An Assessment Methodology for Emergency Vehicle Traffic Signal Priority Systems

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(ABSTRACT)

Emergency vehicle traffic signal priority systems allow emergency vehicles such as fire and emergency medical vehicles to request and receive a green traffic signal indication when approaching an intersection. Such systems have been around for a number of years, however, there is little understanding of the costs and benefits of such systems once they are deployed. This research develops an improved method to assess the travel time impacts of emergency vehicle traffic signal priority systems for transportation planning analyses.

The research investigates the current state of available methodologies used in assessing the costs and benefits of emergency vehicle traffic signal priority systems. The ITS Deployment Analysis System (IDAS) software is identified as a recently developed transportation planning tool with cost and benefit assessment capabilities for emergency vehicle traffic signal priority systems. The IDAS emergency vehicle traffic signal priority methodology is reviewed and recommendations are made to incorporate the estimation of non-emergency vehicle travel time impacts into the current methodology. To develop these improvements, a simulation analysis was performed to model an emergency vehicle traffic signal priority system under a variety of conditions. The simulation analysis was implemented using the CORSIM traffic simulation software as the tool. Results from the simulation analysis were used to make recommendations for enhancements to the IDAS emergency vehicle traffic signal priority methodology. These enhancements include the addition of non-emergency vehicle travel time impacts as a function of traffic volume on the transportation network. These impacts were relatively small and ranged from a 1.1% to 3.3% travel time increase for a one-hour analysis period

to a 0.6% to 1.7% travel time increase for a two-hour analysis period. The enhanced methodology and a sample application of the methodology are presented as the results of this research. In addition, future research activities are identified to further improve assessment capabilities for emergency vehicle traffic signal priority systems.

DEDICATION

I would like to dedicate this work to my parents, Gene and June McHale, for all the sacrifices they made to ensure their children had a good education.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF EQUATIONS

CHAPTER 1. INTRODUCTION

This chapter provides an introduction to emergency vehicle traffic signal priority systems, their potential benefits, and the need to assess these benefits. The need for better assessment techniques is introduced as the primary topic of this research and the research objective is described. A brief outline for the remaining chapters is also provided.

1.1 TRAFFIC SIGNAL PRIORITY SYSTEMS

Traffic congestion on streets and roads is the cause of numerous hours of delay on our transportation networks equating to millions of wasted dollars as well as untold stress on travelers. Included in the mix of vehicles delayed by congestion are emergency vehicles such as fire and emergency medical vehicles. Priority treatments at traffic signalized intersections have been proposed and implemented as one means to alleviate the congestion and delay faced by emergency vehicles using our streets and roads (Obenberger and Collura, 2001).

Traffic signal priority systems allow certain vehicles to request favorable treatment at traffic signalized intersections. The request for priority is essentially a request for a green traffic signal indication. This request for priority can be sent to the traffic signal in a number of ways, with a vehicle-based infrared transmitter being one of the most popular. A priority request that is favorably received will result in a green light on the requesting intersection approach as soon as possible based on the priority level of the requestor. This favorable treatment is typically applied to emergency vehicles and/or transit vehicles. When transit vehicles are recipients of favorable treatment, they may be assigned a lower level of priority as compared with police, fire, and emergency medical vehicles. Therefore, implementation of priority treatments at signalized intersections would likely involve several levels of traffic signal priority corresponding to the different types of vehicles operating under various conditions. When priority is granted to an emergency vehicle, it is usually implemented by immediately interrupting the normal traffic signal operations to service the emergency vehicle, this is known as traffic signal preemption. Another typical application of traffic signal preemption is at railroad grade crossings. The primary purpose of emergency vehicle traffic signal preemption is to allow the emergency vehicle to get to the incident scene faster and more safely.

Priority treatments at signalized intersections have been in existence for a number of years and have a widespread deployment across the United States. In a survey conducted by the Virginia Department of Transportation (VDOT) in 1997, they found that 94% of the 50 agencies that responded had deployed traffic signal preemption systems. Traffic signal preemption systems implement the highest level of priority by immediately preempting current traffic signal operations to give a green signal to emergency vehicles. However, VDOT's study found that for agencies with deployed traffic signal preemption systems, the systems were implemented on only 5.27% of their traffic signals (Asmussen, 1997). This data may be indicative of a number of issues:

- traffic signal preemption is only needed at certain intersections
- there is little benefit associated with the use of traffic signal preemption
- there are disbenefits associated with the use of traffic signal preemption
- there is a poor understanding of the benefits of traffic signal preemption.

The limited use of traffic signal preemption systems is likely related to all of the issues listed above. However, with the current emphasis on the deployment of Intelligent Transportation Systems (ITS) throughout our nation's transportation systems, there has been a renewed interest in assessing the benefits associated with priority treatments at signalized intersections.

1.2 CURRENT ASSESSMENT TECHNIQUES

Current methodologies related to assessing the benefits of priority treatments at signalized intersections includes interviews with stakeholders, field data collection, computer simulation and modeling, or some combination of these. Interviews with stakeholders (e.g., traffic engineers, transit operators, police and fire agencies, and emergency medical providers) give insight into the system benefits; both actual and perceived. Field data collection involves the installation of a system and the collection of data used to assess the performance of the system including the traffic-related benefits on the priority route and the potential disbenefits to non-priority traffic. Due to the extensive cost of field data collection, perhaps the best way to capture the benefits of priority treatments at signalized intersections is through the use of traffic simulation models. This method has been used in the past with success as documented in (Dale, et.al., 1999), (Khasnabis, et.al., 1999), (Bullock, et.al., 1998), and (Nelson and Bullock, 2000).

In addition to assessing the traditional traffic-related benefits of priority treatments at signalized intersections, Khasnabis, et.al., have proposed a method to assess the economic costs and benefits of priority treatments at signalized intersections applied to transit vehicles. Using simulation to determine the traffic-related benefits along a particular transit route, measures of savings with respect to travel time delay, fuel consumption, and emissions are calculated. These measures are then converted to monetary values and their sum total is defined as the threshold for the system cost. This maximum cost value encompasses costs for the purchase, operation, and maintenance of a traffic signal preemption system.

While traffic simulation models are powerful tools for assessing the traffic-related benefits of priority treatments at signalized intersections, they do have their limitations. First, they are extremely data intensive, making them difficult to model more than a limited size transportation network. Second, traffic simulation models do not account for the cost component of assessing and evaluating priority treatments at signalized intersections. Although Khasnabis, et.al., does address the cost component by way of determining the maximum cost permissible to maintain a benefit/cost ratio greater than one, there is no attempt to quantify the actual costs of traffic signal preemption systems, particularly on a regional transportation level.

Essentially, the current assessment techniques have been used for traffic and transit operational analyses and not for transportation planning analyses. This research is proposed to enhance current assessment techniques as applied to the transportation planning level analyses.

1.3 PROPOSED ENHANCEMENTS

There is a need to assess the benefits and costs of traffic signal priority treatments deployed on a regional transportation network. Such a methodology will aid decision makers and transportation planners to quantity system-wide benefits of traffic signal priority treatments on a regional level. Although this methodology could be general to support all types of vehicles, for purposes of this research, the methodology will focus on emergency vehicle traffic signal priority.

Such a methodology currently exists in the recently developed ITS Deployment Analysis System (IDAS) software. The development of IDAS was funded by the Federal Highway Administration (FHWA) to assist transportation planners in assessing the impacts of ITS deployment on regional transportation systems. (Cambridge Systematics, 2000). This research will build upon the current emergency vehicle traffic signal priority methodology in IDAS and make recommendations for its enhancement.

1.4 CENTRAL THESIS

In order to develop an enhanced methodology, this research will focus on a central thesis or hypothesis. This thesis can be stated as follows:

> The travel time impacts of traffic signal priority treatments for emergency vehicles are a function of the *traffic characteristics*, *roadway geometry*, and the *deployment configuration* of the priority system.

As an example, *traffic characteristics* may include factors such as traffic volume and speed, *roadway geometry* may include intersection spacing and number of lanes, and *deployment configuration* may include the number of emergency vehicles responding or the type of traffic signal preemption algorithm used. To develop an enhanced methodology, appropriate parameters that represent traffic characteristics, roadway geometry, and deployment configurations will be identified. However, as described in Chapter 3—Research Methodology, the hypothesis testing was limited to one parameter, namely, *traffic characteristics*, while controlling for *roadway geometry* and *deployment* *configuration*. Using microscopic traffic simulation as a tool, the above thesis will be evaluated. If the hypothesis holds true, the new methodology will be an improvement to the current methodology in terms of the specification of input parameters to produce more accurate results. If the hypothesis proves false, it would indicate that the influence of *traffic characteristics* does not significantly affect the travel time impacts of emergency vehicle priority treatments. However, a false hypothesis could also indicate a flaw in the methodology since in this case, a false hypothesis seems counterintuitive. One of the keys to the hypothesis test, is determining what constitutes statistical versus practical significance for differences in the results.

1.5 Report Organization

The report is organized as follows:

- Chapter 2 – Literature Review discusses recent research related to emergency vehicle traffic signal priority systems, the assessment techniques that have been used, and the assessment techniques that will serve as the foundation for this research.
- Chapter 3 – Research Methodology discusses the overall approach to conducting this research.
- Chapter 4 – Simulation Analysis discusses the approach to use simulation analysis as the primary tool for data collection for this research.
- Chapter 5 – Simulation Results presents the results from the simulation analysis.
- Chapter 6 – Enhanced IDAS Methodology presents the specific recommendations for improving the current IDAS methodology for assessing emergency vehicle traffic signal priority systems.
- Chapter 7 – Conclusions and Recommendations presents the overall conclusions derived from this research and recommendations for future research activities.

CHAPTER 2. LITERATURE REVIEW

This chapter presents a review of guidance documents, research activities, assessment techniques, and analysis tools related to emergency vehicle traffic signal priority systems.

2.1 OVERVIEW

There has been some recent guidance published and a number of recent research activities related to emergency vehicle traffic signal priority systems. A summary of the guidance and some of the relevant research efforts is presented below with a description of the assessment techniques used in the research. Traffic analysis tools have been the primary means to assess emergency vehicle traffic signal priority systems, and are reviewed in this chapter. Specifically, the CORridor SIMulator (CORSIM) traffic simulation software is reviewed in detail because of its use as a tool in this research. Finally, the ITS Deployment Analysis System (IDAS) software and its emergency vehicle traffic signal priority methodology is reviewed and presented to establish the baseline upon which results from this research will be applied.

2.2 TRAFFIC SIGNAL PRIORITY GUIDANCE

Until recently, there has been little guidance for the traffic engineer on emergency vehicle traffic signal priority systems. The Manual on Uniform Traffic Control Devices (MUTCD) is the national standard when it comes to traffic control devices on public roads in the United States. The latest edition of the manual has recently been published, and its guidance related to traffic signal priority is summarized below.

<u>Manual on Uniform Traffic Control Devices</u>, (FHWA et.al., 2001)
The previous edition of the MUTCD was published in 1988 and had very little guidance on traffic signal priority. There was some guidance related to traffic signal preemption, but this was specific to railroad grade crossing and was very limited. In the MUTCD Millennium Edition published in 2001, traffic signal priority systems are explicitly addressed.

The MUTCD, Section 4D.13 “Preemption and Priority Control of Traffic Control Signals” provides standards related to yellow change intervals, red clearance intervals, and pedestrian intervals when transitioning into and out of priority and preemption control. In addition, Section 4A.02 “Definitions Relating to Highway Traffic Signals” provides the following definitions related to priority control systems:

- “Emergency Vehicle Traffic Control Signal—a special traffic control signal that assigns the right-of-way to an authorized emergency vehicle.
- Preemption Control—the transfer of normal operation of a traffic control signal to a special control mode of operation.
- Priority Control—a means by which the assignment of right-of-way is obtained or modified.”

The addition of standards and guidance related to traffic signal priority control in the latest edition of the MUTCD further supports the need to develop improved assessment techniques addressing these systems.

2.3 TRAFFIC SIGNAL PRIORITY SYSTEMS RESEARCH

Recent research activities have been conducted in the area of traffic signal priority systems for both emergency vehicles and transit vehicles. Since some of the assessment techniques used in traffic signal priority for transit vehicles are also relevant to traffic signal priority for emergency vehicles, a discussion of these efforts is also included.

<u>Transition Strategies to Exit Preemption Control: State-of-the-Practice Assessment</u>, (Obenberger and Collura, 2001)

Obenberger and Collura provide a comprehensive review of current practices in the area of traffic signal priority with a focus on traffic signal preemption. The paper describes traffic signal preemption, current standards and guidelines, techniques for coordinated traffic signal control to transition into and exit from preemption, possible impacts of preemption, and different methodologies available to assess these impacts. The authors recommend that research be conducted to study the influence of different traffic signal control transition strategies on the impacts of preemption. The authors further recommend that a "software-in-the-loop" assessment methodology be used that integrates microscopic traffic simulation analysis with traffic signal controller firmware.

<u>Impact Evaluation of Emergency Vehicle Preemption on Signalized Corridor Operation</u>, (Nelson and Bullock, 2000)

In this paper, Nelson and Bullock, report on the results of a microsimulation-based analysis of traffic signal preemption for emergency vehicles. The paper provides a good discussion of the issues surrounding preemption and highlights three types of traffic signal controller transition algorithms for recovering from preemptions events: "smooth", "add only", and "dwell". Transition algorithms determine the method by which a traffic signal controller enters into and exits from a priority or preemption event. These transition algorithms are necessary to allow the traffic signal to regain timing coordination with the other traffic signals in its vicinity. A "smooth" transition allows the traffic signal controller to add or subtract up to a certain percentage of the preempted signal's cycle length per cycle until coordination is reached. The traffic signal controller determines whether it would be quicker to add or subtract this time from the timing cycle. An "add only" transition algorithm is similar to a "smooth" transition except that it will only add the time to the cycle and will not subtract time. Although "add only" insures that no phase in the timing plan will be cut short during transition, it may take longer to regain coordination then a "smooth" transition. A "dwell" transition will pause in the current signal phase until a point in time when coordination is regained. Although this may be the quickest method to regain coordination, Nelson & Bullock point out that this may have the most serious impact on delays to the non-priority traffic.

The study analyzed a section of an arterial with four signalized intersections that included a diamond interchange. The simulation analysis included seven different preemption paths through the network for the emergency vehicles, three different controller transition algorithms, and three levels of preemption events ranging from one to three preemptions during the simulation time of 22 minutes. CORSIM was used as the simulation model and hardware-in-the-loop technology was used to link the simulation to real-world traffic signal controllers in a lab environment. The results indicated that some of the key factors affecting the impact of emergency vehicle signal preemption are:

- intersection spacing
- transitioning algorithm
- saturation of the intersection
- duration of the preemption
- amount of slack time available in each intersection's cycle.

<u>Control Strategies For Transit Priority</u>, (Skabardonis, 2000)

In this paper, Skabardonis reviewed the various types of transit priority systems, the factors influencing their effectiveness, and proposed a methodology to estimate the potential benefit of transit signal priority systems using off-line traffic signal optimization and traffic simulation models. Of particular relevance to this research were the identification of key factors influencing the effectiveness of transit signal priority, namely:

- <u>transportation network configuration and characteristics</u>: single arterial, grid network, traffic signal spacing, number of lanes, pedestrian presence, type and operation of traffic signal control system (e.g., fixed time plan vs. traffic responsive plan)
- <u>network traffic patterns</u>: traffic volumes, turning movements, variability in volumes, level of congestion, interference of traffic congestion with bus operations
- <u>frequency/characteristics of transit service</u>: bus volume, type of bus operations, transit routes, bus stop location/design, amount and variability of dwell times, and communication and monitoring equipment for transit vehicles.

The methodology developed to estimate the benefits of transit priority involved the development of traffic signal timing plans using the TRANSYT-7F software to optimize traffic signals based on bus arrival times at selected intersections. These timing plans were then simulated using CORSIM and the resulting measures of effectiveness (MOEs) reported.

A Macroscopic Model for Evaluating the Impact of Emergency Vehicle Signal Preemption on Traffic, (Casturi, Lin, and Collura, 2000)

In this paper, Casturi, Lin, and Collura present a macroscopic model to assess the impact of emergency vehicle traffic signal preemption on traffic delay. The model combines cell transmission theory and traffic flow theory to assess the impact of an emergency vehicle moving through traffic and preempting a traffic signal. The emergency vehicle is treated as a moving shock wave through traffic with a user adjustable parameter controlling the reduction in flow capacity as the vehicle travels down the road. The effect of preempting the traffic signal at different points in the phasing and the effect of main street preemption versus side street preemption was studied. The model was applied to a simple network of a one lane, one-way street with three intersections. Further application of the model to a more complex network is needed as is validation of the model results.

A Transit Signal Priority Impact Assessment Methodology -- Greater Reliance on Simulation, (Dale, et.al., 1999)

In this paper, Dale, et.al., document the process used in King County, Washington by the King County Department of Transportation to develop a transit signal priority impact assessment methodology. The process involves three main components: stakeholder involvement, field data collection, and simulation. The primary recommendations from this paper are: 1) develop a formal impact assessment methodology that is accepted by the stakeholders, and 2) incorporate a stronger simulation component into the methodology.

Economic Evaluation of Signal Preemption Projects, (Khasnabis, et.al., 1999)

In this paper, Khasnabis, et.al., presents a procedure for the economic evaluation of traffic signal preemption projects. The procedure is a cost/benefit analysis that defines the maximum justified cost of a traffic signal preemption system based on the benefits derived from savings in travel delay, fuel consumption, and emissions. The procedure incorporates the use of the TRAF-NETSIM model (the precursor to CORSIM) as an analysis tool.

Review of Transit Priority Projects and Practice, (Dion, 1999).
In this paper, Dion provides a summary of current activities related to transit priority projects including high level overviews of current traffic signal priority projects, traffic signal priority systems, and traffic signal controllers currently being implemented.

Traffic Signal Preemption Study, (Asmussen, et al., 1997)
In this report, Asmussen, et.al., assesses the feasibility of implementing traffic signal preemption in Northern Virginia. The study was divided into two phases: an examination of current practices and an evaluation of traffic signal preemption technologies. The results indicated a widespread deployment of traffic signal preemption systems among traffic agencies, yet a low number of traffic signals with preemption. The technology evaluation study highlights the need for field evaluation to assess the performance capabilities of each technology under a variety of conditions. The report concludes that preemption is feasible in Northern Virginia at selected intersections.

Evaluation of Emergency Vehicle Signal Preemption on the Route 7, Virginia, Corridor, (Bullock, et.al., 1998)
In this paper, Bullock, et.al., conduct an analysis of the impact of emergency vehicle traffic signal preemption across three coordinated intersections on Route 7 near Landsdowne, Virginia. FHWA's Traffic Software Integrated System (TSIS) package (which includes the CORSIM microscopic traffic simulation) was used to perform the analysis. A hardware-in-the-loop analysis was performed using the Controller Interface Device (CID) which allowed CORSIM to directly interface with Type 170 traffic signal controllers supplied by the Virginia Department of Transportation. Results indicated that for the geometric and operational conditions studied, the impact of the emergency vehicle traffic signal preemption on the corridor was minor.

2.4 TRAFFIC ANALYSIS TOOLS

As evidenced from the above research activities, most of the analysis of impacts of traffic signal priority systems has focused on small transportation networks or corridors. These analyses have typically used traffic analysis methods including highway capacity analysis, traffic signal optimization, and microscopic traffic simulation as the primary tool for assessing impacts. In practice, these tools present the traffic operations analyst with increasing levels of complexity. A highway capacity analysis is typically the first level of analysis tool used to conduct operational analysis of traffic. Traffic signal optimization analysis provides an added level of complexity necessary to fine tune a traffic signal timing plan. Finally, traffic simulation offers the most detailed analysis available to study the nuances of traffic behavior on the individual vehicle level. Each of this categories of analysis tools are discussed in the following subsections.

2.4.1 Highway Capacity Analysis Tools

Highway capacity analysis is used to determine the capacity of a specific type or portion of a transportation facility including roadway sections, intersections (traffic signalized and unsignalized), pedestrian and bicycle facilities, and transit. The capacity of a particular transportation facility is the maximum traffic volume (e.g., vehicles per hour) at which the facility can be expected to operate. Related to the capacity analysis is a determination of quality or level of service based on the traffic demand placed on the particular facility. Highway capacity analysis is often used in the planning, design, and operation of transportation facilities. A number of software packages have been developed to implement the procedures and methodologies of highway capacity analysis.

Although a useful analysis methodology, highway capacity analysis does have its limitations. Highway capacity analysis methodologies were developed for analyzing small portions of a transportation system (e.g., a single intersection or a single section of a freeway) and do not typically do a good job at analyzing a larger transportation systems with multiple components. In addition, highway capacity analysis is based on a static demand or volume level and cannot accurately represent the dynamic operation of a transportation system. In these situations, a traffic simulation analysis should be used.

<u>Highway Capacity Manual</u>, (Transportation Research Board, 2000)
In the United States, the principle guide to highway capacity analysis is the Highway Capacity Manual produced by the Transportation Research Board. This manual was

originally published in 1950 and has been updated numerous times with the most recent update being in 2000. The Highway Capacity Manual provides a series of methodologies for assessing capacity and quality of service that are based on a wealth of empirical data. The current version of the manual includes methodologies in the following areas:

- Urban Streets
- Signalized Intersections
- Unsignalized Intersections
- Pedestrians
- Bicycles
- Two-Lane Highways
- Multilane Highways
- Freeway Facilities
- Basic Freeway Segments
- Freeway Weaving
- Ramps and Ramp Junctions
- Interchange Ramp Terminals
- Transit

As the foundation for much of the traffic analysis methodologies in use today, the Highway Capacity Manual methodologies have been coded into a variety of software packages with the most widely used being the Highway Capacity Software.

<u>Highway Capacity Software</u>, (McTrans, 2000)

The Highway Capacity Software developed by the McTrans Center is perhaps the most widely used capacity analysis tool according to the FHWA (FHWA, 2001). The Highway Capacity Software provides an easy-to-use tool for employing the procedures and methodologies described in the Highway Capacity Manual. The use of the Highway Capacity Software as an analysis tool for this research is described in Chapter 4—Simulation Analysis.

Other examples of software packages that are used for capacity and quality of service analysis include Synchro, TEAPAC, SIDRA, and HCM/Cinema.

2.4.2 Traffic Signal Optimization Tools

Traffic signal optimization is used to develop traffic signal timing plans for signalized intersections along a roadway that produce the best (or most optimal) results for some predefined output measure(s). The techniques used in traffic signal optimization are analogous to linear programming techniques where there is an objective function that defines an output variable to be minimized or maximized subject to a number of constraint variables. Two of the most common objectives in traffic signal optimization include the minimization of delay and the maximization of bandwidth. Delay is defined as the difference between the desired (or free flow) travel time on a particular section of roadway and the travel time that would actually occur. The differences between the desired and actual travel time result from impedances due to other vehicular traffic and traffic signals. Bandwidth is related to the ability to provide for the progression of platoons of vehicles from intersection to intersection by timing the traffic signals so that green lights are presented to the platoon at each successive intersection. The bandwidth is the width (in terms of time) that vehicles are presented with green lights as they travel along a roadway at a predetermined speed. Figure 2.1 shows an example of a traffic signal timing plan time-space diagram where the "green band" and the width of the green band (i.e., the bandwidth) can be seen. This figure is a representation from CORSIM of the traffic signal timing plan used in the simulation analysis portion of this research and described in detail in Chapter 4—Simulation Analysis.

The techniques and methods for traffic signal optimization have been coded into software and a number of different software packages currently exist. Some examples of existing software packages include TRANSYT-7F, Synchro, PASSER, and MAXBAND. As described in Chapter 4—Simulation Analysis, TRANSYT-7F was used in this research to develop a traffic signal timing plan.

<u>TRANSYT-7F</u>, (McTrans, 1998)

The TRANSYT-7F software, which is currently maintained and distributed by the McTrans Software Center at the University of Florida, was originally developed in the United Kingdom and has had widespread use both in the United Kingdom and in the

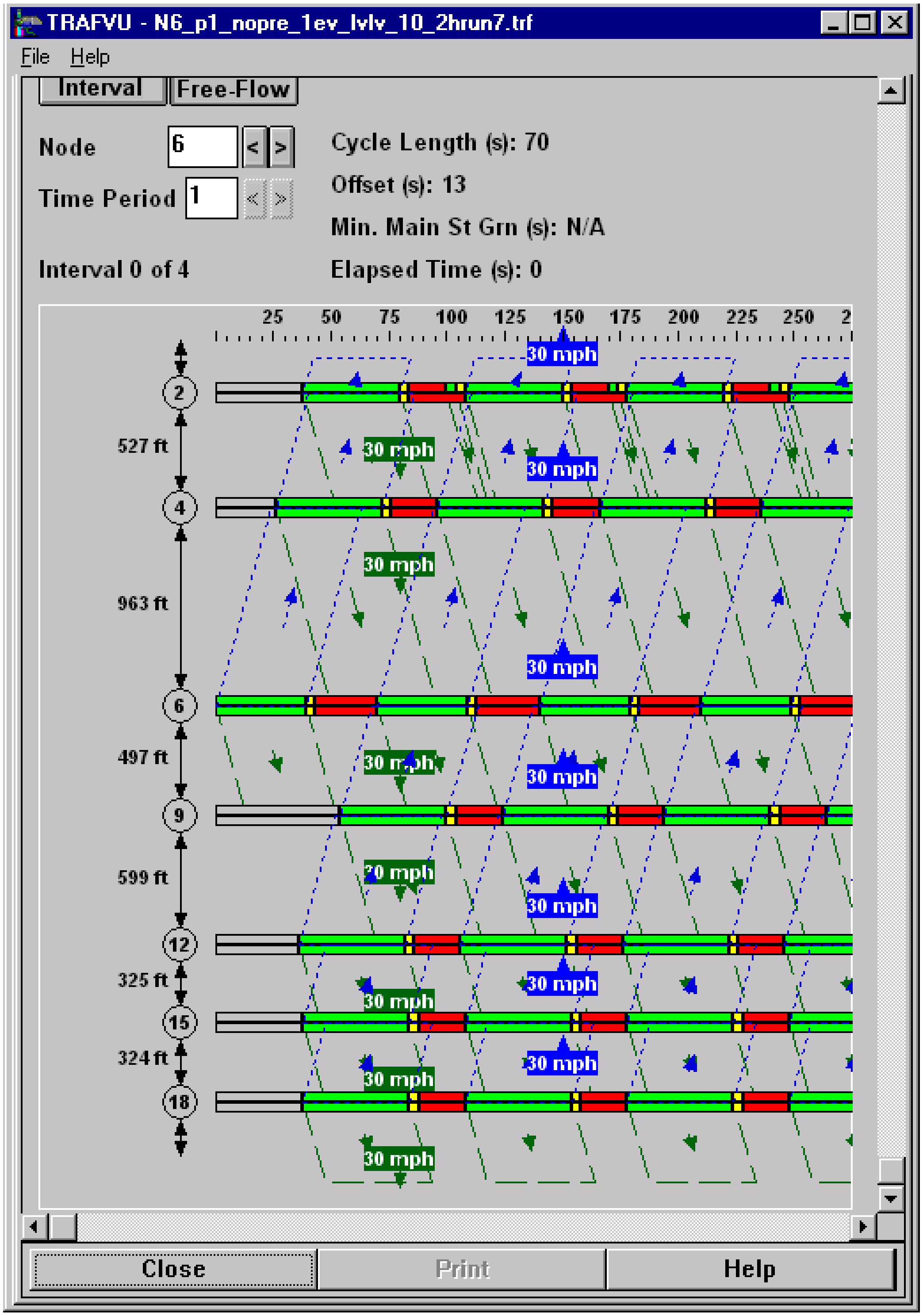


Figure 2.1. Time-Space Diagram and Bandwidth

United States. The software allows a user to develop an optimized traffic signal timing plan for an individual intersection and to develop a set of optimized, coordinated traffic signal timing plans for multiple signalized intersections. The primary optimization function used in TRANSYT-7F is the minimization of traffic delay.

2.4.3 Traffic Simulation Tools

Traffic simulation tools model the dynamic flow of vehicles along a roadway. There are essentially three main categories of traffic simulation models: macroscopic, mesoscopic, and microscopic. Macroscopic simulation tools do not model individual vehicles but instead model traffic flow using aggregate traffic speed, flow, and density relationships. Mesoscopic simulation tools do track individual vehicles, however the movement of these individual vehicles are governed by similar traffic speed, flow, and density relationships. Microscopic simulation tools, on the other hand, track individual vehicles whose movement is governed by individual driver behavior models (e.g., car following models and lane changing models). Historically, macroscopic tools have been used to model larger transportation networks because they require less computing resources as compared to microscopic models. Mesoscopic tools are the most recent of the types of models and strive to incorporate the strengths of both the macroscopic and microscopic approaches. For purposes of this research, references to traffic simulation models and tools will be focused primarily on microscopic models.

Traffic simulation analysis is particularly useful for conducting “what if” scenarios in a simulated environment prior to field implementation. These “what if” scenarios could be related to changes in roadway geometric features, lane configuration, traffic signal timing, transit routes, or any number of other traffic operational strategies or alternatives. Highway capacity analysis and traffic signal optimization are typically conducted prior to simulation analysis to assist in the development of appropriate operational alternatives. Some of the strengths of traffic simulation analysis include its ability to model traffic control devices and individual vehicles on a time step (usually one second) basis and the ability to model uncertainty through stochastic processes.

There are several different traffic simulation tools available and there have been some recent assessments of these tools. Skabardonis conducted an assessment study for the Washington State Department of Transportation where he identified over a dozen simulation models and conducted a detailed assessment of the following five: CORSIM, INTEGRATION, MITSIM, PARAMICS, and VISSIM (Skabadonis, 1999). In addition, Skabadonis provides an extensive bibliography of recent research related to traffic simulation analysis. The Institute of Transport Studies at the University of Leeds also conducted a thorough review of microscopic traffic simulation models (Institute of Transport Studies, 1997). Since the strengths and weaknesses of these simulation models vary, it is important to chosen a model that is appropriate for the analysis at hand. As described in Chapter 3—Research Methodology, the CORSIM tool was chosen as the microscopic traffic simulation software for use on this research and is described in further detail below.

2.5 CORSIM

As mentioned above, there are several microscopic traffic simulation tools available for today's transportation analyst. However, the most widely used and often cited tool has been FHWA's CORSIM (for CORridor SIMulator) software. CORSIM has its beginnings with the development of the Urban Traffic Control System (UTCS-1) in the 1970's. The UTCS-1 eventually evolved into the NETwork SIMulation (NETSIM) microscopic simulation software for surface street networks. The INTRAS microscopic simulation software for freeways was then developed and eventually evolved into the FREeway SIMulation (FRESIM) model. NETSIM and FRESIM were subsequently integrated into the CORSIM microscopic simulation tool for surface streets and freeways. FHWA continues to develop, maintain, and support the resulting CORSIM model that is now integrated into the Traffic Software Integrated System (TSIS) package. The TSIS package includes the supporting tools associated with CORSIM including the TRAFED graphical input editor and the TRAFVU output graphics and simulation animation tool.

The analytical underpinnings of the CORSIM tool have been documented in numerous reports and articles over the years. The primary resource and reference for CORSIM users is the TSIS Users Manual (ITT, 1999). Although extremely comprehensive in describing the use of CORSIM, the TSIS Users Manual does not necessarily provide all the underlying theory and equations of interest to the CORSIM user and researcher. A summary of CORSIM's underlying theory was developed by Halati, Lieu, and Walker and serves as a good reference for the CORSIM user (Halati, Lieu, & Walker, 1997). A briefing presented by Owen at the September, 2001, Traffic Models Conference in Tucson, Arizona also provides a good high level summary of CORSIM's underlying logic and operations (Owen, 2001).

CORSIM is microscopic traffic simulation software that allows a user to model the movement of vehicles on surface streets and freeways and the interaction of vehicles with other vehicles, traffic control devices, and roadway geometry. A high level view of the attributes of the CORSIM model is shown in Figure 2.2. As shown in the figure, CORSIM models the traffic system as the interaction of the roadway, detectors, traffic control devices, and vehicles; each of which has their own set of attributes.

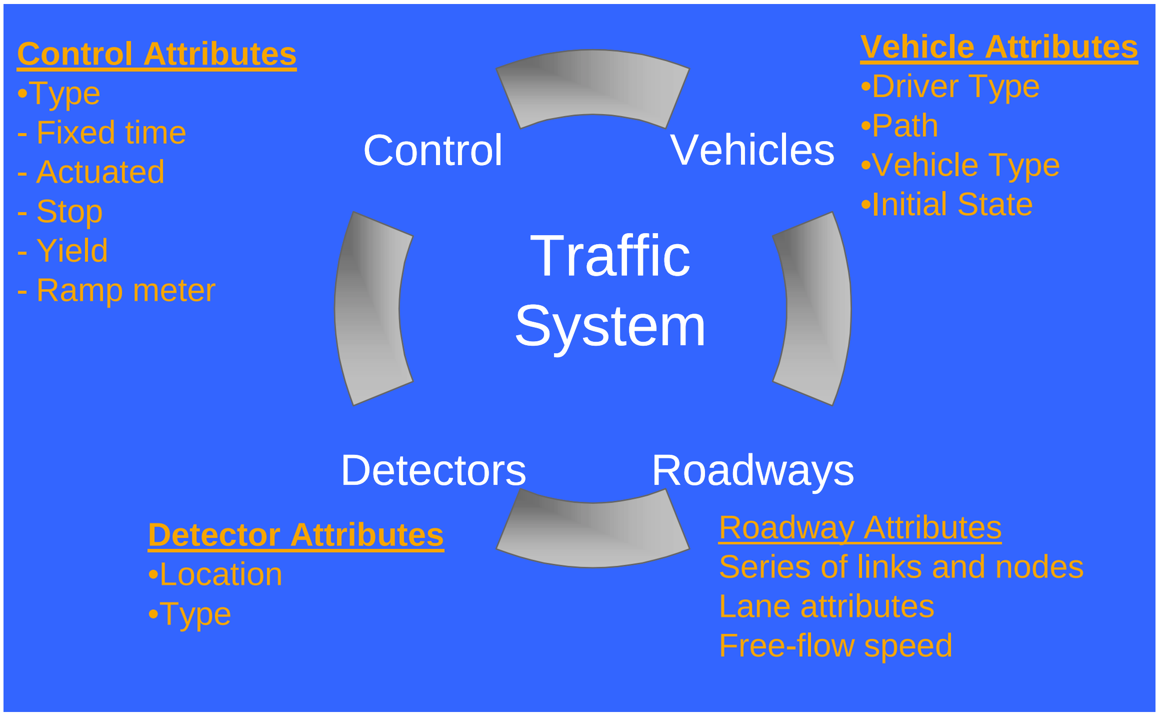


Figure 2.2. CORSIM Attributes (source: Owen, 2001)

The transportation network in CORSIM is made up of a set of nodes and links. The links are defined as the linear connection of two nodes with a user-specified length. The user may specify a link length different than the straight-line distance between the two nodes in order to account for road curvature. Some important attributes of a link include the number of lanes, lane alignment and lane connectivity descriptions, and the desired free flow speed. The desired free flow speed determines the speed vehicles strive to attain as they traverse the link and is a key calibration factor in the model. Within the model, a lane is defined as a line with no width and a vehicle may only be in one lane at any particular time. Lane changing is allowed, however as described later.

Traffic control in CORSIM is determined by stop signs, yield signs, fixed time traffic signals, actuated traffic signals, and ramp meters. The traffic control logic used in CORSIM controls the movement of the vehicles at all intersections. In the case of unsignalized intersections (i.e., stop and yield signs) and permissive turns at signals, the CORSIM gap acceptance logic is critical for vehicle movement. For surface streets, the available time gap is computed by Equation 1 below (Halati, Lieu, & Walker, 1997):

Equation 1. CORSIM Available Time Gap.

$$G = \frac{x_s - x_c}{v}$$

where G = the available time gap
x_s = the distance between the opposing vehicle and the stop line
x_c = the distance between the stop line and the conflict point
v = the opposing vehicle's speed

The acceptability of the available time gap for the moving (or discharging) vehicle is dependent upon the vehicle's driver type, the turning movement being made, and the type of traffic control at the intersection.

Fixed time traffic signal control in CORSIM implements user specified timing plans where the all of the control movements are identified by intersection approach and are assigned the timing interval as specified by the user. Coordination of multiple signals along an arterial is accomplished through the use of cycle offsets. For traffic actuated control, the user must specify more detailed information including yield points, force offs, permissive periods, and the type and location of traffic detectors used to measure the presence or passage of a vehicle over the detector.

One of the major distinguishing factors among traffic simulation tools is the manner in which vehicles are moved. This is certainly the most complex component of any traffic simulation model and is especially true for CORSIM. CORSIM's developmental evolution from the integration of the NETSIM and FRESIM models has made the vehicle movement logic in CORSIM even more complicated. The vehicle movement logic governing the surface street network (i.e., the old NETSIM logic) is not the same as the logic governing the freeway network (i.e., the old FRESIM logic). The transfer of vehicles from the surface street network to the freeway network and visa versa is handled internally in CORSIM via interface nodes to create a seamless simulation environment for the user. Some of the governing principles and theories of the CORSIM vehicle movement logic are presented below. However, since the simulation analysis conducted for this research was on a surface street-only network model, the vehicle movement logic presented corresponds to CORSIM's surface street logic (i.e., the NETSIM logic).

The movement of any particular vehicle in CORSIM depends on the status of the vehicle in terms of whether it is a leader, a follower, or an independent vehicle (Halati, Lieu, & Walker, 1997). A vehicle is a follower or a leader of another vehicle if it within its area of influence defined as a function of the vehicle separation distance and the speeds of each of the vehicles; otherwise the vehicle is an independent. For a leader vehicle or an independent vehicle, barring impedances from traffic control devices, the vehicle will seek to attain its desired free flow speed. When in car-following mode, vehicles strive to avoid collisions, however, due to the way vehicles are processed within CORSIM, sometimes "collisions" do occur. If a "collision" occurs, the vehicle is assigned the maximum deceleration and placed at the rear bumper of its leader vehicle. This method of treating "collisions" as maximum decelerations keeps vehicle crashes from occurring as a result of the vehicle movement logic.

The basic equations of motion governing a vehicle's position and speed in CORSIM are as follows (Owen, 2001):

Equation 2. CORSIM Vehicle Position.

$$X_{T+1} = X_T + V_T \cdot \Delta t + \frac{1}{2} \cdot a \cdot \Delta t^2$$

Equation 3. CORSIM Vehicle Velocity.

$$V_{T+1} = V_T + \Delta t \cdot a$$

Where X_T, X_{T+1} = Vehicle position at time T and T + 1
V_T, V_{T+1} = Vehicle velocity at time T and T + 1
Δt = Simulation time step
a = Vehicle acceleration

The vehicle acceleration is a function of several influencing factors within the model including the desire to attain free flow speed, maintain a safe car following distance, change lanes, and the comply with traffic control devices.

The surface street portion of the CORSIM model supports two types of vehicle lane changing: mandatory and discretionary. Mandatory lane changes are made so that a vehicle can complete a turn at an intersection or must react to a lane closure or lane drop. Discretionary lane changes are made to bypass a slower vehicle, join a shorter queue at an intersection, or bypass a bus station (Halati, Lieu, & Walker, 1997). For discretionary lane changes, the target lane for lane changing is selected based on the lane with the lowest impedance factor.

CORSIM has many other features that were not described here including: bus operations, HOV lane operations, ramp metering operations, incident modeling, and others. The ability of CORSIM to model traffic signal priority systems in discussed in Chapter 3—Research Methodology.

2.6 ITS Deployment Analysis System (IDAS)

The transportation planning community has been using models to assist in their assessment of transportation improvement projects for many years. To forecast travel demand, the traditional "four-step" modeling approach has been used and is embodied in a number of different planning models. The four steps in the approach are trip generation, trip distribution, mode choice, and traffic assignment.

The four-step models have been used to forecast future travel demand on the transportation system and to assess the impacts of alternative transportation improvement strategies. The costs and benefits of these transportation alternatives are then analyzed using such tools as the Surface Transportation Efficiency Analysis Model (STEAM) developed by the FHWA (FHWA, 2001).

For years, these traditional approaches and their corresponding assessment tools have served the needs of the planning community. These tools were designed to assess the impacts of traditional transportation improvements such as adding a lane of freeway, but are not designed to assess the impacts of deploying ITS improvements on the transportation system. For example, the current tools are more than adequate in modeling the effects of adding an additional lane of highway, but they cannot measure the effects of a ramp metering system on the freeway. This is what the ITS Deployment Analysis System (IDAS) is designed to do. IDAS enables the assessment of ITS improvements, using current transportation planning analysis techniques. A description of IDAS and its emergency vehicle traffic signal priority methodology is presented below. Detailed descriptions of IDAS and its methodology are found in the IDAS Users Manual (Cambridge Systematics, 2000).

2.6.1 Overview of IDAS

In general, the IDAS software is designed to pick up where the traditional "four step" planning models leave off. In fact, IDAS takes the output from "four-step" planning models as input to establish a base case scenario. After establishing a base case scenario, the IDAS user selects from a list of ITS components and “deploys” one or more ITS improvements into the base case. IDAS then executes its own travel demand model to determine the new travel patterns that emerge as a result of the ITS improvements. The incremental costs and benefits resulting from the “deployment” of the ITS components are calculated, compared to the base case scenario, and presented to the IDAS user.

This is the overall strategy that serves as the IDAS framework. Within the IDAS software, this strategy is implemented in five major modules as described below.

1. *The Input/Output Interface Module* serves to input the data from the “four step” planning models into the IDAS software. This input serves as the base case scenario for analysis and includes files that describe the regional transportation network in terms of nodes, links, and the number of trips from each origin to each destination for the forecast year being analyzed.

2. *The Alternatives Generator Module* provides the graphical interface for the user to select the ITS components to deploy on the transportation network. The user selects from a list of ITS components and “drags and drops” them onto the graphical depiction of the transportation network. The ITS components are grouped into 11 major categories as shown in Table 2.1. There is a total of 69 individual ITS components from which the user may choice. An example of an individual ITS component is the “Ramp Metering: Pre-Set Timing” option under the Freeway Traffic Management Systems category.

Table 2.1. ITS Component Categories in IDAS

Major ITS Component Categories within IDAS
Arterial Traffic Management Systems
Freeway Traffic Management Systems
Advanced Public Transit Systems
Incident Management Systems
Electronic Payment Collection Systems
Railroad Grade Crossings
Emergency Management Systems
Regional Multimodal Traveler Information Systems
Commercial Vehicle Operations
Advanced Vehicle Control and Safety Systems
Supporting Deployments

3. *The Benefits Module* quantifies the benefits resulting from the deployment of the ITS components. The default benefit values within IDAS are based on ITS deployments and/or research studies with references provided and the ability for the user to change the default values, if desired. It is within this module that IDAS incorporates an internal travel demand model to re-evaluate travel patterns based on the addition of the ITS components. These benefits are calculated as are the benefits from the base case scenario so that only those benefits attributable to the ITS improvements can be identified. The Benefits Module is subdivided into the following four submodules:
    a. Travel Time/Throughput Submodule.
    b. Environment Submodule.
    c. Safety Submodule.
    d. Travel Time Reliability Submodule.

4. *The Cost Module* tracks the estimated costs to deploy the ITS components selected by the user. Each ITS component within IDAS requires one or more pieces of ITS equipment for deployment. The default equipment requirements

and their associated costs may be modified by the user if more customized data is available. In addition to the equipment costs, the percentage of public versus private funding, the deployment schedule, and the use of shared equipment are also factored into the cost analysis.

5. *The Alternative Comparison Module* compares the benefits and the costs of the ITS component improvements to the benefits and costs of the base case scenario, presents the results, and allows for sensitivity and risk analysis on parameters. Part of this module is the conversion of all benefits into a monetary value (e.g., the hourly value of in-vehicle travel time). As with the other modules, the user may change any of the default parameters in the Alternative Comparison Module, if desired.

2.6.2 IDAS Emergency Vehicle Signal Priority Methodology

One of the 69 ITS components within IDAS is the Emergency Vehicle Signal Priority component. The methodology employed by the Emergency Vehicle Signal Priority component within IDAS is currently fairly simplistic. For example it uses an increase in travel speed (current default of 30%) for streets on which Emergency Vehicle Signal Priority is deployed, assumes no effect on cross streets, and asks the user to specify the percentage of emergency vehicle traffic volume (current default of 0.1%) on the street and the total number of vehicles equipped with the signal priority systems (for cost purposes). Using this characterization and the location where the Emergency Vehicle Signal Priority systems are deployed, IDAS computes the overall costs and benefits for the specific transportation network under analysis. The methodology for the characterization of Emergency Vehicle Signal Priority within IDAS is described in further detail in the following sections.

2.6.2.1 Input Data Requirements

IDAS input data requirements can be organized into three main levels: Project & Alternative, Market Sector, and ITS Improvement. The Project & Alternative level is data which characterizes elements in the transportation analysis which effect all Market Sectors and ITS Improvements. The Market Sector level is data which characterizes travelers and trips into distinct groupings (e.g., auto home-based-work trips, transit trips, etc.). The ITS Improvement level is data which describes improvements to the transportation system that may effect one or more Market Sectors. The input data requirements of interest for the Emergency Vehicle Signal Priority improvements are at the ITS Improvement level and are presented below. However, general descriptions of the Project & Alternative level and Market level are also provided to give the reader a better understanding of the input data requirements for IDAS analyses.

Project and Alternative Level Input Data

At the Project & Alternative level, the data required for all IDAS analyses is shown in Table 2.2.

Table 2.2. IDAS Project & Alternative Level Input Data

IDAS Project Level & Alternative Level Input Data Requirements	
Input Data	**Description**
Project name	User defined name of project
Project analysis year	Calendar year representing the analysis
Alternative name	User defined name for alternative(s) being the analyzed
Alternative time period	Time period for which the travel demand data represents (e.g., AM Hour, AM Peak Period, Daily, Other)
Facility type of centroid connector	Identifies the numeric code for the centroid connector types in the node file
Node coordinates file	Name of file containing network node coordinate data (node number, X-coord, Y-coord)
Network links files	Name of file containing network link information (node IDs, distance, volume, speed, capacity, number of lanes, area type, facility type)
Network turn prohibitor file	Identifies the links with turn prohibitions

Market Sector Level Input Data

At the Market Sector level, the data required for all IDAS analyses is shown in Table 2.3.

Table 2.3. IDAS Market Sector Level Input Data

IDAS Market Sector Level Input Data Requirements	
Input Data	**Description**
Market sector name	User defined name of the market sector which represents the trip matrix data
Vehicle type	Type of vehicle represented in the trip matrix file (e.g., auto single occupancy, auto multiple occupancy, commercial vehicle, transit vehicle, other)
Trip type	Type of trip (either Person or Vehicle) represented by the trip matrix file
Average occupancy	Average occupancy for trips represented in the trip matrix file
Trip matrix file	For each origin / destination pair, number of trips.
In-Vehicle Time file	In-vehicle time for each origin / destination pair (optional)
Out-of-Vehicle Time file	Out-of-vehicle time for each origin / destination pair (optional)
Out-of-Pocket-Costs file	Out-of-pocket costs for each origin / destination pair (optional)
Total Time file	Total time for each origin / destination pair (optional)

<u>ITS Improvement Level Input Data</u>

At the ITS Improvement level, the data required for Emergency Vehicle Signal Priority improvements is shown in Table 2.4.

Table 2.4. IDAS Emergency Vehicle Signal Priority Input Data

IDAS Emergency Vehicle Traffic Signal Priority Input Data Requirements	
Input Data	**Description**
Description	User supplied name describing the Emergency Vehicle Signal Priority improvement to be analyzed
Year of opening	Calendar year when the Emergency Vehicle Signal Priority improvement will be completed (used in cost analysis)
Mid-point of construction	Calendar year representing the middle of construction for the Emergency Vehicle Signal Priority improvement (used in cost analysis)
Selected nodes	User specified node(s) (i.e., intersection) where Emergency Vehicle Signal Priority improvement will be located
Selected links	User specified link(s) (i.e., streets) affected by Emergency Vehicle Signal Priority improvement
Number of equipped emergency vehicles	User specified number of emergency vehicles equipped with signal priority capability (used in cost analysis)
Percentage of link volume that is emergency vehicles	User specified percentage of total link traffic volume represented by equipped emergency vehicles (default = 0.1%)

2.6.2.2 IDAS Default Parameter Values

The default parameter values associated with the IDAS Emergency Vehicle Signal Priority improvement methodology are shown below in Table 2.5.

Table 2.5. IDAS Emergency Vehicle Signal Priority Default Parameter Values

IDAS Emergency Vehicle Traffic Signal Priority Default Parameter Values	
Parameter	**Default Value**
Percentage of link volume that is emergency vehicles	0.1 %
Percentage change in link speed for selected links	30.0%
Multiplier for the value of in-vehicle time ($/hr.) for emergency vehicles	30.0
Cell based communication equipment	1 per equipped vehicle, useful life = 10 years, capital cost = $200, annual operations & maintenance cost = $10
Signal preemption processor	1 per equipped vehicle, useful life = 10 years, capital cost = $450, annual operations & maintenance cost = $8
Wireless communications, low usage1	1 per equipped vehicle, useful life = 100 years, capital cost = $0, annual operations & maintenance cost = $190
Signal preemption receiver	1 per selected node (intersection), useful life = 5 years, capital cost = $5,000, annual operations & maintenance cost = $125
Signal controller upgrade for signal preemption	1 per selected node (intersection), useful life = 10 years, capital cost = $3,500, annual operations & maintenance cost = $0

2.6.2.3 IDAS Impact Estimation Methodology

The methodology used in IDAS to estimate the transportation impacts resulting from deployments of Emergency Vehicle Signal Priority systems is described below. This methodology is similar in form and application to the estimation of impacts for other ITS Improvements within IDAS. Estimates of Emergency Vehicle Signal Priority impacts are determined as follows:

- The control alternative (e.g., the base case without any deployed ITS Improvements) is run through the IDAS trip assignment algorithm and the results are saved

- The alternative with deployed ITS Improvements is run through the IDAS trip assignment algorithm (without adjusting link speeds for the Emergency Vehicle Signal Priority) and the results are saved
- The alternative with deployed ITS Improvements is run once more through the IDAS trip assignment algorithm, this time applying speed improvements (default of 30%) on the links identified as having Emergency Vehicle Signal Priority deployed
- The difference between the vehicle-hours-of-travel (VHT) in the results with and without the speed improvement on Emergency Vehicle Signal Priority links is calculated. This difference is multiplied by the percentage of equipped emergency vehicle traffic volume on the link (default of 0.1%) to determine the travel time savings for equipped emergency vehicles.
- This travel time savings for equipped emergency vehicles is multiplied by the value of in-vehicle time for emergency vehicles (default of 30 times normal in-vehicle travel time) to determine the dollar value of time savings for equipped emergency vehicle travel time savings.
- Cost accounting is performed as in other IDAS ITS Improvements and is based on the capital and operations and maintenance costs of deploying the Emergency Vehicle Signal Priority ITS Improvement.

2.6.3 IDAS Summary

IDAS is a tool designed for conducting regional planning level analysis; which by definition implies high level estimates of transportation impacts. However, given these high level estimates are being used to make transportation investment decisions, it is worthwhile to seek to improve these methodologies wherever possible. It is in this light that an attempt will be made to enhance the Emergency Vehicle Signal Priority methodology within IDAS. Some of the limitations to the current IDAS methodology and recommended areas for improvement are presented in the next chapter.

CHAPTER 3. RESEARCH METHODOLOGY

This chapter describes the proposed enhancements to the IDAS emergency vehicle traffic signal priority methodology and the overall research approach that will be used to accomplish these enhancements.

3.1 OVERVIEW

The objective of this research is to improve transportation planning level techniques for the assessment of emergency vehicle traffic signal priority systems. Specifically, the goal is to improve the ITS Deployment Analysis System (IDAS) methodology for assessing the costs and benefits of emergency vehicle traffic signal priority systems. In order to accomplish this research objective, a research methodology comprised of the following components was established:

- Identify areas for improvement in the current IDAS methodology
- Identify data needed to support these improvements
- Identify a method to collect the data
- Develop a data collection plan
- Collect data
- Incorporate data into the improved IDAS methodology
- Assess the impacts of the improved IDAS methodology

This research methodology is described in further detail in the remaining sections of this chapter.

3.2 IDENTIFICATION OF IMPROVEMENTS TO IDAS METHODOLOGY

In Chapter 2—Literature Review, the current IDAS methodology for assessing emergency vehicle traffic signal priority systems was presented. As described, this methodology is somewhat limited in its level of sophistication and improvements to the methodology are proposed as the primary objective of this research. However, before making specific recommendations, the following traits are deemed essential to any proposed improvements:

- consistency with current IDAS methodologies – an improved methodology should be consistent in approach with current IDAS methodologies. It should act within the IDAS framework of planning level data analyses. For example, it would be not be consistent to develop an improved methodology that required IDAS to perform detailed simulation level analyses.
- minimal user data requirements – an improved methodology should not put an undo burden on the IDAS user to specify data that is not typically available at the planning level or data that is not typically collected. For example, requiring IDAS users to specify lane widths, signal timing plans, or detailed emergency vehicle routes would put undo burden on the user so as to make the new methodology unusable.
- ease of implementation in IDAS – another consideration in the development of an improved methodology is the ease to which it may be implemented in IDAS. For example, an improved methodology that requires IDAS to perform several iterations of the traffic assignment module would require significant coding changes to the IDAS software and would increase the IDAS run-time dramatically.

Taking into account the above considerations, one can conclude that in order for an improved methodology to be useful, it must be incremental in nature. This does not imply a lack of complexity in the effort and the analytical procedures required to create the improvements, rather it implies that the impact on the IDAS end user and IDAS software developer should be kept to a minimum. These were some of the governing principals used in selecting the areas for improvement identified below.

The current IDAS methodology for assessing emergency vehicle traffic signal priority systems is limited in that it only considers travel speed improvements for emergency vehicles and does not consider impacts on other travelers. To improve the existing methodology, a new methodology is being proposed that assesses the impact of emergency vehicle traffic signal priority on all travelers, not just the emergency vehicle. Further, it is proposed that the addition of a new parameter into IDAS that characterizes typical traffic volume (or congestion level) will assist in further refining the default benefit values used within the emergency vehicle traffic signal priority methodology. The consideration of congestion level is consistent with the other IDAS assessment methodologies related to arterial traffic signal system deployments. The recommended improvements to the IDAS emergency vehicle traffic signal system priority methodology are summarized in Table 3.1.

Table 3.1. Recommended Improvements to IDAS Methodology

Recommended Improvements to IDAS Emergency Vehicle Traffic Signal Priority Methodology
• Assess the impact of emergency vehicle traffic signal priority systems on all travelers, not just the emergency vehicle • Account for the effect of traffic congestion in the default impact parameters for emergency vehicle traffic signal priority systems

A number of other factors were also considered for incorporation into the improved methodology, however, due to time constraints they could not be included. These factors included: the number of vehicles per preemption event, the path of the emergency vehicle, and the distance from which an emergency vehicle preemption request can be received by the traffic signal controller. These are discussed as topics for further research in Chapter 7—Conclusions and Recommendations.

3.3 Identification of Data Needed to Support Improvements

In order to create the recommended improvements to the IDAS methodology, data is needed to assess the impact of emergency vehicle traffic signal priority systems on all travelers and to assess the effect of traffic volume (i.e., congestion) on these impacts. In the context of the central thesis to this research, that the impacts of emergency vehicle traffic signal priority systems are a function of the traffic characteristics, roadway geometry, and the deployment configuration; the data collected will assist in proving or disproving this thesis. Specific to the recommended IDAS improvements, the data will be used to assess whether there is a measurable impact on all travelers from emergency vehicle traffic signal priority systems and whether the magnitude of this impact is related to the level of traffic congestion.

Working within the current IDAS methodology as a basis, the following data will be needed to implement the improvements:

- Percent change in average travel speed for emergency vehicles with and without traffic signal priority systems employed
- Percent change in average travel time for all travelers with and without traffic signal priority systems employed

Since the IDAS methodology calculates the impacts on a link-by-link basis on the transportation network, these data will need to be collected on each approach to the traffic signalized intersection where the priority system is to be assessed. This data will also need to be collected for varying levels of traffic volume. For this research, it is proposed to investigate three different levels of traffic volume; namely, Low, Medium, and High. These levels of traffic volume are further described in Chapter 4—Simulation Analysis. A summary of the data needed to support the IDAS methodology improvements is shown in Table 3.2.

Table 3.2. Data Needed to Support IDAS Improvements

Data Needed to Support Improvements to IDAS Emergency Vehicle Traffic Signal Priority Methodology
For Each Signalized Intersection Approach and for Each Level of Traffic Volume
• Percent change in average travel speed for emergency vehicles with and without traffic signal priority systems employed • Percent change in average travel time for all travelers with and without traffic signal priority systems employed

3.4 IDENTIFICATION OF DATA COLLECTION METHOD

The data needed for the improvements to the IDAS methodology are the percent change in average travel speed for emergency vehicles and the percent change in travel time for all travelers resulting from traffic signal priority systems. There are essentially two approaches that could be used to collect this data. The first approach is to collect field data from an actual location where emergency vehicle traffic signal priority systems are deployed. However, field data collection studies related to emergency vehicle traffic signal priority systems are complex, time-consuming, expensive, and outside the scope of this research. The second approach is to collect the data from a model of an emergency vehicle traffic signal priority system. Such a model can be created by using one of several traffic simulation tools. This is the recommended data collection approach for this research. The benefits of using a model of the system include the ability to conduct analyses under a variety of conditions, the accessibility of a software package versus a field test environment, and the lower costs associated with computer simulation analyses versus field experiments. Traffic simulation tools do have limitations associated with their ability to reflect reality and the effect of these limitations needs to be considered whenever simulation analysis is used. The limitations of the simulation analysis conducted for this research are discussed in Chapters 4,5, and 6, Simulation Analysis, Simulation Results, and Enhanced IDAS Methodology, respectively.

There are a number of traffic simulation tools that could be used to collect the data for this research, some of which were mentioned in Chapter 2—Literature Review. Only two of these tools were seriously considered however, VISSIM, and CORSIM. VISSIM is a simulation tool developed in Germany that has the capability to model traffic signal priority systems. In addition to its existing capabilities, VISSIM was recently interfaced with the NextPhase traffic signal controller software developed by Gardner Systems, Inc., thus creating a linkage between actual traffic signal controller software and a traffic simulation tool. Despite VISSIM's capabilities, the author's tool of first choice was the CORSIM traffic simulation software developed by the FHWA. CORSIM can model emergency vehicle traffic signal priority systems through "run-time extensions" to the software. This "run-time extensions" capability allows user-developed software code to interface with CORSIM and exchange data on a time step (e.g., second-by-second) basis (ITT Systems, 1999). The author's familiarity with CORSIM and CORSIM's ability to model emergency vehicle traffic signal priority systems were important factors in the selection of CORSIM as the tool for data collection in this research.

3.4.1 Creating the model within CORSIM

Once CORSIM was chosen as the tool for data collection, a model was created to demonstrate the ability to collect the required data for the research. A CORSIM model previously created by the author was used as the basis for the model used in this research. The model represented an arterial network with closed spaced signalized intersections. In order to model emergency vehicle traffic signal systems, some advanced features that are not included or documented in the standard release of the CORSIM software had to be used. These features include the vehicle path following and the traffic signal preemption capabilities of CORSIM as shown in Table 3.3. The vehicle path following capability of CORSIM was demonstrated and required a fairly small amount of effort. The development of the traffic signal preemption logic, however, and its incorporation into the CORSIM model using the "run-time extension" capability was time consuming and took a considerable amount of effort. However, once completed, the capability of CORSIM to model emergency vehicle traffic signal priority systems was demonstrated. A detailed description of the CORSIM modeling analysis is provided in Chapter 4—Simulation Analysis.

Table 3.3. Advanced CORSIM Features Necessary

Advanced Features in CORSIM Necessary to Conduct this Research
• Vehicle Path Following – allows a user to control a specific type of vehicle to be created at a specific time during the simulation and follow a specific path through the road network. This capability is needed to model an emergency vehicle that consistently follows the same path beginning at the same time. Otherwise, vehicles are created at random and follow random paths through the network.
• Traffic Signal Preemption – allows the user to model emergency vehicle traffic signal priority systems. Traffic signal preemption needs to be modeled in CORSIM through separate user-created software code that interfaces with CORSIM on a time-step basis. The capability to interface separate code with CORSIM is known generically as "run-time extensions."

3.5 DEVELOPMENT OF DATA COLLECTION PLAN

Once CORSIM was established as the data collection method, a data collection plan was developed. The purpose of this data collection plan, or simulation analysis plan, is to define the number and types of simulation analyses needed to collect the data required for this research. Specifically, the data collection plan outlines the simulation scenarios, the number of cases to be analyzed, the number of simulation runs necessary for each case, and the simulation output measures needed for each case. In order for CORSIM to model the uncertainty and variation in driver behavior as stochastic processes, it incorporates the use of probability distributions and random number generators. Because of this, multiple runs of the CORSIM model should be made with different random number seeds and the results should be averaged to obtain the output measures of interest. The detailed data collection plan is provided as part of Chapter 4—Simulation Analysis.

3.6 DATA COLLECTION

Data collection is accomplished through the implementation of the data collection plan. For purposes of this research, the data collection is accomplished through the multiple runs of the CORSIM model of the emergency vehicle traffic signal priority and the collection and averaging of the data from these runs. To average the results from the individual CORSIM runs, the output from CORSIM will be imported into a spreadsheet where statistical and graphical techniques can be applied. The detailed results of the data collection effort are reported in Chapter 5—Simulation Results.

3.7 INCORPORATION OF DATA INTO IMPROVED IDAS METHODOLOGY

The results of the data collection effort will be used to develop the improved IDAS methodology for emergency vehicle traffic signal priority systems. The data from the simulation analysis will be used to quantify the effect of traffic volume on emergency vehicle traffic signal priority system impacts. Instead of using a single default parameter that specifies the travel speed impacts on the emergency vehicle, the IDAS methodology will be improved to incorporate a range of default parameter values for travel time impacts on all travelers which are dependent on the traffic congestion typically experienced within the network. These new parameter values will result from the data collected (e.g., the results) from the simulation analysis. The incorporation of the data to develop the improved IDAS methodology is described in detail in Chapter 6—Enhanced IDAS Methodology.

3.8 ASSESSMENT OF IMPACTS OF IMPROVED IDAS METHODOLOGY

The final step in the research methodology is to assess the impact of the improved emergency vehicle traffic signal priority methodology on the IDAS results. In other words, does the improved methodology have a significant effect on the final cost/benefits numbers typically produced by an IDAS analysis. This assessment will be made on a hypothetical IDAS analysis network and the impact of the improved IDAS methodology will be reported. The results will then be extrapolated to estimate the significance of the impacts if they are applied to a larger transportation network analysis.

CHAPTER 4. SIMULATION ANALYSIS

This chapter describes in detail the simulation analysis conducted for this research. The simulation network model and the emergency vehicle traffic signal priority model are described. The simulation analysis plan is presented which details the simulation scenarios and the data collection approach.

4.1 OVERVIEW

As discussed in Chapter 3—Research Methodology, the role of the simulation analysis in this research is to support the data collection needs required to develop the proposed improvements to the IDAS emergency vehicle traffic signal priority methodology. These data needs, as summarized in Table 3.2, are essentially a determination of the travel time impacts of an emergency vehicle traffic signal priority system under varying traffic volume conditions. The simulation analysis is essentially a surrogate method for conducting the data that would otherwise need to be collected from actual field installations of traffic signal priority systems. As described in Chapter 3, CORSIM was chosen as the tool to conduct the simulation analysis. The details associated with the simulation analysis are presented in the remaining sections of this chapter.

As a point of clarification for the remainder of this report, traffic signal *preemption* is specifically modeled in the simulation analysis. However, the term traffic signal *priority* is still used whenever referring to a more generalized description of these systems.

4.2 DESCRIPTION OF THE ROADWAY NETWORK MODEL

4.2.1 Selection of the Roadway Network

In order to study the effects of emergency vehicle traffic signal priority systems, a model of a traffic signalized road network had to be created. The author considered several options for the roadway network for this research. These options ranged from a purely hypothetical example of a single intersection to a detailed grid network with multiple signalized arterial streets. As the research progressed, however, the author discovered that the selection of the roadway network model would be highly dependent on CORSIM's capabilities with respect to traffic signal priority.

CORSIM had previously been used to model emergency vehicle traffic signal preemption on an arterial roadway which employed traffic actuated signal control (Bullock, et.al, 1998). However, because traffic signal preemption is not a standard feature in CORSIM, the previous study required that CORSIM be physically linked to an actual traffic signal controller through a piece of hardware known as the Controller Interface Device (CID). Therefore, to use CORSIM to model traffic signal preemption with the CID required three pieces of hardware, a personal computer, the CID, and a traffic signal controller. This method was unacceptable to the author primarily because it was desirable to demonstrate that CORSIM could be used to simulate traffic signal preemption without the use of the CID and a traffic signal controller which are two pieces of hardware that are not available to the average CORSIM user.

Further investigation revealed that the CORSIM fixed time traffic signal control logic had been duplicated and provided as an example in the CORSIM run-time extension documentation (ITT Systems, 1999). Thus, by modifying the fixed time traffic signal control logic provided as an example CORSIM run-time extension, traffic signal preemption could be modeled with CORSIM using only a personal computer. As part of previous coursework, the author had modeled an arterial network in CORSIM that used fixed time traffic signal control (McHale & Obenberger, 1998). This network, which represented an urban arterial with closely spaced intersections, was re-evaluated by the author and found to meet the needs of this research. The characteristics of this roadway network model are described below.

4.2.2 Roadway Network Geometry

The network model consisted of an urban arterial roadway with seven traffic-signalized intersections and seven corresponding cross streets as shown in Figure 4.1. As seen in the figure, nodes 2, 4, 6, 9, 12, 15, and 18 represent the signalized intersections. Simulated vehicles enter and exit the network via the CORSIM Entry/Exit nodes depicted

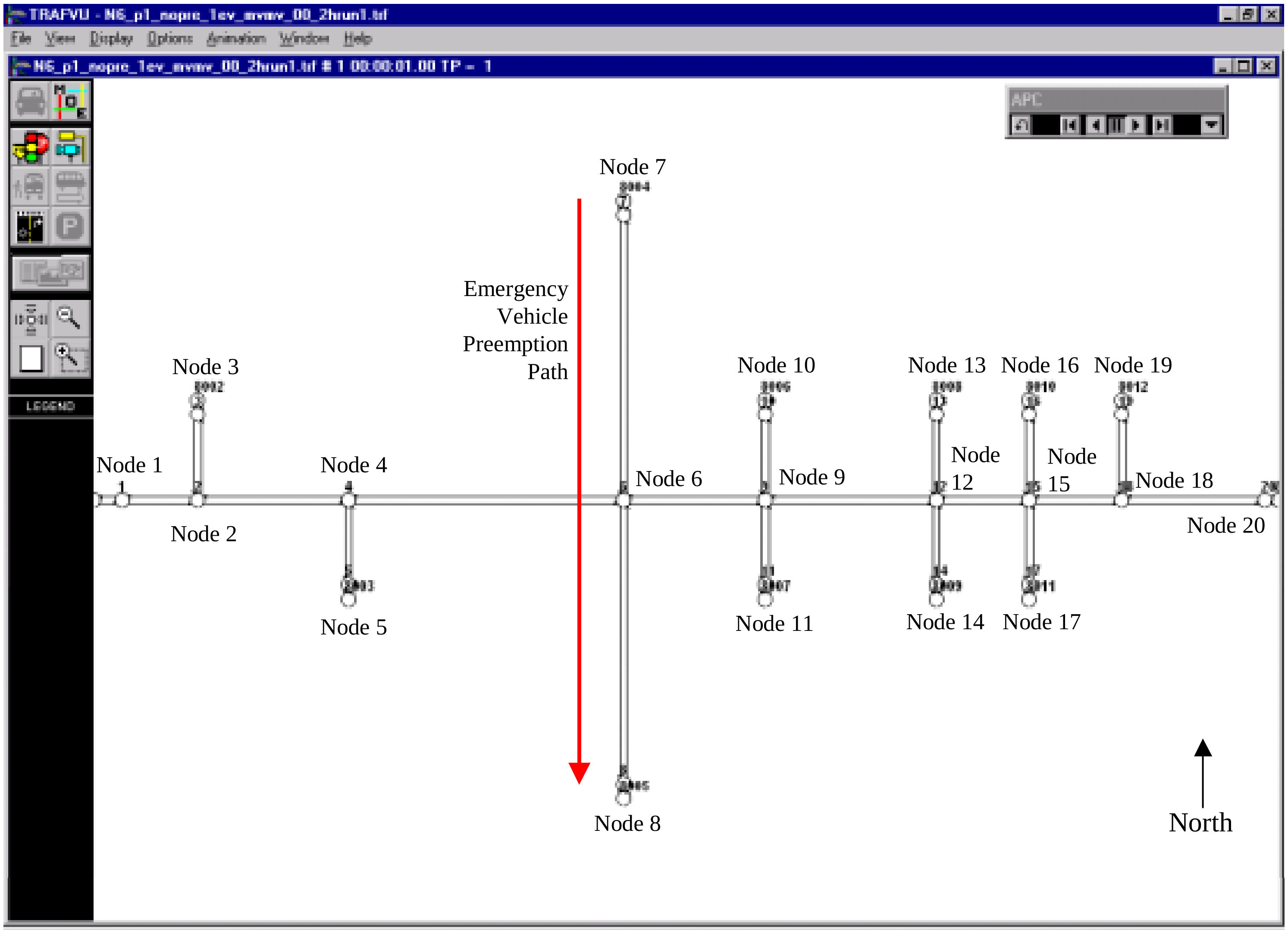


Figure 4.1. Graphical Depiction of Arterial Network Model

by the nodes numbered in the "8000's" in the figure. The total length of the four-lane arterial is 4,000 feet. Additional detail on the arterial roadway network geometry is shown in Table 4.1 and Table 4.2.

Table 4.1. E/W Arterial Model Geometry

East/West Arterial Model Geometry			
Link (Node A, B)	Link Length (ft)	Number of Lanes EB	Number of Lanes WB
(1,2)	265	2 + Left Turn	2
(2,4)	527	2 + Right Turn	2
(4,6)	963	2 + Left Turn	2
(6,9)	497	2	2 + Right Turn
(9,12)	599	2	2
(12,15)	325	2	2
(15,18)	324	2 + Left Turn	2
(18,20)	500	2	2

Table 4.2. N/S Side Street Model Geometry

North/South Side Street Model Geometry			
Link (Node A, B)	Link Length (ft)	Number of Lanes NB	Number of Lanes SB
(3,2)	300	1	2
(5,4)	300	1	1
(7,6)	1000	2	1 + Left Turn
(8,6)	1000	1 + Left Turn	2
(10,9)	300	1	1
(11,9)	300	1	1
(13,12)	300	1	1
(14,12)	300	1	1
(16,15)	300	1	1
(17,15)	300	1	1
(19,18)	300	1	1

4.2.3 Traffic Signal Control

The seven signalized intersections in the arterial network were modeled using a fixed time traffic signal control plan. The overall network geometry and traffic volume demand levels from the previous coursework were used to establish the traffic signal timing on the arterial network. The arterial network was first analyzed using the TRANSYT-7F software to conduct a traffic signal optimization analysis that resulted in a 70-second cycle time and a two-phase signal timing plan for six of the seven intersections. The signal optimization recommended that one of the intersections use a three-phase timing plan. The resulting signalized intersections operate in a coordinated fashion favoring the major westbound progression of traffic. Following the TRANSYT-7F analysis, the Highway Capacity Software (HCS) was used to conduct a capacity and level of service (LOS) analysis. The resulting capacities from HCS were used to determine the volume-to-capacity ratios (V/C) reported later in this chapter. Slight adjustments were made to the original signal timing plan so that it could accommodate the variations in traffic demand volume used in this research. The final traffic signal timing plan for the arterial network is shown in Figure 4.2. In this figure, solid arrows indicate protected vehicle movements and dashed arrows indicate unprotected or permissive vehicle movements.

4.3 EMERGENCY VEHICLE TRAFFIC SIGNAL PREEMPTION MODEL

4.3.1 Intersection Selected for Traffic Signal Preemption

Within the arterial roadway model, only one intersection was selected for modeling emergency vehicle traffic signal preemption. The decision to model the emergency vehicle traffic preemption at only one intersection was based on the desire to maintain consistency with the current IDAS methodology. This consistency relates to the IDAS methodology of applying (or “deploying”) emergency vehicle traffic signal priority systems at an individual network link and network node level. Therefore, to apply emergency vehicle traffic signal priority along the length of an arterial in IDAS, the user must select the individual nodes (e.g., intersections) and individual links (e.g., road segments) rather than selecting the entire arterial as a single integrated system. For these

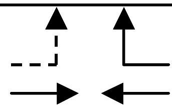
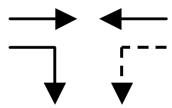
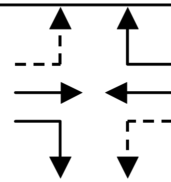
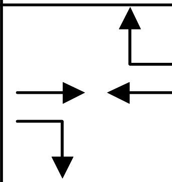
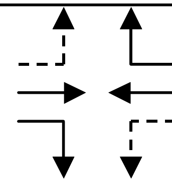
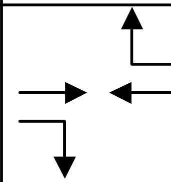
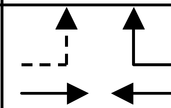
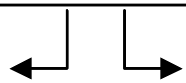
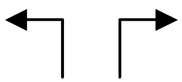
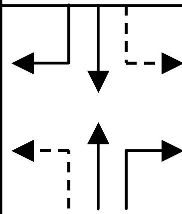
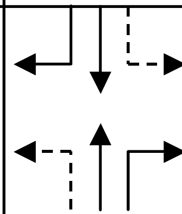
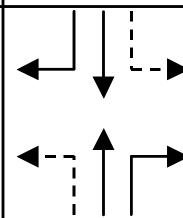
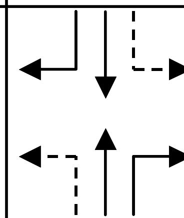
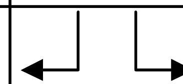
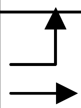
Intersection/ Phase	Node 2	Node 4	Node 6	Node 9	Node 12	Node 15	Node 18
Phase 1	 Green – 42 s Yellow – 4 s	 Green – 46 s Yellow – 4 s	 Green – 39 s Yellow – 4 s	 Green – 46 s Yellow – 4 s	 Green – 46 s Yellow – 4 s	 Green – 46 s Yellow – 4 s	 Green – 46 s Yellow – 4 s
Phase 2	 Green – 12 s Yellow – 4 s	 Green – 16 s Yellow – 4 s	 Green – 23 s Yellow – 4 s	 Green – 16 s Yellow – 4 s	 Green – 16 s Yellow – 4 s	 Green – 16 s Yellow – 4 s	 Green – 16 s Yellow – 4 s
Phase 3	 Green – 4 s Yellow – 4 s						
Offset (sec)	51	39	13	67	49	51	51

Figure 4.2. Traffic Signal Timing Plan

reasons, the analysis of emergency vehicle traffic signal preemption at one of the seven intersections along the arterial road network was deemed appropriate for this research. The remaining six intersections operated under the fixed time traffic signal control described in the previous section.

After deciding that emergency vehicle traffic signal preemption would be modeled at one intersection, the intersection at the midpoint of the arterial network was chosen as the most appropriate intersection. This choice was made for two reasons. First, as the intersection in the middle of the arterial, the impacts of the emergency vehicle traffic signal preemption event could be captured at equal distances for traffic traveling eastbound and westbound along the arterial. Second, this intersection represents a major intersection along the arterial in terms of cross street traffic volume making the choice a realistic scenario. This intersection is identified as node 6 in the network as shown in Figure 4.3. .

4.3.2 Emergency Vehicle Traffic Signal Preemption Model

Since the use of a traffic simulation model is a surrogate for analyzing an actual emergency vehicle traffic signal priority system, it is important to understand the components and functions of an actual system and the corresponding assumptions and limitations required to model them. The purpose of this section is to describe how the various components of the emergency vehicle traffic signal preemption system were modeled using CORSIM and CORSIM run-time extension logic. For purposes of this discussion, the major components of the emergency vehicle traffic signal preemption system are:

- the roadway
- the emergency vehicle
- other vehicular traffic
- pedestrian traffic
- the traffic signal preemption equipment (e.g., transmitter and receiver)
- the traffic signal controller, and
- the traffic signals.

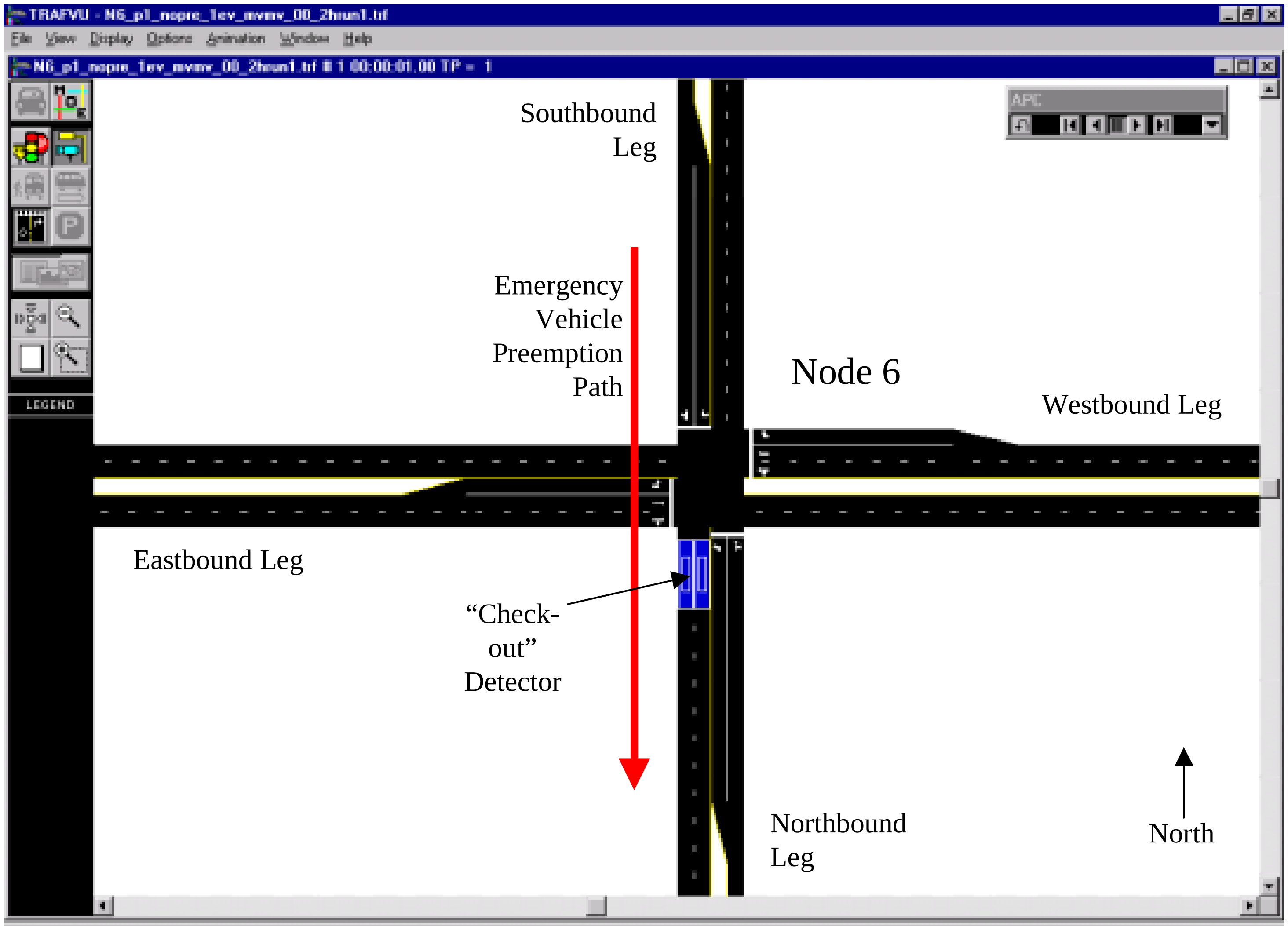


Figure 4.3. Intersection (Node 6) with Traffic Signal Preemption

For illustration purposes, these major components are shown in Figure 4.4. Each of these components will be addressed below and the assumptions, limitations, and corresponding discrepancies with real-world systems will be discussed.

4.3.2.1 The Roadway

In an actual system, the roadway is the surface upon which the emergency vehicle and other vehicular traffic travel. An actual roadway may be comprised of shoulders that could be used for vehicle pull-off or vehicle travel during emergency vehicle operations.

The geometric properties of the roadway modeled for this research has been described above. The characteristics of roadway modeling in CORSIM are sufficient for most traffic-related analyses. However, unlike an actual system, shoulders are not modeled in CORSIM. Thus, the ability for other vehicles to pull-over to the shoulder and the ability for an emergency vehicle to travel along the shoulder is not possible with CORSIM. However, for the urban arterial network modeled in this research, it is likely that an actual roadway would not have shoulders but instead would have the presence of on-street parking. The presence of on-street parking would be consistent with no shoulders and would make this limitation of CORSIM less of an impact for the urban arterial network modeled in this research.

4.3.2.2 The Emergency Vehicle

An actual emergency vehicle would likely travel to the scene of an emergency with lights and sirens activated and travel at as high a speed as possible. An actual emergency vehicle would make an attempt to pass other vehicles, even crossing a double-yellow line to do so. An actual emergency vehicle would likely enter into a major intersection somewhat cautiously, but would not be constrained by the requirement to obey the traffic signal indications.

The characteristics of vehicle movement in CORSIM limits its ability to realistically model emergency vehicle behavior. The simulated emergency vehicle will not attempt to travel at as high a speed as possible, but instead will attempt to travel at the desired speed that has been assigned to the road segment (link) upon which it is traveling. The

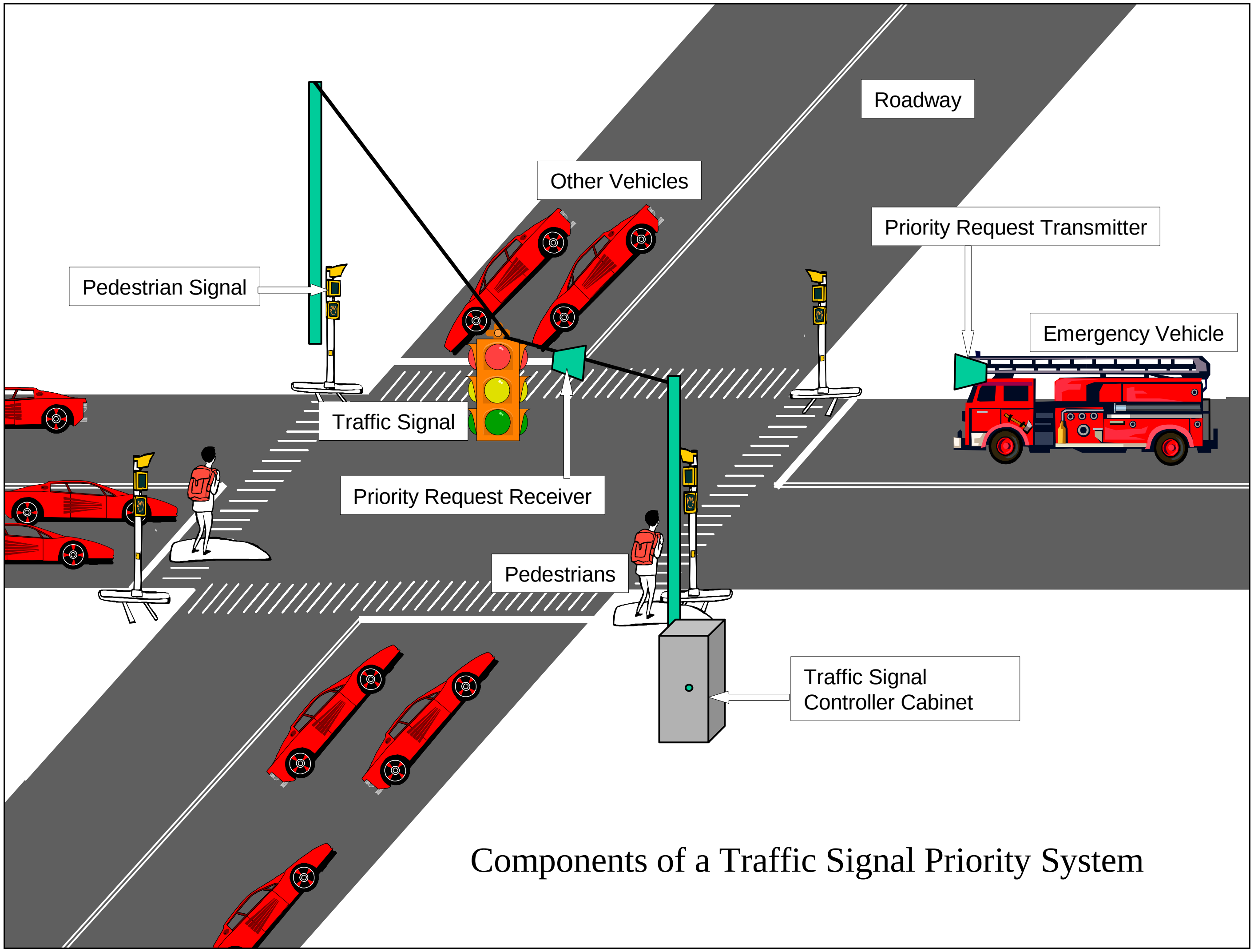


Figure 4.4. Major Components of Emergency Vehicle Traffic Signal Priority System

simulated emergency vehicle will only attempt to pass other vehicles if necessary to reach its desired speed. Passing would only occur as a result of a lane change maneuver into an adjacent lane in the same direction on a multiple lane road segment. However, the emergency vehicle modeled in this research travels along a two lane road segment (one lane in each direction) and therefore will not pass any vehicles. The simulated emergency vehicle will also obey all traffic signal indications. That is, it will stop for all red lights.

These characteristics of a simulated emergency vehicle will result in longer travel times than would actually be experienced. The simulated vehicle will be constrained by vehicles in front of it and by the traffic signal indications. However, since these constraints exist in the model for both cases of “with” and “without” (analogous to “before” and “after”) emergency vehicle traffic signal preemption, the impact on the relative differences will be reduced.

4.3.2.3 Other Vehicular Traffic

As alluded to earlier, in an actual system, other vehicles should react to the lights and sirens of an emergency vehicle by pulling over to the right hand side, moving to the shoulder, clearing an intersection, or using some other means to allow the emergency vehicle to pass.

In general, the non-emergency vehicles modeled in CORSIM will exhibit the same behavior as the emergency vehicle in that they will not try to pass each other, they will attempt to reach the desired speed assigned to the roadway, and they will obey all traffic signal indications. As mentioned above, the characteristics of this behavior limits the ability of the vehicles to operate in a realistic fashion in response to an emergency vehicle. However, when assessing the impact of the emergency vehicle traffic signal priority system, it is postulated that the majority of the impact on travelers is a result of the traffic signal preemption event, not necessarily the actions of the emergency vehicle and the vehicles in its near vicinity. Although it is recognized that those vehicles required to pull-over, move through an intersection, or otherwise change their behavior will be impacted (most negatively, but some positively) by the emergency vehicle operations. The relative impact of the signal preemption event versus the emergency vehicle activity is difficult to assess as the author was unable to find any real world results for traffic-related impact measures for emergency vehicles and vehicles in the near vicinity. Again, focusing on the relative differences "with" and "without" emergency vehicle traffic signal preemption should help to minimize some of the limiting assumptions of the model.

4.3.2.4 Pedestrian Traffic

In an actual urban arterial system, the majority of the pedestrians would cross the street at the crosswalks at the intersection. A number of pedestrians would also cross the street anywhere along its length. Pedestrian crossings at urban arterial intersections are typically accommodated with pedestrian signals showing a "Walk" and "Don't Walk" indication. The time allotted to the pedestrians is typically related to the pedestrian volume at the intersection, the width of the intersection, and the average walking speed of pedestrians. Pedestrian reaction to an emergency vehicle would likely be to hurry across a crosswalk if already entered, double-back, or to defer from entering a crosswalk if not already entered.

CORSIM does not explicitly model the actions of individual pedestrians. However, it can take into account the effects of pedestrian activity on traffic signal systems. For fixed time traffic signal systems four levels of pedestrian volume (None, Light, Moderate, Heavy) can be designated in CORSIM which affect vehicles attempting to perform right-turn-on-red movements. For actuated traffic signal control systems, the pedestrian timing plans and pedestrian volumes can be specified in CORSIM to simulate a pedestrian signal operation.

As mentioned previously, fixed time control logic was used for this research. Although the pedestrian volumes were set to zero (or None) in CORSIM, the right turn movements at the preempted intersection were specified as "no right turn on red" to account for a high pedestrian volume. The needs of pedestrians were considered in this research and the traffic signal preemption logic written in the CORSIM run time extensions was designed to emulate an immediate transition from a WALK indication to a flashing DON'T WALK indication. For a fixed time traffic signal timing plan, the state of the pedestrian signal timing can be ascertained at any point in the timing plan cycle. Therefore, based on the point in the timing plan cycle at which an emergency vehicle preemption was requested, the appropriate response due to pedestrian signal needs could be determined. A detailed explanation of the emergency vehicle signal preemption logic and the accommodation of pedestrians is provided in Section 4.3.3—Traffic Signal Preemption Logic.

4.3.2.5 Traffic Signal Priority Equipment

In a traffic signal priority system there would typically be equipment in place to enable a vehicle to communicate its desire to receive priority treatment at a traffic signalized intersection. There would also be equipment to receive this communication from the vehicle, perhaps confirm its reception, process the priority level if applicable, and interface with the traffic signal controller. Equipment used to communicate an emergency vehicle's desire for priority may be an infrared transmitter, some other type of radio transmitter, a special pavement sensor in the roadway, or the vehicle's siren. Each of these vehicle-based transmitters would have a corresponding receiver usually located at the intersection on the mast arm or cable support for the traffic signal heads. Depending on the type of equipment used, the distance from which a vehicle's request for priority can be transmitted and received can vary. Once the priority request is received, it is sent from the receiver to the traffic signal controller. Some traffic signal priority systems also take into account when the requesting vehicle has passed beyond the receiver to determine when the priority request can be cancelled.

To model traffic signal priority equipment in CORSIM, some advanced features were exercised along with the CORSIM run-time extensions. Standard CORSIM surveillance detectors were placed on the southbound entry (i.e., link 7 to 6) and exit (i.e., link 6 to 8) to the intersection modeled with the traffic signal preemption system. The leading edge of the surveillance detector on the southbound entry link was located 578 feet from the stop bar at the intersection and acted as a “check-in” detector to sense the presence of a simulated emergency vehicle. This distance of 578 feet was chosen to model a typical city block and is consistent with the range of typical priority request transmission and reception. The surveillance detector on the southbound exit link was located just beyond the intersection itself to act as a “check-out” detector to sense when the emergency vehicle had passed through the intersection.

The simulated emergency vehicle was created using the advanced “Path Following” feature in CORSIM that is not documented in the standard CORSIM Users Manual. To use this feature, the user creates a path file in the TSIS project folder called “PATH.DAT” which specifies a path to be followed through the network. For the southbound preemption path used in this research, the following path through the network nodes was used: node 8004 to 7 to 6 to 8 to 8005. In addition to the path file, the user creates a vehicle file in the TSIS project folder called “VEHICLE.DAT” which specifies the type of vehicle, the time the vehicle is to enter the network, and the path number it is to follow (as read from the path file). The vehicle and path files were used to simulate an emergency vehicle following a particular path through the network.

Using the CORSIM run time extensions, a routine was created to determine when a vehicle following a specified path (in this case, path number one) passed over the “check-in” surveillance detector. A similar routine was created to determine when a vehicle following the same path passed over the “check-out” surveillance detector. These indications from the “check-in” and “check-out” detectors were used as input to the traffic signal preemption logic also coded via a CORSIM run time extension. A detailed explanation of the traffic signal preemption logic is described in Section 4.3.3—Traffic Signal Preemption Logic. Coding the traffic signal preemption logic into the CORSIM run time extension interface was performed with assistance from Dr. Li Zhang at the FHWA Traffic Research Laboratory.

4.3.2.6 Traffic Signal Controller

In an actual traffic signal priority system the traffic signal controller manages the request for preemption and changes the signal states accordingly. The controller will interrupt the traffic signal timing plan to implement a preemption timing plan. After servicing the preemption timing plan, the traffic signal controller than manages the transition back to the original timing plan. There are several transition strategies that can be used including hold or dwell, maximum dwell, long way or add, short way, best way or smooth (Nelson & Bullock, 2000), (Obenberger & Collura, 2001); some of which were described in Chapter 2—Literature Review.

CORSIM has the capability to model traffic controllers running fixed or traffic actuated timing plans in isolation or in coordination with other controllers. CORSIM does not have the built-in ability to model traffic signal preemption, but can do so with the use of run-time extensions. The run-time extension logic developed for this research accepts the notification from the “check-in” detector to begin preemption and the notification from the “check-out” detector to end the preemption. The logic created for the run-time extension takes into account pedestrian crossing needs prior to transitioning into the preemption timing plan. The preemption timing plan gives a green indication for the intersection approach on which the emergency vehicle is traveling and a red indication for all other approaches. When transitioning out of the preemption timing plan, the goal is to return to the fixed timing plan as soon as possible even if skipping phases is required. This signal timing and controller logic is further explained in Section 4.3.3—Traffic Signal Preemption Logic.

4.3.2.7 Traffic Signals

In an actual traffic signalized arterial, the traffic signals would change color indications from the familiar “green” to “amber” to “red” in response to instructions from the traffic signal controller. The traffic signal timing plan running on the traffic signal controller would dictate the time spent for each of these signal indications on each approach to the intersection. Drivers in turn would typically obey these signals by proceeding on the "green", proceeding with caution or slowing to a stop on the "amber", and stopping on the "red".

Within CORSIM, simulated vehicles will always obey traffic signals and will proceed on "green", proceed on "amber" if they can do so without exceeding maximum acceleration otherwise stop, and stop on "red". In the run-time extension logic that was created, the appropriate codes for these signal states were assigned to the appropriate portions of the signal timing plan and the preemption timing plan to simulate the operation of the traffic signals.

4.3.3 Traffic Signal Preemption Logic

To model the emergency vehicle traffic signal preemption system, logic was developed using CORSIM run-time extension technology. As mentioned previously, an emergency vehicle "check-in" detector was used to emulate a call for preemption and an emergency vehicle "check-out" detector was used to determine when the vehicle had successfully cleared the intersection. When the "check-in" detector was activated a variable was set in the software and logic was used to transition from the fixed time traffic signal plan to the preemption traffic signal plan. Subsequently, when the "check-out" detector was activated a different variable was set and separate logic was used to transition from the preemption back to the fixed time signal plan.

The preemption logic developed was specifically tied to the fixed time traffic signal plan used at the intersection (node 6) including the pedestrian signal timing. Although for fixed time traffic control pedestrian signals are not explicitly modeled in CORSIM, it is important to take these into account in the preemption logic. To develop the pedestrian signal timing, it was first necessary to determine the time it would take for a pedestrian to cross the intersection. Referring back to Figure 4.3. , the east/west portion of the intersection has a width of five lanes and the north/south portion has a width of four lanes. Given that CORSIM uses 12-foot lane widths (unless otherwise specified), the following intersection crossing widths are calculated:

East/West portion = (5 lanes) x (12 ft/lane) = 60 ft,

North/South portion = (4 lanes) x (12 ft/lane) = 48 ft.

Assuming a pedestrian walking speed of four feet per second as recommended by the Manual on Uniform Traffic Control Devices, Section 4E.09, the following pedestrian crossing times are calculated (FHWA, et.al., 2001):

East/West portion = (60 ft) / (4 ft/sec) = 15 sec,

North/South portion = (48 ft) / (4 ft/sec) = 12 sec.

Taking these times as the pedestrian crossing times, and assuming that the pedestrian phases are active through the entire cycle length results in the pedestrian timing plan depicted in Figure 4.5. This figure also shows the traffic signal timing plan and represents the foundation upon which the preemption logic was built.

The traffic signal preemption logic developed for this research is presented here at a high level. The logic for transitioning from the fixed time traffic signal plan to the preemption plan is shown in Table 4.3. The descriptions within the table are written in “pseudo code” style in a series of If-Then statements. The governing principle for this logic is to transition to the preemption as soon as possible while taking into consideration the needs of the pedestrians to safely cross the intersection. As described in the table, the transition to preemption begins once the emergency vehicle is detected at the “check-in” detector. Once the transition has occurred, a preemption state exists such that the:

- Southbound approach has a green signal
- All other approaches have a red signal.

Once the emergency vehicle has cleared the intersection and is detected at the “check-out” detector, the transition back to the fixed time plan begins. This transition is described in Table 4.4. The general rule applied for the transition back to the fixed timing plan is to return to Phase 1 (E/W) either transitioning back immediately, if pedestrian crossings can be accommodated, or to dwell in preemption, skipping Phase 2 (N/S), until Phase 1 can be started. This transition strategy can be characterized as a modified dwell with a one-cycle recovery period. This approach for transition was chosen because it was consistent with other approaches found in the literature and was fairly straightforward to understand and implement.

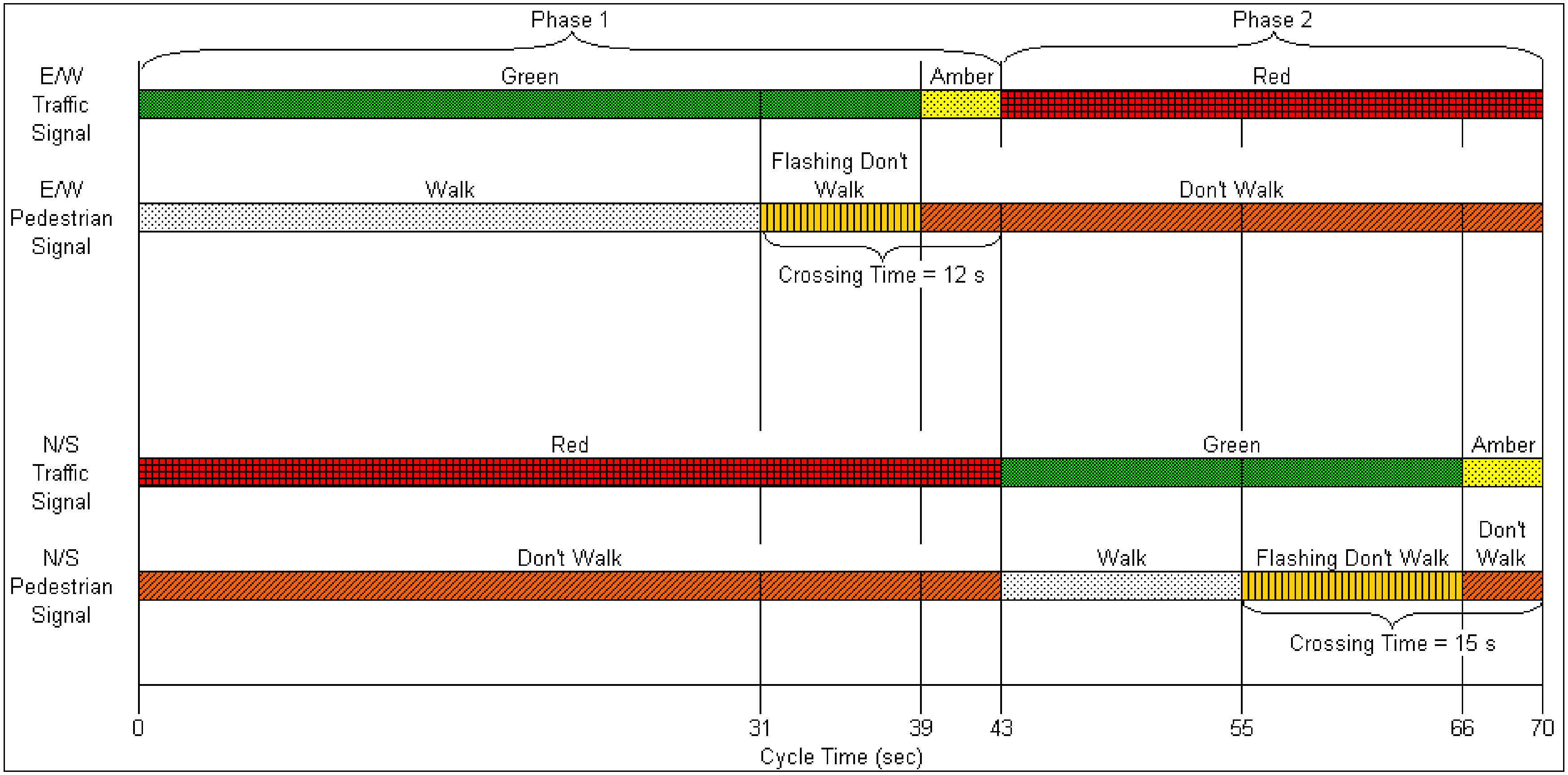


Figure 4.5. Node 6 Traffic Signal and Pedestrian Timing Plan

Table 4.3. Logic – Transition to Preemption

Logic Used to Transition from the Fixed Timing Plan at Node 6 to the Preemption Plan

If emergency vehicle has been detected at Check-In detector
- Then, determine the current point in the timing plan cycle

If the current point is in Phase 1 (i.e., E/W phase)

- If current point is E/W “Walk” interval (i.e., 0 <= current point <= 31 s)
  - Then, at next time step show E/W “Flashing Don’t Walk”
  - 8 seconds later, show E/W “Don’t Walk” and “Amber” for Eastbound and Westbound approaches
  - 4 seconds later, show “Red” for Eastbound and Westbound approaches and “Green” for Southbound approach
  - (Status: signal is currently preempted with Southbound approach “Green” and all other approaches “Red”)

- If current point is E/W “Flashing Don’t Walk” or “Don’t Walk” interval (i.e., 32 <= current point <= 42 s)
  - Then, finish Phase 1 and preempt signal at beginning of Phase 2
  - (Status: signal is currently preempted with Southbound approach “Green” and all other approaches “Red”)

If the current point is in Phase 2 (i.e., N/S phase)

- If current point is N/S “Walk” interval (i.e., 43 <= current point <= 54 s)
  - Then, at next time step, show N/S “Flashing Don’t Walk”
  - 11 seconds later, show N/S “Don’t Walk” and “Amber” for Northbound approach
  - 4 seconds later, show “Red” for Northbound approach
  - (Status: signal is currently preempted with Southbound approach “Green” and all other approaches “Red”)

- If current point is N/S “Flashing Don’t Walk” or “Don’t Walk” interval (i.e., 55 <= current point <= 69 s)
  - Then, finish Phase 2 and preempt signal at beginning of Phase 1
  - (Status: signal is currently preempted with Southbound approach “Green” and all other approaches “Red”)

Table 4.4. Logic – Transition from Preemption

Logic Used to Transition from the Preemption Plan at Node 6 to the Fixed Timing Plan

If emergency vehicle has been detected at Check-Out detector
    Then, determine the current point in the timing plan cycle
 	
If the current point is in Phase 1 (i.e., E/W phase)
 	
    If current point will allow a 12 sec E/W “Walk” interval (i.e., 0 <= current point <= 26 s)
        Then, at next time step, show “Amber” for Southbound approach
        4 seconds later, enter original timing plan at current point (in E/W phase)
        (Status: signal is back to original timing plan, in Phase 1)
 	
    If current point will not allow a 12 sec E/W “Walk” interval (i.e., 27 <= current point <= 42 s)
        Then, dwell in preemption
        At current point = 66 s, show “Amber” for Southbound approach
        4 seconds later, enter original timing plan at current point (start of E/W phase)
        (Status: signal is back to original timing plan, start of Phase 1)
 	
If the current point is in Phase 2 (i.e., N/S phase)
 	
    If current point will allow normal Phase 1 start time (i.e., 43 <= current point <= 65 s)
        Then, dwell in preemption
        At current point = 66 s, show “Amber” for Southbound approach
        4 seconds later, enter original timing plan at current point (start of E/W phase)
        (Status: signal is back to original timing plan, start of Phase 1)
 	
    If current point will not allow normal Phase 1 start time (i.e., 66 <= current point <= 69 s)
        Then, at next time step, show “Amber” for Southbound approach
        4 seconds later, enter original timing plan at current point (in E/W phase)
        (Status: signal is back to original timing plan, in Phase 1)

While a plan that accommodates a transition back to Phase 2 (instead of skipping Phase 2) could also be developed, it was not done for this research. Below are some reasons why a transition to Phase 2 was not part of the plan developed:

- Phase 1 (E/W) is the major movement on the arterial and all efforts should be made to return to Phase 1 even if some portion of Phase 2 could be accommodated. E/W travelers would have little tolerance for a transition back to a N/S movement (even if short) after they have been stopped for the preemption.
- The entire green time for Phase 2 was 23 seconds. So a transition back to Phase 2 would vary from 11 seconds of green (to accommodate the cross time of 15 seconds, including 4 seconds of amber) to a maximum of 23 seconds. For this short amount of time, it was postulated that it may be more beneficial to consistently transition back to Phase 1 so that driver expectancy can be maintained.
- Any dwell time spent in the preemption state (southbound green) can be used to clear away those vehicles on the southbound approach that were forced to pull over to the side to allow the emergency vehicle to pass.

4.4 Simulation Analysis Plan

Prior to conducting the simulation analysis, it is necessary to first create the simulation analysis plan. As described in Chapter 3—Research Methodology, this simulation analysis plan fills the role of the data collection plan for the research. It must identify the specific data to be collected, the data collection methodology, and the individual simulation runs to be performed. Each of these areas is discussed in the following subsections.

4.4.1 Data Identification

The data collection plan must be designed to collect the supporting data necessary to quantify the data requirements as described in Table 3.2, namely, the:

- percent change in average travel speed for emergency vehicles with and without traffic signal priority systems employed

- percent change in average travel time for all travelers with and without traffic signal priority systems employed.

These data must be quantified for each of the three traffic volume levels proposed (Low, Medium, and High) and for each approach to the intersection where the traffic signal priority system is deployed. In addition, when investigating the impact on all travelers, it is necessary to quantify how the impact of the preemption event changes (e.g., dissipates) over time. To quantify the impact over time, cumulative data will need to be collected over the entire duration of the simulation run. After an initial trial with one of the High Volume cases, a simulation time period of two hours was chosen to be sufficient to capture the changing nature of the impacts over time. The data elements to collect and their related CORSIM output measures are presented in Table 4.5. To compute the "Average Travel Time for All Travelers" data element, the CORSIM average vehicle travel time will be calculated. For purposes of this research, the vehicle travel time and traveler travel time are assumed to be equal (i.e., average vehicle occupancy equals 1.0). Also, for purposes of this research, truck and bus volumes on the network were assumed to be zero.

4.4.2 Data Collection Methodology

As described in Table 4.5, the Average Travel Time for All Travelers will be computed from CORSIM output statistics and the Emergency Vehicle Travel Time data will be computed from the CORSIM Run Time Extension emergency vehicle preemption logic. Each of these sources of data require different techniques to compute and collect as described below.

4.4.2.1 CORSIM Output Statistics

There are two "standard" methods for collecting output statistics and measures of effectiveness (MOEs) from CORSIM simulation runs. The first is the CORSIM Output file with the file extension ".OUT" that is produced for each CORSIM simulation run. Included in this text file is an echo print of the CORSIM input and summary statistics at reporting time steps specified by the user. Although there is a wealth of information in this ".OUT" file, the text format makes it difficult to conduct supplemental data analysis on the contents of the file. The second "standard" method for collecting CORSIM output

Table 4.5. Data Elements and Related CORSIM Measures

Data Elements and Related CORSIM Measures		
Data Element	**Description**	**Related CORSIM Measures**
Cumulative Time	Cumulative value of simulation time (seconds)	Cumulative simulation statistics are determined by the CORSIM time interval duration specified by the user
Emergency Vehicle Travel Time	Time for emergency vehicle to travel on intersection approach link and clear the intersection (seconds)	Internally calculated in the traffic signal preemption logic as the time for the emergency vehicle to travel from the "check-in" detector to the "check-out" detector (seconds). Implemented using the CORSIM Run Time extension technique.
Average Travel Time for All Travelers	For each link, or intersection approach, the average time (seconds) it takes for vehicles to travel on the link. The relationship between vehicle travel time and traveler travel time is discussed above.	The total link travel time is the summation of the CORSIM movement specific (e.g., left, right, and through) link travel times (vehicle-minutes). The total number of trips on a link is the summation of the CORSIM movement specific trips (vehicles). The average link travel time (minutes) is then computed as the total link travel time divided by the total number of trips and converted into seconds.

statistics is to use the table and graphs feature of TRAFVU, CORSIM's animation and graphing post-processor. TRAFVU has the capability to produce graphs and tables for user selected MOEs on user-specified links. However, these tables and graphs cannot be easily manipulated so that supplemental data analysis can be performed.

As described above, there are limitations to the extent to which users can conduct supplemental data analyses on the two "standard" CORSIM output methods. To overcome these limitations some experienced CORSIM users have created their own methods for analyzing CORSIM output (Martimo, 2000) (Leonard, 2000). Some of these methods include software that will read the ".OUT" file and parse the file for user specified data and save it to a more flexible format. Others have created software to read the two files used by the TRAFVU package, namely, the ".TSD" file and the ".TID" file. The ".TSD" file is the Time Step Data file and contains information on all vehicles and all traffic control devices for every simulation time step. This file is used by the animation portion of TRAFVU. The ".TID" file is the Time Interval Data file and contains cumulative MOEs for the CORSIM user specified reporting time interval. This file is used by the tables and graphs portion of TRAFVU. It is the data from ".TID" file will be used to supply the CORSIM output data.

In order to read the ".TID" file, a software technique developed by Dr. John Leonard, Associate Professor, School of Civil and Environmental Engineering, Georgia Institute of Technology will be used. Dr. Leonard developed a method to read the ".TID" file contents into a Microsoft Excel spreadsheet by coding a Microsoft Excel macro. Dr. Leonard maintains a website, at Georgia Tech and provides this and other software as free "CORSIM Goodies" for advanced CORSIM users (Leonard, 2000). This ".TID" reader software was modified so that multiple ".TID" files could be read and the MOEs of interest could be extracted and manipulated. The data elements (i.e., movement specific link travel times and movement specific vehicle trips) described in Table 4.5 will be read from the ".TID" file.

4.4.2.2 CORSIM Run Time Extension Output Data

Data specifically related to the emergency vehicle traffic signal preemption event will be collected from output statements coded in the preemption logic. The output from the preemption logic is written to a file with the same filename as the CORSIM output file, but with the ".XLS" extension so that it can be read easily by Microsoft Excel. The output of key interest from the preemption logic is the Emergency Vehicle Travel Time.

4.4.3 Simulation Scenarios

Simulation scenarios are groupings of simulation runs that can be distinguished by certain characteristics being simulated. There are essentially four distinguishing characteristics (or factors) that pertain to the simulation scenarios used for this research. These four characteristics are shown in Table 4.6 and described in detail below.

Table 4.6. Simulation Scenarios Distinguishing Characteristics

Distinguishing Characteristics and Number of Simulation Scenarios		
Distinguishing Characteristic	**Possible Values**	**Number of Possible Values**
Traffic volume	Low, Medium, High	3
Preemption capability	Yes or No	2
Point of emergency vehicle entry in 70-second cycle (sec)	0, 10, 20, 30, 40, 50, 60	7
Random Runs	10 random number seeds	10
		Total Runs: 420

Since a central thesis to this research is that the impact of emergency vehicle traffic signal priority systems is dependent on traffic volume, traffic volume will serve as the <u>first</u>, and key, distinguishing characteristic for the simulation scenarios. Three values of traffic volume, Low, Medium, and High, will be used in the simulation scenarios. Volumes were varied in these three cases for the southbound approach (e.g., same as the emergency vehicle path) and westbound approach to node 6, the preempted intersection. The volume on the southbound approach to node 6 was varied to simulate the impact of volume along the emergency vehicle path and the westbound arterial volume was varied to simulate the major directional flow of traffic. Volumes on the eastbound and northbound approaches to node 6 were held constant for all three cases. The flow rates and the volume to capacity (V/C) ratios for each approach to node 6 for each of the three cases are shown in Table 4.7. The flow rates and V/C ratios are presented in terms of each lane group on the approach (e.g., left, through, and right). The V/C ratios and the critical lane groups were computed using the Highway Capacity Software with the average hourly traffic volumes from the "without preemption" simulation results. As seen in the table the V/C ratios for the left and through movements on the westbound approach for the Low, Medium, and High volume cases were 0.53, 0.76, and 0.87, respectively.

Table 4.7. Simulation Scenarios Volume Levels

Simulation Scenario Volume Levels and V/C Ratios									
		Approach							
		Eastbound		Westbound		Northbound		Southbound	
		Lane Group		Lane Group		Lane Group		Lane Group	
		Left	Through Right	Left Through	Right	Left	Through Right	Left	Through Right
Low Volume	Flow Rate	47	475	957	83	179	105	181	182
	V/C Ratio	0.15	0.24	# 0.53	0.09	# 0.47	0.18	0.42	0.31
Medium Volume	Flow Rate	47	474	1,362	118	179	105	273	272
	V/C Ratio	0.23	0.24	# 0.76	0.13	0.60	0.18	# 0.63	0.47
High Volume	Flow Rate	47	473	1,566	136	179	105	317	318
	V/C Ratio	0.32	0.24	# 0.87	0.15	# 0.69	0.18	0.74	0.55
Note: Flow Rate in (veh/hr), # indicates critical lane group									

The hourly flow rates for the high volume case were determined by observing the simulation results and choosing a flow rate just below the point at which normal traffic flow conditions deteriorated. At higher volume levels, the arterial experienced spillback into the intersections that resulted in a breakdown of normal operating conditions. One reason for this spillback is that the intersection spacing along the arterial is short so there is very little storage for queued vehicles on the arterial.

In order to employ a “with vs. without” or a “before vs. after” basis of research comparison, the <u>second</u> distinguishing characteristic will be the capability for traffic signal preemption. The two possibilities for this distinguishing characteristic are “with traffic signal preemption” and “without traffic signal preemption”. To accomplish this in the simulation analysis, the logic necessary to enable the preemption in the CORSIM run time extension was removed for the “without traffic signal preemption” case.

The <u>third</u> distinguishing characteristic of the simulation scenarios is needed to account for the uncertainty related to when an emergency vehicle will request a traffic signal preemption. It is assumed that an emergency vehicle could request a traffic signal preemption at any time, that is, it is a purely random event. However, the impact of the preemption will vary based on the current state of the traffic signal at the time of the preemption request. For example, if a traffic signal is already “green” and an emergency vehicle requests a “green”, the impact could be small. However, if the traffic signal is “red” and an emergency vehicle requests a “green”, the impact could be large. In order to account for this uncertainty, emergency vehicles will be simulated entering the approach link to the intersection at a series of 10-second increments within the traffic signal timing plan. Since the traffic signal timing plan has a cycle length of 70 seconds, this results in seven separate scenarios for the point at which the emergency vehicle enters the approach link (e.g., at 0, 10, 20, 30, 40, 50, and 60 seconds into the traffic signal cycle length). The results of these seven scenarios will then be averaged to produce one set of results that accounts for the uncertainty related to when an emergency vehicle requests preemption. A better approach would have been to create one simulation scenario for each of the 70 seconds in the traffic signal cycle (e.g., 0, 1, 2, 3,…, 68, 69). However, this would have increased the total number of simulation runs by a factor of 10. The use of 10-second increments was selected as being adequate for purposes of this research.

The <u>fourth</u> distinguishing characteristic of the simulation scenarios is the random number seeds used in the CORSIM simulations. Many of the processes simulated in CORSIM are stochastic in nature and are modeled through the use of probability distributions and random numbers. Therefore, the results of any one simulation are dependent on the initial random number seeds used in the random number generators within CORSIM. To obtain a better representation of the range of results that could be observed from the stochastic processes, multiple simulation runs should be performed using different random number seeds for each run.

Determining an appropriate number of simulation runs is typically based on a general “rule-of-thumb” or through a statistical analysis of sample size. Recent CORSIM training courses have proposed the “rule-of-thumb” of conducting between five to ten simulation runs with different random number seeds and averaging the results. However, these general “rules-of-thumb” have no mathematical basis and a statistical determination of sample size is the appropriate method to determine the number of simulation runs. Determining a statistical sample size is an iterative process where the sample mean and sample variance are used to compute the required sample size for a desired level of error. Such a formula using the t-distribution is shown in Equation 4 below.

Equation 4. T-Distribution Sample Size Determination.

$$n = \frac{t^2 \sigma^2}{E^2}$$

where n = required sample size

t = value of t variable for desired confidence level

σ^2 = sample variance

E = allowable sampling error

After the sample size is computed, another sample is taken using the computed sample size and the new sample mean and variance are used to compute a revised sample size. This process is repeated until the computed sample size is less than the actual sample size used.

For purposes of this research, a sample of 10 runs was performed to compute a confidence interval on the results. Since sample sizes less than 30 are considered small, a t-distribution should be used. For samples greater than 30, a standard normal distribution can be used. A sample set of 10 CORSIM runs was made using the traffic signal preemption logic, the low volume case, and an emergency vehicle point of entry in the cycle of 0 seconds. The emergency vehicle travel times (in seconds) between the "check-in" and "check-out" detectors were recorded, resulting in the following set of values (16, 20, 25, 19, 22, 23, 21, 21, 20, 16). This set yields an average value of 20.3 seconds with a standard deviation of 2.83 seconds. To compute a 95% confidence interval on these results using the t-distribution, the following equation is used:

Equation 5. T-Distribution Confidence Level Determination.

$$\bar{x} \pm t_{\alpha/2,n-1} \cdot \frac{s}{\sqrt{n}}$$

Where: $\bar{x}$ = sample mean
t = value of t variable
$1-\alpha$ = confidence interval
n = sample size
s = sample standard deviation

Applying this formula with the appropriate t-value of 2.262, to the sample results yields a 95% confidence interval of (18.3, 22.3) or 20.3 seconds +/- 2.0 seconds. These results were judged to be sufficient for purposes of this research and the decision was made to use 10 simulation runs for each scenario.

As mentioned in Chapter 3—Research Methodology, other distinguishing characteristics were also considered such as the number of vehicles per preemption event, the path of the emergency vehicle, and the distance from which an emergency vehicle preemption request can be received by the traffic signal controller. However, due to time constraints, these other distinguishing factors were not investigated at this time but will be recommended for future investigation.

A summary of the simulation scenarios is shown in Figure 4.6. This figure illustrates the total number of simulation runs to be conducted for this research and the characteristics around which the results will be analyzed. As shown in the figure, the results for each of the 10 individual simulation runs distinguished by the different random number seeds will be averaged. This average is depicted by $\bar{x}_1, \bar{x}_2, ..., \bar{x}_6, \bar{x}_7$ and $\bar{y}_1, \bar{y}_2, ..., \bar{y}_6, \bar{y}_7$, which represents the scenario averages for each of the seven 10-second increments of emergency vehicle entry point into the network for cases "with preemption" and "without preemption", respectively. The averages depicted by $\bar{\bar{x}}$ and $\bar{\bar{y}}$ represent the overall scenario averages across all emergency vehicle entry times (e.g., $\bar{\bar{x}}$ equals the average of $\bar{x}_1, \bar{x}_2, ..., \bar{x}_6, \bar{x}_7$) for the cases "with preemption" and "without preemption",

Volume	Low													
Preemption	Yes							No						
EV Entry Time	0	10	20	30	40	50	60	0	10	20	30	40	50	60
Run Number (random number seed identical across rows)	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	4	4	4	4	4	4	4	4	4	4	4	4	4	4
	5	5	5	5	5	5	5	5	5	5	5	5	5	5
	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	7	7	7	7	7	7	7	7	7	7	7	7	7	7
	8	8	8	8	8	8	8	8	8	8	8	8	8	8
	9	9	9	9	9	9	9	9	9	9	9	9	9	9
	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Avg. by EV Entry Time	$\bar{x}_1$	$\bar{x}_2$	$\bar{x}_3$	$\bar{x}_4$	$\bar{x}_5$	$\bar{x}_6$	$\bar{x}_7$	$\bar{y}_1$	$\bar{y}_2$	$\bar{y}_3$	$\bar{y}_4$	$\bar{y}_5$	$\bar{y}_6$	$\bar{y}_7$
Avg. by Preemption	$\bar{\bar{x}}_l$							$\bar{\bar{y}}_l$						
Std. Dev. by EV Entry Time	S_{x1}	S_{x2}	S_{x3}	S_{x4}	S_{x5}	S_{x6}	S_{x7}	S_{y1}	S_{y2}	S_{y3}	S_{y4}	S_{y5}	S_{y6}	S_{y7}
Std. Dev. by Preemption	S_{xl}							S_{yl}						

Volume	Medium													
Preemption	Yes							No						
EV Entry Time	0	10	20	30	40	50	60	0	10	20	30	40	50	60
Run Number (random number seed identical across rows)	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	4	4	4	4	4	4	4	4	4	4	4	4	4	4
	5	5	5	5	5	5	5	5	5	5	5	5	5	5
	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	7	7	7	7	7	7	7	7	7	7	7	7	7	7
	8	8	8	8	8	8	8	8	8	8	8	8	8	8
	9	9	9	9	9	9	9	9	9	9	9	9	9	9
	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Avg. by EV Entry Time	$\bar{x}_1$	$\bar{x}_2$	$\bar{x}_3$	$\bar{x}_4$	$\bar{x}_5$	$\bar{x}_6$	$\bar{x}_7$	$\bar{y}_1$	$\bar{y}_2$	$\bar{y}_3$	$\bar{y}_4$	$\bar{y}_5$	$\bar{y}_6$	$\bar{y}_7$
Avg. by Preemption	$\bar{\bar{x}}_m$							$\bar{\bar{y}}_m$						
Std. Dev. by EV Entry Time	S_{x1}	S_{x2}	S_{x3}	S_{x4}	S_{x5}	S_{x6}	S_{x7}	S_{y1}	S_{y2}	S_{y3}	S_{y4}	S_{y5}	S_{y6}	S_{y7}
Std. Dev. by Preemption	S_{xm}							S_{ym}						

Volume	High													
Preemption	Yes							No						
EV Entry Time	0	10	20	30	40	50	60	0	10	20	30	40	50	60
Run Number (random number seed identical across rows)	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	4	4	4	4	4	4	4	4	4	4	4	4	4	4
	5	5	5	5	5	5	5	5	5	5	5	5	5	5
	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	7	7	7	7	7	7	7	7	7	7	7	7	7	7
	8	8	8	8	8	8	8	8	8	8	8	8	8	8
	9	9	9	9	9	9	9	9	9	9	9	9	9	9
	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Avg. by EV Entry Time	$\bar{x}_1$	$\bar{x}_2$	$\bar{x}_3$	$\bar{x}_4$	$\bar{x}_5$	$\bar{x}_6$	$\bar{x}_7$	$\bar{y}_1$	$\bar{y}_2$	$\bar{y}_3$	$\bar{y}_4$	$\bar{y}_5$	$\bar{y}_6$	$\bar{y}_7$
Avg. by Preemption	$\bar{\bar{x}}_h$							$\bar{\bar{y}}_h$						
Std. Dev. by EV Entry Time	S_{x1}	S_{x2}	S_{x3}	S_{x4}	S_{x5}	S_{x6}	S_{x7}	S_{y1}	S_{y2}	S_{y3}	S_{y4}	S_{y5}	S_{y6}	S_{y7}
Std. Dev. by Preemption	S_{xh}							S_{yh}						

Figure 4.6. Simulation Scenarios

respectively. The subscripts of l, m, and h on the $\overline{\overline{x}}$ and $\overline{\overline{y}}$ represent the low, medium, and high volume cases, respectively. The $\overline{\overline{x}}$ and $\overline{\overline{y}}$ values for the output measures of interest for each of the three levels of volume will serve as the key results of the simulation analysis and will be reported in the next chapter.

CHAPTER 5. SIMULATION RESULTS

The chapter presents the results of the simulation analysis and provides a discussion of the results.

5.1 OVERVIEW

The purpose of this chapter is to present the results of the simulation analysis. As presented in Table 4.5, the key data elements collected during the simulation analysis are the cumulative simulation time, the emergency vehicle travel time, and the average travel time for all travelers. These data elements will be used to calculate the primary data of interest for this research as presented in Table 3.2, namely, the percent change in average travel speed for emergency vehicles with and without preemption, and the percent change in average travel time for all travelers with and without preemption. The simulation travel time output results will be presented in terms of the distinguishing scenario characteristics and the following three levels of network aggregation:

1. Link level – results will be reported for each of the four approach links to node 6, the preemption-enabled intersection (Northbound, Southbound, Eastbound, and Westbound).
2. Intersection level – results for each of the approaches to node 6 will be aggregated to create intersection level results.
3. Arterial level – results for all travelers on the network will be aggregated to produce an arterial level set of results. For the arterial level results, the average travel time measures are only presented for one of the scenarios; the case representing the emergency vehicle entry point in the network at 30 seconds into the traffic signal cycle. This was done to minimize the extensive time needed to analyze the data for the entire network. The selection of the 30-second emergency vehicle entry in the traffic cycle was chosen as a representative case because the average emergency vehicle travel time results for this case were close to the overall average results for all cases.

5.2 TRAVEL TIMES—EMERGENCY VEHICLE

The results for the emergency vehicle travel times are presented in this subsection.

The results for the Low Volume case "without preemption", "with preemption", and a comparison of the differences are presented in Table 5.1, Table 5.2, and Table 5.3, respectively. Table 5.1 and Table 5.2 present the emergency vehicle travel time results for each individual simulation run for the Low Volume case. In addition, the emergency vehicle travel time averages for each of the emergency vehicle entry times in the traffic signal cycle are calculated for "without preemption" ($\bar{y}_1, \bar{y}_2, ..., \bar{y}_6, \bar{y}_7$) and "with preemption" ($\bar{x}_1, \bar{x}_2, ..., \bar{x}_6, \bar{x}_7$). An overall emergency vehicle travel time average for "without preemption", $\bar{\bar{y}}$, and "with preemption", $\bar{\bar{x}}$, is also presented. The standard deviation of emergency vehicle travel times for each entry time in the traffic signal cycle (s_1, s_2, …, s_6, s_7) and the overall average standard deviation, S, are shown. Table 5.3 presents the numerical differences ("with" minus "without" preemption) in the average emergency vehicle travel time by entry time in the traffic cycle, the overall difference in the average emergency vehicle travel times and the corresponding percentage differences.

Table 5.4 through Table 5.6 presents the results for the Medium Volume case and Table 5.7 through Table 5.9 presents the results for the High Volume case in a similar format.

A summary of the average emergency vehicle travel times and the percent differences in these travel times are shown in Figure 5.1 and Figure 5.2, respectively.

When viewing the results, the first observation to make is that the average percent difference in emergency vehicle travel time was fairly consistent across all three levels of volume:

- Low Volume Case: -40.1% difference in emergency vehicle travel time
- Medium Volume Case: -40.2% difference in emergency vehicle travel time
- High Volume Case: -41.4% difference in emergency vehicle travel time.

Table 5.1. EV Travel Times, Low Volume, Without Preemption

Low Volume, Without Preemption EV Travel Time (sec) Entry Time in Cycle (sec)								
Run No.	0	10	20	30	40	50	60	AVG
1	43	31	23	14	13	13	51	26.9
2	46	39	29	23	14	69	60	40.0
3	49	39	30	23	18	12	54	32.1
4	44	35	22	15	12	13	53	27.7
5	46	39	29	19	12	13	51	29.9
6	46	39	25	15	13	63	55	36.6
7	45	37	30	21	13	12	55	30.4
8	45	37	30	19	12	58	50	35.9
9	44	34	26	16	15	13	53	28.7
10	40	30	25	14	14	59	56	34.0
Mean	$\bar{y}_1$ 44.8	$\bar{y}_2$ 36	$\bar{y}_3$ 26.9	$\bar{y}_4$ 17.9	$\bar{y}_5$ 13.6	$\bar{y}_6$ 32.5	$\bar{y}_7$ 53.8	$\bar{\bar{y}}$ 32.2
Std.Dev.	s_1 2.35	s_2 3.40	s_3 3.07	s_4 3.57	s_5 1.84	s_6 25.77	s_7 2.94	S 4.29

Table 5.2. EV Travel Times, Low Volume, With Preemption

Low Volume, With Preemption EV Travel Time (sec) Entry Time in Cycle (sec)								
Run No.	0	10	20	30	40	50	60	AVG
1	16	18	19	14	13	13	21	16.3
2	20	25	26	23	14	20	30	22.6
3	25	25	26	23	18	12	24	21.9
4	19	21	22	15	12	13	23	17.9
5	22	25	26	19	12	13	21	19.7
6	23	25	22	15	13	18	25	20.1
7	21	23	27	21	13	12	25	20.3
8	21	25	27	19	12	17	20	20.1
9	20	19	22	16	15	13	23	18.3
10	16	15	18	14	14	13	20	15.7
Mean	$\bar{x}_1$ 20.3	$\bar{x}_2$ 22.1	$\bar{x}_3$ 23.5	$\bar{x}_4$ 17.9	$\bar{x}_5$ 13.6	$\bar{x}_6$ 14.4	$\bar{x}_7$ 23.2	$\bar{\bar{x}}$ 19.3
Std.Dev.	s_1 2.83	s_2 3.67	s_3 3.34	s_4 3.57	s_5 1.84	s_6 2.84	s_7 3.05	S 2.23

Table 5.3. Differences in EV Travel Times, Low Volume

Low Volume, Comparing With vs. Without Preemption Differences in EV Travel Time Entry Time in Cycle (sec)								
	0	10	20	30	40	50	60	AVG
Difference in Means	-24.5	-13.9	-3.4	0.0	0.0	-18.1	-30.6	-12.9
Percent Difference	-54.7%	-38.6%	-12.6%	0.0%	0.0%	-55.7%	-56.9%	-40.1%

Table 5.4. EV Travel Times, Medium Volume, Without Preemption

Medium Volume, Without Preemption EV Travel Time (sec)								
	Entry Time in Cycle (sec)							
Run No.	0	10	20	30	40	50	60	AVG
1	43	37	29	21	18	60	46	36.3
2	46	41	31	24	15	60	50	38.1
3	46	38	35	26	18	64	57	40.6
4	42	37	26	18	13	61	52	35.6
5	47	42	36	32	21	12	54	34.9
6	47	39	34	30	20	15	50	33.6
7	46	38	34	24	19	12	51	32.0
8	46	37	32	19	69	64	56	46.1
9	50	42	36	26	17	66	57	42.0
10	49	42	24	20	17	63	58	39.0
Mean	$\bar{y}_1$	$\bar{y}_2$	$\bar{y}_3$	$\bar{y}_4$	$\bar{y}_5$	$\bar{y}_6$	$\bar{y}_7$	$\bar{\bar{y}}$
	46.2	39.3	31.7	24	22.7	47.7	53.1	37.8
Std.Dev.	s_1	s_2	s_3	s_4	s_5	s_6	s_7	S
	2.39	2.21	4.19	4.64	16.43	24.03	3.93	4.27

Table 5.5. EV Travel Times, Medium Volume, With Preemption

Medium Volume, With Preemption EV Travel Time (sec)								
	Entry Time in Cycle (sec)							
Run No.	0	10	20	30	40	50	60	AVG
1	19	23	25	21	18	15	18	19.9
2	16	27	30	24	15	16	19	21.0
3	23	26	32	26	18	16	27	24.0
4	23	23	24	18	13	19	23	20.4
5	23	28	36	32	21	12	24	25.1
6	22	25	30	30	20	15	23	23.6
7	22	24	32	24	19	12	19	21.7
8	23	23	28	19	24	17	26	22.9
9	26	29	32	26	17	18	27	25.0
10	26	28	21	20	17	22	25	22.7
Mean	$\bar{x}_1$	$\bar{x}_2$	$\bar{x}_3$	$\bar{x}_4$	$\bar{x}_5$	$\bar{x}_6$	$\bar{x}_7$	$\bar{\bar{x}}$
	22.3	25.6	29	24	18.2	16.2	23.1	22.6
Std.Dev.	s_1	s_2	s_3	s_4	s_5	s_6	s_7	S
	2.98	2.32	4.52	4.64	3.08	3.05	3.38	1.85

Table 5.6. Differences in EV Travel Times, Medium Volume

Medium Volume, Comparing With vs. Without Preemption Differences in EV Travel Time								
	Entry Time in Cycle (sec)							
	0	10	20	30	40	50	60	AVG
Difference in Means	-23.9	-13.7	-2.7	0.0	-4.5	-31.5	-30.0	-15.2
Percent Difference	-51.7%	-34.9%	-8.5%	0.0%	-19.8%	-66.0%	-56.5%	-40.2%

Table 5.7. EV Travel Times, High Volume, Without Preemption

High Volume, Without Preemption EV Travel Time (sec) Entry Time in Cycle (sec)								
Run No.	0	10	20	30	40	50	60	AVG
1	46	36	30	20	14	13	50	29.9
2	40	30	26	20	16	13	51	28.0
3	46	34	28	17	19	67	55	38.0
4	45	39	37	27	16	12	57	33.3
5	46	39	38	31	73	66	56	49.9
6	53	47	36	26	14	67	59	43.1
7	40	36	32	30	21	13	52	32.0
8	51	37	35	24	14	62	55	39.7
9	53	44	88	20	22	70	62	51.3
10	44	37	29	21	68	64	54	45.3
Mean	$\bar{y}_1$	$\bar{y}_2$	$\bar{y}_3$	$\bar{y}_4$	$\bar{y}_5$	$\bar{y}_6$	$\bar{y}_7$	$\bar{\bar{y}}$
	46.4	37.9	37.9	23.6	27.7	44.7	55.1	39.0
Std.Dev.	s_1	s_2	s_3	s_4	s_5	s_6	s_7	S
	4.70	4.82	18.07	4.74	22.77	27.58	3.67	8.25

Table 5.8. EV Travel Times, High Volume, With Preemption

High Volume, With Preemption EV Travel Time (sec) Entry Time in Cycle (sec)								
Run No.	0	10	20	30	40	50	60	AVG
1	19	24	26	20	14	13	20	19.4
2	17	16	23	20	16	13	21	18.0
3	22	22	24	17	19	21	25	21.4
4	23	25	33	27	16	12	27	23.3
5	23	25	35	31	21	18	26	25.6
6	29	34	32	26	14	21	29	26.4
7	16	22	29	30	21	13	21	21.7
8	27	26	27	24	14	17	25	22.9
9	29	32	43	20	22	21	32	28.4
10	21	24	26	21	20	15	24	21.6
Mean	$\bar{x}_1$	$\bar{x}_2$	$\bar{x}_3$	$\bar{x}_4$	$\bar{x}_5$	$\bar{x}_6$	$\bar{x}_7$	$\bar{\bar{x}}$
	22.6	25	29.8	23.6	17.7	16.4	25.0	22.9
Std.Dev.	s_1	s_2	s_3	s_4	s_5	s_6	s_7	S
	4.62	5.08	6.09	4.74	3.23	3.69	3.77	3.19

Table 5.9. Differences in EV Travel Times, High Volume

High Volume, Comparing With vs. Without Preemption Differences in EV Travel Time Entry Time in Cycle (sec)								
	0	10	20	30	40	50	60	AVG
Difference in Means	-23.8	-12.9	-8.1	0.0	-10.0	-28.3	-30.1	-16.2
Percent Difference in Means	-51.3%	-34.0%	-21.4%	0.0%	-36.1%	-63.3%	-54.6%	-41.4%

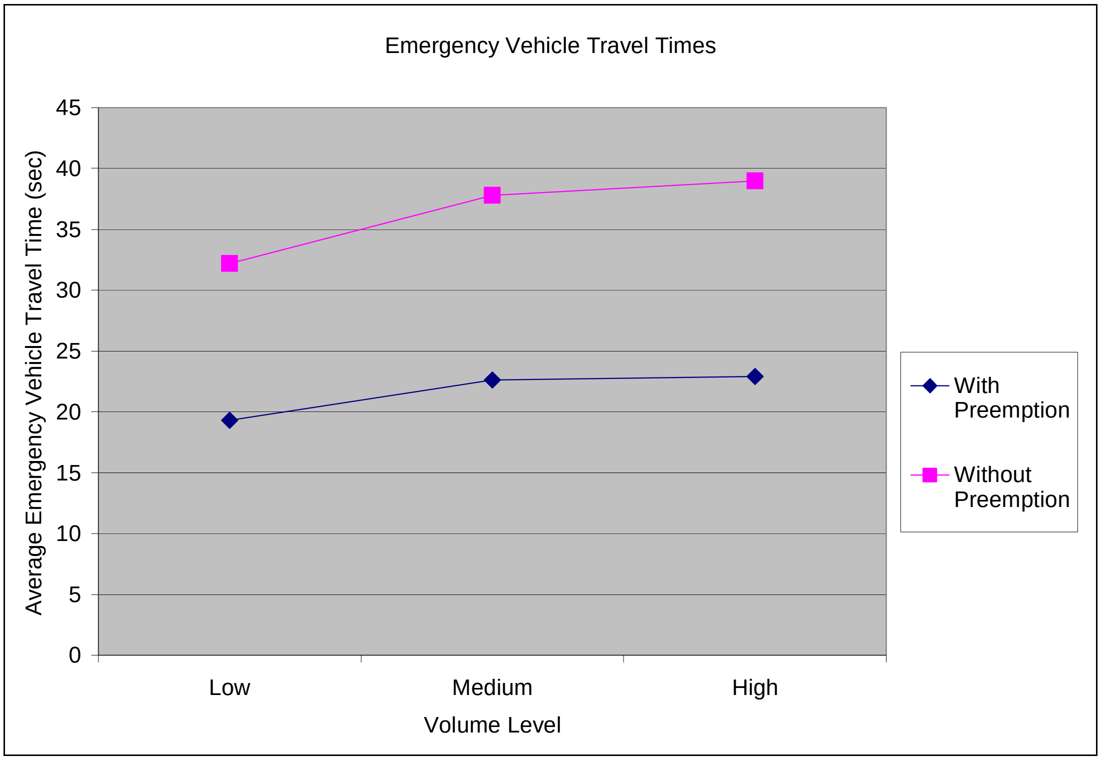


Figure 5.1. Emergency Vehicle Travel Times, Summary

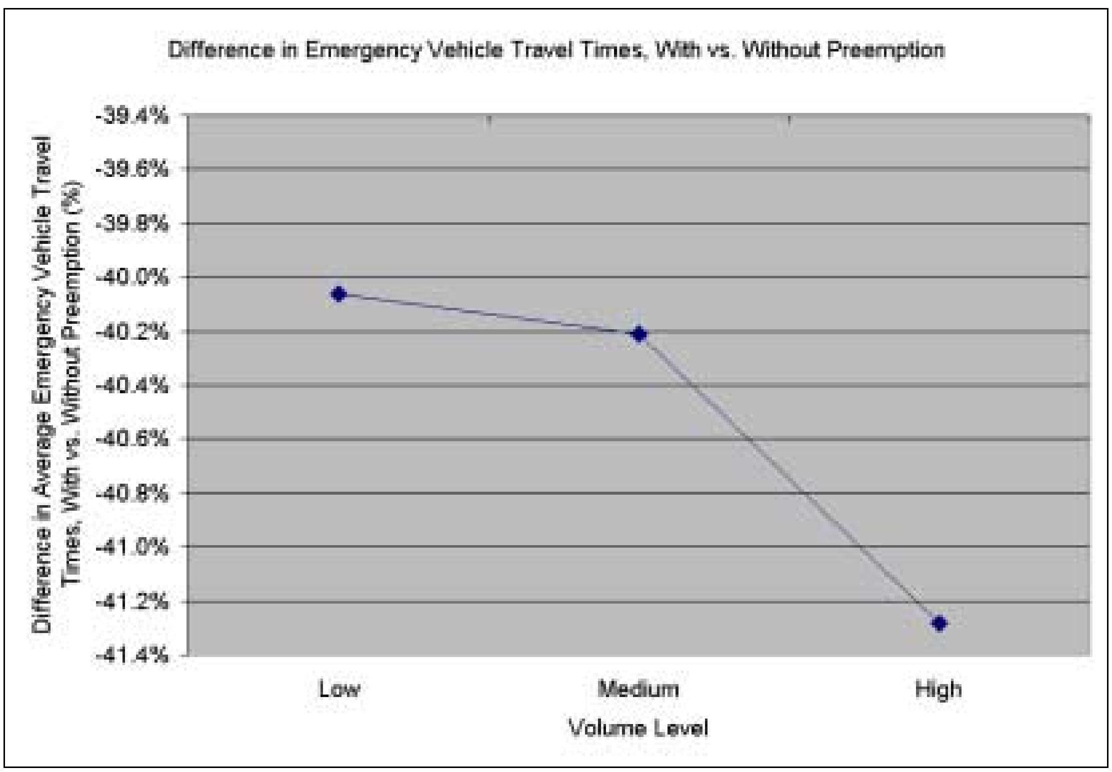


Figure 5.2. Difference in Emergency Vehicle Travel Time, Summary

Another observation to make is that the range in emergency vehicle travel time savings was dependent on the point in the traffic signal cycle at which the emergency vehicle entered the network. On the low side, there was no (0%) average travel time savings for the following cases:

- Low Volume Case: At the 30-sec and 40-sec entry points in the signal cycle
- Medium Volume Case: At the 30-sec entry point in the signal cycle
- High Volume Case: At the 30-sec entry point in the signal cycle.

At the other extreme, the following were the highest average differences in emergency vehicle travel times and their corresponding emergency vehicle entry points in the traffic signal cycle:

- Low Volume Case: -56.9% difference at the 60-sec entry point in the signal cycle
- Medium Volume Case: -66.0% difference at the 50-sec entry point in the signal cycle
- High Volume Case: -63.3% difference at the 50-sec entry point in the signal cycle.

These large swings in results with respect to the emergency vehicle entry point in the traffic signal cycle can be expected given the nature of the simulation model. The emergency vehicle entry points and their relationship to the traffic signal timing plan at the intersection is shown in Figure 5.3. Examining the case of the emergency vehicle entry on the network at the 30 or 40-second point, we see that the timing plan is near the latter portion of Phase 1 (East/West movement). By the time the emergency vehicle reaches the intersection, the timing plan is at the beginning or in the early portion of Phase 2 (North/South movement). Hence, we see little or no difference when comparing emergency vehicle travel times for these cases. If, on the other hand, the emergency vehicle entry on the network is at the 50 or 60-second point, Phase 2 is nearing completion or has just ended by the time the emergency vehicle reaches the intersection. The emergency vehicle without preemption would then need to wait for the entire Phase 1 completion before proceeding, resulting in large differences in the travel time comparison of emergency vehicles with preemption.

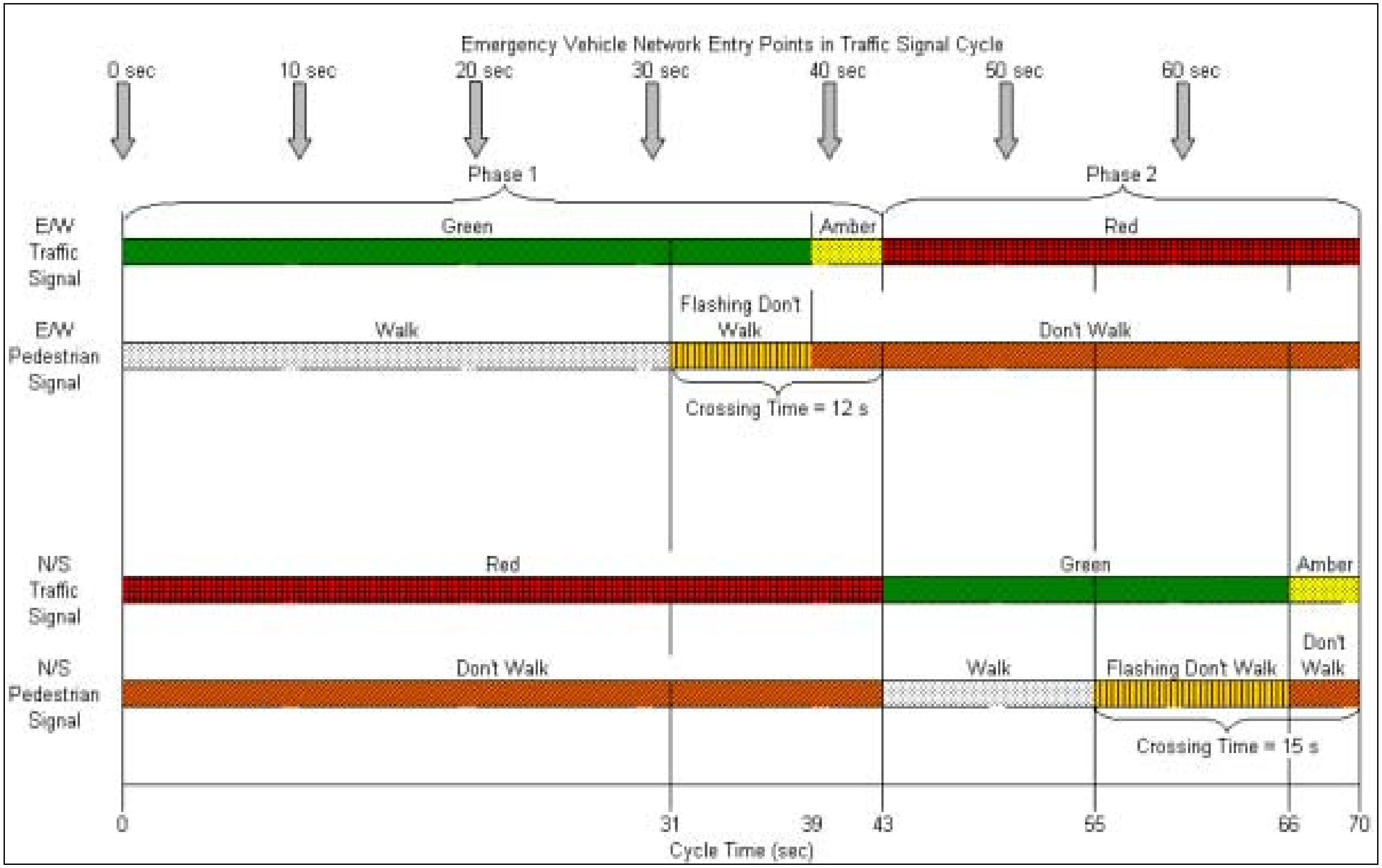


Figure 5.3. Emergency Vehicle Entry Points in Traffic Signal Timing Plan

The effect of the emergency vehicle entry point in the cycle is also illustrated in Table 5.10, Table 5.11, and Table 5.12 which show the time that the traffic signal spent in preemption for the Low, Medium, and High Volume Cases, respectively. We can observe large variances at the 10-second entry point in the cycle for all cases and a large variance at the 60-second entry point in the cycle for the High Volume Case. The large variances for these cases results from the preemption logic either dwelling in preemption (higher values for the time spent in preemption) or transitioning back to Phase 1 (lower values for time spent in preemption) depending on the exact point in the cycle where the emergency vehicle crossed over the "check-out" detector. The stochastic nature of the simulation model accounts for these differences within the 10-second incremental emergency vehicle entry points in the cycle.

Table 5.10. Time Traffic Signal Spent in Preemption, Low Volume Case

Low Volume Case Time Traffic Signal Spent in Preemption (sec)								
	Entry Time in Cycle (sec)							
Run No.	0	10	20	30	40	50	60	AVG
1	12	43	35	27	12	8	13	21.4
2	16	45	34	27	11	16	22	24.4
3	55	45	35	27	11	8	19	28.6
4	15	45	31	27	11	8	15	21.7
5	52	45	34	27	11	8	13	27.1
6	54	45	34	27	12	16	18	29.4
7	55	45	34	27	12	9	17	28.4
8	55	41	34	27	10	15	13	27.9
9	16	45	35	27	11	8	16	22.6
10	12	44	34	27	12	10	13	21.7
Mean	34.2	44.3	34.0	27.0	11.3	10.6	15.9	25.3
Std.Dev.	21.1	1.3	1.2	0.0	0.7	3.6	3.1	3.3

Table 5.11. Time Traffic Signal Spent in Preemption, Medium Volume Case

Medium Volume Case Time Traffic Signal Spent in Preemption (sec) Entry Time in Cycle (sec)								
Run No.	0	10	20	30	40	50	60	AVG
1	53	45	35	27	11	11	14	28.0
2	12	45	32	27	12	12	12	21.7
3	54	43	34	27	11	13	19	28.7
4	52	45	33	27	12	14	15	28.3
5	54	45	32	30	14	9	17	28.7
6	53	45	35	28	13	10	16	28.6
7	55	45	33	27	12	8	11	27.3
8	54	45	35	27	17	14	18	30.0
9	55	44	35	27	12	14	20	29.6
10	54	45	34	27	12	21	19	30.3
Mean	49.6	44.7	33.8	27.4	12.6	12.6	16.1	28.1
Std.Dev.	13.2	0.7	1.2	1.0	1.8	3.7	3.1	2.4

Table 5.12. Time Traffic Signal Spent in Preemption, High Volume Case

High Volume Case Time Traffic Signal Spent in Preemption (sec) Entry Time in Cycle (sec)								
Run No.	0	10	20	30	40	50	60	AVG
1	15	43	35	27	10	8	13	21.6
2	13	44	34	27	9	8	13	21.1
3	55	43	35	27	12	16	18	29.4
4	53	45	35	27	11	8	19	28.3
5	54	45	34	29	14	14	19	29.9
6	55	44	35	27	11	18	61	35.9
7	12	45	34	28	14	9	13	22.1
8	55	42	34	27	11	16	18	29.0
9	55	43	39	27	15	16	61	36.6
10	54	44	34	27	13	11	17	28.6
Mean	42.1	43.8	34.9	27.3	12.0	12.4	25.2	28.2
Std.Dev.	19.9	1.0	1.5	0.7	1.9	4.0	19.0	5.4

Another observation is related to the large values of the “without preemption” standard deviation of emergency vehicle travel time within some of the 10-second entry points. For all volume levels, the 50-second entry point in the traffic signal cycle had the highest standard deviation of emergency vehicle travel times. This can be explained by again referring back to Figure 5.3. Vehicles entering the network at the 50-second point in the traffic signal cycle will arrive at the intersection either toward the end of Phase 2 and be able to proceed, or at the beginning of Phase 1 and be forced to wait until the completion of Phase 1. We then observe the large variance in emergency vehicle travel times such as in the High Volume case where values ranging from 12 seconds to 70 seconds.

A final observation related to variance in the emergency vehicle travel times is in the comparison of standard deviation for the "with" versus "without" preemption cases. The values of standard deviation are much lower with preemption. While this result can be expected, it supports a benefit to emergency vehicle traffic signal preemption in addition to travel time savings; namely, "travel time reliability." Travel time reliability is a measure of effectiveness that is being touted within the ITS community as perhaps the most noteworthy benefit of many ITS systems. This travel time reliability benefit to emergency vehicles may result is better route planning for emergency vehicle operators.

5.2.1 Statistical Comparison of Emergency Vehicle Travel Times

To compare the average values of emergency vehicle travel times for the "with" and "without" preemption cases, a statistical test comparing the significance of the two means can be performed. The t-test is an appropriate test for small sample sizes assuming that the underlying populations follow a normal distribution with equal variances. The t-value can be computed as shown in Equation 6 below.

Equation 6. T-test for Two Samples.

$$t = \frac{\mu_1 - \mu_2}{S_p \sqrt{1/m + 1/n}}$$

Where: μ_1 = Sample mean 1

μ_2 = Sample mean 2

S_p = Pooled estimate of standard deviation

m = Sample size 1

n = Sample size 2

and

$$S_p^2 = \frac{(m-1)s_1^2 + (n-1)s_2^2}{(m+n-2)}$$

where: s_1^2 = Sample variance 1

s_2^2 = Sample variance 2

A t-test was performed on the 10 average emergency vehicle travel time results for the "with" and "without" preemption scenarios to test for statistical differences in the results at the three different volume levels. The results of the t-test are shown in Table 5.13 and Table 5.14. Interpreting the results from Table 5.13, we can say that for the "with preemption" scenario the average emergency vehicle travel times for the Low and Medium volume cases are different at the 99.8% confidence level. Similarly, we can say that the Low and High volume cases are different at the 99.1% confidence level. The average emergency vehicle travel times are not statistically different for the Medium and High volume cases, however. For the "without preemption" scenario, from Table 5.14 we can say that the Low and Medium volume cases are different at the 99.1% confidence level and that the Low and High volume cases are different at the 96.8% confidence level. Again, we cannot say that the average emergency vehicle travel times are different for the Medium and High volume cases.

Table 5.13. T-test Comparison of EV Travel Times, With Preemption

T-Test P-Values for the 10 Average Emergency Vehicle Travel Times				
		With Preemption		
		Low Volume	Medium Volume	High Volume
With Preemption	Low Volume	-------	99.8%	99.1%
	Medium Volume	99.8%	-------	16.3%
	High Volume	99.1%	16.3%	-------

Table 5.14. T-test Comparison of EV Travel Times, Without Preemption

T-Test P-Values for the 10 Average Emergency Vehicle Travel Times				
		Without Preemption		
		Low Volume	Medium Volume	High Volume
Without Preemption	Low Volume	-------	99.1%	96.8%
	Medium Volume	99.1%	-------	31.9%
	High Volume	96.8%	31.9%	-------

5.3 TRAVEL TIMES—ALL TRAVELERS

Travel times for all travelers are presented in the following subsections. As mentioned above, results are presented with respect to the following aggregate levels (link, intersection, and arterial) and for each volume level (Low, Medium, and High). Travel times and the percent difference in travel times are presented in a series of graphs for the "with" and "without" preemption cases. Each of these graphs represents the two-hour simulation analysis period and the cumulative average travel time values over the two-hour period.

5.3.1 Link Travel Times—All Travelers

The link travel times for all travelers are presented here.

5.3.1.1 Northbound Link

Results for the northbound link to node 6 (i.e., link 8-6) are presented in Figure 5.4 through Figure 5.7. The traffic volume on the northbound link remains constant at 284 veh/hour for all cases. As seen in these figures and all subsequent figures, the spike in the cumulative travel times at the beginning of the simulation analysis for the "with preemption" cases is a result of the traffic signal preemption. As shown in Figure 5.7, the difference in average cumulative travel time for all travelers was large and positive with values at the 5-minute point approximately 18.0%, 21.0%, and 25.0% for the Low, Medium, and High Cases, respectively. By the 15-minute point, the differences in these cumulative values had dropped to approximately 5.9%, 7.5%, and 7.0%, respectively. The differences continued to drop asymptotically for the remainder of the two-hour analysis period and stayed below 2.0% at the following points in time for the Low, Medium, and High Volume Cases, respectively: 48-minutes, 61-minutes, and 61-minutes.

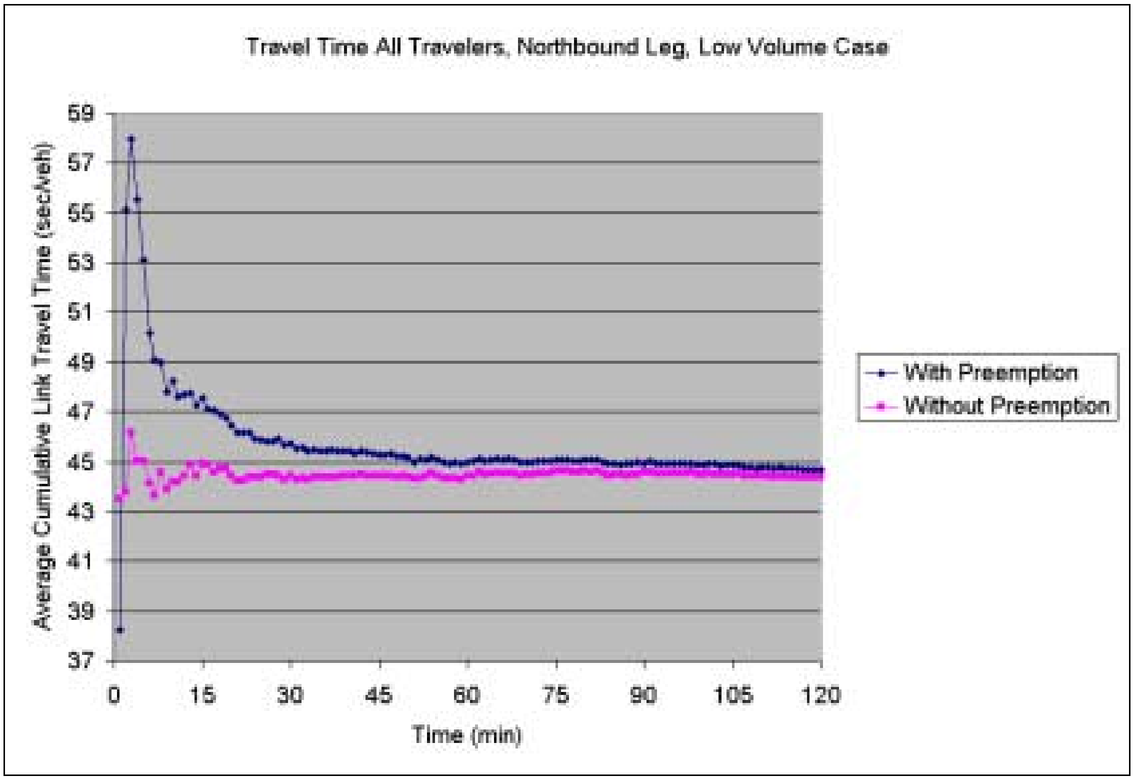


Figure 5.4. Approach Link Travel Time, Northbound, Low Volume Case

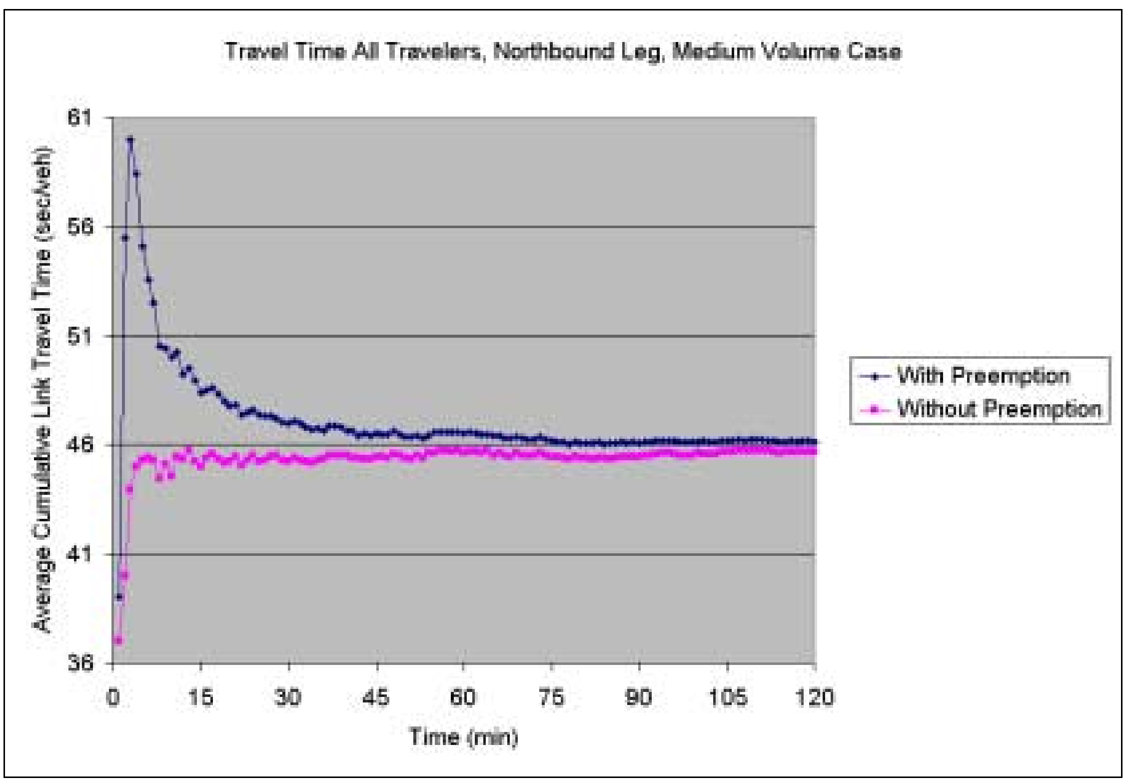


Figure 5.5. Approach Link Travel Time, Northbound, Medium Volume Case

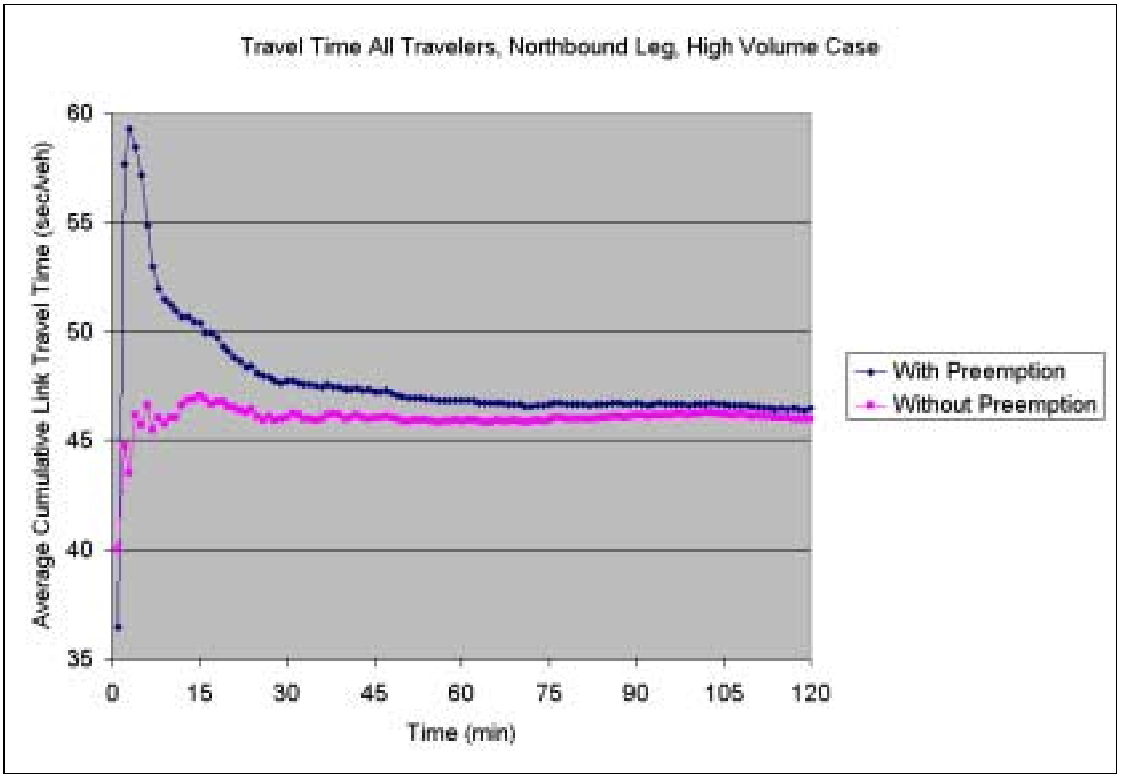


Figure 5.6. Approach Link Travel Time, Northbound, High Volume Case

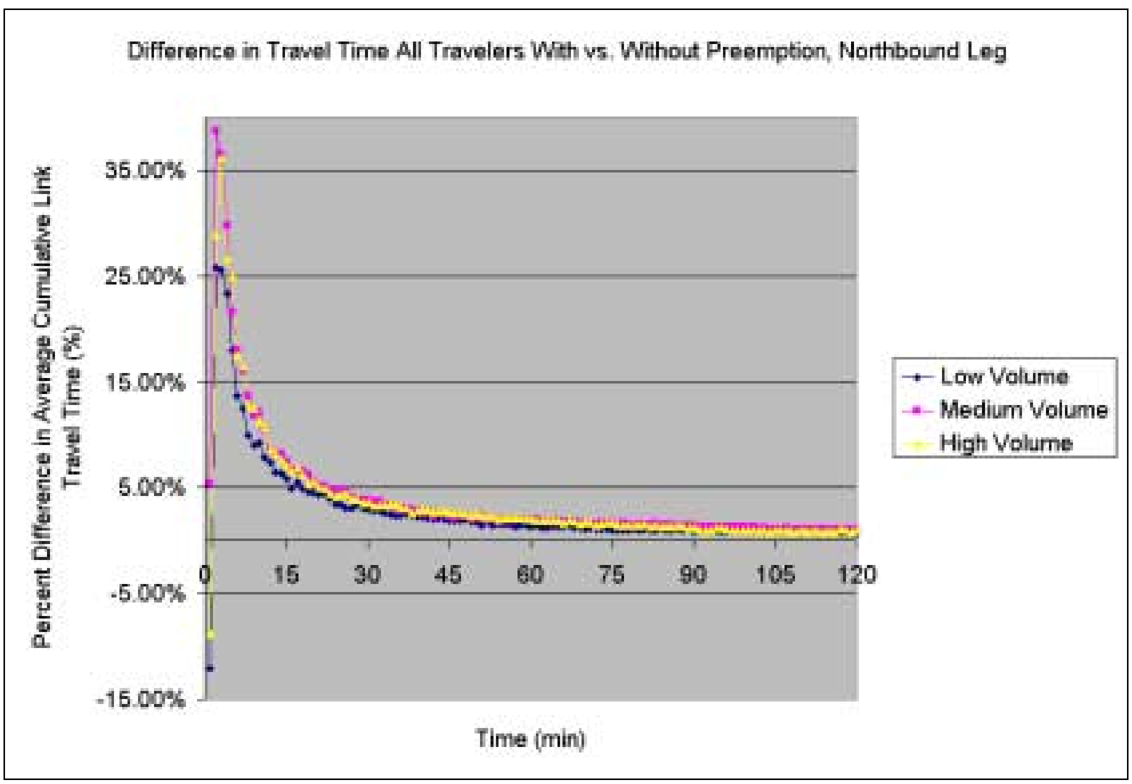


Figure 5.7. Percent Difference in Approach Link Travel Time, Northbound

5.3.1.2 Southbound Link

Results for the southbound link to node 6 (i.e., link 7-6) are presented in Figure 5.8 through Figure 5.11. The southbound link is the preemption path for the emergency vehicle. The traffic volume on the southbound link varied for each of the three volume cases as follows: 362 veh/hour, 545 veh/hour, and 634 veh/hour. As shown in Figure 5.11, the difference in average cumulative travel time for all travelers was moderate and negative for a short period of time with values at the 5-minute point of –4.7%, -3.4%, and –6.1% for the Low, Medium, and High Cases, respectively. By the 15-minute point, the differences in these cumulative values had risen to –1.3%, -1.2%, and –1.8%, respectively. The differences continued to rise asymptotically for the remainder of the two-hour analysis period and stayed above –1.0% at the following points in time for the Low, Medium, and High Volume Cases, respectively: 25-minutes, 22-minutes, and 21-minutes.

Figure 5.8. Approach Link Travel Time, Southbound, Low Volume Case

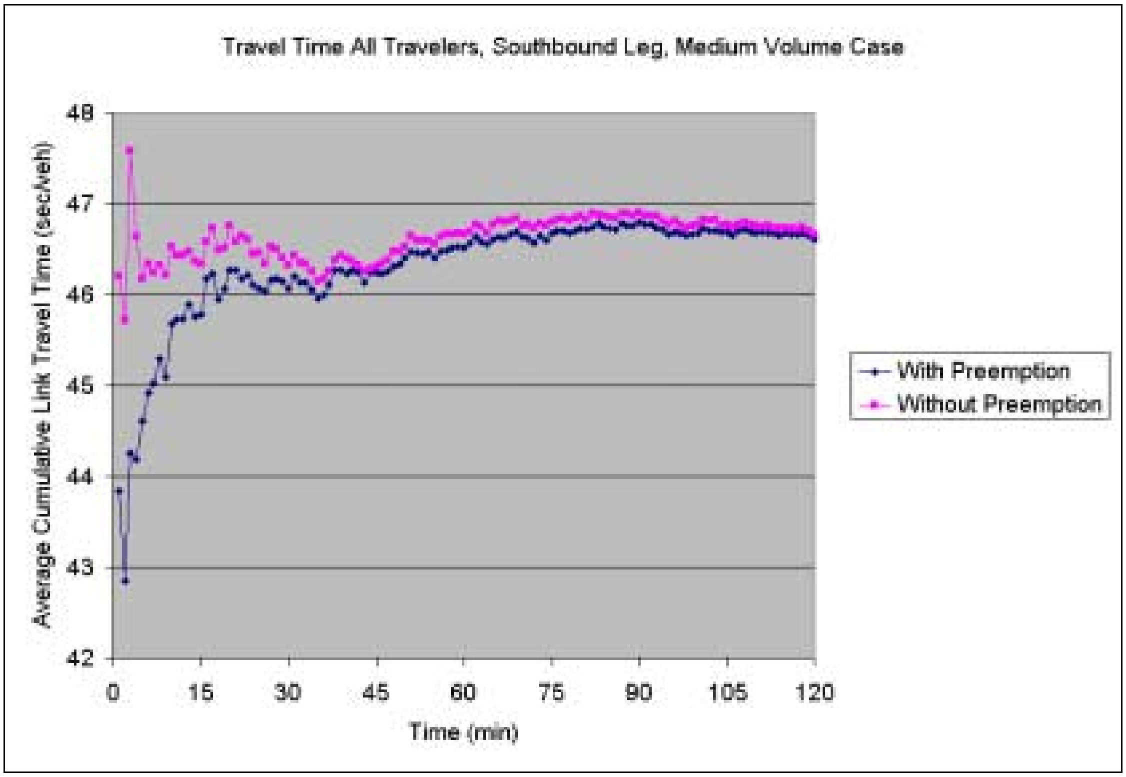


Figure 5.9. Approach Link Travel Time, Southbound, Medium Volume Case

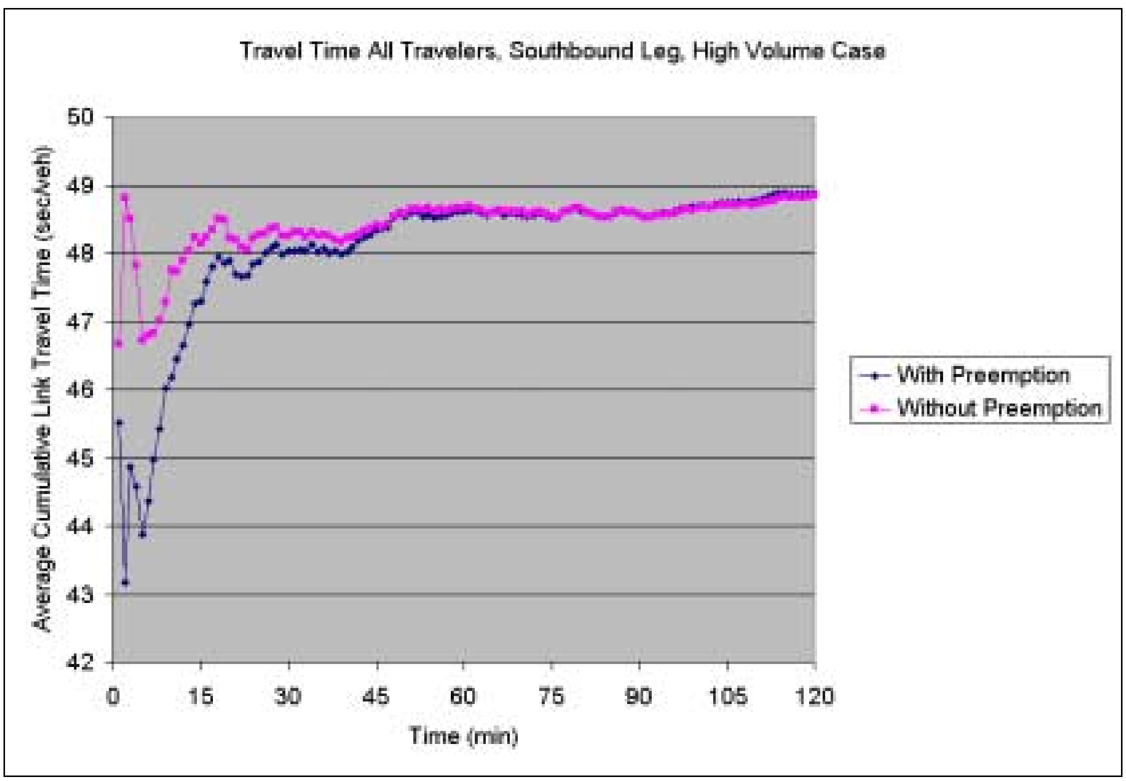


Figure 5.10. Approach Link Travel Time, Southbound, High Volume Case

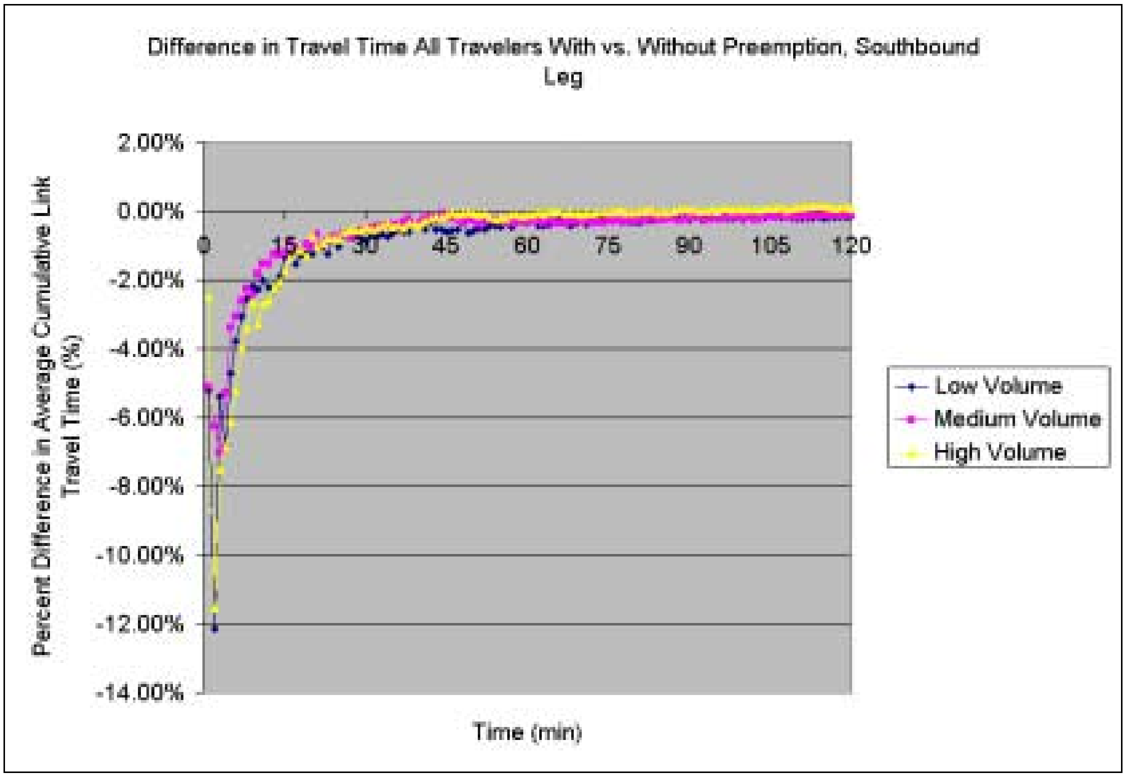


Figure 5.11. Percent Difference in Approach Link Travel Time, Southbound

5.3.1.3 Eastbound Link

Results for the eastbound link to node 6 (i.e., link 4-6) are presented in Figure 5.12 through Figure 5.15. The traffic volume on the eastbound link remains constant at 521 veh/hour for all cases. As shown in Figure 5.15, the difference in average cumulative travel time for all travelers was fairly small with values at the 5-minute point approximately 2.2%, 4.3%, and 2.2% for the Low, Medium, and High Cases, respectively. By the 15-minute point, the differences in these cumulative values had dropped to approximately 0.6%, 0.4%, and –0.1%, respectively, and began to converge to 0%. The differences stayed below +/- 1.0% at the following points in time for the Low, Medium, and High Volume Cases, respectively: 13-minutes, 55-minutes, and 39-minutes.

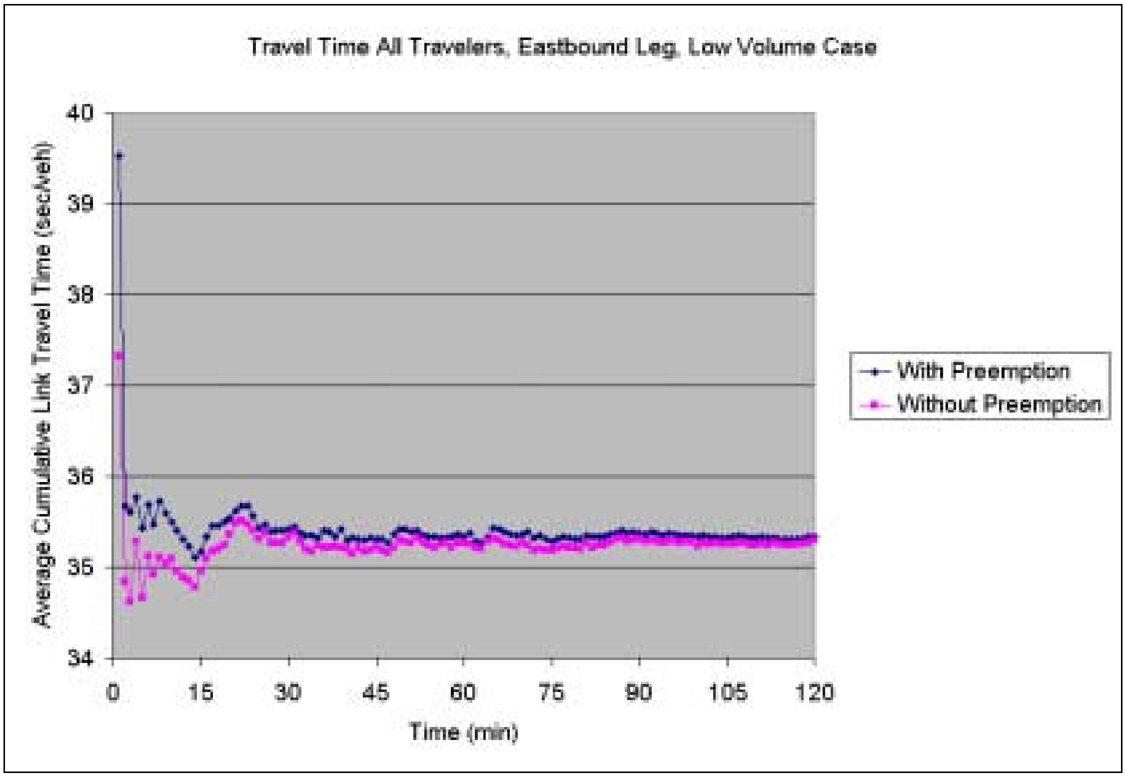


Figure 5.12. Approach Link Travel Time, Eastbound, Low Volume Case

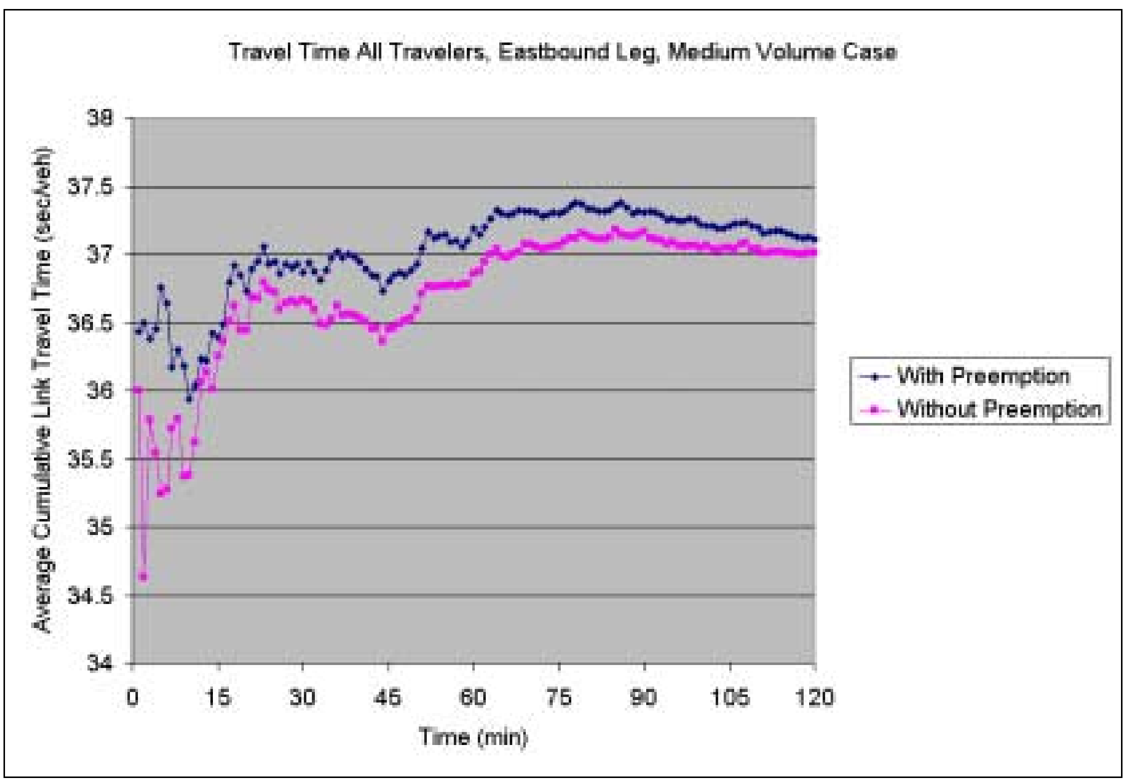


Figure 5.13. Approach Link Travel Time, Eastbound, Medium Volume Case

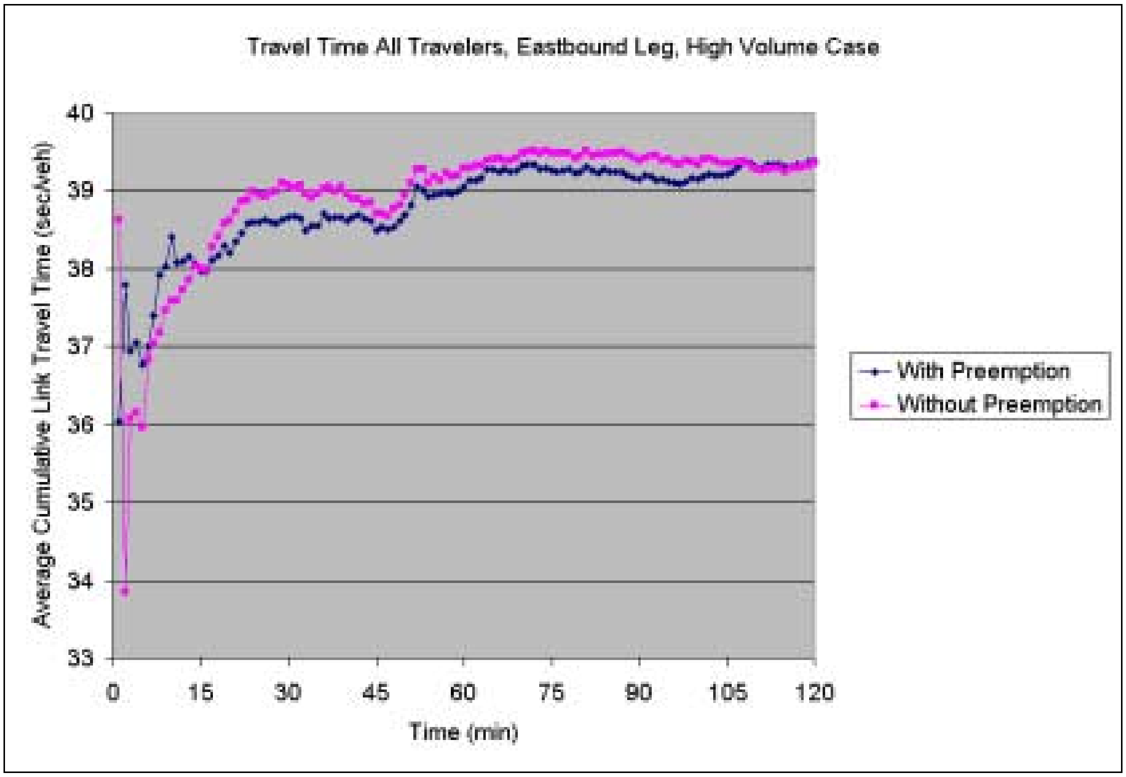


Figure 5.14. Approach Link Travel Time, Eastbound, High Volume Case

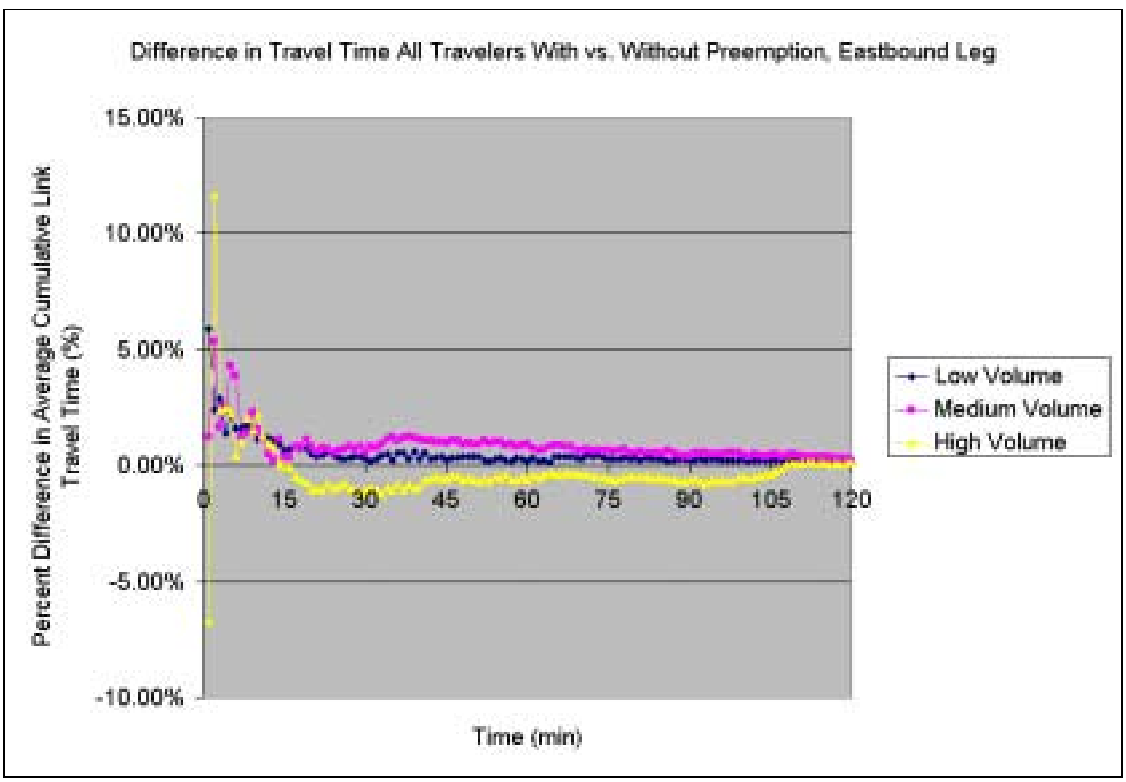


Figure 5.15. Percent Difference in Approach Link Travel Time, Eastbound

5.3.1.4 Westbound Link

Results for the westbound link to node 6 (i.e., link 9-6) are presented in Figure 5.16 through Figure 5.19. The westbound link is the major flow direction on the arterial and is the primary direction for traffic signal progression. The traffic volume on the westbound link varied for each of the three volume cases as follows: 1,040 veh/hour, 1,480 veh/hour, and 1,702 veh/hour. As shown in Figure 5.19, the difference in average cumulative travel time for all travelers was large and positive with values at the 5-minute point approximately 11.0%, 26.9%, and 33.1% for the Low, Medium, and High Cases, respectively. By the 15-minute point, the differences in these cumulative values had dropped to approximately 3.8%, 8.9%, and 12.2%, respectively. The differences continued to drop asymptotically for the remainder of the two-hour analysis period and stayed below 2.0% at the following points in time for the Low, Medium, and High Volume Cases, respectively: 32-minutes, 72-minutes, and 97-minutes.

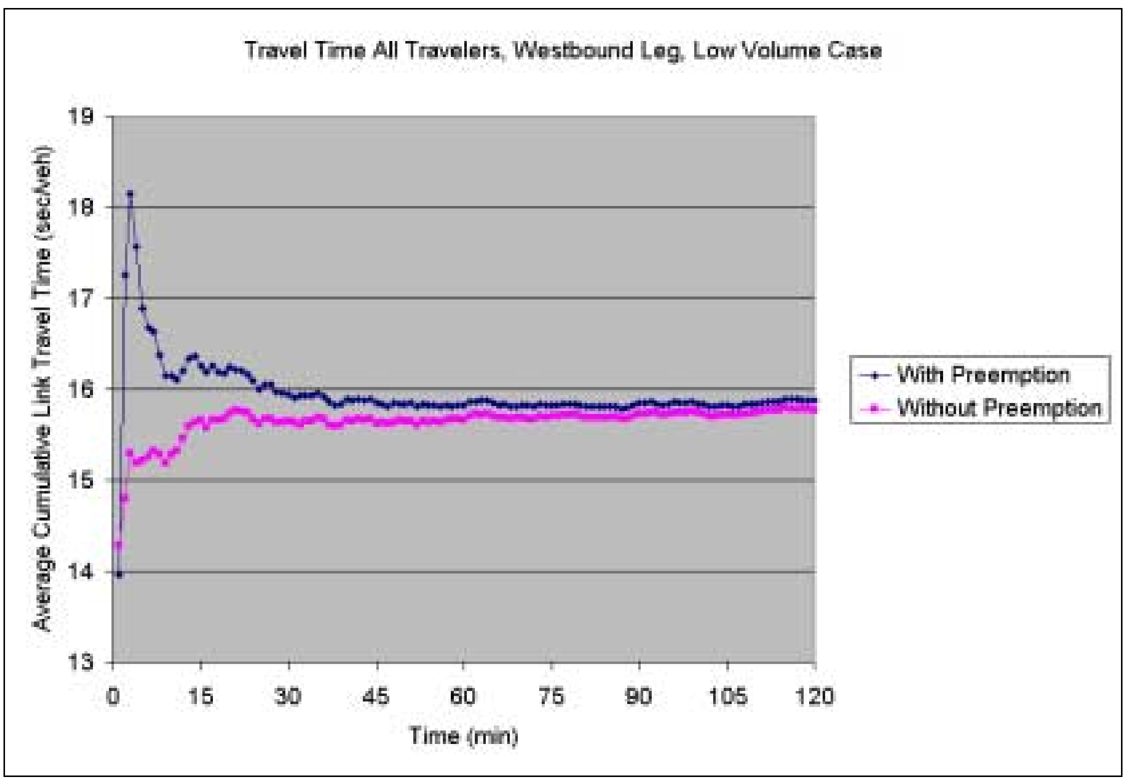


Figure 5.16. Approach Link Travel Time, Westbound, Low Volume Case

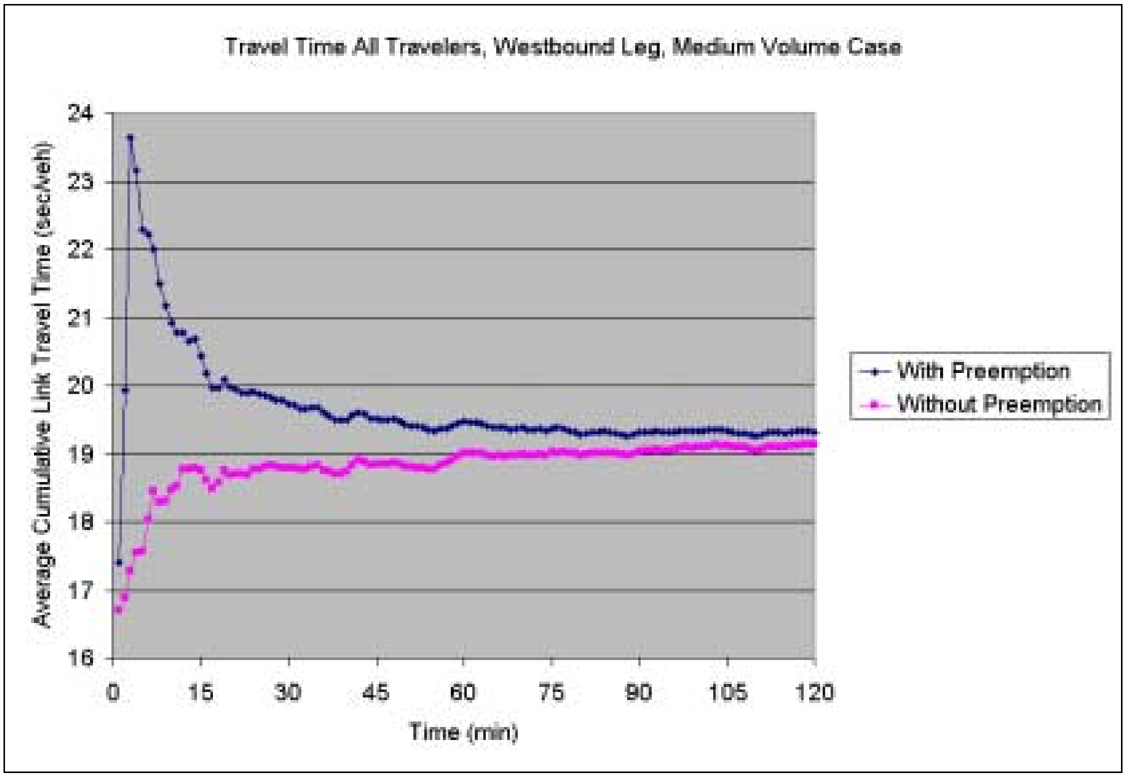


Figure 5.17. Approach Link Travel Time, Westbound, Medium Volume Case

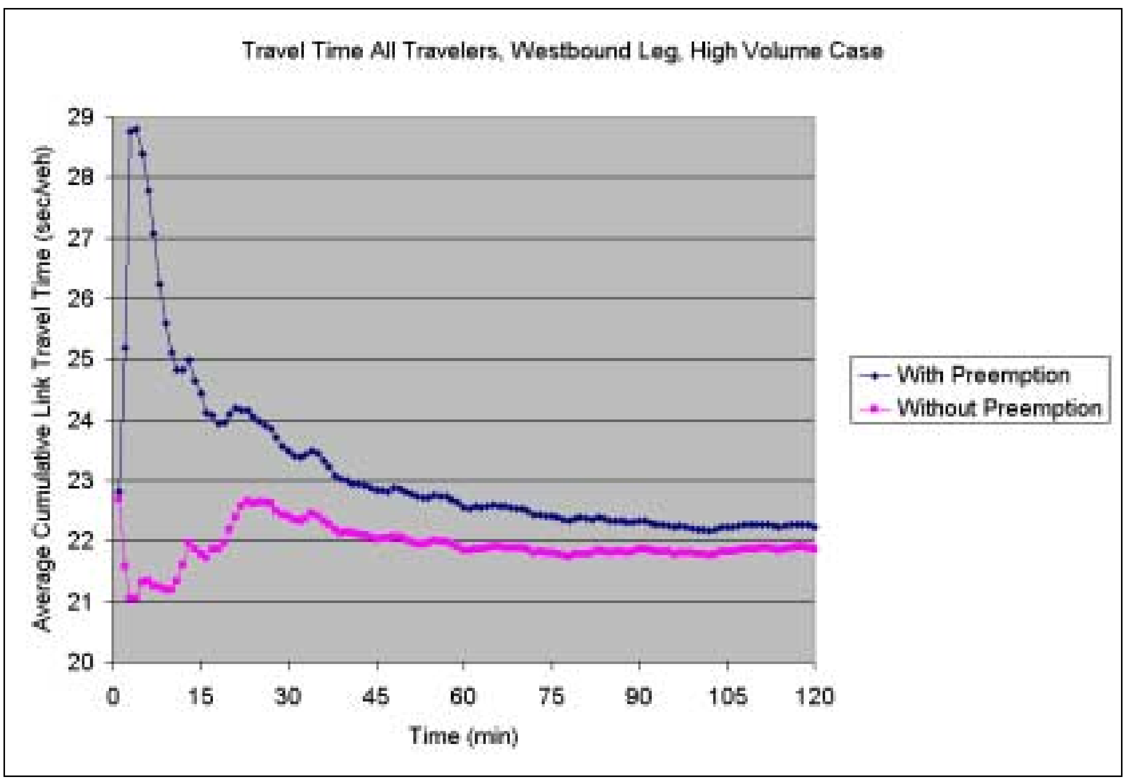


Figure 5.18. Approach Link Travel Time, Westbound, High Volume Case

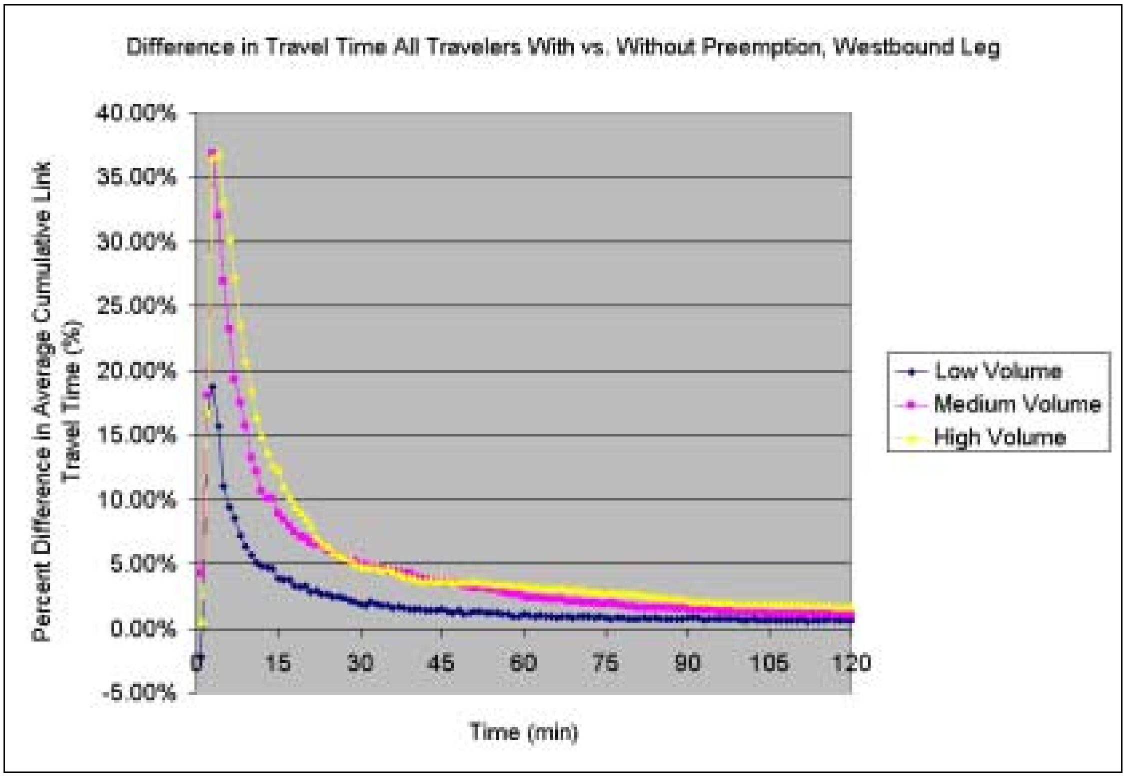


Figure 5.19. Percent Difference in Approach Link Travel Time, Westbound

5.3.2 Intersection Travel Times—All Travelers

Results for travel times for all approaches to node 6 are presented in Figure 5.20 through Figure 5.23. The average cumulative intersection link travel times represent the summation of the average cumulative travel time spent on the four approaches to Node 6 (i.e., Northbound, Southbound, Eastbound, and Westbound) divided by the summation of the average cumulative number of vehicle trips made on these approaches. As shown in Figure 5.23, the difference in average cumulative travel time for all travelers on all intersection approaches was large and positive with values at the 5-minute point approximately 5.7%, 11.8%, and 14.7% for the Low, Medium, and High Cases, respectively. By the 15-minute point, the differences in these cumulative values had dropped to approximately 2.0%, 3.8%, and 4.9%, respectively. The differences continued to drop asymptotically for the remainder of the two-hour analysis period and stayed below 2.0% at the following points in time for the Low, Medium, and High Volume Cases, respectively: 15-minutes, 39-minutes, and 28-minutes. The differences stayed below 1.0% at the following points in time for the Low, Medium, and High Volume Cases, respectively: 32-minutes, 70-minutes, and 84-minutes.

Comparing Figure 5.19, the percent difference in the average cumulative travel time for the Westbound Approach to Figure 5.23, the difference in the average cumulative travel time for all approaches to the intersection, reveals graphs of similar shape. This can be expected since the Westbound Approach is the dominant approach to the intersection in terms of traffic volume. The percent of hourly traffic volume attributed to each of the intersection approaches is shown in Table 5.15.

Table 5.15. Percent of Intersection Volume by Approach

Percent of Total Intersection Volume				
Volume Level	Approach			
	Eastbound	Westbound	Southbound	Northbound
Low	24%	47%	16%	13%
Medium	18%	52%	19%	10%
High	17%	54%	20%	9%

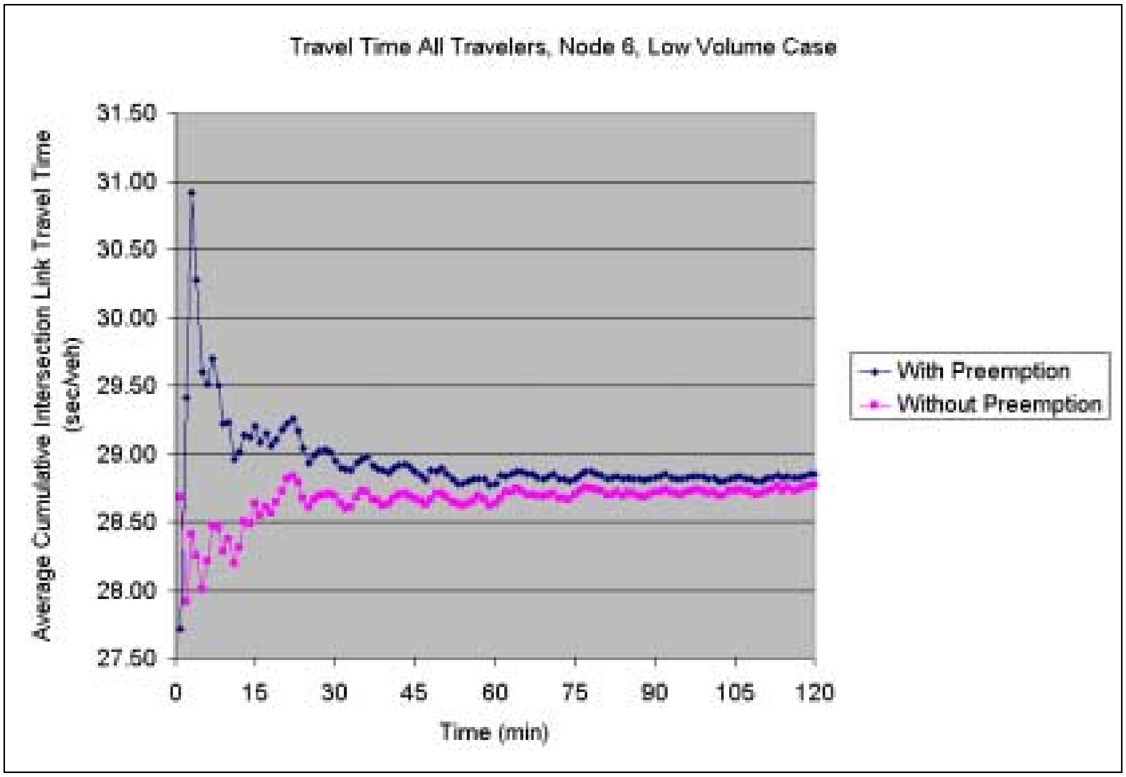


Figure 5.20. Intersection Link Travel Time, Low Volume Case

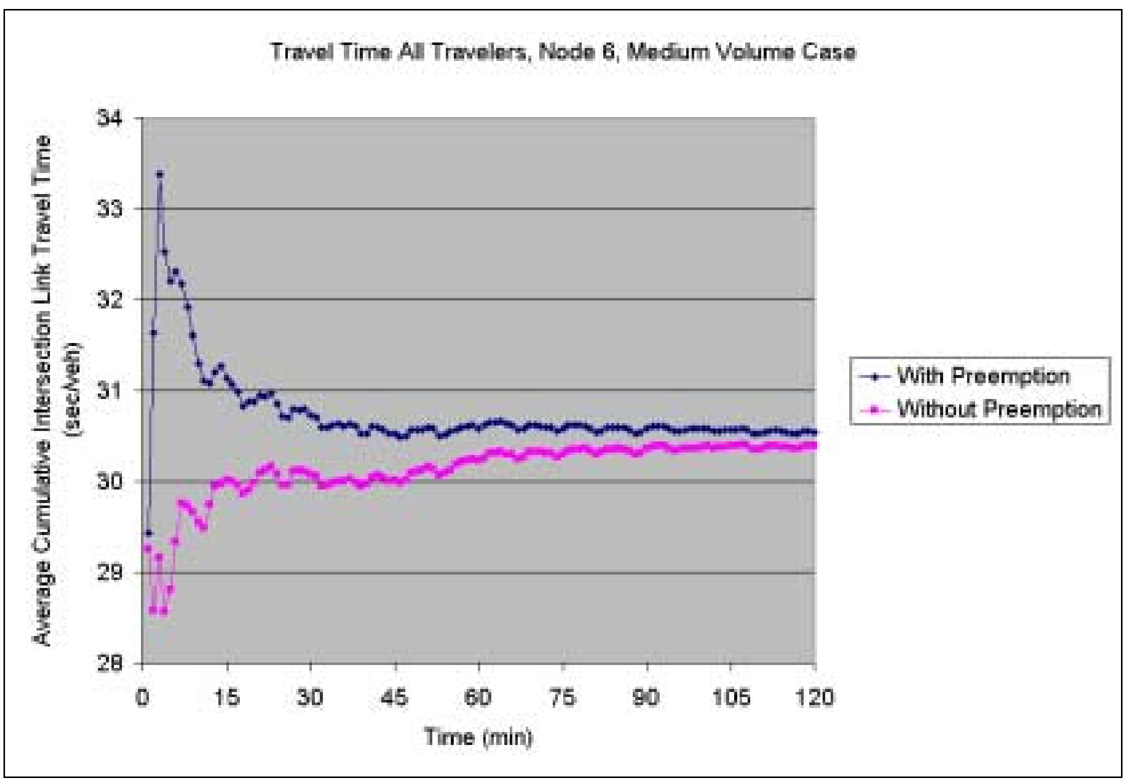


Figure 5.21. Intersection Link Travel Time, Medium Volume Case

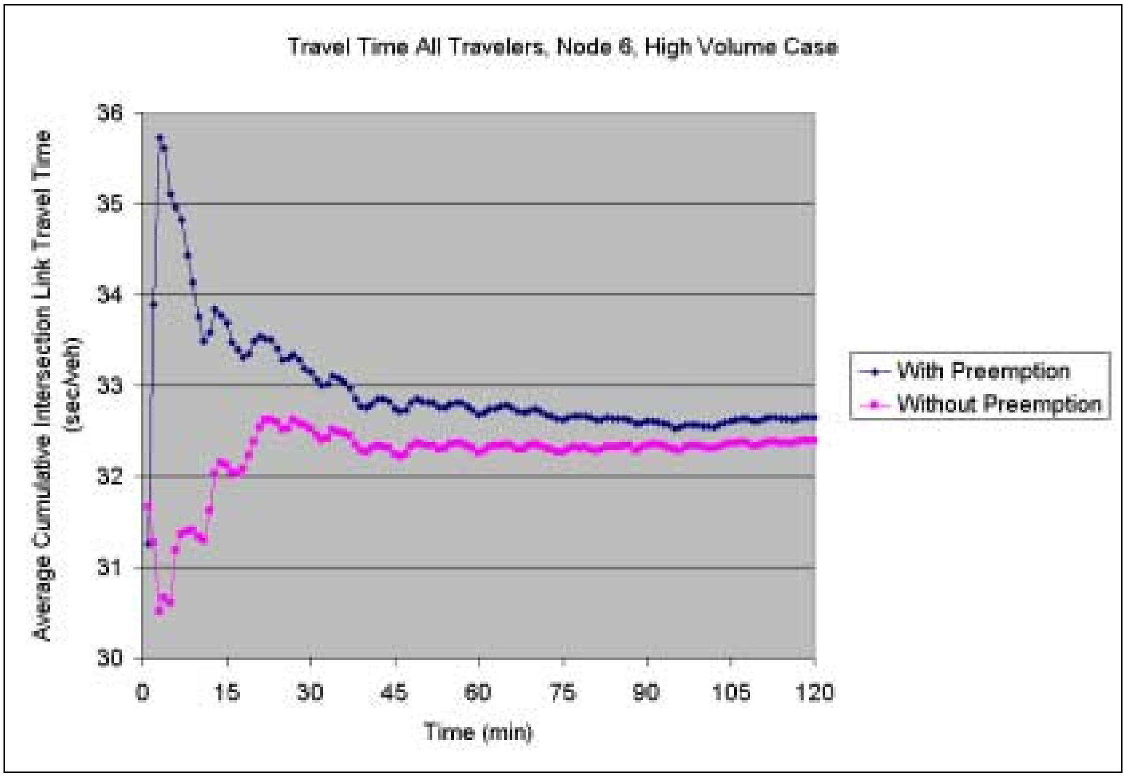


Figure 5.22. Intersection Link Travel Time, High Volume Case

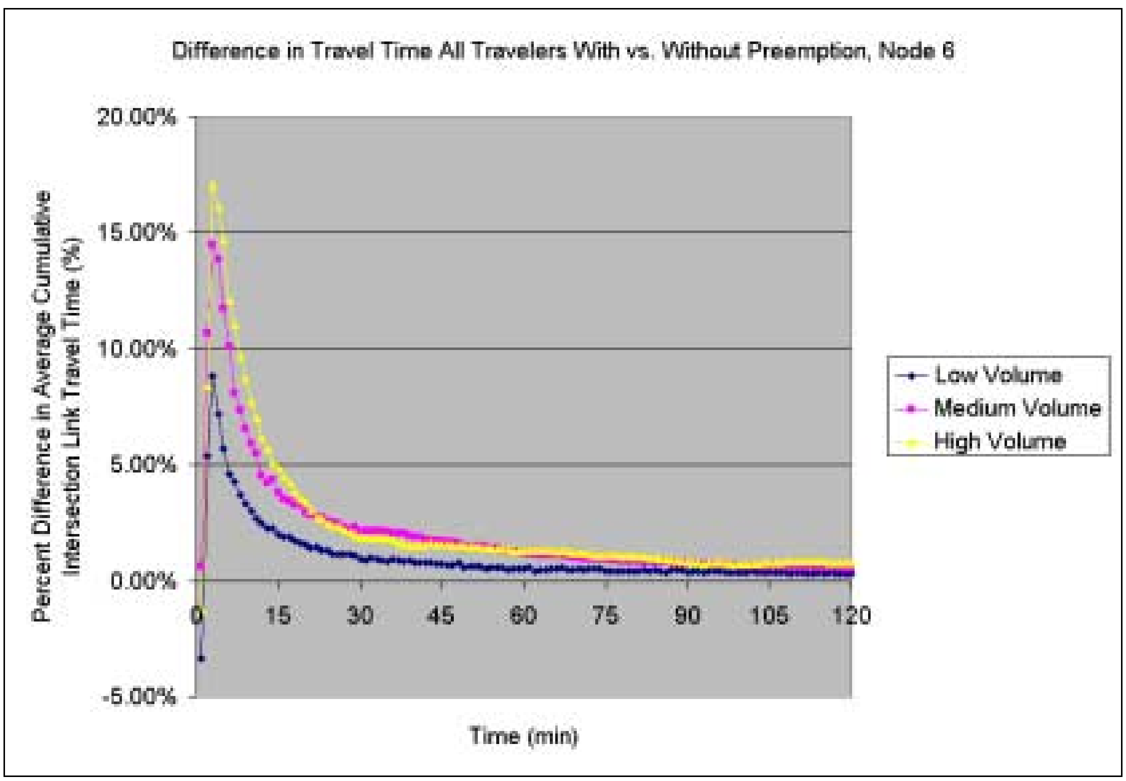


Figure 5.23. Percent Difference in Intersection Link Travel Time

5.3.3 Arterial Travel Times—All Travelers

Results for travel times across the entire arterial for the case of the emergency vehicle entry point of 30 seconds into the traffic signal cycle are presented in Figure 5.24 through Figure 5.27. The average cumulative arterial link travel times represent the summation of the average cumulative travel time spent on all links (including the East/West arterial and the North/South side street links) in the simulation network model divided by the summation of the average cumulative number of vehicle trips made on all links. As shown in Figure 5.27, the difference in the average cumulative arterial link travel time for all travelers was small with the values staying below +/- 1.0% at the following points in time for the Low, Medium, and High Volume Cases, respectively: 8-minutes, 11-minutes, and 13-minutes.

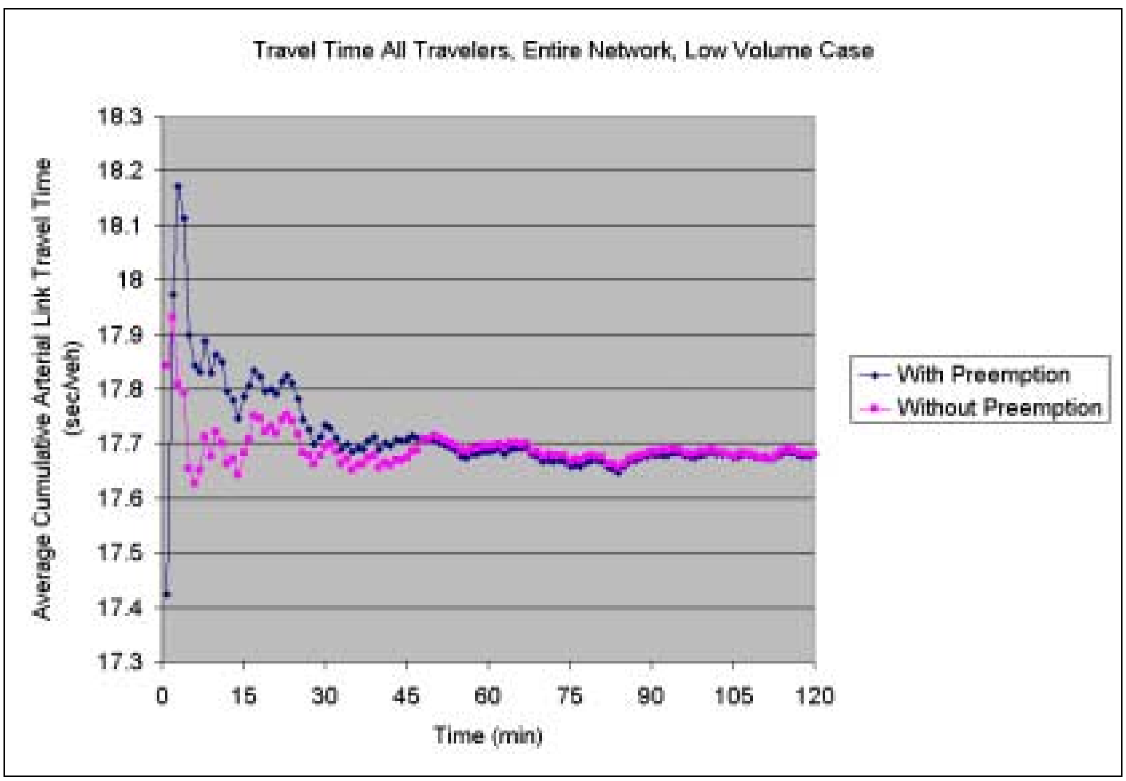


Figure 5.24. Arterial Link Travel Time, Low Volume Case

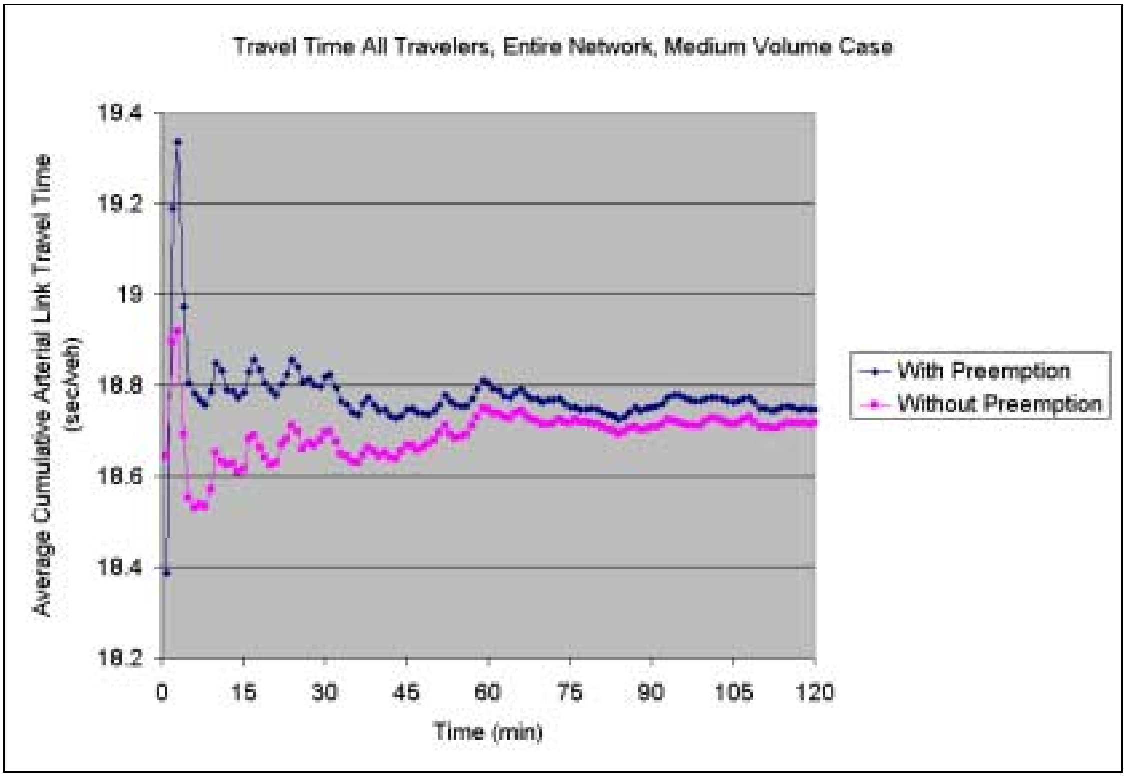


Figure 5.25. Arterial Link Travel Time, Medium Volume Case

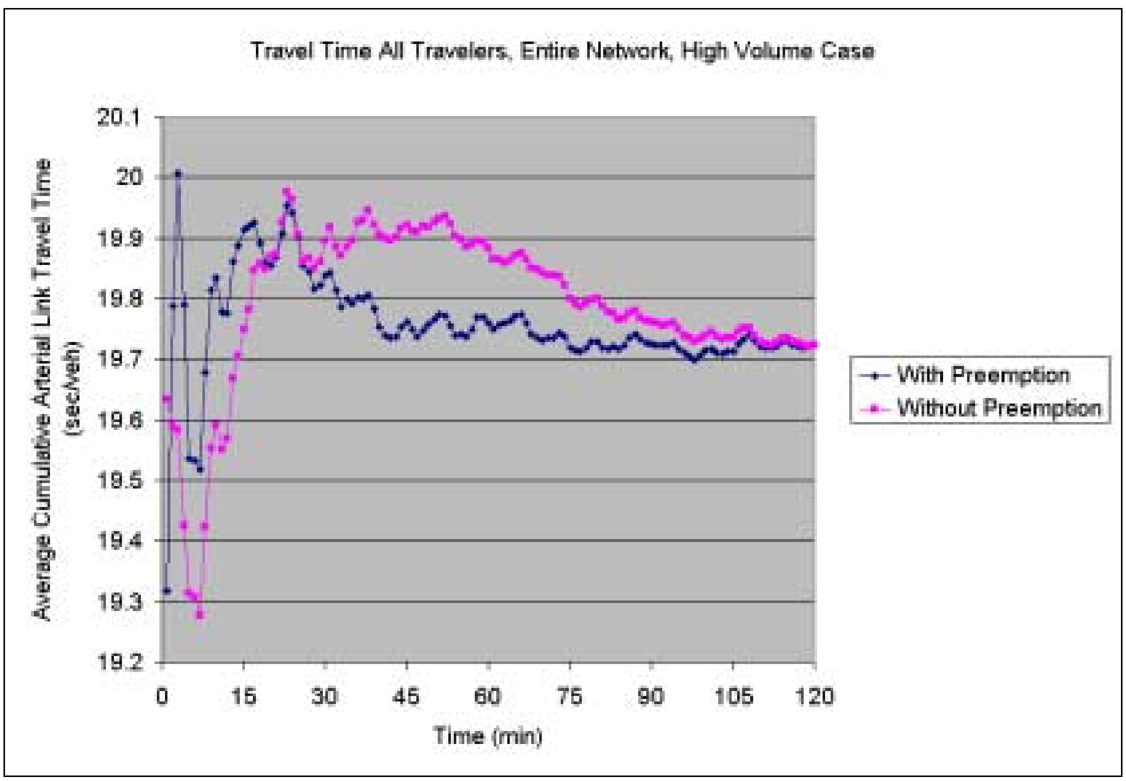


Figure 5.26. Arterial Link Travel Time, High Volume Case

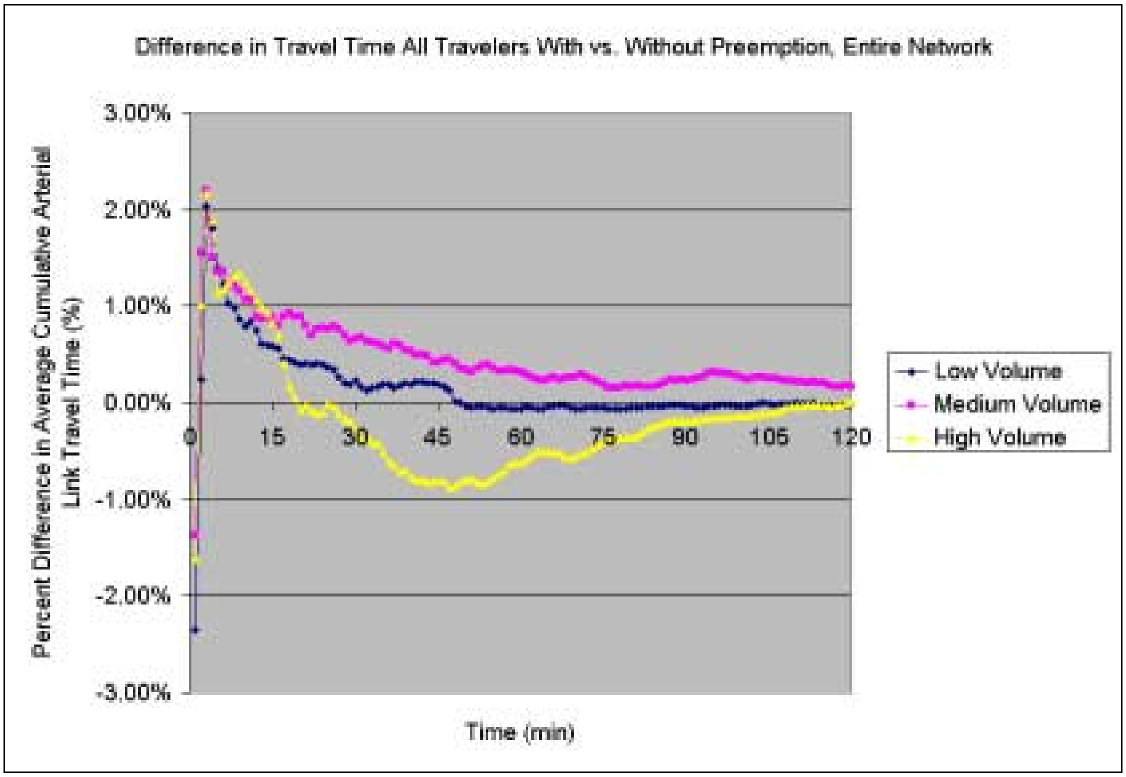


Figure 5.27. Percent Difference in Arterial Link Travel Time

5.4 COMMENTS AND SUMMARY OF SIMULATION ANALYSIS RESULTS

When viewing the simulation results, the reader may notice that in several cases it appears that the simulation has not reached stability or equilibrium. Equilibrium is defined in CORSIM as the point at which entering vehicles on the network are equal (or nearly equal) to exiting vehicles. In all cases, the simulation runs reached equilibrium as reported by CORSIM. However, in some cases, see Figure 5.25 for example, when viewing the "without preemption" travel times for all travelers, it appears that the simulation is still reaching equilibrium. This phenomenon should not effect the results when comparing the differences of "with" versus "without" preemption, however, for future studies, the author recommends that CORSIM users allow the simulation to run beyond reported equilibrium prior to inserting an event such as a traffic signal preemption.

The results of the simulation analysis were presented in terms of travel time impacts to emergency vehicles and all other travelers over the two-hour simulation analysis period. While the focus of this research is to support the data needed for IDAS improvements, namely, cumulative travel time impacts, other traffic operational data can be collected from the simulation analysis. This data includes typical measures such as delay, queue length, and stop time. When observing some of these traffic measures, it is evident that traffic operations on the network return to normal much sooner than it takes for the cumulative traffic measures to converge. This is illustrated below in Figure 5.28 which shows the difference in incremental (e.g., non-cumulative) queue delay on the westbound approach for each of the three volume cases. As shown in the figure, the large differences in queue delay on the westbound approach dissipate after about 7-1/2 minutes into the simulation. This observation is generally confirmed when viewing animations of the simulation results. So, from a traffic operations point of view, operations return to normal much sooner than the measurable differences in cumulative impacts are reduced.

In summary, from the results, we can see that there are differences in the emergency vehicle travel times and the travel times for all travelers that are dependent on the characteristics of the particular scenario under analysis. This was the central thesis to this research, to show that these differences do exist and that they are measurable. The challenge now is to take these simulation results and use them to make enhancements to the IDAS emergency vehicle traffic signal priority methodology. This is addressed in the next chapter.

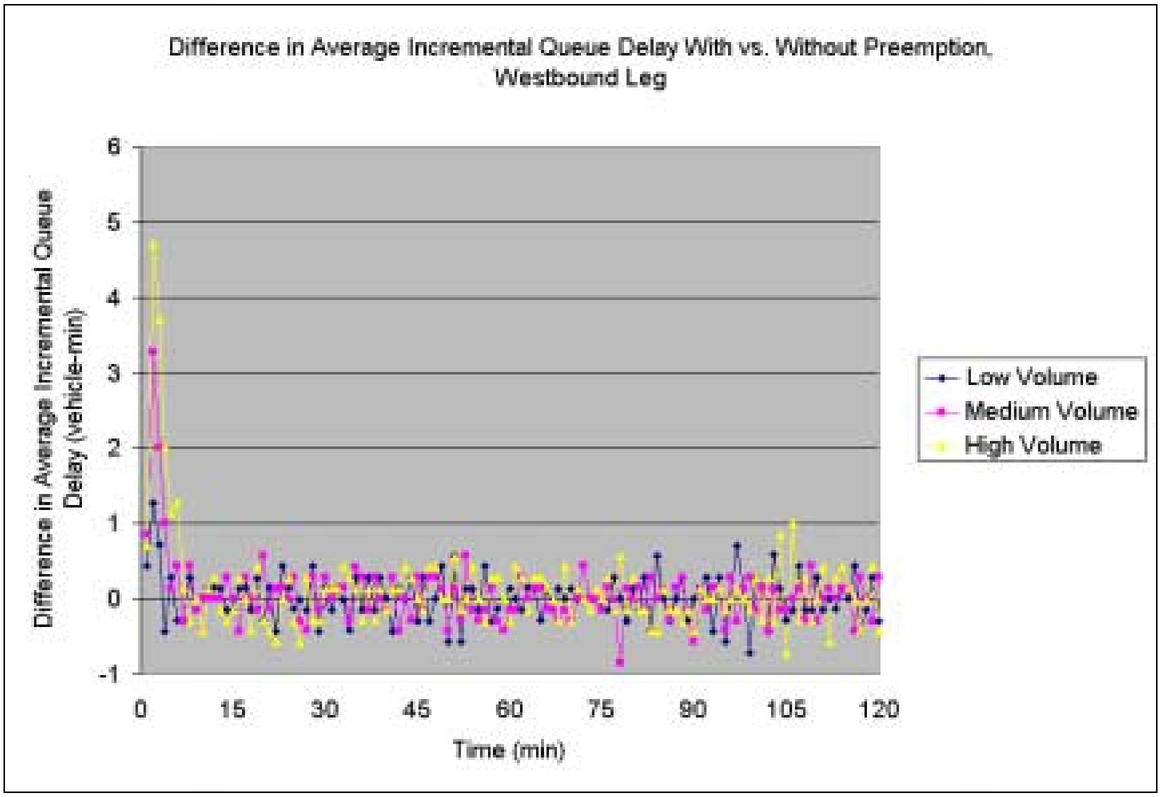


Figure 5.28. Difference in Incremental Queue Delay, Westbound Approach

CHAPTER 6. ENHANCED IDAS METHODOLOGY

This chapter describes how the results of the simulation analysis are used to make recommendations for an enhanced IDAS methodology. The enhanced methodology is described and the impacts of using this new methodology are examined.

6.1 OVERVIEW

As discussed in Chapter 3—Research Methodology, the purpose of the data collected from the simulation analysis is to assist in improving the current IDAS emergency vehicle traffic signal priority methodology. These improvements will be incorporated by adding sensitivity to traffic volume in the current IDAS parameters and by adding new parameters to take into account the impact on other travelers, not just the emergency vehicle. The impacts of these proposed enhancements will then be evaluated. The proposed enhancements and their impacts are discussed in this chapter.

6.2 IDAS ENHANCEMENTS

Making general recommendations for IDAS enhancements based on the results of the limited research scenarios should be done cautiously. Extending the specific results of any research work to create or enhance a generic methodology will have implications long after the research is completed. This is especially true when the methodology in question is incorporated into a software package used to assist in transportation investment decisions, such as IDAS. The assumptions and limitations of the research work are often times forgotten after the methodology has been developed and is in practical use, thus resulting in the potential misuse of the particular methodology. Nonetheless, an attempt will be made here to generalize these research results into recommendations for IDAS enhancements.

The proposed enhancements to IDAS are related to two categories of travel time impacts: 1) impacts to emergency vehicles, and 2) impacts to other travelers. Each of these will be discussed separately below.

6.2.1 Travel Time Enhancements—Emergency Vehicle

As discussed previously, the current IDAS default for emergency vehicle travel time savings due to traffic signal priority systems is a 30% increase in travel speed. When viewing the simulation results, the average value of emergency vehicle link travel time savings was 40.1%, 40.2%, and 41.4% for the Low, Medium, and High volume cases, respectively. In order to compare these values with the IDAS default of 30% increase in travel speed, the travel time savings first have to be converted into increases in travel speed. The travel times reported from the simulation analysis represented the time it took the emergency vehicle to travel between the "check-in" and "check-out" detectors. Knowing the location of the detectors on the link and the width of the intersection, the distance between the detectors can be calculated to be 763 feet. Using this distance, the travel time savings can be converted into travel speed increases of 67.0%, 67.1%, and 70.7% for Low, Medium, and High volume cases, respectively. These numbers are significantly higher than the IDAS default of 30%. One reason for this discrepancy could be the short distance (763 ft) used for this analysis. As the length of the travel segment increases, the percent difference in the results due to the single traffic signal preemption would be expected to decrease. Another reason for the discrepancy could be that the IDAS default value is incorrect. However, a more fundamental reason why these numbers are different are the assumptions and limitations within the simulation analysis. These are discussed below.

Considering that the assumptions and limitations of the simulation analysis impact both the "with preemption" and "without preemption" scenarios, some of these limitations will "cancel each other out." For example, a limitation of the simulation is that other vehicles do not pull-over or move out of the way to allow the emergency vehicle to pass. This limitation equally affects the results of the "with" and "without" preemption scenarios. So, what are the key limitations of the simulation analysis that do not "cancel each other out?" One answer to this question, probably the most significant, is that the emergency vehicle obeys traffic signals for the "without preemption" scenarios. This limitation results in travel times that are greater than otherwise would be encountered in the real world for the "without preemption" cases. Although it is intuitive that an emergency vehicle would be able to travel faster through an intersection if the traffic signal was preempted versus operating on "lights and siren" alone, the true magnitude of this difference is difficult to quantify due to the limitations of the simulation.

Since the limitations of the simulation likely overestimated the emergency vehicle travel time for the "without preemption" case, systematic decreases in the these travel times were made to assess the impact on the resulting percent increase in emergency vehicle travel speed. These systematic decreases and the results are presented in Table 6.1. As shown in the table, decreasing the "without preemption" emergency vehicle travel times by 10% leads to emergency vehicle travel speed increases near the 50% range for all three volume levels. Decreases of 20% in the "without preemption" emergency vehicle travel times results in emergency vehicle travel speed increases in the 33% range. The results of further decreases in the "without preemption" emergency vehicle travel times are shown in the table.

Table 6.1. Systematically Decreasing "Without Preemption" EV Travel Times

Percent Reduction in "Without Preemption" Travel Time	Volume	Average EV Travel Time (sec)		Average Equivalent EV Speed (mi/hr)		Difference in Speed (%)
		Without Preemption	With Preemption	Without Preemption	With Preemption	
0%	Low	32.2	19.3	16.1	27.0	67.0%
	Medium	37.8	22.6	13.8	23.0	67.1%
	High	39.0	22.9	13.3	22.7	70.7%
10%	Low	29.0	19.3	17.9	27.0	50.3%
	Medium	34.0	22.6	15.3	23.0	50.4%
	High	35.1	22.9	14.8	22.7	53.6%
20%	Low	25.8	19.3	20.2	27.0	33.6%
	Medium	30.3	22.6	17.2	23.0	33.7%
	High	31.2	22.9	16.7	22.7	36.6%
30%	Low	22.6	19.3	23.1	27.0	16.9%
	Medium	26.5	22.6	19.7	23.0	17.0%
	High	27.3	22.9	19.0	22.7	19.5%
40%	Low	19.3	19.3	26.9	27.0	0.2%
	Medium	22.7	22.6	22.9	23.0	0.3%
	High	23.4	22.9	22.2	22.7	2.4%

Due to the uncertainty in the emergency vehicle travel times from the simulation limitations and the high sensitivity of these values to the resulting emergency vehicle travel speed increases, a modification to the existing IDAS default of 30% increase in travel speed will not be recommended. Therefore, as shown in Table 6.2, it is recommended to keep the current default value of a 30% travel speed increase for the emergency vehicle within IDAS.

Table 6.2. IDAS Emergency Vehicle Travel Speed Enhancements

IDAS Enhancements for Emergency Vehicle Travel Speed
It is recommended that the current default of a 30% travel speed increase for emergency vehicles remain as the IDAS default. The limitations of the simulation analysis with respect to emergency vehicle operations were such that replacing the current default could not be recommended.

Although it is recommended to keep the current IDAS default value for the percentage speed increase to emergency vehicles, it is interesting to investigate the sensitivity of this parameter. In Table 6.3 below, the value for percentage increase in travel speed for emergency vehicles with traffic signal priority is varied from 10% to 50% for three different underlying emergency vehicle travel speeds of 25, 35, and 45 miles per hour. The travel time savings per mile of travel are calculated and converted into annual cost savings per mile using the IDAS default value for emergency vehicle travel time of 30 times the normal value (i.e., 30 x $8.50/hr = $225.00/hr). The annual cost savings per mile is computed assuming 247 analysis periods per year. In the table, results for the IDAS default value of 30% are shaded. As shown in the table, there is typically at least a $100 cost per mile difference for each 10% difference in the value of percentage emergency vehicle travel speed increase. The overall cost impacts for an IDAS analysis would depend on the number of miles where the emergency vehicle traffic signal priority systems are deployed, the volume of emergency vehicle traffic, and the number of analysis periods to be analyzed.

Table 6.3. Sensitivity of IDAS EV Travel Speed Increase Parameter

Sensitivity of IDAS Emergency Vehicle (EV) Travel Speed Increase Value								
EV Speed (mph)	EV Travel Time per Mile (sec)	Percent EV Speed Increase with Signal Priority	New EV Speed (mph)	New EV Travel Time per Mile (sec)	EV Travel Time Saving Per Mile (sec)	IDAS Default Value of EV Travel Time ($/hr)	Value of EV Travel Time Savings per Mile ($/mi)	Annual Value of EV Travel Time Savings per Mile (247 periods)
25	144.0	10%	27.5	130.9	13.1	$255	$0.93	$229
25	144.0	20%	30.0	120.0	24.0	$255	$1.70	$420
25	144.0	30%	32.5	110.8	33.2	$255	$2.35	$581
25	144.0	40%	35.0	102.9	41.1	$255	$2.91	$720
25	144.0	50%	37.5	96.0	48.0	$255	$3.40	$840
35	102.9	10%	38.5	93.5	9.4	$255	$0.66	$164
35	102.9	20%	42.0	85.7	17.1	$255	$1.21	$300
35	102.9	30%	45.5	79.1	23.7	$255	$1.68	$415
35	102.9	40%	49.0	73.5	29.4	$255	$2.08	$514
35	102.9	50%	52.5	68.6	34.3	$255	$2.43	$600
45	80.0	10%	49.5	72.7	7.3	$255	$0.52	$127
45	80.0	20%	54.0	66.7	13.3	$255	$0.94	$233
45	80.0	30%	58.5	61.5	18.5	$255	$1.31	$323
45	80.0	40%	63.0	57.1	22.9	$255	$1.62	$400
45	80.0	50%	67.5	53.3	26.7	$255	$1.89	$467

6.2.2 Travel Time Enhancements—All Travelers

Making recommendations for enhancements related to "travel time impacts for all travelers" is more difficult than the enhancements related to the emergency vehicle travel time. Because the research results were based on a specific arterial with specific traffic volume, traffic signal control settings, and emergency vehicle operations, it is difficult to generalize these into generic IDAS recommendations. Some of the characteristics that need to be considered in creating the recommended IDAS enhancements include:

- Time period of IDAS analysis
- Type of intersection approach
- Typical traffic volume or level of congestion
- Number of emergency vehicle preemption events per IDAS analysis time period

The research results will need to be put into a format that is consistent with the above characteristics in order to apply them in IDAS. These relationships between the simulation results and the IDAS enhancement characteristics are shown in Table 6.4. The summary of simulation results for the "travel time impacts for all travelers" is shown in Table 6.5 with the relationships to the IDAS enhancement characteristics shown in parentheses within the table. The enhancement characteristic of "number of preemption events per analysis period" does not appear in these tables but will be discussed below.

Table 6.4. Relationships Between Simulation Results and Enhancement Characteristics

Relating Simulation Results to IDAS Enhancement Characteristics	
Simulation Scenario Term	**Corresponding IDAS Enhancement Characteristic Term**
Volume level	Typical level of congestion
Cumulative time	Analysis Period
Westbound approach	Main street movement with traffic signal progression
Northbound approach	Side street movement opposing preemption path
Southbound approach	Side street movement with preemption path
Eastbound approach	Main street movement opposing traffic signal progression

The results depicted in Table 6.5 will serve as the basis to make the recommendations for the IDAS enhancements. From the table, it can be seen that the impacts for the Southbound and Eastbound movements were very minor. With the exception of the first time period (15 minutes), all of the impacts for the Southbound and Eastbound movements were below 1%. It is therefore proposed that the results from the Southbound and Eastbound movements not be incorporated into the IDAS enhancements. Instead, only the results from the Westbound and Northbound movements will be used thereby limiting the characteristics related to Type of Approach to the following two:

Table 6.5. Summary of Percent Difference in Travel Time for All Travelers

Percent Difference in Travel Time for All Travelers				
		Volume (Typical Level of Congestion)		
Intersection Approach (Type of Approach)	Cumulative Time (min) (Analysis Period)	Low	Medium	High
Westbound, varying volume (Main street movement with traffic signal progression)	15	3.8%	8.9%	12.2%
	30	1.9%	4.9%	4.8%
	45	1.5%	3.5%	3.7%
	60	1.1%	2.4%	3.3%
	75	0.8%	1.9%	2.8%
	90	0.8%	1.5%	2.1%
	105	0.7%	1.1%	1.8%
	120	0.6%	1.0%	1.7%
Northbound, constant light volume (Side street movement opposing preemption path)	15	5.9%	7.5%	7.0%
	30	2.9%	3.9%	3.7%
	45	1.9%	2.3%	2.6%
	60	1.3%	1.9%	2.0%
	75	1.0%	1.6%	1.7%
	90	0.8%	1.4%	1.2%
	105	0.8%	1.1%	1.0%
	120	0.7%	1.0%	1.0%
Southbound, varying volume (Side street movement with preemption path)	15	-1.3%	-1.2%	-1.8%
	30	-0.9%	-0.5%	-0.5%
	45	-0.6%	-0.1%	-0.1%
	60	-0.3%	-0.3%	-0.1%
	75	-0.2%	-0.3%	0.0%
	90	-0.3%	-0.2%	0.0%
	105	-0.2%	-0.2%	0.1%
	120	-0.1%	-0.1%	0.1%
Eastbound, constant volume (Main street movement opposing traffic signal progression)	15	0.6%	0.4%	-0.1%
	30	0.3%	0.6%	-1.0%
	45	0.2%	1.0%	-0.6%
	60	0.2%	0.9%	-0.6%
	75	0.3%	0.6%	-0.6%
	90	0.2%	0.4%	-0.6%
	105	0.2%	0.4%	-0.4%
	120	0.1%	0.2%	0.1%

- Main Street Non Preemption Path
- Uncongested Side Street Non Preemption Path

Essentially, this is saying that for IDAS purposes, the travel time impacts for those traveling along the same path of the emergency vehicle traffic signal preemption will not be considered. It is generalizing the Westbound case (Main street movement with traffic signal progression) into Main Street Non Preemption Path and generalizing the Northbound case (Side street movement opposing preemption path) into Uncongested Side Street Non Preemption Path. For cases where there is only one emergency vehicle signal preemption per IDAS analysis period, the impacts for the Main Street Non Preemption Path and Uncongested Side Street Non Preemption Path can be read directly from the Table 6.5 Westbound and Northbound movements. Cases where the number of preemption events per analysis period does not equal one are discussed below.

IDAS is designed primarily to analyze travel demands representing time periods of a single hour, multiple hours (e.g., a peak period), or a day. Therefore the lowest unit for the analysis time period is typically one hour. The simulation analysis was performed over a period of two hours and for purposes of this research it will be assumed that the percent differences in results converge to zero at the three-hour point. Since only one emergency vehicle and one preemption event was modeled in each simulation run, the results will be representative of one emergency vehicle and one preemption event in the analysis time period. There will be no attempt to estimate the impacts of multiple preemption events or multiple emergency vehicles during an analysis period, instead, this is a recommendation for future research. Therefore, the final results, as recommended for incorporation into IDAS are shown in Table 6.6. The impacts of fractional (on average) preemption events occurring during an analysis period can be estimated by multiplying the impacts in Table 6.6 by the corresponding fractional number. For example, referring to Table 6.6, a Main Street Non Preemption Path link with Medium Volume and a 1-hour analysis period uses a value of 2.4% for the "travel time impact for all travelers." However, for the same analysis, assuming only 0.5 (on average) emergency vehicle traffic signal preemption events for the analysis period, the resulting value for the "travel time impact for all travelers" would be 0.5 x 2.4%, or 1.2%. As mentioned previously, it is not recommended that these values be multiplied by any factor greater than one since it was outside the scope of this research to analyze multiple preemption events in the same analysis time period.

Table 6.6. Recommended Values for IDAS Enhancements

Percent Difference in Travel Time for All Travelers Assuming One EV and One Preemption Event per Analysis Period				
		Typical Level of Congestion		
Type of Approach	Analysis Period (hours)	Low	Medium	High
Main Street Non Preemption Path	1	1.1%	2.4%	3.3%
	2	0.6%	1.0%	1.7%
	3	0.0%	0.0%	0.0%
Uncongested Side Street Non Preemption Path	1	1.3%	1.9%	2.0%
	2	0.7%	1.0%	1.0%
	3	0.0%	0.0%	0.0%

6.3 IMPACTS OF ENHANCED METHODOLOGY

The impacts of the proposed enhancements to the IDAS methodology will vary depending on the particular transportation network and extent of the Emergency Vehicle Traffic Signal Priority System deployment being analyzed. The proposed enhancements will incorporate the impact of travel time for all travelers into the current IDAS methodology. It is recommended that the impacts associated with increased emergency vehicle travel speeds and all equipment costs (e.g., including purchase, installation, operations, and maintenance) of emergency vehicle traffic signal priority systems remain as currently implemented in IDAS.

As described in the IDAS User Manual (Cambridge Systematics, 2000), the process to determine the impacts or costs of an ITS Option such as an Emergency Vehicle Traffic Signal Priority System is as follows:

- Use the performance measure value estimated in the IDAS benefits module (e.g., travel time in person hours)
- Convert the daily value of the performance measure to an annual value using the IDAS defaults or a user-specified conversion (e.g., IDAS default equals 247 typical days per year)
- Multiply the annual benefits by the per unit dollar cost to convert benefits to cost (e.g., IDAS default of $8.50 per person hour of travel)
- Report the resulting values in the cost/benefit comparison summary sheet.

Since all of the proposed enhancements to IDAS shown in Table 6.6 are positive values, implementing the proposed enhancements will result in an increased user travel time cost as compared to the current methodology. However, if future simulation scenarios were broadened to include cases where the preemption path coincides with the major flow of traffic, it would not necessarily be the case that all values in the proposed enhancements were positive. Thus, application of these proposed enhancements should only be used in cases that are similar to the simulation scenarios. It is also important to recall that the travel time results are based on simulated vehicle trips with no trucks or buses on the network. Therefore, these results, which represent a vehicle occupancy of 1.0 and 100% automobile trips, may require adjustments as necessary by future users.

While considering the above cautions related to indiscriminate application of the proposed enhancements, it is interesting to apply them to an IDAS-type analysis and compare the results. The results from the simulation scenarios will be used as the basis to approximate the impacts of the new IDAS methodologies on an "IDAS-type" analysis. The results from this exercise will be the net annualized cost impacts of applying the new IDAS methodology to the simulation cases using the following formula:

Equation 7. Additional Annual Cost Calculation.

$$AdditionalAnnualCost = AdditionalTravelTime \times ValueOfTravelTime \times NumOfAnnualPeriods$$

Where:

AdditionalAnnualCost = Additional travel time applying new methodology (person-hrs)

ValueOfTravelTime = Cost of travel time, IDAS default equals $8.50/hr

NumOfAnnualPeriods = Number of analysis periods per year, IDAS default equals 247

The above formula will be used to estimate the additional costs of applying the new methodology to the single intersection from the simulation scenarios. For illustration purposes, a one-hour analysis period will be assumed and the calculations will be applied for each of the three volume levels. The IDAS defaults of $8.50/hr for travel time cost and 247 analysis periods/year will be used. The calculations are shown in Table 6.7. As shown in the table, the total travel time for each approach to the intersection is calculated by multiplying the average cumulative travel time per vehicle ("without preemption" values from Figure 5.4 through Figure 5.18) and the total hourly volume. The additional total travel times are calculated by multiplying the appropriate new IDAS methodology factor to the total travel time. The monetary value of the additional travel time is then calculated and the annual cost is presented.

For this particular example, the cost impacts are small. For other examples, the cost impacts could be larger depending on the number of intersections under analysis, the number of analysis periods, and the value of travel time. Certainly, for a region-wide analysis there will be many intersections under analysis. Likewise, the number of analysis periods would likely increase to include the study of AM Peak Period, PM Peak Period, and off-peak periods for example. Finally, the value of travel time is a typically adjusted to meet the needs of the particular region or metropolitan area conducting the analysis.

6.4 Summary of IDAS Enhancements

The results from the simulation analysis were used to recommend improvements to the current IDAS emergency vehicle traffic signal priority methodology. The improvements that were recommended were the addition of new travel time factors for non-emergency vehicles (i.e., all travelers) as summarized in Table 6.6. However, based on the limitations of the simulation analysis, it was recommended not to change the default parameter reflecting the percentage increase in emergency vehicle travel speed.

To incorporate these new factors into IDAS, the current IDAS parameter of "percentage of link volume that is emergency vehicles" would be replaced with the new link-based

Table 6.7. Additional Cost Calculated from Applying New Methodology

Low Volume Case								
Approach	Hourly Volume (veh/hr)	Avg. Cum. Travel Time at 1 hour (sec/veh)	Total Travel Time (min)	New Factor for Low Volume	Calculated Additional Travel Time (min)	Value of Travel Time ($/hr)	Cost of Additional Travel Time	Annual Cost of Additional Travel Time (247 periods)
Eastbound	522	35.3	307	1.1%	3.38	$8.50	$0.48	$118
Westbound	1,040	15.7	271	1.1%	2.99	$8.50	$0.42	$104
Southbound	362	44.1	266	0.0%	0.00	$8.50	$0.00	$0
Northbound	284	44.4	210	1.3%	2.73	$8.50	$0.39	$96
TOTAL							$1.29	$318
Medium Volume Case								
Approach	Hourly Volume (veh/hr)	Avg. Cum. Travel Time at 1 hour (sec/veh)	Total Travel Time (min)	New Factor for Medium Volume	Calculated Additional Travel Time (min)	Value of Travel Time ($/hr)	Cost of Additional Travel Time	Annual Cost of Additional Travel Time (247 periods)
Eastbound	521	36.9	320	2.4%	7.68	$8.50	$1.09	$269
Westbound	1,480	19.0	469	2.4%	11.26	$8.50	$1.59	$394
Southbound	545	46.7	424	0.0%	0.00	$8.50	$0.00	$0
Northbound	284	45.6	216	1.9%	4.10	$8.50	$0.58	$144
TOTAL							$3.26	$806
High Volume Case								
Approach	Hourly Volume (veh/hr)	Avg. Cum. Travel Time at 1 hour (sec/veh)	Total Travel Time (min)	New Factor for High Volume	Calculated Additional Travel Time (min)	Value of Travel Time ($/hr)	Cost of Additional Travel Time	Annual Cost of Additional Travel Time (247 periods)
Eastbound	520	39.3	341	3.3%	11.24	$8.50	$1.59	$393
Westbound	1,702	21.8	620	3.3%	20.45	$8.50	$2.90	$716
Southbound	634	48.7	514	0.0%	0.00	$8.50	$0.00	$0
Northbound	284	45.9	217	2.0%	4.34	$8.50	$0.62	$152
TOTAL							$5.10	$1,261

parameter of "number of preemption events per analysis period" with an allowable range from 0 to 1. Application of the current percent increase in emergency vehicle travel speed would also be accomplished through this new link-based parameter with the parameter acting as a factor multiplier to the calculated emergency vehicle link travel time benefit. Application of the travel time impacts to non-emergency vehicles would require the additional parameters of "typical level of congestion" (Low, Medium, or High), and the "type of approach" (Main Street Non Preemption Path or Uncongested Side Street Non Preemption Path).

Future research would allow for additional parameters including "number of preemption events per analysis period", "number of emergency vehicles per preemption event", and additional options under "type of approach".

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes the research and makes recommendations for future research.

7.1 OVERVIEW

This research studied the impacts of emergency vehicle traffic signal priority systems and their effect on traffic operations. An attempt was made to improve upon an existing regional transportation assessment methodology found in the IDAS software by incorporating the results of a simulation analysis using the CORSIM traffic simulation software. Suggestions were made to improve the current IDAS emergency vehicle traffic signal priority methodology and in some cases the recommendation was to not change the existing methodology. Summaries of the research approach, IDAS recommendations, and recommendations for future research are described below.

7.2 APPLICABILITY OF RESEARCH APPROACH

Overall, the approach to use microscopic traffic simulation analysis as a surrogate for conducting a real-world experiment is sound. Simulation provides a safe, controllable environment where the effects of individual characteristics can be analyzed in a systematic way. However, in the case were the simulation model is not valid or is used beyond its design, simulation may not always be an appropriate surrogate for reality or real-world experimentation.

7.2.1 Limitations to Simulation Analysis

The major limitation to the simulation analysis conducted under this research was the ability to model the operations of an emergency vehicle within a stream of traffic. The CORSIM software was not designed to model emergency vehicle operations and thus treated the emergency vehicle like any other vehicle. This had a major effect on the "before-and-after" or "with-and-without" analysis, especially with respect to quantifying the percentage increase in emergency vehicle travel speed due to traffic signal priority systems. However, the limitations of the simulation had a lesser affect on the analysis of the impacts of a traffic signal preemption on traffic at an intersection. A large part of the impact of traffic at an intersection is due to the traffic signal operations as was evidenced by the significant travel time impacts during and long after the signal preemption occurred.

7.2.2 Ability to Generalize Results

The results of the research were limited to the simulation scenarios undertaken. Namely, a single intersection within an urban arterial experiencing a single emergency vehicle preemption event from a side street approach. Many other limiting factors were discussed in this report including the effect of the traffic signal timing plan, intersection geometry, location of emergency vehicle detection, and traffic volume. However, in the case of applying these results to conduct a high level planning assessment, the author feels that they can be generalized within the framework they are presented. For example, the impacts for the High Volume cases should be applied to high volume situations and impacts pertaining to Main Street Non Preemption Path should be applied to like circumstances.

7.3 RECOMMENDATIONS FOR IDAS

To summarize the recommendations for IDAS, it is recommended that current default of 30% travel speed increase for emergency vehicles employing traffic signal priority systems remain unchanged. This recommendation is notmade not because the research supported the 30% value, but because the research results could not support any changes to this value due to the limitations of the simulation analysis. It is further recommended that IDAS incorporate travel time impacts on other travelers within its emergency vehicle traffic signal priority methodology. These impacts were summarized in Table 6.5 and Table 6.6. For the most part, these impacts are small, but when applied at the regional transportation network level for multiple analysis periods, these impacts and their cost values should be tracked. In order to apply these methods to IDAS, it may be necessary to change the current IDAS input parameter of "percent emergency vehicles within the traffic stream" to the "number of preemption events per analysis period". As mentioned in Chapter 6—Enhanced IDAS Methodology, these research results are only representative of one preemption event per analysis period and should not be extrapolated to multiple preemption events per analysis period. In addition, the results may require further analysis prior to implementing directly into IDAS.

7.4 RECOMMENDATIONS FOR FUTURE RESEARCH

The area of emergency vehicle traffic signal priority is vast in terms of potential research needs. Because of the difficulty in collecting detailed generalizable results from field studies of deployed emergency vehicle signal priority systems, simulation analysis remains a candidate research tool for future studies. The recommendations for future research are presented here is terms of additional emergency vehicle traffic signal priority scenarios and traffic simulation needs.

7.4.1 Additional Scenarios

As mentioned previously in Chapter 3—Research Methodology, there were other possible emergency vehicle traffic signal priority characteristics considered for analysis in this research. These included:

Multiple vehicles per preemption event,

Multiple paths of the emergency vehicle,

Varying the distance from which an emergency vehicle preemption request can be received by the traffic signal controller.

In addition to the above items considered for this research, other characteristics could be studied for future research including:

- Effect of traffic signal transition algorithm controlling transition into and out of signal preemption,
- Effect of traffic signal timing plan such as pre-timed, actuated, or adaptive traffic control systems,
- Effect of network geometry such as number of lanes, single intersection vs. signalized arterial, and intersection spacing,
- Effect of pedestrian volume levels on the travel time impacts

7.4.2 Traffic Simulation Needs

In order to better analyze emergency vehicle traffic signal priority, improvements to the current traffic simulation software is needed. These improvements include the ability to better simulate the operation of an emergency vehicle within a traffic stream (e.g., emergency vehicle maneuvers and other vehicle reactionary maneuvers) and the ability to better simulate the traffic signal control systems.

In order to improve the emergency vehicle operations within the simulation models, it may be necessary to conduct some field studies to ascertain the range of typical emergency vehicle maneuvers and the range of other vehicles driver reactions to these maneuvers. This would be a major undertaking requiring the development of models, field data collection, and the incorporation of these models into existing traffic simulation software packages.

There are several areas for improvement with respect to the traffic signal control systems within the simulation models. First of all, there currently seems to be only limited capability within simulation models to accurately model an emergency vehicle traffic signal preemption event. In order to use CORSIM, the somewhat cumbersome run-time extension technique had to be used. Other traffic simulation software packages may have some capabilities in this area, but the author is not aware of any package that provides traffic signal priority features that are easy to use and understand. Recent improvements in this area that should continue are the creation of devices such as the Controller Interface Device (CID) to interface real traffic controller hardware to simulation software and software to software interfaces such as was created in linking the Gardner Systems NextPhase traffic control software to simulation software. In general, there is a need to make modeling of advanced traffic signal control logic much easier for the typical user of traffic simulation software.

7.5 FINAL SUMMARY

The central thesis of this research as presented in Chapter 1—Introduction, is as follows:

> "The travel time impacts of traffic signal priority treatments for emergency vehicles are a function of the *traffic characteristics*, *roadway geometry*, and the *deployment configuration* of the priority system."

This central thesis was partially proven in that the travel time impacts of emergency vehicle traffic signal priority was demonstrated to be a function of traffic volume, which is one type of *traffic characteristic*.   The other factors, *roadway geometry* and *deployment configuration*, were the controlling parameters and remain to be analyzed in future research.

However, the key value of this research is in demonstrating an approach that can be used to develop improved methodologies for assessing the costs and benefits of emergency vehicle traffic signal priority systems at a transportation planning level. These systems may prove to be a valuable resource for our public safety system, but are often times dismissed as being too detrimental to traffic. Providing methodologies and tools that more accurately assess the costs and benefits will allow decision makers to make more informed decisions with respect to the deployment of emergency vehicle traffic signal priority systems.

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VITA

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Gene M. McHale was born in 1964 in Flushing, New York and moved to northern Virginia before his first birthday. He grew up in Springfield, Virginia and graduated from West Springfield High School in 1982. Gene attended the University of Virginia in Charlottesville and graduated with a Bachelors of Science degree in Systems Engineering in 1986. He continued at the University of Virginia and completed his Masters of Engineering in Systems Engineering in 1987.

While pursuing his undergraduate degree, Gene spent his summers working at the Federal Highway Administration (FHWA) Turner Fairbank Highway Research Center in McLean, Virginia. Following his graduation in 1987, Gene began his employment with the Scientex Corporation in Arlington, Virginia, providing engineering contract support to FHWA's Roadside Safety program focusing on simulation analysis and full-scale crash testing of roadside safety devices. In 1991, Gene joined the Mitre Corporation in Washington, D.C., providing systems engineering support to FHWA's Intelligent Transportation Systems (ITS) program focusing primarily on the Automated Highway System (AHS) program. Gene returned to the FHWA and the Turner Fairbank Highway Research Center as an employee in 1995 where he remains today. His recent duties at the FHWA have been focused in the area of traffic models and his assignments have included project manager for the ITS Deployment Analysis System (IDAS) development and project manager for the Traffic Software Integrated System (TSIS) development, maintenance, and support.

Gene currently lives in Fairfax, Virginia with his wife, Beth, and their three children, Michael, Kelly, and Hannah.