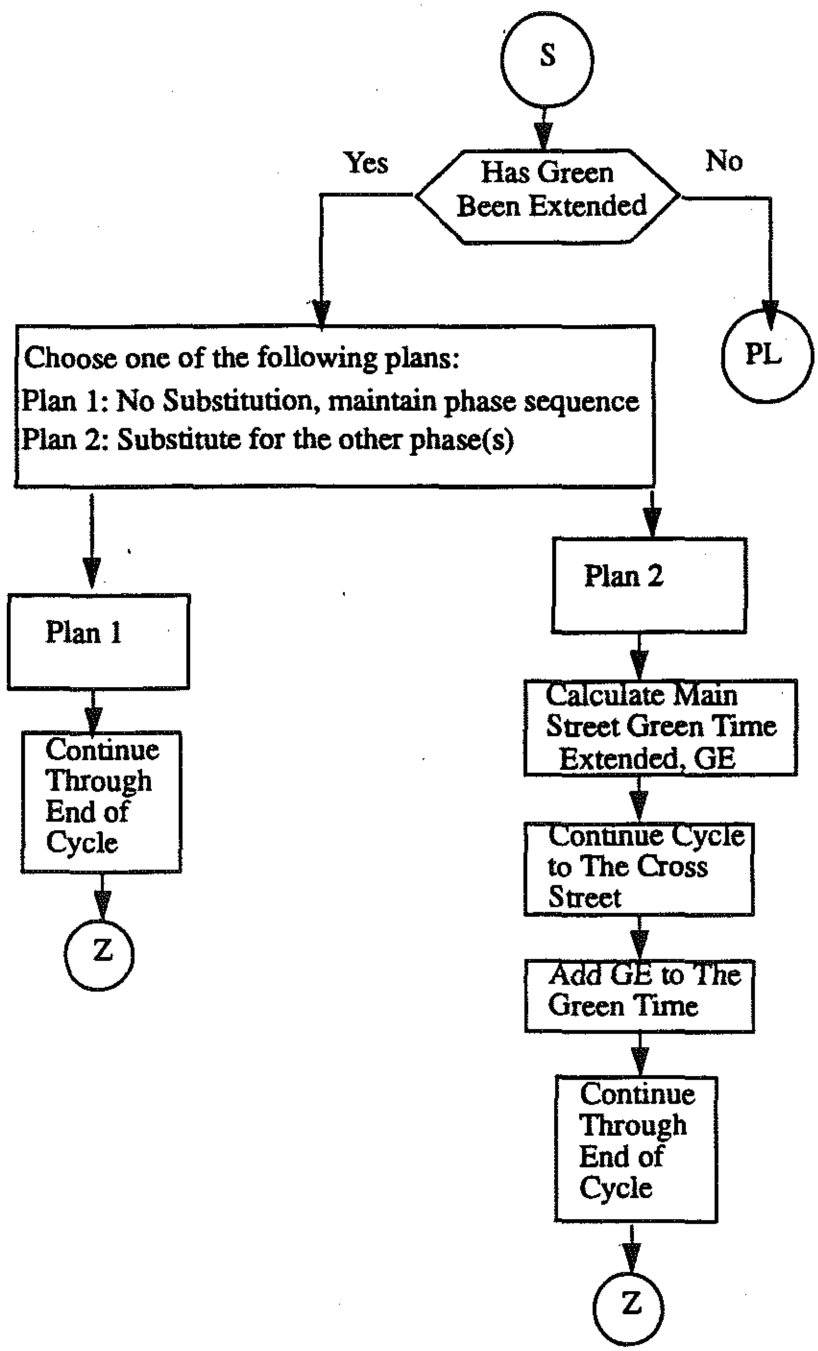


Figure B-2: Continued.

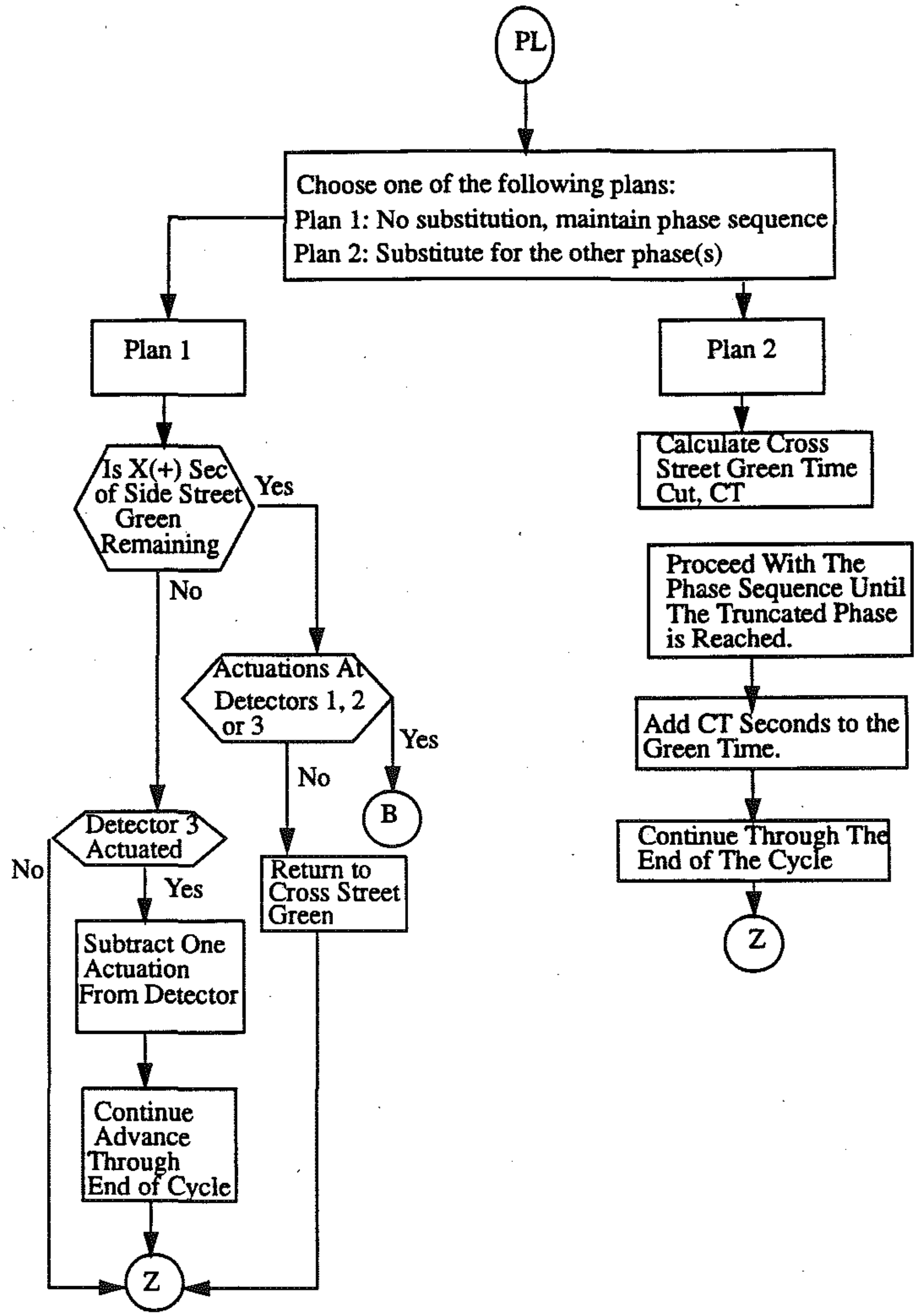


Figure B-2: Continued.

Appendix C

Case 1 Preemption Results

Table C.1: Time Period Specific Statistics as a Result of Preemption For Intersection Number 6. 10-Seconds of Advance Green For Main Street EB / 10-Seconds Cut From Cross Street NB and Main Street WB left. Period Extended is The Third Time Period. Bus Direction is East Bound.

Link	Direction	Measures of Effectiveness	1st Time Period 60 -Seconds T = 5:13		2nd Time Period 60-Seconds T = 5:14		3rd Time Period 60-Seconds T = 5:15		4th Time Period 60-Seconds T = 5:16		5th Time Period 60-Seconds T = 5:17	
			L	R	L	R	L	R	L	R	L	R
5-6	West Bound	Veh-Trips	13	15	15	5	11	15	16	9	15	6
		Delay (Veh-Min)	1.7	2.2	3.6	0.8	1.4	1.8	4.9	1.3	1.5	0.6
		Delay (Sec/Veh)	7.8	8.6	14.2	10.0	7.7	7.2	18.3	8.3	5.8	6.3
			Total		Total		Total		Total		Total	
7-6	East Bound	Veh-Trips	7		11		14		5		15	
		Delay (Veh-Min)	2.0		6.1		9.3		2.0		14.1	
		Delay (Sec/Veh)	17.1		33.0		39.9		24.0		56.4	
24-6	North Bound	Veh-Trips	12		13		12		16		11	
		Delay (Veh-Min)	1.6		2.4		2.6		2.2		1.9	
		Delay (Sec/Veh)	8.0		11.1		13.2		8.3		10.4	

Intersection Statistics:	3 Periods Before Preemption	3 Periods After Preemption
Veh-Trips	143	145
Delay (Veh-Min)	31.8	43.6
Delay (Sec/Vehicle)	13.3	18.0

Table C.2: <u>Time Period Specific</u> Statistics as a Result of Preemption For Intersection Number 10. Main Street (E-W) Green is Extended for 3-Seconds / Cross Street (N-S) is Cut by 3-Seconds. Third Time Period is Preempted. Bus Direction is East Bound.

Link	Direction	Measures of Effectiveness	1st Time Period 60-Seconds T=5:22	2nd Time Period 60-Seconds T=5:23	3rd Time Period 60-Seconds T=5:24	4th Time Period 60-Seconds T=5:25	5th Time Period 60-Seconds T=5:26
9-10	West Bound	Veh-Trips	10	11	10	14	10
		Delay (Veh-Min)	2.4	1.0	1.2	2.7	1.5
		Delay (Sec/Veh)	14.4	5.4	7.3	11.6	9.0
32-10	East Bound	Veh-Trips	9	8	11	8	9
		Delay (Veh-Min)	1.1	0.3	0.9	0.5	0.9
		Delay (Sec/Veh)	7.3	2.4	4.7	3.8	6.0
31-10	South Bound	Veh-Trips	1	1	2	1	1
		Delay (Veh-Min)	0.4	0.6	1.0	0.3	0.5
		Delay (Sec/Veh)	24.0	34.4	28.9	18.0	30.0
30-10	North Bound	Veh-Trips	2	2	2	3	2
		Delay (Veh-Min)	0.2	0.1	0.8	0.9	0.7
		Delay (Sec/Veh)	6.0	4.2	25.2	18.0	21.0

<u>Intersection Statistics:</u>	<u>3 Periods Before Preemption</u>	<u>3 Periods After Preemption</u>
Veh-Trips	69	73
Delay (Veh-Min)	9.6	11.8
Delay (Sec/Vehicle)	8.3	9.7

Table C.3: Time Period Movement Specific Statistics as a Result of Preemption For Intersection Number 11. Main Street (E-W) R & T are Advanced for 10-Seconds / Main Street (S-N) Left Turns are Cut by 10-Seconds. Third Time Period is Preempted. Bus Direction is East Bound.

Link	Direction	Measures of Effectiveness	First Time Period 120-Seconds T=5:23			Second Time Period 120-Seconds T=5:25			Third Time Period 120-Seconds T=5:27			Fourth Time Period 120-Seconds T=5:29			Fifth Time Period 120-Seconds T=5:31		
			L	T	R	L	T	R	L	T	R	L	T	R	L	T	R
33-11	West Bound	Veh-Trips	2	32	4	1	37	5	3	39	11	3	33	8	0	38	4
		Delay (Veh-Min)	1.1	71.0	10.8	1.7	84.7	10.6	3.1	74.7	21.4	3.1	54.4	14.4	0.0	59.7	10.3
		Delay (Sec/Veh)	33.3	133.1	162.6	103.2	137.3	127.6	62.8	115.0	116.5	61.4	98.9	107.6	0.0	94.2	153.9
1-11	East Bound	Veh-Trips	14	29	6	12	22	2	7	27	5	14	24	4	13	29	5
		Delay (Veh-Min)	57.6	23.6	6.6	45.5	15.4	1.7	29.9	19.6	3.0	71.1	21.2	1.85	67.2	24.1	3.5
		Delay (Sec/Veh)	246.8	48.9	65.7	227.3	42.1	49.5	256.4	43.6	36.2	304.8	53.1	27.8	310.3	49.8	41.5
17-11	South Bound.	Veh-Trips	12	12	7	2	13	6	14	14	9	9	10	9	11	6	10
		Delay (Veh-Min)	11.2	11.9	16.3	3.1	20.5	13.8	14.1	22.6	25.2	7.0	7.8	22.3	12.2	6.0	27.4
		Delay (Sec/Veh)	55.8	59.6	139.9	93.0	94.6	138.0	60.5	96.9	168.3	46.7	46.6	148.9	66.6	59.5	164.4
16-11	North Bound.	Veh-Trips	5	8	5	5	14	0	4	11	1	3	11	2	10	10	1
		Delay (Veh-Min)	3.1	4.4	2.7	4.1	10.7	0.0	4.1	9.3	0.7	3.0	10.2	0.9	9.9	7.7	1.3
		Delay (Sec/Veh)	37.0	33.2	32.2	49.3	45.7	0.0	62.0	50.9	43.2	60.8	55.7	27.0	59.3	46.0	79.2

Intersection Statistics:	3 Periods Before Preemption	3 Periods After Preemption
Veh-Trips	392	412
Delay (Veh-Min)	651.9	674.0
Delay (Sec/Vehicle)	99.8	98.2

Table C.4: <u>Time Period Specific</u> Statistics as a Result of Preemption For Intersection Number 6. 10-Seconds of Advance Green For Main Street EB / 10-Seconds Cut From Cross Street NB and Main Street WB left. Period Extended is The Third Time Period. Bus Direction is East Bound.

Link	Direction	Measures of Effectiveness	1st Time Period 60 -Seconds T = 5:29		2nd Time Period 60-Seconds T = 5:30		3rd Time Period 60-Seconds T = 5:31		4th Time Period 60-Seconds T = 5:32		5th Time Period 60-Seconds T = 5:33	
			L	R	L	R	L	R	L	R	L	R
5-6	West Bound	Veh-Trips	9	7	19	11	3	9	13	19	4	4
		Delay (Veh-Min)	0.9	0.8	4.1	1.7	0.3	1.0	2.4	3.0	0.7	0.5
		Delay (Sec/Veh)	6.3	6.4	12.9	9.1	6.0	6.6	10.9	9.3	10.4	7.5
			Total		Total		Total		Total		Total	
7-6	East Bound	Veh-Trips	6		12		20		3		12	
		Delay (Veh-Min)	3.5		10.1		14.5		3.0		9.2	
		Delay (Sec/Veh)	35.0		50.6		43.5		60.0		46.0	
24-6	North Bound	Veh-Trips	14		12		9		16		13	
		Delay (Veh-Min)	2.1		1.9		1.8		3.8		3.3	
		Delay (Sec/Veh)	9.0		9.4		12.3		14.3		15.2	

<u>Intersection Statistics:</u>	<u>3 Periods Before Preemption</u>	<u>3 Periods After Preemption</u>
Veh-Trips	141	129
Delay (Veh-Min)	37.1	43.5
Delay (Sec/Vehicle)	15.8	20.9

Table C.5: Time Period Specific Statistics as a Result of Preemption For Intersection Number 3. Main Street (E-W) Green is Advanced for 3-Seconds / Cross Street (N-S) is Cut by 3-Seconds. Third Time Period is Preempted. Bus Direction is East Bound.

Link	Direction	Measures of Effectiveness	1st Time Period 60-Seconds T=5:34	2nd Time Period 60-Seconds T=5:35	3rd Time Period 60-Seconds T=5:36	4th Time Period 60-Seconds T=5:37	5th Time Period 60-Seconds T=5:38
2-3	West Bound	Veh-Trips	25	23	28	30	23
		Delay (Veh-Min)	5.0	7.7	9.3	12.2	4.0
		Delay (Sec/Veh)	12.0	20.1	19.8	25.4	10.4
4-3	East Bound	Veh-Trips	28	28	19	26	32
		Delay (Veh-Min)	15.8	15.2	9.2	15.7	24.6
		Delay (Sec/Veh)	33.9	32.6	28.9	36.2	46.1
20-3	North Bound	Veh-Trips	11	11	12	8	8
		Delay (Veh-Min)	17.0	17.0	16.3	4.7	4.8
		Delay (Sec/Veh)	92.7	92.8	81.7	35.3	35.3
21-3	South Bound	Veh-Trips	8	7	7	9	7
		Delay (Veh-Min)	2.6	2.3	3.6	4.2	2.8
		Delay (Sec/Veh)	19.5	19.5	31.1	28.0	24.0

Intersection Statistics:	3 Periods Before Preemption	3 Periods After Preemption
Veh-Trips	220	209
Delay (Veh-Min)	129.9	109.4
Delay (Sec/Vehicle)	35.4	31.4

Table C.6: Time Period Specific Statistics as a Result of Preemption For Intersection Number 6. 10-Seconds of Green Extension For Main Street EB / 10-Seconds Cut From Cross Street NB and Main Street WB left. Period Extended is The Third Time Period. Bus Direction is East Bound.

Link	Direction	Measures of Effectiveness	1st Time Period 60 -Seconds T = 5:44		2nd Time Period 60-Seconds T = 5:45		3rd Time Period 60-Seconds T = 5:46		4th Time Period 60-Seconds T = 5:47		5th Time Period 60-Seconds T = 5:48	
			L	R	L	R	L	R	L	R	L	R
5-6	West Bound	Veh-Trips	16	18	2	6	16	13	10	13	17	13
		Delay (Veh-Min)	2.7	2.7	0.5	0.7	1.8	2.0	4.0	2.1	1.8	1.7
		Delay (Sec/Veh)	10.1	8.8	13.5	7.0	6.8	9.1	24.0	9.6	6.5	7.7
			Total		Total		Total		Total		Total	
7-6	East Bound	Veh-Trips	8		10		13		20		10	
		Delay (Veh-Min)	2.2		5.9		10.0		13.8		5.6	
		Delay (Sec/Veh)	16.5		35.4		46.1		39.0		33.6	
24-6	North Bound	Veh-Trips	15		11		16		13		13	
		Delay (Veh-Min)	3.0		1.8		3.5		2.2		1.6	
		Delay (Sec/Veh)	12.0		9.8		13.2		10.2		7.4	

Intersection Statistics:	3 Periods Before Preemption	3 Periods After Preemption
Veh-Trips	144	143
Delay (Veh-Min)	36.6	41.4
Delay (Sec/Vehicle)	15.3	17.4

Table C.7: <u>Time Period Specific</u> Statistics as a Result of Preemption For Intersection Number 10. Main Street (E-W) Green is Extended for 3-Seconds / Cross Street (N-S) is Cut by 3-Seconds. Third Time Period is Preempted. Bus Direction is East Bound.

Link	Direction	Measures of Effectiveness	1st Time Period 60-Seconds T=5:52	2nd Time Period 60-Seconds T=5:53	3rd Time Period 60-Seconds T=5:54	4th Time Period 60-Seconds T=5:55	5th Time Period 60-Seconds T=5:66
9-10	West Bound	Veh-Trips	17	16	17	11	13
		Delay (Veh-Min)	6.5	3.4	3.5	1.3	2.3
		Delay (Sec/Veh)	22.9	12.9	12.2	7.1	10.6
32-10	East Bound	Veh-Trips	9	8	9	9	10
		Delay (Veh-Min)	1.0	0.2	0.6	1.1	1.0
		Delay (Sec/Veh)	6.7	1.4	4.2	7.3	6.0
31-10	South Bound	Veh-Trips	1	1	2	1	1
		Delay (Veh-Min)	0.3	0.6	0.9	0.2	0.5
		Delay (Sec/Veh)	18.0	34.4	28.4	12.0	30.0
30-10	North Bound	Veh-Trips	1	3	3	2	3
		Delay (Veh-Min)	0.1	1.0	1.1	0.2	0.9
		Delay (Sec/Veh)	6.0	20.9	21.5	6.0	18.0

<u>Intersection Statistics:</u>	<u>3 Periods Before Preemption</u>	<u>3 Periods After Preemption</u>
Veh-Trips	80	81
Delay (Veh-Min)	17.0	13.7
Delay (Sec/Vehicle)	12.8	10.1

Table C.8: Time Period Specific Statistics as a Result of Preemption For Intersection Number 9. Main Street (E-W) Green is Extended for 5-Seconds / Cross Street (N-S) is Cut by 5-Seconds. Third Time Period is Preempted. Bus Direction is East Bound.

Link	Direction	Measures of Effectiveness	1st Time Period 60-Seconds T=5:53	2nd Time Period 60-Seconds 5:54	3rd Time Period 60-Seconds T=5:55	4th Time Period 60-Seconds T=5:56	5th Time Period 60-Seconds T=5:57
8-9	West Bound	Veh-Trips	19	11	5	16	10
		Delay (Veh-Min)	3.6	0.7	1.4	4.4	2.6
		Delay (Sec/Veh)	11.4	3.6	16.8	16.5	15.6
10-9	East Bound	Veh-Trips	10	9	12	10	10
		Delay (Veh-Min)	2.1	1.0	3.3	1.0	1.2
		Delay (Sec/Veh)	12.6	6.5	16.5	6.0	7.2
29-9	South Bound	Veh-Trips	3	2	3	2	2
		Delay (Veh-Min)	1.1	0.5	1.0	0.5	0.1
		Delay (Sec/Veh)	22.4	16.4	20.0	15.0	3.0
28-9	North Bound	Veh-Trips	6	7	7	8	5
		Delay (Veh-Min)	1.8	2.4	3.1	2.9	2.4
		Delay (Sec/Veh)	17.9	20.9	26.6	21.8	28.8

Intersection Statistics:	3 Periods Before Preemption	3 Periods After Preemption
Veh-Trips	100	90
Delay (Veh-Min)	22.8	24.0
Delay (Sec/Vehicle)	13.7	16.0

Appendix D

Case 3 Preemption Results

Table D.1: Time Period Movement Specific Statistics as a Result of Preemption For Intersection Number 11. Cross Street (N-S) T & R Phase is Cut By 11-Seconds, Main Street (E-W) Left Phase is Skipped, And Main Street (E-W) R & T Phase is Started 35-Seconds Earlier. 3rd Period is Preempted. Bus Direction is WB.

Link	Direction	Measures of Effectiveness	First Time Period 120-Seconds T=5:07			Second Time Period 120-Seconds T=5:09			Third Time Period 120-Seconds T=5:11			Fourth Time Period 120-Seconds T=5:13			Fifth Time Period 120-Seconds T=5:15		
			L	T	R	L	T	R	L	T	R	L	T	R	L	T	R
33-11	West Bound	Veh-Trips	1	30	7	2	38	5	0	39	9	3	29	6	0	36	5
		Delay (Veh-Min)	0.4	39.5	10.1	0.7	50.4	7.5	0.0	23.3	5.6	7.0	29.4	6.8	0.0	43.6	6.6
		Delay (Sec/Veh)	21.6	79.0	86.8	19.5	79.6	90.2	0.0	35.8	37.5	140.2	60.8	67.5	0.0	72.6	79.7
1-11	East Bound	Veh-Trips	13	12	2	10	22	1	0	25	3	13	21	4	10	23	5
		Delay (Veh-Min)	24.0	7.0	1.0	22.9	12.2	0.2	0.0	7.9	0.7	63.2	13.8	3.0	66.9	39.9	3.9
		Delay (Sec/Veh)	110.9	35.1	29.7	137.3	33.2	10.2	0.0	19.0	13.4	291.9	39.3	44.7	401.6	104.1	47.3
17-11	South Bound.	Veh-Trips	14	10	9	13	8	4	13	8	3	15	15	5	11	9	9
		Delay (Veh-Min)	17.5	8.8	9.9	18.5	6.0	3.1	23.7	10.3	3.8	19.9	22.6	9.7	9.4	10.2	20.3
		Delay (Sec/Veh)	75.0	52.8	65.9	85.2	44.9	47.0	109.6	77.6	75.0	79.7	90.4	116.2	51.1	68.0	135.6
16-11	North Bound.	Veh-Trips	8	8	4	7	7	3	5	8	0	4	17	4	3	9	3
		Delay (Veh-Min)	8.1	3.8	3.8	4.8	5.0	3.3	4.3	10.1	0.0	3.09	21.0	4.7	1.7	9.1	1.4
		Delay (Sec/Veh)	61.1	28.2	56.7	40.9	43.1	66.8	52.0	76.1	0.0	44.7	74.1	70.7	33.4	60.5	28.2

Intersection Statistics:	3 Periods Before Preemption	3 Periods After Preemption
Veh-Trips	351	374
Delay (Veh-Min)	367.8	505.3
Delay (Sec/Vehicle)	62.9	81.0

Table D.2: Time Period Specific Statistics as a Result of Preemption For Intersection Number 6. 10-Seconds of Early Start For Main Street EB / 10-Seconds Cut From Cross Street NB and Main Street WB left. Third Time Period is Preempted. Bus Direction is East Bound.

Link	Direction	Measures of Effectiveness	1st Time Period 60 -Seconds T = 5:13		2nd Time Period 60-Seconds T = 5:14		3rd Time Period 60-Seconds T = 5:15		4th Time Period 60-Seconds T = 5:16		5th Time Period 60-Seconds T = 5:17	
			L	R	L	R	L	R	L	R	L	R
5-6	West Bound	Veh-Trips	13	15	15	5	11	15	16	9	15	6
		Delay (Veh-Min)	1.7	2.2	3.6	0.8	1.4	1.8	4.9	1.3	1.5	0.6
		Delay (Sec/Veh)	7.8	8.6	14.2	10.0	7.7	7.2	18.3	8.3	5.8	6.3
			Total		Total		Total		Total		Total	
7-6	East Bound	Veh-Trips	7		11		14		5		15	
		Delay (Veh-Min)	2.0		6.1		9.3		2.0		14.1	
		Delay (Sec/Veh)	17.1		33.0		39.9		24.0		56.4	
24-6	North Bound	Veh-Trips	12		13		12		16		11	
		Delay (Veh-Min)	1.6		2.4		2.6		2.2		1.9	
		Delay (Sec/Veh)	8.0		11.1		13.2		8.3		10.4	

Intersection Statistics:	3 Periods Before Preemption	3 Periods After Preemption
Veh-Trips	143	145
Delay (Veh-Min)	31.8	43.6
Delay (Sec/Vehicle)	13.3	18.0

Table D.3: <u>Time Period Specific</u> Statistics as a Result of Preemption For Intersection Number 3. Main Street (E-W) Green Has Started 3-Seconds Earlier / Cross Street (N-S) is Cut by 3-Seconds. Third Time Period is Preempted. Bus Direction is East Bound.

Link	Direction	Measures of Effectiveness	1st Time Period 60-Seconds T=5:19	2nd Time Period 60-Seconds T=5:20	3rd Time Period 60-Seconds T=5:21	4th Time Period 60-Seconds T=5:22	5th Time Period 60-Seconds T=5:23
2-3	West Bound	Veh-Trips	30	25	29	22	29
		Delay (Veh-Min)	11.3	3.7	6.8	4.5	8.3
		Delay (Sec/Veh)	22.6	8.9	14.1	12.3	17.2
4-3	East Bound	Veh-Trips	31	21	26	34	27
		Delay (Veh-Min)	18.9	3.9	16.6	12.1	14.8
		Delay (Sec/Veh)	36.6	11.1	38.3	21.4	33.0
20-3	North Bound	Veh-Trips	4	6	10	8	4
		Delay (Veh-Min)	2.7	4.8	9.0	9.1	2.5
		Delay (Sec/Veh)	40.5	48.2	54.0	68.3	36.8
21-3	South Bound	Veh-Trips	8	9	6	7	9
		Delay (Veh-Min)	2.0	2.7	1.7	2.9	4.0
		Delay (Sec/Veh)	15.0	17.7	17.0	24.9	26.8

<u>Intersection Statistics:</u>	**<u>3 Periods Before Preemption</u>**	**<u>3 Periods After Preemption</u>**
Veh-Trips	198	211
Delay (Veh-Min)	75.1	92.3
Delay (Sec/Vehicle)	22.8	26.2

Table D.4: Time Period Specific Statistics as a Result of Preemption For Intersection Number 10. Main Street (E-W) Green is Extended for 3-Seconds / Cross Street (N-S) is Cut by 3-Seconds. Third Time Period is Preempted. Bus Direction is East Bound.

Link	Direction	Measures of Effectiveness	1st Time Period 60-Seconds T=5:22	2nd Time Period 60-Seconds T=5:23	3rd Time Period 60-Seconds T=5:24	4th Time Period 60-Seconds T=5:25	5th Time Period 60-Seconds T=5:26
9-10	West Bound	Veh-Trips	13	16	10	16	13
		Delay (Veh-Min)	3.7	2.5	1.7	4.4	1.9
		Delay (Sec/Veh)	17.1	9.4	10.2	16.5	8.8
32-10	East Bound	Veh-Trips	9	8	11	8	9
		Delay (Veh-Min)	1.0	0.3	0.9	0.5	1.0
		Delay (Sec/Veh)	6.7	2.3	4.9	3.4	6.7
31-10	South Bound	Veh-Trips	1	1	2	1	1
		Delay (Veh-Min)	0.4	0.6	0.9	0.3	0.5
		Delay (Sec/Veh)	24.0	36.0	27.0	18.0	30.0
30-10	North Bound	Veh-Trips	2	2	2	3	2
		Delay (Veh-Min)	0.3	0.1	0.9	0.9	0.7
		Delay (Sec/Veh)	9.0	3.0	27.0	18.0	21.0

Intersection Statistics:	3 Periods Before Preemption	3 Periods After Preemption
Veh-Trips	74	78
Delay (Veh-Min)	12.3	14.6
Delay (Sec/Vehicle)	10.0	11.2

Table D.5: Time Period Movement Specific Statistics as a Result of Preemption For Intersection Number 11. Main Street (E-W) R & T Phase is Extended For 25-Seconds, While Cross Street (N-S) Left Phase is Skipped. Part of the 2nd and Part of the 3rd Time Periods are Preempted. Bus Direction is WB.

Link	Direction	Measures of Effectiveness	First Time Period 120-Seconds T=5:23			Second Time Period 120-Seconds T=5:25			Third Time Period 120-Seconds T=5:27			Fourth Time Period 120-Seconds T=5:29			Fifth Time Period 120-Seconds T=5:31		
			L	T	R	L	T	R	L	T	R	L	T	R	L	T	R
33-11	West Bound	Veh-Trips	2	31	5	1	43	6	3	33	10	3	30	7	0	36	2
		Delay (Veh-Min)	1.1	43.7	6.9	1.8	60.2	6.8	3.1	17.9	7.0	3.0	24.2	8.0	0.0	38.1	3.0
		Delay (Sec/Veh)	33.3	84.5	83.2	109.2	84.0	67.8	62.2	32.5	41.7	59.0	48.4	68.7	0.0	63.6	90.3
1-11	East Bound	Veh-Trips	11	27	9	11	29	3	16	27	6	14	19	6	14	24	4
		Delay (Veh-Min)	70.8	40.4	10.9	69.8	42.9	3.4	100.2	31.5	4.8	86.8	17.3	4.4	92.0	32.3	2.3
		Delay (Sec/Veh)	386.3	89.9	72.3	380.3	88.7	68.8	375.8	69.9	47.8	370.2	54.8	47.8	394.4	80.7	34.8
17-11	South Bound.	Veh-Trips	7	13	6	3	11	9	2	15	6	16	10	9	12	6	10
		Delay (Veh-Min)	7.1	14.7	13.5	3.0	16.1	18.2	7.1	24.9	14.8	47.0	7.8	22.3	27.0	6.0	27.4
		Delay (Sec/Veh)	61.3	67.7	135.3	60.0	87.8	121.2	213.0	99.7	147.8	176.4	46.6	148.9	134.9	59.5	164.4
16-11	North Bound.	Veh-Trips	5	8	5	1	14	0	4	11	1	7	11	2	9	10	1
		Delay (Veh-Min)	3.0	4.4	3.4	0.2	10.7	0.0	11.9	9.3	0.7	9.9	10.2	1.0	9.8	2.7	1.3
		Delay (Sec/Veh)	36.6	33.1	40.8	10.2	45.7	0	178.2	50.9	43.2	85.1	55.7	29.1	65.2	46.0	79.2

Intersection Statistics:	3 Periods Before Preemption	3 Periods After Preemption
Veh-Trips	403	396
Delay (Veh-Min)	690.4	721.8
Delay (Sec/Vehicle)	102.8	109.4

Table D.6: Time Period Specific Statistics as a Result of Preemption For Intersection Number 6. 10-Seconds of advanced Green For Main Street EB / 10-Seconds Cut From Cross Street NB and Main Street WB left. Period Extended is The Third Time Period. Bus Direction is East Bound.

Link	Direction	Measures of Effectiveness	1st Time Period 60 -Seconds T = 5:29		2nd Time Period 60-Seconds T = 5:30		3rd Time Period 60-Seconds T = 5:31		4th Time Period 60-Seconds T = 5:32		5th Time Period 60-Seconds T = 5:33	
			L	R	L	R	L	R	L	R	L	R
5-6	West Bound	Veh-Trips	11	10	15	10	14	10	21	12	6	8
		Delay (Veh-Min)	1.1	1.1	2.7	1.5	0.4	1.1	4.7	1.9	1.0	0.9
		Delay (Sec/Veh)	5.8	6.5	11.0	8.9	1.7	6.5	13.4	9.3	9.8	6.8
			Total		Total		Total		Total		Total	
7-6	East Bound	Veh-Trips	7		11		20		3		12	
		Delay (Veh-Min)	4.4		8.8		14.8		2.9		9.3	
		Delay (Sec/Veh)	37.7		48.0		44.4		58.0		46.5	
24-6	North Bound	Veh-Trips	14		12		9		16		13	
		Delay (Veh-Min)	2.4		1.6		1.8		3.8		3.4	
		Delay (Sec/Veh)	10.3		8.0		12.3		14.3		15.7	

Intersection Statistics:	3 Periods Before Preemption	3 Periods After Preemption
Veh-Trips	140	134
Delay (Veh-Min)	34.6	45.9
Delay (Sec/Vehicle)	14.8	20.6

Table D.7: Time Period Specific Statistics as a Result of Preemption For Intersection Number 2. Main Street (E-W) Right & Thru Phase is Extended For 16 Seconds / Cross Street (N-S) is Skipped. Third Time Period is Preempted. Bus Direction is East Bound.

Link	Direction	Measures of Effectiveness	First Time Period 60-Seconds T=5:35			Second Time Period 60-Seconds T=5:36			Third Time Period 60-Seconds T=5:37			Fourth Time Period 60-Seconds T=5:38			Fifth Time Period 60-Seconds T=5:39		
			L	T	R	L	T	R	L	T	R	L	T	R	L	T	R
1-2	West Bound	Veh-Trips	1	23	2	3	29	6	2	14	1	4	27	10	2	19	6
		Delay (Veh-Min)	0.2	8.4	0.4	1.7	11.4	2.7	2.1	1.7	0.1	1.9	9.9	3.5	1.6	4.6	1.6
		Delay (Sec/Veh)	13.8	21.9	12.9	33.5	23.5	26.6	61.8	7.1	7.2	28.7	22.0	21.1	48.6	14.5	16.2
3-2	East Bound	Veh-Trips	7	27	3	7	24	8	0	27	7	10	23	9	7	25	4
		Delay (Veh-Min)	4.7	14.5	1.7	4.3	10.6	4.7	0.0	7.4	2.4	14.1	8.5	2.9	9.4	8.4	1.8
		Delay (Sec/Veh)	40.4	32.2	34.4	36.5	26.4	35.6	0.0	16.5	20.8	84.8	22.0	19.1	80.1	20.1	27.3
18-2	South Bound.	Veh-Trips	NA	NA	3	NA	NA	2	NA	NA	2	NA	NA	3	NA	NA	1
		Delay (Veh-Min)	NA	NA	0.7	NA	NA	0.3	NA	NA	0.2	NA	NA	0.4	NA	NA	0.1
		Delay (Sec/Veh)	NA	NA	13.4	NA	NA	7.8	NA	NA	5.4	NA	NA	7.4	NA	NA	3.6
19-2	North Bound.	Veh-Trips	NA	NA	3	NA	NA	2	NA	NA	5	NA	NA	3	NA	NA	4
		Delay (Veh-Min)	NA	NA	0.7	NA	NA	0.6	NA	NA	1.1	NA	NA	0.4	NA	NA	1.1
		Delay (Sec/Veh)	NA	NA	13.4	NA	NA	17.1	NA	NA	13.4	NA	NA	7.2	NA	NA	15.8

Intersection Statistics:	3 Periods Before Preemption	3 Periods After Preemption
Veh-Trips	226	215
Delay (Veh-Min)	98.0	85.2
Delay (Sec/Vehicle)	26.0	23.8

Table D.8: <u>Time Period Movement Specific</u> Statistics as a Result of Preemption For Intersection Number 11. Main Street (E-W) R & T Phase Started Earlier, While Cross Street (N-S) T & R and Main Street Left Phases Were Skipped. 3rd Time Periods is Preempted. Bus Direction is WB.

Link	Direction	Measures of Effectiveness	First Time Period 120-Seconds T=5:37			Second Time Period 120-Seconds T=5:39			Third Time Period 120-Seconds T=5:41			Fourth Time Period 120-Seconds T=5:43			Fifth Time Period 120-Seconds T=5:45		
			L	T	R	L	T	R	L	T	R	L	T	R	L	T	R
33-11	West Bound	Veh-Trips	1	30	7	6	35	6	0	48	3	3	34	4	3	33	4
		Delay (Veh-Min)	1.4	40.6	12.7	8.2	46.5	6.8	0.0	20.4	1.0	6.1	27.5	4.4	1.3	29.8	3.1
		Delay (Sec/Veh)	85.2	81.1	109.1	82.0	79.7	67.8	0.0	25.5	20.8	122.4	48.6	66.0	25.0	54.1	46.8
1-11	East Bound	Veh-Trips	11	20	5	12	25	7	0	36	3	12	21	5	13	22	3
		Delay (Veh-Min)	79.2	32.3	3.8	85.7	40.5	7.7	0.0	46.2	1.1	107.9	35.7	3.5	120.1	34.3	1.9
		Delay (Sec/Veh)	432.2	96.8	45.2	428.7	97.3	66.2	0	77.0	21.2	539.4	102.0	41.6	554.5	93.5	37.0
17-11	South Bound.	Veh-Trips	13	12	8	13	11	8	10	0	0	13	13	10	12	13	8
		Delay (Veh-Min)	29.7	14.5	26.8	27.2	12.3	26.7	18.2	0.0	0.0	25.7	39.5	46.6	15.2	35.3	32.9
		Delay (Sec/Veh)	137.3	72.3	201.0	125.6	67.1	200.5	109.1	0.0	0.0	118.8	182.4	279.4	76.2	162.8	246.9
16-11	North Bound.	Veh-Trips	6	12	3	5	5	9	2	0	0	5	17	3	3	16	6
		Delay (Veh-Min)	6.2	10.7	1.6	2.1	3.8	3.5	3.2	0.0	0.0	4.0	38.2	9.1	2.0	24.0	11.1
		Delay (Sec/Veh)	61.5	53.6	31.2	25.8	45.0	23.1	95.6	0.0	0.0	47.9	134.7	182.8	39.2	89.8	111.4

<u>Intersection Statistics:</u>	<u>3 Periods Before Preemption</u>	<u>3 Periods After Preemption</u>
Veh-Trips	403	378
Delay (Veh-Min)	790.1	749.4
Delay (Sec/Vehicle)	117.6	118.9

Table D.9: Time Period Specific Statistics as a Result of Preemption For Intersection Number 9. Main Street (E-W) Green Has Started 5-Seconds Earlier / Cross Street (N-S) is Cut by 5-Seconds. Third Time Period is Preempted. Bus Direction is East Bound.

Link	Direction	Measures of Effectiveness	1st Time Period 60-Seconds T=5:38	2nd Time Period 60-Seconds 5:39	3rd Time Period 60-Seconds T=5:40	4th Time Period 60-Seconds T=5:41	5th Time Period 60-Seconds T=5:42
8-9	West Bound	Veh-Trips	13	11	13	15	15
		Delay (Veh-Min)	7.0	3.9	3.3	2.4	2.6
		Delay (Sec/Veh)	32.3	21.3	15.2	9.6	10.4
10-9	East Bound	Veh-Trips	11	10	9	10	12
		Delay (Veh-Min)	3.2	1.7	2.8	1.3	2.2
		Delay (Sec/Veh)	17.5	10.2	18.7	7.8	11.0
29-9	South Bound	Veh-Trips	1	3	2	3	2
		Delay (Veh-Min)	0.2	1.2	0.5	0.9	0.4
		Delay (Sec/Veh)	12.0	24.0	15.0	18.0	12.0
28-9	North Bound	Veh-Trips	8	7	6	7	9
		Delay (Veh-Min)	2.4	2.2	1.4	3.1	3.7
		Delay (Sec/Veh)	18.0	18.9	14.0	26.6	24.7

Intersection Statistics:	3 Periods Before Preemption	3 Periods After Preemption
Veh-Trips	91	93
Delay (Veh-Min)	27.8	23.8
Delay (Sec/Vehicle)	18.3	15.4

Table D.10: Time Period Specific Statistics as a Result of Preemption For Intersection Number 9. Main Street (E-W) Green is Extended for 19 Seconds / Cross Street (N-S) Phase is Skipped. Third Time Period is Preempted. Bus Direction is West Bound.

Link	Direction	Measures of Effectiveness	1st Time Period 60-Seconds T=5:42	2nd Time Period 60-Seconds 5:43	3rd Time Period 60-Seconds T=5:44	4th Time Period 60-Seconds T=5:45	5th Time Period 60-Seconds T=5:46
8-9	West Bound	Veh-Trips	15	14	14	10	16
		Delay (Veh-Min)	2.6	0.4	5.0	0.7	7.4
		Delay (Sec/Veh)	10.4	6.0	21.4	4.2	27.8
10-9	East Bound	Veh-Trips	12	9	9	7	12
		Delay (Veh-Min)	2.2	1.2	0.8	2.5	1.3
		Delay (Sec/Veh)	11.0	8.0	5.3	21.4	6.5
29-9	South Bound	Veh-Trips	2	2	0	4	3
		Delay (Veh-Min)	0.4	0.4	0.0	3.6	1.4
		Delay (Sec/Veh)	12.0	12.0	0.0	54.0	28.0
28-9	North Bound	Veh-Trips	9	6	1	9	10
		Delay (Veh-Min)	3.7	1.0	0.3	11.2	10.2
		Delay (Sec/Veh)	24.7	10.0	18.0	74.7	61.2

Intersection Statistics:	3 Periods Before Preemption	3 Periods After Preemption
Veh-Trips	84	97
Delay (Veh-Min)	18.8	43.4
Delay (Sec/Vehicle)	13.4	26.8

Appendix E

Case 4 Preemption Results

Table E.1: <u>Time Period Movement Specific</u> Statistics as a Result of Preemption For Intersection Number 11. Cross Street (N-S) T & R Phase is Cut By 11-Seconds, Main Street (E-W) Left Phase is Skipped, And Main Street (E-W) R & T Phase Started 35-Seconds Earlier. Preemption and Compensation are in the 3rd and 4th Periods, respectively. Bus Direction is West Bound.

Link	Direction	Measures of Effectiveness	First Time Period 120-Seconds T=5:07			Second Time Period 120-Seconds T=5:09			Third Time Period 120-Seconds T=5:11			Fourth Time Period 120-Seconds T=5:13			Fifth Time Period 120-Seconds T=5:15			Sixth Time Period 120-Seconds T=5:17		
			L	T	R	L	T	R	L	T	R	L	T	R	L	T	R	L	T	R
33-11	W. Bound	Veh-Trips	1	30	7	2	38	5	0	39	9	3	7	2	0	32	5	1	30	4
		Delay (Veh-Min)	0.4	39.5	10.1	0.7	50.4	7.5	0.0	23.3	5.6	7.0	12.0	3.8	0.0	81.1	13.2	0.2	81.1	13.2
		Delay (Sec/Veh)	21.6	79.0	86.8	19.5	79.6	90.2	0.0	35.8	37.5	140.2	102.8	114.6	0.0	152.0	159.0	13.8	170.8	186.9
1-11	E. Bound	Veh-Trips	13	12	2	10	22	1	0	25	3	21	8	2	12	36	4	15	39	6
		Delay (Veh-Min)	24.0	7.0	1.0	22.9	12.2	0.2	0.0	7.9	0.7	98.6	9.2	2.4	53.4	78.8	7.2	76.4	53.4	10.3
		Delay (Sec/Veh)	110.9	35.1	29.7	137.3	33.2	10.2	0.0	19.0	13.4	281.7	69.1	72.9	267.0	131.4	107.8	305.6	82.2	103.2
17-11	S. Bound.	Veh-Trips	14	10	9	13	8	4	13	8	3	19	15	5	4	11	12	9	13	8
		Delay (Veh-Min)	17.5	8.8	9.9	18.5	6.0	3.1	23.7	10.3	3.8	21.9	22.6	9.7	5.8	9.4	22.2	10.9	11.6	12.8
		Delay (Sec/Veh)	75.0	52.8	65.9	85.2	44.9	47.0	109.6	77.6	75.0	69.0	90.4	116.2	87.6	51.5	111.2	72.7	53.7	95.7
16-11	N. Bound.	Veh-Trips	8	8	4	7	7	3	5	8	0	4	17	4	3	9	3	5	12	4
		Delay (Veh-Min)	8.1	3.8	3.8	4.8	5.0	3.3	4.3	8.1	0.0	2.4	21.3	4.7	3.2	7.6	1.0	3.7	11.5	3.7
		Delay (Sec/Veh)	61.1	28.2	56.7	40.9	43.1	66.8	52.0	61.0	0.0	36.5	75.1	70.7	65.0	50.4	20.2	44.3	57.7	56.0

Table E.2: Time Period Specific Statistics as a Result of Preemption For Intersection Number 6. 10-Seconds of Early Start For Main Street EB / 10-Seconds Cut From Cross Street NB and Main Street WB left. Third Time Period is Preempted. Bus Direction is East Bound.

Link	Direction	Measures of Effectiveness	1st Time Period 60 -Seconds T = 5:13		2nd Time Period 60-Seconds T = 5:14		3rd Time Period 60-Seconds T = 5:15		4th Time Period 60-Seconds T = 5:16		5th Time Period 60-Seconds T = 5:17	
			L	R	L	R	L	R	L	R	L	R
5-6	West Bound	Veh-Trips	20	17	10	6	6	14	13	15	13	9
		Delay (Veh-Min)	2.4	2.2	1.9	0.7	1.0	2.1	3.8	2.4	1.4	1.0
		Delay (Sec/Veh)	7.3	7.8	11.3	7.0	9.6	9.0	17.4	9.5	6.4	6.9
			Total		Total		Total		Total		Total	
7-6	East Bound	Veh-Trips	7		12		13		5		16	
		Delay (Veh-Min)	2.0		6.6		8.7		2.0		14.3	
		Delay (Sec/Veh)	17.1		33.0		39.9		24.0		53.6	
24-6	North Bound	Veh-Trips	12		13		12		16		11	
		Delay (Veh-Min)	1.6		2.7		2.6		2.2		1.9	
		Delay (Sec/Veh)	8.0		12.5		13.2		8.3		10.4	

Table E.3: Time Period Specific Statistics as a Result of Preemption For Intersection Number 3. Main Street (E-W) Green Has Started 3-Seconds Earlier / Cross Street (N-S) is Cut by 3-Seconds. Third Time Period is Preempted. Bus Direction is East Bound.

Link	Direction	Measures of Effectiveness	1st Time Period 60-Seconds T=5:19	2nd Time Period 60-Seconds T=5:20	3rd Time Period 60-Seconds T=5:21	4th Time Period 60-Seconds T=5:22	5th Time Period 60-Seconds T=5:23
2-3	West Bound	Veh-Trips	24	22	30	20	24
		Delay (Veh-Min)	5.2	2.4	6.1	3.2	5.5
		Delay (Sec/Veh)	13.0	6.5	12.2	9.6	13.8
4-3	East Bound	Veh-Trips	29	21	34	26	27
		Delay (Veh-Min)	18.1	4.7	16.2	6.4	14.7
		Delay (Sec/Veh)	37.4	13.4	28.6	14.8	32.7
20-3	North Bound	Veh-Trips	1	4	8	8	4
		Delay (Veh-Min)	0.3	3.6	9.8	12.0	2.6
		Delay (Sec/Veh)	18.0	54.0	73.5	90.0	39.0
21-3	South Bound	Veh-Trips	9	8	7	9	7
		Delay (Veh-Min)	3.0	2.2	2.3	3.5	2.7
		Delay (Sec/Veh)	20.0	16.5	19.7	23.3	23.1

Table E.4: Time Period Specific Statistics as a Result of Preemption For Intersection Number 5. Main Street (E-W) Green is Extended / Cross Street (N-S) is Skipped. Third Time Period is Preempted. No Compensation. Bus Direction is West Bound.

Link	Direction	Measures of Effectiveness	1st Time Period 60-Seconds T=5:19	2nd Time Period 60-Seconds T=5:20	3rd Time Period 60-Seconds T=5:21	4th Time Period 60-Seconds T=5:22	5th Time Period 60-Seconds T=5:23
4-5	West Bound	Veh-Trips	28	22	28	22	21
		Delay (Veh-Min)	10.3	13.1	8.1	8.3	6.3
		Delay (Sec/Veh)	22.1	35.7	17.4	22.6	18.0
6-5	East Bound	Veh-Trips	19	19	28	20	20
		Delay (Veh-Min)	2.7	2.9	2.8	2.4	3.6
		Delay (Sec/Veh)	8.5	9.2	6.0	7.2	10.8
22-5	North Bound	Veh-Trips	3	3	3	2	3
		Delay (Veh-Min)	1.2	1.2	0.6	0.7	0.8
		Delay (Sec/Veh)	24.0	24.0	12.0	21.0	16.0
23-5	South Bound	Veh-Trips	2	1	1	2	2
		Delay (Veh-Min)	0.6	0.3	0.9	1.3	0.3
		Delay (Sec/Veh)	18.0	18.0	54.0	39.0	9.0

Table E.5: Time Period Specific Statistics as a Result of Preemption For Intersection Number 10. Main Street (E-W) Green is Extended for 3-Seconds / Cross Street (N-S) is Cut by 3-Seconds. Third Time Period is Preempted. Bus Direction is East Bound.

Link	Direction	Measures of Effectiveness	1st Time Period 60-Seconds T=5:22	2nd Time Period 60-Seconds T=5:23	3rd Time Period 60-Seconds T=5:24	4th Time Period 60-Seconds T=5:25	5th Time Period 60-Seconds T=5:26
9-10	West Bound	Veh-Trips	16	14	10	21	10
		Delay (Veh-Min)	3.8	2.0	2.2	3.9	1.8
		Delay (Sec/Veh)	14.2	8.6	13.2	11.1	10.8
32-10	East Bound	Veh-Trips	7	10	11	8	9
		Delay (Veh-Min)	1.0	0.6	0.8	0.5	1.0
		Delay (Sec/Veh)	8.6	3.6	4.4	3.8	6.7
31-10	South Bound	Veh-Trips	1	1	2	1	1
		Delay (Veh-Min)	0.4	0.5	1.0	0.2	0.5
		Delay (Sec/Veh)	24.0	30.0	30.0	12.0	30.0
30-10	North Bound	Veh-Trips	3	2	2	3	2
		Delay (Veh-Min)	0.4	0.2	0.8	0.9	0.8
		Delay (Sec/Veh)	8.0	6.0	24.0	18.0	24.0

Table E.6: Time Period Movement Specific Statistics as a Result of Preemption For Intersection Number 11. Cross Street (N-S) T & R & Main Street (E-W) Left Phases are Skipped, And Main Street (E-W) R & T Phase Started Earlier. Preemption and Compensation are in the 3rd and 4th Periods, respectively. Bus Direction is West Bound.

Link	Direction	Measures of Effectiveness	First Time Period 120-Seconds T=5:23			Second Time Period 120-Seconds T=5:25			Third Time Period 120-Seconds T=5:27			Fourth Time Period 120-Seconds T=5:29			Fifth Time Period 120-Seconds T=5:132			Sixth Time Period 120-Seconds T=5:33		
			L	T	R	L	T	R	L	T	R	L	T	R	L	T	R	L	T	R
33-11	W. Bound	Veh-Trips	2	28	6	1	37	5	0	65	15	6	0	0	0	32	8	3	36	2
		Delay (Veh-Min)	1.1	82.5	22.8	1.8	118.5	16.8	0.0	111.6	24.6	12.6	0.0	0.0	0.0	96.8	26.7	2.5	114.2	7.1
		Delay (Sec/Veh)	31.5	176.8	228.3	109.2	192.2	201.6	0.0	103.0	98.4	126.2	0.0	0.0	367.3	164.2	145.8	387.9	146.0	107.7
1-11	E. Bound	Veh-Trips	10	27	7	10	26	1	0	25	3	24	0	0	13	34	7	13	34	9
		Delay (Veh-Min)	43.3	24.4	6.6	48.6	19.9	0.8	0.0	14.4	0.9	156.5	0.0	0.0	79.6	93.1	17.0	84.0	82.7	16.2
		Delay (Sec/Veh)	259.7	54.2	57.0	291.6	46.0	46.2	0.0	34.6	17.2	391.1	0.0	0.0	367.3	164.2	145.8	387.9	146.0	107.7
17-11	S. Bound.	Veh-Trips	11	12	7	3	13	6	13	0	0	19	16	10	2	14	16	12	5	12
		Delay (Veh-Min)	10.5	11.9	16.3	3.8	20.5	13.8	14.7	0.0	0.0	12.3	55.6	48.2	4.1	23.4	56.2	16.8	4.6	31.0
		Delay (Sec/Veh)	57.2	59.6	139.9	76.8	94.7	138.0	67.9	0.0	0.0	39.0	208.4	289.2	123.6	100.5	210.9	84.2	55.2	154.8
16-11	N. Bound.	Veh-Trips	5	8	5	6	14	0	4	0	0	8	22	2	3	10	2	8	11	2
		Delay (Veh-Min)	3.1	4.4	3.4	4.2	10.7	0.0	4.7	0.0	0.0	5.4	48.9	4.0	4.1	5.4	2.3	5.1	10.0	2.6
		Delay (Sec/Veh)	37.0	33.1	40.8	42.4	45.8	0.0	70.4	0.0	0.0	40.7	133.4	118.8	81.4	32.2	68.7	38.5	54.4	77.1

Table E.7: <u>Time Period Specific</u> Statistics as a Result of Preemption For Intersection Number 6. 10-Seconds of Advance Green For Main Street EB / 10-Seconds Cut From Cross Street NB and Main Street WB left. Period Extended is The Third Time Period. Bus Direction is East Bound.

Link	Direction	Measures of Effectiveness	1st Time Period 60 -Seconds T = 5:29		2nd Time Period 60-Seconds T = 5:30		3rd Time Period 60-Seconds T = 5:31		4th Time Period 60-Seconds T = 5:32		5th Time Period 60-Seconds T = 5:33	
			L	R	L	R	L	R	L	R	L	R
5-6	West Bound	Veh-Trips	10	8	14	15	3	6	20	14	3	6
		Delay (Veh-Min)	1.1	1.0	3.8	2.4	0.3	0.7	4.1	2.2	0.5	0.5
		Delay (Sec/Veh)	6.5	7.5	16.5	9.4	6.0	6.7	12.3	9.5	10.2	7.1
			Total		Total		Total		Total		Total	
7-6	East Bound	Veh-Trips	7		11		20		3		13	
		Delay (Veh-Min)	4.5		8.7		14.6		2.9		9.9	
		Delay (Sec/Veh)	37.7		47.5		43.8		58.0		45.7	
24-6	North Bound	Veh-Trips	14		12		9		16		13	
		Delay (Veh-Min)	2.4		1.6		1.9		3.8		4.2	
		Delay (Sec/Veh)	10.3		8.0		12.7		14.3		19.4	

Table E.8: Time Period Specific Statistics as a Result of Preemption For Intersection Number 3. Main Street (E-W) Green Has Started 3-Seconds Earlier / Cross Street (N-S) is Cut by 3-Seconds. Third Time Period is Preempted. Bus Direction is East Bound.

Link	Direction	Measures of Effectiveness	1st Time Period 60-Seconds T=5:35	2nd Time Period 60-Seconds T=5:36	3rd Time Period 60-Seconds T=5:37	4th Time Period 60-Seconds T=5:38	5th Time Period 60-Seconds T=5:39
2-3	West Bound	Veh-Trips	31	30	31	25	20
		Delay (Veh-Min)	8.0	6.7	6.7	6.8	4.2
		Delay (Sec/Veh)	15.5	13.4	13.0	16.3	12.6
4-3	East Bound	Veh-Trips	26	17	34	33	30
		Delay (Veh-Min)	15.4	11.7	17.4	24.1	13.4
		Delay (Sec/Veh)	35.5	41.3	30.7	43.8	26.8
20-3	North Bound	Veh-Trips	7	8	6	8	8
		Delay (Veh-Min)	2.4	3.3	2.7	4.4	4.6
		Delay (Sec/Veh)	20.6	24.7	27.0	33.0	34.5
21-3	South Bound	Veh-Trips	7	9	7	8	9
		Delay (Veh-Min)	2.4	3.5	2.5	3.2	3.1
		Delay (Sec/Veh)	20.6	23.3	21.4	24.0	20.7

Table E.9: Time Period Specific Statistics as a Result of Preemption For Intersection Number 9. Main Street (E-W) Green Has Started 5-Seconds Earlier / Cross Street (N-S) is Cut by 5-Seconds. Third Time Period is Preempted. Bus Direction is East Bound.

Link	Direction	Measures of Effectiveness	1st Time Period 60-Seconds T=5:38	2nd Time Period 60-Seconds 5:39	3rd Time Period 60-Seconds T=5:40	4th Time Period 60-Seconds T=5:41	5th Time Period 60-Seconds T=5:42
9	West Bound	Veh-Trips	7	8	14	7	18
		Delay (Veh-Min)	2.4	3.9	7.4	2.2	6.4
		Delay (Sec/Veh)	20.6	29.3	31.7	18.9	21.3
10-9	East Bound	Veh-Trips	13	8	10	10	11
		Delay (Veh-Min)	3.1	0.7	3.0	1.1	2.1
		Delay (Sec/Veh)	14.3	5.2	18.0	6.6	11.5
29-9	South Bound	Veh-Trips	1	3	2	3	2
		Delay (Veh-Min)	0.1	1.2	0.5	0.7	0.4
		Delay (Sec/Veh)	6.0	24.0	15.0	14.0	12.0
28-9	North Bound	Veh-Trips	7	8	6	6	10
		Delay (Veh-Min)	2.4	2.2	1.5	3.3	4.5
		Delay (Sec/Veh)	20.6	16.5	15.0	33.0	27.0

Table E.10: <u>Time Period Movement Specific</u> Statistics as a Result of Preemption For Intersection Number 11. Cross Street (N-S) T & R Phase is Cut By 11-Seconds, Main Street (E-W) Left Phase is Skipped, And Main Street (E-W) R & T Phase Started 35-Seconds Earlier. Preemption and Compensation are in the 3rd and 4th Periods, respectively. Bus Direction is West Bound.

Link	Direction	Measures of Effectiveness	First Time Period 120-Seconds T=5:37			Second Time Period 120-Seconds T=5:39			Third Time Period 120-Seconds T=5:41			Fourth Time Period 120-Seconds T=5:43			Fifth Time Period 120-Seconds T=5:45			Sixth Time Period 120-Seconds T=5:47		
			L	T	R	L	T	R	L	T	R	L	T	R	L	T	R	L	T	R
33-11	W. Bound	Veh-Trips	1	29	9	6	29	7	0	75	8	3	0	0	3	33	5	0	38	3
		Delay (Veh-Min)	1.4	95.4	29.4	8.2	96.3	26.4	0.0	142.1	16.8	6.2	0.0	0.0	1.4	109.9	17.0	0.0	127.8	9.5
		Delay (Sec/Veh)	85.2	197.3	196.0	82.0	199.3	226.0	0.0	113.7	125.6	123.6	0.0	0.0	28.2	199.8	204.1	0.0	201.7	190.6
1-11	E. Bound	Veh-Trips	12	27	4	10	29	5	0	33	3	21	0	0	11	33	7	14	26	4
		Delay (Veh-Min)	81.5	43.3	3.8	66.9	54.8	6.3	0.0	26.9	0.9	183.4	0.0	0.0	90.8	65.8	14.9	114.7	52.8	6.1
		Delay (Sec/Veh)	407.7	96.3	57.7	401.3	113.4	76.2	0.0	48.9	18.6	524.0	0.0	0.0	495.0	119.6	127.4	491.4	121.8	91.4
17-11	S. Bound.	Veh-Trips	11	12	9	12	11	8	14	0	0	15	15	12	5	22	14	13	12	7
		Delay (Veh-Min)	17.9	14.5	31.1	20.8	12.3	26.7	19.2	0.0	0.0	13.3	45.2	55.3	7.1	36.2	36.0	11.9	10.8	16.3
		Delay (Sec/Veh)	97.5	72.4	207.4	104.2	67.1	200.4	82.3	0.0	0.0	53.2	180.6	276.3	85.7	98.8	154.3	55.1	54.1	139.9
16-11	N. Bound.	Veh-Trips	5	12	3	5	5	7	2	0	0	5	20	3	3	13	7	2	13	3
		Delay (Veh-Min)	5.4	10.7	1.6	2.2	3.8	3.5	3.2	0.0	0.0	3.2	44.5	9.1	3.7	11.6	8.9	1.4	10.3	3.2
		Delay (Sec/Veh)	65.0	53.6	31.2	26.5	45.0	29.7	95.7	0.0	0.0	38.8	133.6	182.8	74.0	53.0	76.0	42.6	47.4	64.2

Appendix F

Volume Sensitivity Results

Table F.1: Cumulative Network Statistics; With and Without Preemption.

		Veh-Trips	Delay Veh-Hours	Delay Min/Veh-Trips
U2:1	No Preemption	4721	90.42	1.15
	Preemp., No Comp.	4648	116.02	1.50
	Preemp. W/ Comp.	4704	104.87	1.34
U3:1	No Preemption	4860	74.12	0.92
	Preemp., No Comp.	4833	89.96	1.12
	Preemp. W/ Comp.	4732	94.11	1.19
U5:1	No Preemption	4417	32.91	0.45
	Preemp., No Comp.	4409	33.67	0.46
	Preemp. W/ Comp.	4369	35.75	0.49
M2:1	No Preemption	4140	36.31	0.53
	Preemp., No Comp.	4118	53.96	0.79
	Preemp. W/ Comp.	4143	44.68	0.65
M3:1	No Preemption	3690	22.87	0.37
	Preemp., No Comp.	3690	23.75	0.39
	Preemp. W/ Comp.	3690	23.25	0.38
M5:1	No Preemption	3324	16.83	0.30
	Preemp., No Comp.	3324	17.32	0.31
	Preemp. W/ Comp.	3324	17.46	0.32
L2:1	No Preemption	2770	14.96	0.32
	Preemp., No Comp.	2769	15.88	0.34
	Preemp. W/ Comp.	2770	15.53	0.34
L3:1	No Preemption	2462	11.78	0.29
	Preemp., No Comp.	2460	12.01	0.29
	Preemp. W/ Comp.	2460	12.14	0.30
L5:1	No Preemption	2218	8.96	0.24
	Preemp., No Comp.	2218	9.08	0.25
	Preemp. W/ Comp.	2218	9.35	0.25

Table F.2: Cumulative Network-Wide Bus Statistics; With and Without Preemption. Route 1.

		Bus Trips	T-Travel-Time (Bus-Min)	Mean T-Time (Sec/Bus)	Person Trips	Person T-Time (Min)
U2:1	No Preemption	7	15.4	131.7	175	383.8
	Preemp., No Comp.	7	14.2	122.0	175	355.8
	Preemp. W/ Comp.	7	14.4	123.8	175	361.3
U3:1	No Preemption	7	15.6	134.1	175	391.3
	Preemp., No Comp.	7	14.5	123.8	175	362.2
	Preemp. W/ Comp.	7	15.0	127.9	175	374.2
U5:1	No Preemption	7	14.3	122.4	175	357.5
	Preemp., No Comp.	7	14.1	120.4	175	351.3
	Preemp. W/ Comp.	7	14.0	121.9	175	530.4
M2:1	No Preemption	7	15.4	131.8	175	383.8
	Preemp., No Comp.	7	14.4	123.9	175	360.8
	Preemp. W/ Comp.	7	14.5	124.5	175	362.5
M3:1	No Preemption	7	15.3	131.2	175	382.1
	Preemp., No Comp.	7	14.3	122.7	175	357.5
	Preemp. W/ Comp.	7	14.4	123.8	175	360.0
M5:1	No Preemption	7	14.3	122.5	175	357.1
	Preemp., No Comp.	7	14.0	120.4	175	350.0
	Preemp. W/ Comp.	7	14.1	120.9	175	352.1
L2:1	No Preemption	7	15.1	129.8	175	378.3
	Preemp., No Comp.	7	14.1	121.3	175	353.3
	Preemp. W/ Comp.	7	14.2	121.7	175	354.6
L3:1	No Preemption	7	14.5	124.7	175	363.3
	Preemp., No Comp.	7	14.0	120.0	175	349.6
	Preemp. W/ Comp.	7	14.0	120.6	175	350.8
L5:1	No Preemption	7	14.1	125.0	175	351.7
	Preemp., No Comp.	7	13.8	118.3	175	345.0
	Preemp. W/ Comp.	7	13.8	118.3	175	345.0

Table F.3: Cumulative Network-Wide Bus Statistics. With and Without Preemption. Route 2

		Bus Trips	T-Travel-Time (Bus-Min)	Mean T-Time (Sec/Bus)	Person Trips	Person T-Time (Min)
U2:1	No Preemption	10	23.1	132.6	250	578.3
	Preemp., No Comp.	10	21.3	122.7	250	533.3
	Preemp. W/ Comp.	10	21.4	123.1	250	535.4
U3:1	No Preemption	10	23.8	142.5	250	594.2
	Preemp., No Comp.	10	23.6	134.8	250	590.4
	Preemp. W/ Comp.	10	25.2	143.5	250	629.6
U5:1	No Preemption	10	22.4	128.0	250	558.8
	Preemp., No Comp.	10	21.2	121.7	250	529.6
	Preemp. W/ Comp.	10	21.2	121.9	250	530.4
M2:1	No Preemption	10	21.6	129.4	250	540.8
	Preemp., No Comp.	10	20.5	123.0	250	513.3
	Preemp. W/ Comp.	10	20.5	123.0	250	513.3
M3:1	No Preemption	10	21.3	127.1	250	531.3
	Preemp., No Comp.	10	20.3	121.2	250	506.3
	Preemp. W/ Comp.	10	20.3	121.2	250	506.3
M5:1	No Preemption	10	21.2	126.9	250	530.0
	Preemp., No Comp.	10	20.0	120.0	250	500.4
	Preemp. W/ Comp.	10	20.0	120.0	250	500.4
L2:1	No Preemption	10	21.1	126.5	250	527.1
	Preemp., No Comp.	10	20.1	120.6	250	502.1
	Preemp. W/ Comp.	10	20.1	120.6	250	502.1
L3:1	No Preemption	10	21.9	125.8	250	548.3
	Preemp., No Comp.	10	21.1	121.3	250	528.3
	Preemp. W/ Comp.	10	21.1	121.3	250	528.3
L5:1	No Preemption	10	21.8	125.2	250	545.4
	Preemp., No Comp.	10	20.6	118.8	250	516.3
	Preemp. W/ Comp.	10	20.6	118.8	250	516.3

Table F.4: Cumulative NETSIM Person Measures of Effectiveness For; Before and After Preemption.

		Person Trips	Travel Time (Person-Min)	Delay (Person-Min)	Avge. Delay Sec / Person
U2:1	No Preemption	6543	8803	6665	61.1
	Preemp., No Comp.	6448	10735	8628	80.3
	Preemp. W/ Comp.	6520	9917	7786	71.7
U3:1	No Preemption	6698	7677	5488	49.2
	Preemp., No Comp.	6690	8912	6726	60.3
	Preemp. W/ Comp.	6521	9309	7168	66.0
U5:1	No Preemption	6148	4191	2182	21.3
	Preemp., No Comp.	6141	4235	2282	21.8
	Preemp. W/ Comp.	6121	4435	2435	23.9
M2:1	No Preemption	5773	4337	2450	25.5
	Preemp., No Comp.	5755	5714	3833	40.0
	Preemp. W/ Comp.	5782	5001	3112	32.3
M3:1	No Preemption	5718	3141	1431	16.6
	Preemp., No Comp.	5181	3214	1521	17.6
	Preemp. W/ Comp.	5181	3174	1481	17.1
M5:1	No Preemption	4706	2560	1022	13.0
	Preemp., No Comp.	4706	2598	1059	13.5
	Preemp. W/ Comp.	4706	2610	1072	13.7
L2:1	No Preemption	3985	2241	939	14.1
	Preemp., No Comp.	3994	2314	1009	15.2
	Preemp. W/ Comp.	3994	2291	984	14.8
L3:1	No Preemption	3613	1905	724	12.0
	Preemp., No Comp.	3613	1922	741	12.3
	Preemp. W/ Comp.	3615	1936	754	12.5
L5:1	No Preemption	3297	1606	528	9.6
	Preemp., No Comp.	3297	1616	538	9.8
	Preemp. W/ Comp.	3297	1624	560	10.2

Table F.5: Cumulative NETSIM Bus Statistics; With and Without Preemption.

		Total Links Bus-Trips	Travel Time (Min)	Delay Time (Min)	Avg. Delay (Min)
U2:1	No Preemption	18	19.8	14.0	46.7
	Preemp., No Comp.	18	18.4	11.5	38.3
	Preemp. W/ Comp.	18	18.6	11.8	39.3
U3:1	No Preemption	17	20.7	15.3	54.0
	Preemp., No Comp.	18	19.6	13.7	45.7
	Preemp. W/ Comp.	18	21.6	15.6	52.0
U5:1	No Preemption	18	18.2	12.3	41.0
	Preemp., No Comp.	18	17.2	11.3	37.7
	Preemp. W/ Comp.	18	17.2	11.3	37.7
M2:1	No Preemption	17	18.2	12.6	44.5
	Preemp., No Comp.	17	16.6	11.0	38.8
	Preemp. W/ Comp.	17	16.7	11.1	39.2
M3:1	No Preemption	17	17.8	12.2	43.1
	Preemp., No Comp.	17	16.3	10.7	37.8
	Preemp. W/ Comp.	17	16.4	10.8	38.1
M5:1	No Preemption	17	16.9	11.4	40.2
	Preemp., No Comp.	17	16.1	10.7	37.1
	Preemp. W/ Comp.	17	18.2	10.6	37.4
L2:1	No Preemption	17	17.8	12.2	43.1
	Preemp., No Comp.	17	16.2	10.7	37.8
	Preemp. W/ Comp.	17	16.3	10.8	38.1
L3:1	No Preemption	18	18.0	12.1	40.3
	Preemp., No Comp.	18	17.0	11.1	37.0
	Preemp. W/ Comp.	18	17.0	11.1	37.0
L5:1	No Preemption	18	17.6	11.7	39.0
	Preemp., No Comp.	18	16.6	10.7	35.7
	Preemp. W/ Comp.	18	16.6	10.7	35.7

Table F.6: Cumulative Network Statistics; Four Periods Before and Four Periods After For Each of the Four Selected Preemptions. (No Compensation).

	Preemption #	Before / After	Veh-Trips	Delay Veh-Hours	Delay Min/Veh-Trips
U2:1	1	Before	351	301.6	51.56
	1	After	348	323.5	55.78
	2	Before	323	399.7	74.25
	2	After	342	454.7	79.77
	3	Before	335	521.1	93.33
	3	After	329	568.6	103.7
	4	Before	339	648.3	114.74
	4	After	329	631.3	115.13
U3:1	1	Before	360	226.7	37.78
	1	After	332	237.7	42.96
	2	Before	348	344.3	59.36
	2	After	352	407.2	69.41
	3	Before	355	324.6	54.86
	3	After	312	327.0	62.88
	4	Before	371	571.2	92.38
	4	After	347	416.7	72.05
U5:1	1	Before	332	92.7	16.75
	1	After	316	98.1	18.63
	2	Before	302	140.0	27.36
	2	After	327	167.0	30.64
	3	Before	333	107.7	19.41
	3	After	316	105.6	20.05
	4	Before	325	96.2	17.76
	4	After	315	118.5	22.57
M2:1	1	Before	398	177.4	35.72
	1	After	307	202.9	39.65
	2	Before	301	249.2	49.67
	2	After	301	175.5	34.98
	3	Before	300	186.8	37.36
	3	After	293	217.7	44.58
	4	Before	311	209.2	40.36
	4	After	279	220.7	47.46

	Preemption #	Before / After	Veh-Trips	Delay Veh-Hours	Delay Min/Veh-Trips
M3:1	1	Before	264	71.4	16.23
	1	After	272	85.1	18.77
	2	Before	263	85.0	19.39
	2	After	269	76.8	17.13
	3	Before	274	77.9	17.06
	3	After	265	94.8	21.46
	4	Before	264	66.8	15.18
	4	After	264	105.1	24.00
M5:1	1	Before	241	52.4	13.05
	1	After	243	58.8	14.52
	2	Before	246	66.9	16.32
	2	After	242	53.6	13.29
	3	Before	240	53.6	13.40
	3	After	243	60.8	15.01
	4	Before	244	51.3	12.61
	4	After	240	59.5	14.88
L2:1	1	Before	202	51.6	15.33
	1	After	206	50.1	14.59
	2	Before	206	80.1	23.33
	2	After	200	50.3	15.09
	3	Before	201	46.4	13.85
	3	After	202	62.0	18.42
	4	Before	201	47.4	14.15
	4	After	204	63.5	18.68
L3:1	1	Before	183	38.3	12.56
	1	After	181	32.5	10.77
	2	Before	182	52.5	17.31
	2	After	178	34.0	11.46
	3	Before	178	36.6	12.34
	3	After	180	46.9	15.63
	4	Before	179	37.6	12.60
	4	After	183	40.1	13.15

	Preemption #	Before / After	Veh-Trips	Delay Veh-Hours	Delay Min/Veh-Trips
L5:1	1	Before	161	26.5	9.88
	1	After	164	29.3	10.72
	2	Before	163	36.0	13.25
	2	After	159	29.4	11.09
	3	Before	157	25.2	9.63
	3	After	163	25.9	9.53
	4	Before	160	22.2	8.32
	4	After	160	27.9	10.46

Appendix G

Results of Carpools

Table G.1: Cumulative Network Statistics; With and Without Preemption*.

	Veh-Trips	Delay Veh-Hours	Delay Min/Veh-Trips
Base Case Volume	3041	121.16	2.39
Preemption	3043	121.15	2.39
5.0% Carpool	3048	114.76	2.26
Preemption	3035	115.06	2.27
10.0% Carpool	3020	106.97	2.13
Preemption	2880	116.23	2.42

* Results are based on a 20-minute simulation period.

Table G.2: Cumulative NETSIM Person MOEs; Before and After Preemption.

	Person Trips	Person Mile	Travel Time (Person-Min)	Delay (Person-Min)	Avge. Delay Sec / Person
Base Volume	13150	4581	16078	8933	40.8
With Preemption	13208	4602	16113	8935	40.6
5.0% Carpool	13622	4767	16101	8661	38.1
With Preemption	13564	4772	16034	8589	38.0
10% Carpool	13632	4794	15639	8159	35.9
With Preemption	13139	4668	16003	8721	39.8

Table G.3: Cumulative NETSIM Bus Statistics; With and Without Preemption.

	Total Links Bus-Trips	Travel Time (Min)	Delay Time (Min)	Avge. Delay Sec / B-Trip
Base Case Volume	28	55.9	38.3	82.1
With Preemption	28	55.7	38.1	81.6
5.0% Carpool	29	56.5	38.1	78.8
With Preemption	28	54.7	36.8	78.9
10% Carpool	29	56.2	38.0	78.6
With Preemption	29	55.4	37.1	76.8

Table G.4: Cumulative Network-Wide Bus Statistic; With and Without Preemption.

	Route	Bus Trips	Total Travel-Time (Bus-Min)	Mean Travel-Time (Sec/Bus)	Person Trips	Person Travel-Time (Min)
Base Case Volume	1	1	29.3	1314.0	25	732.5
	2	1	26.5	1208.4	25	662.9
With Preemption	1	1	29.1	1304.3	25	728.8
	2	1	26.4	1200.9	25	660.0
5.0% Carpool	1	1	31.1	1329.7	25	778.8
	2	1	25.3	1136.0	25	631.3
With Preemption	1	1	29.7	1329.1	25	743.3
	2	1	25.0	1113.0	25	625.4
10.0% Carpool	1	1	31.1	1327.6	25	778.8
	2	1	26.8	1110.7	25	668.8
With Preemption	1	1	30.3	1275.8	25	757.9
	2	1	25.0	1114.0	25	625.0

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