Methodology to Assess Traffic Signal Transition Strategies Employed to Exit Preemption Control

Jon T. Obenberger

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Dissertation Research Committee Members:
John Collura, Co-chair
Shinya Kikuchi, Co-chair
Denis Gracanin
Hesham Rahka
Sam Tignor

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ABSTRACT

Enabling vehicles to preempt the normal operation of traffic signals has the potential to improve the safety and efficiency of both the requesting vehicle and all of the other vehicles. Little is known about which strategy is the most effective to exit from preemption control and transition back to the traffic signals normal timing plan. Common among these traffic signal transition strategies is the method of either increasing or decreasing the cycle length of the signal timing plan, as the process followed to return to the coordination point of the effected signal timing plan, to coordinate its operation with adjacent traffic signals. This research evaluates commonly available transition strategies: best way, long, short, and hold strategies.

The major contribution of this research is enhancing the methodology to evaluate the impacts of using these alternative transition strategies. Part of this methodology consists of the "software-in-the-loop" simulation tool which replicates the stochastic characteristics of traffic flow under different traffic volume levels. This tool combines the software from a traffic signal controller (Gardner NextPhase Suitcase Tester, version 1.4B) with a microscopic traffic simulation model (CORSIM, TSIS 5.2 beta version).

The research concludes that a statistically significant interaction exists between traffic volume levels and traffic signal transition strategies. This interaction eliminates the ability to determine the isolated effects of either the transition strategies on average travel delay and average travel time, or the effects of changes in traffic volume levels on average travel delay and average travel time. Conclusions, however, could be drawn on the performance of different transition strategies for specific traffic volume levels. As a result, selecting the

most effective transition strategy needs to be based on the traffic volume levels and conditions specific to each traffic signal or series of coordinated traffic signals.

The research also concludes that for the base traffic volume and a 40% increase in traffic volume, the most effective transition strategies are the best way, long or hold alternatives. The best way was the most effective transition strategy for a 20% increase in traffic volume. The least effective strategy is the short transition strategy for both the base and 40% increase in traffic volume, and the long and short for a 20% increase in traffic volume. Further research needs to be conducted to assess the performance of different transition strategies in returning to coordinated operation under higher levels of traffic volume (e.g., approaching or exceeding congested flow regime), with varying cycle lengths, with different signal timing plans, and when different roadway geometric configurations (e.g., turn lanes, length of turn lanes, number of lanes, spacing between intersections) are present.

DEDICATION

This dissertation is dedicated to my parents, Tom and Joanne Obenberger, whose support and sacrifices provided me with the encouragement to pursue educational opportunities. This research is also dedicated to my children, Alyssa and Evan, with the hope that they will continue to pursue and enjoy educational pursuits throughout their lives.

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It is also appropriate to mention several others who have shaped this research as it has evolved from its initial conception: Dr. Pitu Mirchandani at the University of Arizona for identifying the need for research on using traffic signal transition strategies in the late 1990s; Dr. Michel Van Aerde, formerly of Virginia Tech who was truly an international expert in traffic engineering that passed away before his time, for supporting this research and his confidence with being able to develop the develop the capability needed to simulate and evaluate preemption control and traffic signal transition strategies; Dr. Larry Head at the University of Arizona for providing technical expertise and assistance on traffic signal control concepts and for providing access to the NextPhase Suitcase Tester software that was used in this research, while he was still at Siemens Gardner Transportation Systems; and Dr. Darcy Bullock at Purdue University for offering technical expertise and assistance on traffic signal control concepts and shared experiences on related research.

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CHAPTER 1. INTRODUCTION

This chapter provides a brief overview of traffic signal preemption control along with the strategies used to exit preemption control and transition to the coordinated operation of the normal signal timing plan. The purpose of this dissertation is to evaluate the impacts of the most commonly available transition strategies to traffic signal controllers in performing this transition. The need for an enhanced evaluation methodology and analysis tool to assess the effectiveness of these transition strategies for different levels of traffic volume was one of the primary reasons for this research. This research demonstrates the application of such a methodology and analysis tool to evaluate these strategies. A brief summary of the remaining chapters of this dissertation follows.

1.1 Traffic Signal Preemption Control

Traffic signal priority control is an established strategy that is available to traffic managers and transportation providers to improve the operational performance of their respective systems or services. Traffic signal priority control involves modifying the operation of a traffic signal's timing plan based on a request from a pre-approved vehicle. Priority control attempts to enhance the efficiency and safety of the identified vehicles to receive special consideration in the operation of a traffic signal without negatively impacting the safety and operation of traffic at the intersection or a series of coordinated traffic signals.

The Manual on Uniform Traffic Control Devices (MUTCD) has established different levels of priority control corresponding to the degree signal timing plans may be modified by different types of vehicles and under different conditions (FHWA, 2001). Traffic signal preemption control is the highest level or most restrictive priority control strategy. Preempting the operation of a traffic signal unconditionally interrupts the normal timing plan by inserting a special plan or phase to accommodate such a request.

The Traffic Engineering Handbook describes preempting the normal traffic signal operation as having the potential to impact the safety, efficiency, and trip reliability of the requesting vehicle and flow of traffic for all other vehicles approaching and traveling through the preempted traffic signal (Institute of Transportation Engineers (ITE), 1999). Depending on the approach to a preempted traffic signal, vehicles may be either positively or negatively impacted (e.g. decreases or increases in travel time, stops and delay may occur). As described by Head in the Transit Cooperative Research Report (TCRP) Project A-16 Interim Report (1998), the potential also exists to disrupt the progression of traffic between other traffic signals whose operation is coordinated along the same roadway or corridor. The negative impacts of preempting the operation of a traffic signal typically increase with the length of time the preemption control plan is in operation along with the time required to transition back to the signal timing plan's normal operation.

1.2 Strategies to Exit Preemption Control

If a traffic signal is isolated or operating in an uncoordinated mode, decisions regarding how to exit from a preemption control plan can be made without considering the potential impacts to the operation of other traffic signals. When the preempted signal is located within a coordinated traffic signal system, the potential exists to disrupt the flow of traffic at the preempted traffic signal and other traffic signals within this system. To maintain coordinated operation with adjacent traffic signals, signal transition strategies can be used to automatically perform the necessary adjustments to reach the desired reference or coordination point in the normal signal timing plan.

Obenberger and Collura (2001) presented the range of strategies available to most traffic controllers to exit from a preemption control plan and transition to the coordinated operation of the normal signal timing plan. These strategies follow different processes requiring varying lengths of time to complete the transition. The four most commonly available traffic signal transition strategies are called the best way (or smooth), long (or add), short, and hold (or dwell). These strategies are described in Section 2.6. Common among these strategies is the method of either increasing or decreasing the signal timing plans cycle length in returning to the coordination or offset point. This allows traffic controllers to select the strategy determined appropriate for the conditions specific to each traffic signal.

1.3 Performance of Traffic Signal Transition Strategies

The majority of the research performed to date on traffic signal transition strategies has centered on their potential impacts on the operation of traffic signals and traffic. Very few studies have evaluated the impacts of preempting the operation of traffic signals. Even fewer studies have evaluated the impacts of using various transition strategies to exit from a preemption control plan and return to the coordinated operation of a series of traffic signals. The use of these strategies could result in either positive or negative impacts involving either increases or decreases in travel time, delay, speed and stops.

Shelby, Bullock, and Gettman (2006) evaluated the performance of different strategies to transition between traffic signal timing plans. This research developed the ability for the CORSIM simulation model to replicate the operation and evaluate the influence of these traffic signal strategies. This analysis concluded that the best way transition strategy is most effective when focusing on the impacts on travelers, measured in delay and travel time. In general, under very congested conditions, the add (or long) transition strategies resulted in lower delays, while the dwell (or hold) exhibited higher delays.

Bullock, Morales, and Sanderson (1998) assessed the impact of emergency vehicle preemption at three coordinated traffic signals. This study found that for the geometric and operational conditions studied, emergency vehicle preemption had a minor impact on the flow of traffic and the coordinated operation of the traffic signals. The use and assessment of different transition strategies in returning to the coordinated operation of the normal traffic signal timing plan was not the focus of this study.

Nelson and Bullock (2000) assessed the impacts of emergency vehicle preemption. This evaluation assessed seven different paths that were followed by the preempting vehicle, up to three preemption requests per simulation run, and three transition strategies to exit from preemption control and transition to normal operation of the coordinated traffic signal timing plan. The preemption paths varied to include preemption requests from both the arterial and side streets. The “hardware-in-the-loop” simulation tool was used to replicate and assess the test network consisting of four closely spaced coordinated traffic signals, uncongested traffic conditions, and two intersections located at a diamond interchange.

The traffic signal transition strategies evaluated were the smooth (or best way), add (or long), and dwell (or hold) transition strategies in exiting from preemption control plan and returning to the coordinated operation of the normal signal timing plan (Nelson, et al., 2000). The smooth (or best way) transition strategy was determined to perform the best for the scenarios evaluated based on the impacts to traffic flow on both the arterial and side streets. The evaluation indicated a single preemption call had a minimal effect on the overall travel time and delay throughout the network, however, when there were multiple preemptions at close intervals, the impacts were more severe.

1.4 Current Evaluation Methodologies

Until recently, researchers and practitioners have relied primarily on field tests and macroscopic traffic simulation models to estimate the potential impacts of enabling vehicles to preempt the operation of traffic signals. Macroscopic models are limited by their inability to replicate the operation of traffic signals, stochastic variations in traffic, vehicle operating characteristics, and interaction between vehicles. Microscopic simulation models have evolved over time and now have limited ability to simulate and evaluate preemption and priority control.

However, the majority of microscopic simulation models do not have the ability to simulate and evaluate the impacts of preemption and priority control within a coordinated traffic signal control system. Many of these models remain limited in their ability to replicate traffic signal transition strategies in exiting from preemption control and returning to coordinated operation. The development of the “hardware-in-the-loop” simulation tool provided the ability to select, simulate, and evaluate these transition strategies.
Urbanik and Venglar (1995) developed the “hardware-in-the-loop” simulation tool, integrating a traffic signal controller operation with a microscopic traffic simulation model. This tool allows for stochastic travel conditions, coordinated traffic signal operation, traffic

control functions, control algorithms, preemption control, and transition strategies to be replicated and for their performance to be quantified. One limitation of this tool is the need for each traffic controller being analyzed to be configured and interfaced with a personal computer containing the microscopic simulation model in a laboratory or shop environment.

The "software-in-the-loop" simulation tool was developed to perform the traffic simulation runs that generated the data that was analyzed and provided the basis for the results presented in this research. The "software-in-the-loop" tool allows for the entire analysis to be completed on a personal computer, eliminating the physical need for traffic signal controllers to be used to perform this simulation and analysis. This tool consists of the CORSIM (FHWA TSIS 5.2 beta version, 2004) microscopic traffic simulation model, the Gardner Transportation Systems NextPhase Suitcase Tester (Version 1.4B, 1999) traffic signal controller software, and a run time extension (RTE) file (C++) to exchange data between these programs allowing them to operate on the same personal computer.

The Nextphase traffic signal software, which was modified to run on a personal computer and called the Nextphase Suitcase Tester, was initially developed to interface with the VISSIM microscopic simulation model Gardner (2000). This "software-in-the-loop" configuration was used to simulate and analyze the impacts of the operation of light rail vehicles on traffic signals. There have not been any other documented applications using this tool to evaluate preemption control or traffic signal transition strategies. This "software-in-the-loop" simulation tool is similar in concept to analysis tools that are developed and used in other fields of engineering.

After the simulation runs were completed for this dissertation in 2005, CORSIM (TSIS 5.2, fall of 2005) was enhanced incorporating the commonly available traffic signal transition strategies directly into the software, thereby providing the capability to transition between coordinated traffic signal timing plans or preemption control (Shelby, et al., 2006). The VISSIM microscopic simulation model (release 3.7) was also updated in 2005, providing the ability to use either the best way (or smooth) or hold (or dwell) traffic simulation strategies (PTV America, 2007). Even with these recent advancements, the evaluation methodology and “software-in-the-loop” simulation tool developed in this dissertation is still needed to simulate and evaluate the use of different strategies to exit from preemption control and return to coordinated operation. This methodology along with the “software-in-the-loop” simulation model provide an option for researchers to develop the capability to simulate traffic control functions, signal timing features, and other issues (e.g., types of vehicles) that may not already exist in CORSIM (FHWA, 2003) or in other microscopic simulation models.

1.5 Research Problem

Traffic controllers and their software (firmware) typically provide a number of different strategies to select from in transferring between traffic signal timing plans. Each of these strategies results in varying amounts of time to complete the transition based on the specific procedure or algorithm each one follows. As a result of these varying lengths of time, each strategy has the potential to also impact travel differently based on the length of time it takes to complete this transition (Obenberger, et al., 2001).

The length of time needed to complete this transition has the potential to impact the flow of traffic at each traffic signal and between any series of coordinated signals. Preempting the operation of traffic signals in a coordinated system poses considerably more complex issues to be considered in selecting and evaluating the performance of transition strategies to exit from preemption control. Consequently, there is a need to assess the efficacy and impact of these different strategies when exiting from a preemption control plan and transitioning to the coordinated operation of the normal traffic signal timing plan.

Current national standards do not specify when these different strategies should be used in exiting from preemption control and returning to the coordinated operation of the normal signal timing plan. This is because recommended practices and guidance have not been developed articulating which strategies are more appropriate under different types of traffic control (e.g., pre-timed, actuated), traffic factors (e.g., volumes, speeds), and conditions specific to each intersection or series of traffic signals (e.g., spacing, geometry, coordinated operation) (Obenberger, et al., 2001).

An evaluation methodology and analysis tools are therefore needed to allow practitioners to evaluate, replicate and assess the impacts of these different traffic signal transition strategies, preferably without requiring a laboratory setting. If such analysis could be completed on a personal computer, practitioners could readily simulate, evaluate the performance, and quantify the potential impacts on traffic flow associated with each transition strategy. The feasibility of this methodology would allow the analysis to be based on conditions specific to each signalized intersection, along with a series of traffic signals where the operation of their signal timing plans are coordinated. This methodology and tool are also flexible enough to provide the capability to assess other traffic control capabilities that are not supported by microscopic simulation models.

This research will enhance current tools that have been applied to assess the impacts of using different strategies to exit from preemption control and transition to the coordinated operation of the normal signal timing plan. This research along with the use of the "software-in-the-loop" simulation tool can be used to analyze different types of operational strategies, traffic control functions, and/or priority control applications. However, for the purposes of this research, only preemption control and transition strategies used to recover to coordinated operation of traffic signal were analyzed.

1.6 Research Objectives, Central Premise and Hypothesis

The purpose of the research presented in this dissertation is to assess the effectiveness of the commonly available traffic signal strategies being used in practice to exit from a preemption control plan and transition to the coordinated operation of the normal signal timing plan. These strategies will be evaluated based on their ability to minimize the negative impacts (e.g. increases in travel time, stops, and/or delay) on traffic flow associated with performing the transition, during which time the operation of these traffic signals is not coordinated.

The central premise of this research as stated below will be examined with the use of an enhanced evaluation methodology which includes the “software-in-the-loop” simulation tool. The central premise can be stated as follows:

> Motorists will benefit from strategies that minimize the adverse impacts associated with exiting from a preemption control plan and transitioning to the coordinated operation of the normal traffic signal timing plan. The degree of these benefits and impacts is dependent on each transition strategy and a function of the effects resulting from the interaction of the key factors of its environment. These key factors include the vehicle issuing a preemption request, traffic volume (e.g., number of vehicles, direction of travel), roadway geometry (e.g., spacing between traffic signals, turn lane storage capacity), signal timing plan at each traffic signal, progression of traffic and coordinated traffic signal operation.

The two primary objectives of this research are to:

1. Assess the performance of commonly available traffic signal transition strategies in exiting from preemption control and transitioning to the coordinated operation of the normal signal timing plan; and
2. Quantify the influence increases in traffic volume may have on the effectiveness of these strategies in performing this transition.

Many factors influence the negative impacts that may result from preemption control and the use of these strategies in performing the transition back to coordinated operation. These negative impacts may include increases in travel times (seconds per vehicle), delays (seconds per vehicle), stops (number) and travel speed (miles per hour). The scope of this research, however, is limited to assessing the influence of changing or varying levels of traffic volume, with the other factors remaining constant. The following hypotheses, developed from the previously stated premise, provided the basis for the evaluation conducted in this research:

1. Motorists will realize benefits from the traffic signal transition strategies that minimize the negative impacts associated with exiting from a preemption control plan and transitioning to the coordinated operation of the normal traffic signal timing plan; and
2. Motorists will realize benefits from the selection of the most effective transition strategy, which will minimize negative impacts resulting from changing or varying levels of traffic volume.

1.7 Research Contributions

A review of published literature identified only a few documented studies that have evaluated the performance of different traffic signal transition strategies. Even fewer studies have evaluated the use of these transition strategies to exit from preemption control and return to coordinated operation of the traffic signal's normal signal timing plan. Prior to this very recent CORSIM and VISSIM microscopic simulation model enhancement, microscopic simulation models were not able to transition between different signal timing plans with different coordination points or cycle lengths. Microscopic simulation models in general however remain limited in their ability to replicate the stochastic nature of vehicles preempting the operation of traffic signals or to replicate traffic signal transition strategies. As a result, little is known about which strategy is the most effective to exit from preemption control and transition back to coordinated operation.

The primary contribution of this research is the enhancement and application of an innovative evaluation methodology and analytical tool known as the "software-in-the-loop" simulation tool to replicate stochastic characteristics and assess the impacts of preemption control. This research also presents how this methodology and tool can be used to assess the performance of different transition strategies to exit from preemption control and return to the coordinated operation of the normal traffic signal timing plan, requiring only a personal computer. This research adds to the greater body of knowledge and advances the state-of-the-art in the control and operation traffic signal control systems by:

- Enhancing the evaluation methodology and applying the “software-in-the-loop” simulation tool to replicate stochastic characteristics and assess the impacts of preemption control entirely on a personal computer;

- Evaluating the effectiveness of the most commonly available transition strategies to exit from preemption control and transition to the coordinated operation of the normal traffic signal timing plan including the best way, long, short, and hold strategies;

- Assessing the impacts of varying levels of traffic volume (e.g., 0.40 to 0.60 v/c) on the performance of different transition strategies to exit from preemption control and in transitioning to coordinated operation of the traffic signal.

- Enhancing the methodology and “software-in-the-loop” simulation tool to evaluate preemption control, traffic signal transition strategies, traffic control functions, and other features not currently supported by microscopic traffic simulation models, requiring only a personal computer.

The results of this research should be of interest to traffic engineers and researchers involved in developing or operating coordinated traffic signal control systems. The primary contribution of this research is the enhancement of this innovative evaluation methodology and application of the “software-in-the-loop” simulation tool to assess the impacts of preemption control and the performance of different strategies to the coordinated operation of the normal signal timing plan, using only a personal computer. This research expands upon previously completed research that relied on the use of the “hardware-in-the-loop” simulation tool to perform this analysis. In addition, this research demonstrates the potential of the evaluation methodology and simulation tool to assess other traffic control functions, features and operational strategies not currently supported by microscopic simulation tools.

1.8 Report Organization

The remaining chapters of this dissertation report are organized in the following manner:

- Chapter 2 – Literature Review. This chapter summarizes research related to preemption control, traffic signal transition strategies, analysis methodologies and tools, and relevant studies that provide a basis and support for this research.
- Chapter 3 – Research Methodology. This chapter introduces the evaluation framework, methodology, and overall approach to performing this research.
- Chapter 4 – Analysis. This chapter details the experimental design that was followed including the "software-in-the-loop" traffic simulation tool that was developed and the analysis that was performed in conducting this research.
- Chapter 5 – Results. This chapter presents the results of the analysis to determine which transition strategies likely are the most effective for varying levels of traffic.
- Chapter 6 – Conclusions and Recommendations. This chapter offers conclusions based on the analysis performed, tools utilized, and recommendations for future research.

CHAPTER 2: LITERATURE REVIEW

This chapter reviews published research, industry guidance, and current research activities related to preemption control, traffic signal transition strategies, evaluation methodologies and analysis tools, and relevant studies that provide a basis for this research. The remaining sections of this chapter present the results of this review which focus on: traffic signal priority control, traffic signal preemption control, traffic signal transition strategies, exiting from preemption control, industry standards and recommended practices, evaluation methods, and tools.

2.1 Overview

The purpose of this literature review is to synthesize the research and references available on preemption control and the use of traffic signal transition strategies. This synthesis will present a review of the current state-of-the-practice associated with preemption control, traffic signal transition strategies, and other related topics and issues. These key topics and issues include evaluation methodologies and traffic analysis tools, traffic simulation models, traffic signal priority control and systems, national standards, and recommended practices.

The information captured in this review provides the justification or basis for the objectives, thesis, and supporting hypothesis of this research. This review considered: industry standards and recommended practices; published guidance and reports from professional organizations (e.g., Institute of Transportation Engineers, ITS America, U.S.DOT, FHWA); current practices captured on web pages; published research (e.g., technical journals); conference papers; and other related sources. The developments and significant research which have occurred over the past decade involving personal computers, evaluation methodologies, traffic analysis tools, computer capabilities being integrated into traffic controllers and other applications, deployment of intelligent transportation systems (ITS), telecommunications, and widespread deployment of technology have significantly advanced the state-of-the-practice and state-of-the-art of both traffic signal priority and preemption control.

2.2 Traffic Signal Priority Control

Traffic signal priority control is an established strategy that is available to traffic managers and transportation providers to improve the operational performance of their respective systems or services. Traffic signal priority control provides the capability to modify the normal traffic signal operation and timing plan. The objectives of priority control are to improve schedule adherence, efficiency and safety of the requesting vehicle, along with improved overall operation of the roadway network. The physical architecture of a signal priority and preemption control system is summarized in Figure 1 (Obenberger, et al., 2001).

The MUTCD has established different levels of priority control corresponding to the degree that signal timing plans may be modified by different vehicles and conditions (FHWA, 2001). Priority control strategies can range from unconditional preemption to lower levels of priority which only modify the operation of a traffic signal's timing plan. These lower levels of priority may include, but are not limited to: extending the green phase, early green phase activation, skipping a phase, actuated phase for requesting vehicle, and phase insertion or rotation within the context of the existing signal timing plan. This range of priority control options allows a strategy to be selected that modifies the signal timing plan based on the conditions specific to each intersection, time of day, requesting vehicle and its status, and traffic control policies of an agency.

The sequence of events, intervals, and decision points that may occur in a signal timing plan during the process of responding to a vehicle's request for priority control may involve issuing, receiving, processing, implementing, servicing, and exiting or recovering from any request to modify the operation of a traffic signal's normal timing plan (TCRP Project A-16 Interim Report, 1998). The events and traffic control intervals associated with responding to a priority control request are summarized in Figure 2.

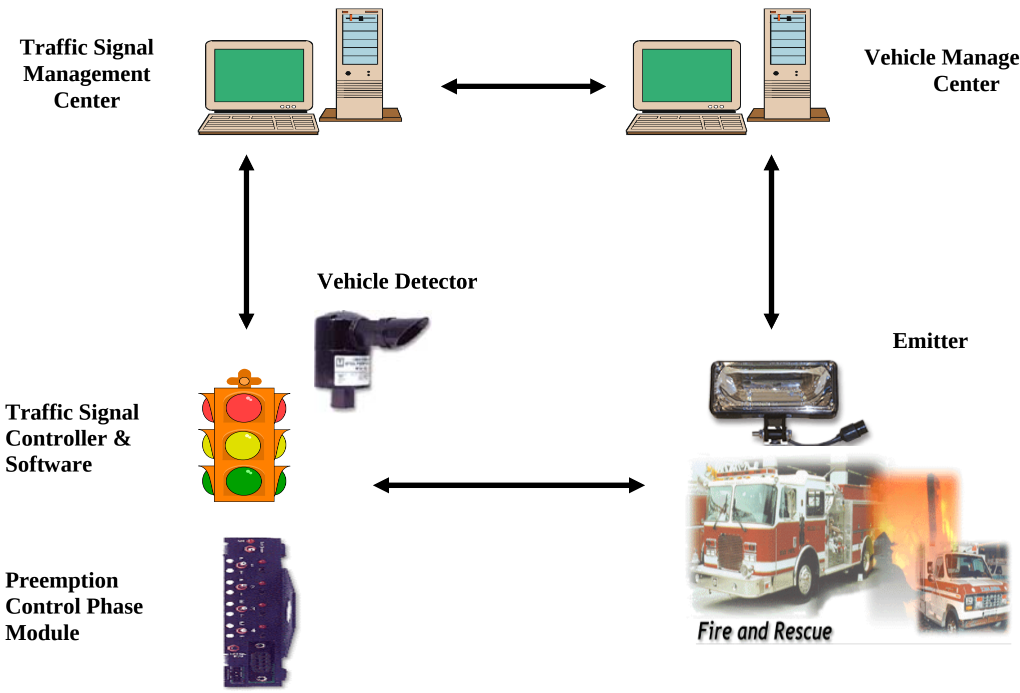


Figure 1. Traffic Signal Priority and Preemption System Control Architecture

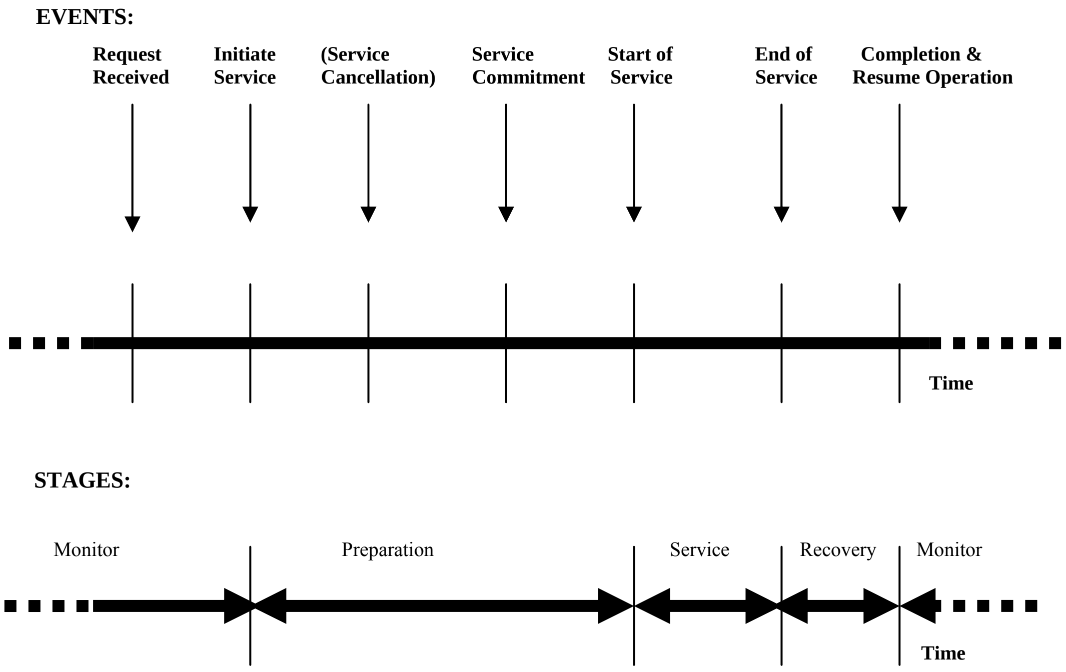


Figure 2. Signal Priority and Preemption Control Events (adapted from TCRP Project A-16 Interim Report, 1998)

The benefits of priority control, as reported by ITS America in "An Overview of Transit Signal Priority" (2002), may include improved schedule performance, reduced travel time, improved travel time reliability, reduced number of stops, and overall efficiency of the requesting vehicles that benefit from preemption control. Potential negative impacts of priority control may involve other vehicles, typically vehicles on the cross or minor side street approaches to these traffic signals. The benefits of priority control, based on reported experiences from around the country indicate approximately a 15% reduction in travel time, along with improved travel time reliability. Priority control may negatively impact vehicles on the cross or minor side street approaches to traffic signals.

While the benefits of preemption control may appear to be minor, given that they apply to a relatively smaller number of vehicles in comparison to all vehicles traveling through an intersection, the potential exists for significant improvements in the performance of the vehicles receiving preferential treatment at signalized intersections. Transit vehicles, for instance, may encounter approximately 40% of their delay while traveling through traffic signals. The ITS America "Traffic Signal Priority: A Planning and Implementation Handbook" (2005) states that a 15% reduction in travel time of a transit vehicle with a 60-minute round trip travel time on a route with a 5-minute headway between vehicles, would mean that only 11 buses would be required instead of 12, resulting in a significant improvement in the performance and cost of operating this route.

Priority control systems have the potential to improve performance by tracking the location and speed of the requesting vehicle on its approach to a traffic signal. These enhanced capabilities allow for the selection and implementation of the priority control strategy based on the performance of the requesting vehicle, traffic conditions at the intersection, and the traffic signal timing plan. Depending upon the type of detection used to identify and track vehicles requesting priority control, varying amounts of information can be collected, allowing for more accurate (e.g., exact location of requesting vehicle known) and effective techniques (e.g., early green, extend green) to be used in managing the signal timing plan (ITA America, 2005).

2.3 Traffic Signal Preemption Control

The National Electrical Manufacturers Association (NEMA) TS-2 Standard (1998) has defined traffic signal preemption as the transfer of the normal operation of a traffic signal to a special control mode for the purpose of servicing special vehicles and other tasks, which requires terminating the normal traffic control to provide for the priority needs of the special vehicle or task. Preemption control is used to accommodate trains or light rail vehicles at rail crossings, direct access by emergency vehicles to roadways, and pedestrians at mid-block crossings or at signalized intersections. Preemption control is recommended when and where there is a need from a safety perspective to assign the highest level of priority to specific types of vehicles or movements.

At signalized intersections, the focus of preemption control is on improving the operation of light rail vehicles, express route transit vehicles, and emergency vehicles. Preempting a traffic signal results in the reallocation of the time required to serve the special timing plan implemented to accommodate the request and to transition back to the normal operation of the signal timing plan. This reallocation of time is performed without regard to the impacts and potential disruption to the coordinated progression of traffic between signals, and thus has the potential to impact the flow of traffic at several intersections.

The research performed, evaluation methods and analysis tools developed, testing completed, technologies developed and deployed have significantly increased the effectiveness and utilization of preemption control in the United States. Even though the basic functional capability has been available for over 30 years, until recently the technology required to efficiently accommodate preemption control in the management of the operation of traffic signals was not available. As a result, the deployment and use of preemption control has been fragmented and not widespread across the country. The technology advancements and software enhancements realized in the 1990s, along with the priority within industry to deploy ITS, have significantly improved the environment and capabilities necessary to support the deployment and operation of both priority and preemption control (Obenberger, et al., 2001).

FHWA's development of the Urban Traffic Control System (UTCS) was the first major initiative in the United States that focused on developing and testing the use of preemption control at traffic signals where their operation was coordinated. MacGowan reported (1975) this initiative and specified requirements to develop the capability to support the operation of a bus priority control system in the early 1970s. This system allowed equipped transit vehicles to unconditionally preempt the normal operation of the signal timing plans at coordinated traffic signals. The tests performed on the initial system capabilities were limited by the structure of its preemption control algorithm, location of bus stops, and the traffic controller's inability to skip phases or modify the length of the signal timing plan phases. These restrictions limited the ability of traffic controllers to return to the offset or coordination point, which is necessary to maintain or achieve coordinated operation of the signal timing plans between signalized intersections.

The potential negative impacts of preemption control on traffic flow, the inability to estimate these possible impacts prior to implementation, and a variety of institutional issues have been major barriers limiting the use of preemption control. Until traffic controllers had the ability to return to coordinated operation, the use of preemption control was primarily limited to isolated intersections. The key institutional issue that limited the use of preemption control can be summarized as the differences that existed between the policies and operational objectives of the agencies responsible for controlling traffic and the objectives of those desiring the capability to modify or preempt the operation of a traffic signal (Obenberger, et al., 2001).

Advancements in traffic control technologies over the past decade have overcome the deficiencies that once limited or served as barriers to the widespread implementation and use of preemption control. A combination of local and national initiatives has contributed to overcoming the institutional barriers that have limited preemption control by state and local agencies. National initiatives have included conducting research, developing technologies, performing operational tests, preparing technical guidance, and facilitating outreach efforts to advance both the state-of-the-practice and use of preemption control.

Noyce (1996) identified a number of institutional barriers and proposed strategies to overcome the challenges with implementing and operating a signal priority system for transit. The identified barriers included institutional (e.g., financial, liability), operational (e.g., traffic volumes, frequency of requests), and human factors (e.g., driver and pedestrian expectancies). Some of the strategies proposed to overcome these barriers include understanding technical issues, receiving management support, and demonstrating viability and benefits. These barriers and challenges also apply to preemption control.

McHale (2002) developed an improved transportation planning tool to assess the travel time impacts of emergency vehicle preemption control systems at uncoordinated or isolated traffic signals. This research identified enhancements to be made to the ITS Deployment Analysis System (IDAS) software which could support development of the ability to estimate the impacts of emergency vehicle preemption control on the travel times of non-emergency vehicles as a function of traffic volumes on the transportation network. The estimated impacts were relatively small and ranged from 1.1% to 3.3% travel time increases for a one-hour analysis period to a 0.6% to 1.7% travel time increase for a two-hour period. This research focused on evaluating the impacts of preempting the operation of only one uncoordinated traffic signal. Due to the focus and methodology of this research, the results are not directly comparable to the research completed in this dissertation.

Bullock, et al., (1998) used the "hardware-in-the-loop" simulation tool to assess the impacts of emergency vehicle preemption at three coordinated traffic signals. The study found that the impacts of preempting a signal on the progression of travel along the arterial were minor for the geometric and operating conditions specific to the time period analyzed. An average increase in travel time of only 2.4% resulted from the various preemption scenarios that were evaluated. These lower than expected impacts may have been due to: 1) long spacing between signalized intersections; 2) modest traffic volume; 3) emergency vehicle detectors located too close to the intersection; and 4) very long cycle lengths. The use and assessment of transition strategies to return to coordinated operation of the traffic signals was not a focus of this study.

Gkritza, Collura, Tignor, and Teodorovic (2007) assessed the potential and need to implement preemption control in support of emergency vehicles along major arterials in the Washington, D.C. region. This study addressed the travel characteristics of emergency vehicles along with how these characteristics may influence preemption control and impact the operation of traffic signals. The characteristics considered included: temporal and spatial distribution of emergency vehicle travel; frequency and duration of preemption requests; vehicle platoon responses to responding emergency vehicles; and crashes involving these vehicles. The resulting research findings demonstrated the need to further assess the potential benefits of preemption control.

2.4 Exiting Preemption Control

A review of current practices for exiting from preemption control identified coordinated and uncoordinated signal operation as having two distinctly different sets of practices and factors to be considered. If a traffic signal is isolated or operating in an uncoordinated mode (e.g., fully actuated or free), decisions on how to exit from preemption control can occur without considering potential impacts on the progression of traffic between coordinated signals. For these situations, all that may be required is specifying a return interval or phase, or sequence of phases, to be served (Obenberger, et al., 2001).

When the operation of a signal timing plan is coordinated with other signals, traffic signal transition strategies are used to exit from preemption control and transition to the coordinated operation of the normal signal timing plan. For coordinated signals, this requires specifying both the strategy to perform this transition and the first phase to serve in the signal plan upon exiting preemption control.

2.4.1 Exiting to Free or Uncoordinated Operation

If a traffic signal is isolated or its signal timing plan is not coordinated with other signals, the common practice within industry involves specifying one or a sequence of phases to serve upon exiting preemption control. The phase or sequence of phases to be served should be determined based on an assessment of the conditions specific to each signalized intersection. The conditions and factors to consider may include: turning movement volumes, turn lane capacity, signal timing plan phases and features, changes in traffic volume during the day, and accommodation of pedestrians (Obenberger, et al., 2001). Examples of approaches to address these conditions may include:

- preempted phase: Return to the phase that was preempted, if it was terminated early, based on a user-specified minimum green time to be served. If the preempted phase was served for a period of time that exceeded the specified minimum green time, based on volume (e.g., detector call), the controller would advance to the next phase in normal sequence; or
- designated phase: Return to programmed phase and advance through signal timing plans in normal sequence. Options for selecting a return phase include:
  -first complete phase that was skipped due to preemption;
  -major or minor intersection movements;
  -left turn movement on main or minor streets that exceed capacity; and
  -movements split into different phases on main or minor streets.

2.4.2 Exiting to Coordinated Signal Operation

Traffic signal transition strategies are commonly used in practice to exit from preemption control and return to coordinated operation. These strategies automatically perform the necessary adjustments in the normal signal timing plan, to reach the desired coordination or offset point, which represents coordinated operation with respect to the adjoining signals. The processes that these strategies follow involves either holding or resting in the desired return phase, or the signal timing plan is either reduced or expanded and cycles until the desired coordination or offset point is reached.

To mitigate the potential negative impacts associated with preemption control, the time required to return to coordinated operation should be minimized. This transition time will vary depending on where the normal signal timing plan would have been if its operation was not interrupted, compared to where it is upon exiting preemption control (TCRP Project A-16 Interim Report, 1998) . The strategy selected will influence the time required to perform this transition, with the time required to perform this transition ranging from zero to a maximum of one second less than the signal plan's cycle length.

The literature review revealed that traffic controllers and their software provide a range of traffic signal transition strategies to select from to perform this transition. Unless public agencies specify the need to develop a unique exit transition strategy, they will be restricted to the options that are already available on a specific product. As an example, a software user group in the State of Oregon identified a range of recommended strategies to recover to the desired coordination point in a signal timing plan (Wapiti, 2000). The group identified functional and performance requirements in support of developing these new transition strategies. These requirements provided a starting point for an agency to consider in developing a new traffic signal transition strategy, or in comparing these requirements to those currently available from a traffic signal or software manufacturer.

2.5 Industry Standards and Recommended Practices

The operational policies and procedures of a local agency typically establish the control parameters and hierarchy of vehicles determined eligible to issue requests to preempt the operation of a traffic signal. This structure should provide the flexibility to consider the conditions at each intersection in making decisions to implement and operate preemption control. It should also assist with establishing preemption control plans, system capabilities and technologies, and conditions appropriate to implement preemption requests from specific types of vehicles. The Oregon DOT Traffic Signal Policies and Guidelines (1999) and North Carolina DOT Guidelines for Emergency Vehicle Initiated Preemption (1997) are policies being used to implement and operate preemption control.

2.5.1 Traffic Signal Controller

Prior to the early 1990s there were no national or industry traffic controller standards that supported preemption control operational requirements, functions, and logic. Marshall and Berg (1989) examined how actuated traffic controllers available on the market supported preemption control and compared these capabilities to the corresponding NEMA standard. At the time this standard did not provide any definition, specified processes, or capabilities related to preemption control. Their review indicated that current controllers provided only the basic capabilities to support preemption control with many different features existing that were supported by various manufacturers.

The approved NEMA TS-2 standard (NEMA, 1998) established the minimum operational requirements and functions to be provided by traffic-responsive controllers. This standard required these controllers to provide an internal preemption program with the capability to support and establish priorities for six different inputs or preemption requests for different types of vehicles. It also established the hierarchy and procedures to follow in responding to situations when one of the preemption inputs should supersede a preemption input from another vehicle. This standard specifies the internal preemption program shall have the capability to:

- accept commands from six different types of preemption inputs;
- provide the timing and signal displays programmed for each preemption input;
- provide transition timing and signal displays for all programmed preemptions;
- recognize the current signal display at the time of preemption; and
- upon satisfying preemption requests (inputs), provide a strategy and signal display for the programmed return-to-normal condition for the six preemption inputs.

This standard also requires the preemption program to provide an exit transition scheme to reach a programmed point in the normal traffic signal timing plan. This provides the controller with the logic to transition from preemption control to either a higher level preemption request or to return to the normal operation of the signal timing plan. An example of this situation may be a railroad preemption request canceling, terminating early, or following the preemption control plan implemented for an emergency vehicle. Traffic controllers typically offer the option of specifying either a period of time, or number of cycles, before allowing an equal or lower level request to be served in preempting the operation of a signal timing plan (TCRP Project A-16 Interim Report, 1998).

The transportation industry has developed the National Transportation Communications for ITS Protocol (NTCIP), which provides standard rules for communicating (called protocols) and sharing information data and command (called objects) between traffic controllers and other devices. These standards are used by agencies in specifying and selecting traffic control devices and their accompanying software, often developed by different manufacturers. The standards cover many different traffic control applications and devices with the intent of seamlessly facilitating the sharing of information between devices produced by different manufacturers. Specific standards have been developed in support of different signal priority control applications. The NTCIP standards effort is also working with the Transit Communications Interface Profiles (TCIP) standards effort to address priority control for transit vehicles (TRB, 2003).

2.5.2 Preemption Control

The local authority or official having jurisdiction over the operation of a particular roadway has the responsibility of determining how preemption control should operate at each traffic signal. The two major factors that agencies typically use to determine when the traffic controller should implement specific preemption requests are the time required to terminate the current phase in operation and the time to clear the queue of vehicles on the approach to an intersection. The Traffic Engineering Handbook provides only limited guidance on the process and time to transition into and out of preemption control. It recommends instead, an engineering study be performed, to analyze the following factors as the basis for making decisions on how to transition into and out of preemption control:

- when to grant requests for preemption control for different vehicles;
- when the controller should begin the process of implementing preemption requests;
- what is the duration needed for the requested preemption control plan; and
- what is the most effective strategy to exit preemption control (ITE, 1999).

The MUTCD has established the hierarchy of vehicles that may be allowed to issue requests to preempt a traffic signal. The MUTCD is the national standard for traffic control devices that are used on all roads open to public travel. The standards and recommended practices established in the MUTCD pertain to the operation of traffic signals, timing plans, and indications displayed on an approach to an intersection. These standards are intended to achieve national consistency in processing individual and multiple or conflicting preemption requests (FHWA, 2001).

This hierarchy in the levels of priority for implementing preemption control is applicable to rail, boat, fire and emergency medical, transit, and other vehicles. The MUTCD specifies three distinct stages shall occur when the normal control of a traffic signal is preempted. These phases involve transitioning into, serving, and transitioning out of preemption control. The only standard that applies to all three stages is the restriction against shortening or omitting a yellow change or red clearance interval (FHWA, 2001). The following standards are unique to the respective stages:

Stage 1:

- shortening or omitting any pedestrian walk or change interval shall be permitted;
- display of the previous green indication shall be permitted following a steady yellow indication on the same signal face, and omitting red clearance interval if any;

Stages 2 and 3:

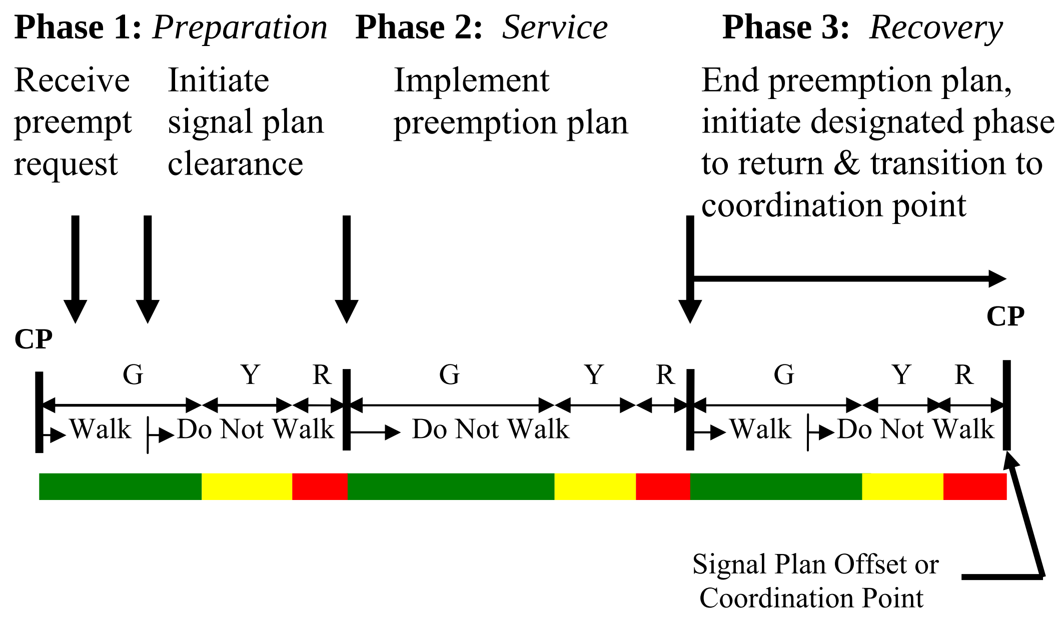
- signal indication sequence from steady yellow to steady green shall not be permitted.

The sequence of events and control intervals for these three preemption control phases are presented in Figure 3 (TCRP Project A-16 Interim Report, 1998). To date there are no national standards or industry recommended practices specifying or identifying a preferred procedure to follow in exiting from a preemption control plan and transitioning back to the coordinated operation of the normal signal timing plan, or how the use of transition strategies should vary based on different conditions.

2.6 Traffic Signal Transition Strategies

A review of traffic signal controller manuals and documented research was performed to identify current practices and the strategies commonly used to exit from a preemption control plan and transition to the coordinated operation of the normal signal timing plan. The following reports and traffic controller and software product manuals were reviewed to identify these commonly available transition strategies:

- NextPhase Intersection Management Software (Gardner, 2004);
- W4IKS Software (Wapiti, 2000);
- ASC/2 Controller (Econolite Control Products, 1995 and 1997); and
- EPAC 3000 Intersection Controller (Eagle, 1996).



LEGEND:

Walk	Walk Interval
Do Not Walk	Pedestrian Clearance Interval
G	Green Interval
Y	Yellow Clearance Interval
R	All Red Clearance Interval
CP	Coordination Point or Signal Plan Offset

Figure 3. Preemption Control Phases: 1 Preparation; 2 Service and 3 Recovery or Transition (adapted from TCRP Project A-16 Interim Report, 1998)

These available reports and product manuals provided only high-level descriptions of the different exit transition strategies that each manufacturer supports. These traffic signal controller software products all have the capability to specify one, or a sequence of, intervals to serve after completing a preemption control plan. Specific details relating to the processes or algorithms followed for each transition strategy are not available in these manuals. Consequently, practitioners must contact the developer of each product directly if more information is needed (Obenberger, et al., 2001). The commonly available traffic signal transition strategies identified in these product manuals include:

1. hold (or dwell) - rests or increases the length of the coordinated phase until the coordination or offset point is reached within one cycle of the signal timing plan, with no other phases adjusted due to the plan not cycling;
2. maximum dwell - dwells for a predetermined maximum time in the coordinated phase or until the coordination or offset point is reached. If the maximum dwell time is obtained prior to reaching this offset, the signal timing plan cycles through the remaining phases. This process is repeated until this offset point is achieved;
3. long (or add) - increases proportionally the green interval for each phase by a predetermined time and cycles through the signal timing plan until the coordination or offset point is reached. This process is repeated using the increased cycle length until the coordination point is achieved;
4. short - decreases proportionally the green interval for each phase by a predetermined time and cycles through the signal timing plan until the coordination or offset point is reached. This process is repeated using the decreased cycle length until coordination is achieved; and
5. best way (or smooth) - selects either the long or short strategy that transitions to the coordination or offset point in the least amount of time.

Common among these strategies is the method of either increasing or decreasing the cycle length as the process followed in transitioning to the coordination or offset point in the traffic signal timing plan. The best way, long and short strategies rely on a predetermined percentage established by the manufacturer which is used to either increase or decrease the phases and overall cycle length in the process that is followed to recover to coordinated operation. The details associated with the percentages that these strategies follow are proprietary and unique to each manufacturer. These different transition strategies allow for the selection of the strategy that may be appropriate based on the agency’s control policies and the conditions specific to each traffic signal. For example, if a pedestrian movement must be served, shortening the cycle length may not be possible without omitting or reducing the pedestrian clearance interval.

The hold (or dwell) strategy has been available for the longest period of time, because it was the only option available on electro-mechanical controllers to maintain coordinated operation of signal timing plans between coordinated traffic signals. This strategy requires the controller to rest or dwell in the green interval containing the coordination or yield offset point until the signal timing plan reaches this point, or until the request for coordination is dropped or lost. This strategy achieves coordination in less than one complete cycle of the signal timing plan. However, once the phase, which contains the coordination or offset point is served is served, the signal timing plan will no longer cycle, resting as long as required until the signal timing plan reaches this point.

A signal timing plan could lose coordination if: the controller's time clock drifts; operation of the signal timing plan is preempted; a transition occurs between timing plans with different cycle lengths or offsets; the requirement for coordinated operation is dropped (e.g., switch to isolated operation in off peak period); or the communication link is lost between intersections removing the command for coordinated operation. Based on the delay that may be incurred by vehicles on the intersection approaches that are not served by the interval containing the coordination point, this strategy has the greatest potential to adversely or negatively impact travel.

A limited number of research projects conducted to date have evaluated the impacts of using different traffic signal transition strategies. These studies have focused on the potential impacts associated with using these strategies to transition between different signal timing plans. Very few studies evaluated the impacts associated with using these strategies to exit from preemption control and transition to the coordinated operation of the traffic signal. These studies identified the following factors that may influence the impacts preemption control and these strategies may have on a traffic signal's operation (Obenberger, et al., 2001), (TCRP Project A-16 Interim Report, 1998), (Nelson, et al., 2000):

- frequency and travel direction of vehicles issuing preemption requests;
- presence of turn lanes with sufficient capacity;
- congested versus uncongested travel conditions;
- cycle length, phases and available time beyond minimum green times;

- existence of pedestrian phases; and
- spacing and progression of traffic between traffic signals.

A review of currently available traffic signal transition strategies and previously completed research that evaluated the use of different strategies in transitioning between traffic signal timing plans provided the basis to develop the commonly available transition strategies directly into CORSIM (Shelby, et al., 2006). CORSIM (TSIS 5.2, fall of 2005) was used to assess the performance of these transition strategies at an isolated intersection and a series of four coordinated traffic signals. This research concluded the best way (or smooth) transition strategy is most effective in general and showed that under very congested conditions, the add (or long) transition strategy resulted in lower delays, with the dwell (or hold) exhibiting higher delays.

Nelson, et al., (2000) assessed the impacts of emergency vehicle preemption by varying the paths of the requesting vehicles, frequency of requests, and using different transition strategies to exit from preemption control and transition to coordinated operation of four traffic signals in the test network. The findings showed that a single preemption call had a minimal effect on the overall travel time and delay to all vehicles traveling through the four coordinated traffic signals. When multiple emergency vehicles preempted traffic signals at closely spaced time intervals, the impacts of preemption were more severe.

This analysis was performed using the “hardware-in-the-loop” simulation tool to replicate the test network that consisted of four coordinated traffic signals, which included two signals located at a diamond interchange. The smooth (or best way), add (or long), and dwell (or hold) transition strategies were evaluated in exiting from a preemption control plan and returning to the coordinated operation of the normal signal timing plan at each intersection in the test network. The smooth transition strategy was determined to perform the best for the scenarios and path of the preempting vehicle evaluated.

2.7 Evaluation Methods and Tools

The Federal Transit Administration (FTA) report titled, "Suggested Procedures for Evaluating the Effectiveness of Freeway Facilities," and FHWA report titled "Generic IVHS Operational Test Evaluation Guidelines," provide guidance and recommended practices for evaluating ITS applications and operation strategies. Obenberger and Rupert (2000) provide a recommended evaluation methodology, procedures, and issues to consider in evaluating HOV facilities. Their report further urged agencies to develop continuous monitoring and evaluation of the performance of programs, policies, roadway facilities, operational strategies, traffic management systems, and traffic control plans.

FHWA has also developed the Traffic Analysis Toolbox that provides a decision support resource to use in selecting traffic analysis tools and applying traffic simulation models. These decision support resources provide a process, criteria, worksheet, and guidance for selecting the appropriate type of traffic analysis tool for a particular analysis task. The guide for applying microscopic simulation software provides a seven-step process for performing an operational analysis from start to finish (FHWA, 2004).

The procedures that are followed in developing preemption control plans should consider the impacts they may have on the operation of the preempting vehicle and other vehicles. This requires the evaluation methodology and analysis tools to account for the conditions specific to each vehicle, signalized intersection and surrounding roadway network. To accurately assess these potential impacts, the selected evaluation methodology needs to incorporate a microscopic traffic simulation model.

Until recently, researchers and practitioners have had to rely primarily on field tests and macroscopic traffic simulation models to estimate the potential impacts of enabling vehicles to preempt the operation of traffic signals. Traffic simulation models have been developed providing the capability to replicate, quantify and assess traffic flow and control strategies. These models utilize the traffic flow theory and fundamentals to provide a basis to estimate and to quantify the impacts of traffic flow and various control functions or operational strategies (e.g., traffic signals, signal timing plans, preemption control). The two primary types of traffic simulation models that have been developed are macroscopic and microscopic traffic simulation models (Skarbardonis, 1999).

The traffic flow theory, concepts and variables supporting the quantification of uninterrupted and interrupted flow of traffic, provide the fundamentals upon which this research was based. These fundamentals were utilized to analyze, evaluate and develop conclusions that are based on the cause and effects of the unique aspects of the research performed in this dissertation. The Traffic Engineering Handbook identifies volume, speed and density as the key variables for quantifying traffic flow (ITE, 1999).

Volume represents the traffic volume or rate at which vehicles operate on a section of roadway for a period or time. The density of the flow of vehicles is defined as the number of vehicles on a section of roadway for a specific time period. The formula to calculate traffic density is presented in Equation 1 and is based on the average speed and average volume of vehicles on a roadway facility. Speed represents the rate at which vehicles travel a section of roadway (special) over a period of time (temporal). The formula to calculate vehicle speeds is presented in Equation 2 and is based on the cumulative average travel times of all vehicles traveling over a length of a highway segment.

Equation 1: Vehicle Density

$D = v/s$ Where: D = density of traffic (vehicles per mile per lane)
s = average travel speed (miles per hour)
v = flow rate (vehicles per hour per lane)

Equation 2: Vehicle Speeds

$S = n*l/ \sum t$ Where: S = average vehicle speed on section (miles/hour)
n = number of travel times observed
l = length of highway segment (miles)
t = vehicle travel times on section (seconds)

The relationship between these fundamental variables provides the ability to qualify the characteristics and quantify the performance or flow of traffic traveling on a particular section of roadway. These variables represent the overall performance of all individual vehicles on a section of roadway. Integrating and quantifying the influence of traffic signals on traffic flow introduces a larger number and more complex set of variables than with uninterrupted traffic flow. Greenshields developed a theory and a set of fundamentals that allow for the influence of traffic signals on traffic flow to be evaluated and quantified.

Two of the key variables that Greenshield developed were the concepts of saturation flow rate and lost time of vehicles accelerated from a stopped or delayed position prior to departing a traffic signal upon receipt of the green indication. Lost time is defined as the average time required for motorists to accelerate and depart a traffic signal, from a stopped condition when the green indication is displayed for a particular phase of a traffic signal timing plan. The saturation flow is defined as the rate at which these vehicles accelerate and depart from this stopped or delayed position in a queue of vehicles waiting on the approach to a traffic signal. The saturation flow rate formula presented in Equation 3 allows for the headway specific to a particular roadway to be considered.

Equation 3: Saturation Flow Rate

$s = 3{,}600/h$

Where: s = saturation flow rate (vehicles per hour per lane)

h = headway between vehicles at saturation flow rate (seconds)

3600 = number of seconds per hour

The use of saturation flow rate, lost time and fundamentals of queuing theory can be used to analyze and quantify the flow of traffic approaching and traveling through a traffic signal. The Highway Capacity Manual (HCM) details how the fundamental queuing theory may be applied along with Greenshields developed formulas, to analyze the flow of vehicles through an intersection as a function of time. Queuing theory allows for the quantification of the influence of vehicles arriving on an approach to a signalized intersection: 1) at a rate exceeding the capacity of the intersection; or 2) when other vehicles are stopped at the intersection due to the traffic signal operation. The formula to calculate the duration of a queue that may be formed at a traffic signal is presented in Equation 4, which is based on the traffic signal timing plan, discharge of vehicles at the intersection, and arrival or flow rate of traffic to the intersection (TRB, 2000).

Equation 4: Duration of Vehicle Queue

$t = s * r / (s-v)$ Where: t = time queue of vehicles formed (seconds)

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

r = effective red time (seconds) for signal approach

v = arrival or flow rate of traffic (vehicles per hour)

Vehicle delay, travel time and stops are several of the key measures that are used to quantify the performance of vehicles traveling on a section of roadway and through traffic signals. Delay and travel time are used to evaluate the operation of traffic signals, signal timing plans and traffic traveling through these intersections. Delay is defined as the additional travel time a vehicle encounters when it is not traveling at its desired speed due to interruptions to the normal flow of traffic on its approach to or through an intersection. Delay is typically measured in terms of hours, minutes or seconds of delay per vehicle.

Variables that are used to calculate vehicle delay associated with traffic signals includes the time a vehicle decelerates, is stopped, and accelerates for its departure from the intersection. The HCM calculates the delay experienced by vehicles traveling through traffic signals and is presented in Equation 5, which consists of three variables: vehicle arrival at traffic signals; progression of traffic between signals; and vehicle queues.

Equation 5: Delay at Traffic Signals

$D = D_1 + D_2 * PF + D_3$ Where: D = total delay due to signal (seconds)

D_1 = delay due to traffic signal delay (sec.)

D_2 = delay due to random vehicle arrival (sec.)

PF = factor – signal affects on traffic progression

D_3 = delay due to vehicle queue (sec.)

Travel time is defined as the average time spent by vehicles traveling through a particular segment of a roadway. Travel time includes delays caused by interruptions to the traffic flow (e.g., intersections, traffic signals) and is typically measured in terms of minutes or seconds of delay per vehicle. The variables which influence delay at an intersection include traffic volume, capacity (e.g., number, type of lanes), cycle length, number of phases in signal timing plan, green time, and clearance time in signal timing plan.

Traffic simulation models have the capability to automatically calculate the average travel time and average delay performance measures for a range of different roadway facilities. These models have incorporated the traffic flow theory and fundamentals described above to allow for an assessment and quantification of the influence of traffic signals, formation of traffic queues at traffic signals, and traffic control functions on traffic flow. Mesoscopic, macroscopic and microscopic simulation models differ based on the traffic flow theory and fundamentals that are incorporated into these models.

Mesoscopic and macroscopic models incorporate deterministic variables and concepts to replicate and quantify traffic flow, thereby limiting their ability to replicate traffic signal operation, stochastic variations in traffic flow, vehicle operating characteristics, and interaction between vehicles. Microscopic traffic simulation models have the ability to consider these issues and factors based on the car following, lane changing, and queue discharge algorithms. These algorithms provide the logic and capability to replicate and quantify the behavior and performance of individual vehicles operating on the section of roadway being analyzed (FHWA, 2004).

Several microscopic simulation models have been enhanced to simulate the basic traffic signal priority and preemption control functions. The majority of microscopic simulation models do not, however, have the ability to simulate and evaluate priority and preemption control within a coordinated traffic signal system. These models are limited by their inability to replicate and quantify the performance of coordinated signal timing plans when changes require using different cycle lengths or offsets to establish coordination between these signals. As a result, they are not able to simulate traffic signal transition strategies that are necessary to reestablish coordination between traffic signal timing plans.

Microscopic simulation models currently are unable to replicate the operation (e.g., acceleration, deceleration) of different vehicles (e.g., emergency, transit, light rail) that issue requests to preempt the operation of a traffic signal. They are also not able to simulate the operation of emergency vehicles operating with an emergency beacon or siren. These models are unable to replicate the influence vehicles using an emergency beacon or siren may have on the behavior of other drivers and thus the interaction with other vehicles.

Nevertheless, a microscopic simulation model can be used with simplifying assumptions to assess the probable impacts of vehicles preempting the operation of coordinated traffic signals. These assumptions apply to the preempting vehicle as well as other vehicles traveling at the posted speed limit or prevailing speed, observing motor vehicle laws and traffic rules, and traveling in the normal progression or flow of traffic between traffic signals. They also assume the responding emergency vehicle: does not use a flashing beacon or siren; does not influence the operation or flow of traffic; travels at the posted speed limit or prevailing speed; travels within the normal traffic stream; and observes all motor vehicle laws, regulations, and traffic rules. If these assumptions are consistently applied in an evaluation, the results can be quantified and conclusions drawn regarding the likely impacts of preemption control and different transition strategies.

The literature review did not identify any research documenting the influence or impact on traffic flow resulting from a responding emergency vehicle using flashing beacons or sirens. This information would provide the basis for developing the car-following logic, driver behavior, and vehicle interaction between these vehicles. In some extreme situations, emergency vehicles may violate a signal indication or perform an illegal vehicle movement to clear a queue of vehicles on an approach to or through an intersection in order to improve their response time. For the purposes of this research, the stated assumption is the preempting vehicle to be analyzed will not perform these maneuvers.

Urbanik and Venglar (1995) developed the “hardware-in-the-loop” simulation tool, integrating the real-time operation and exchange of data between a traffic signal controller and a microscopic traffic simulation model. This tool allows for stochastic travel conditions, coordinated traffic signal operation, traffic control functions, control algorithms, preemption control, and transition strategies to be replicated and their performance quantified. One limitation of this tool is the need for each traffic controller being analyzed to be configured and interfaced with a personal computer containing the microscopic simulation model in a laboratory or shop environment. The “hardware-in-the-loop” simulation tool is presented in Figure 4.

Bullock and Catarella (1996) applied this same analysis tool in assessing the impacts of preemption control on traffic flow. There have been only a few studies that have used the “hardware-in-the-loop” traffic simulation tool to analyze either traffic signal priority or preemption control. One limitation associated with this tool is the need for a lab or shop environment to accommodate this configuration. The “hardware-in-the-loop” simulation tool provided the ability to simulate and analyze the use of transition strategies with the preemption of coordinated traffic signal timing plans.

The commonly available transition strategies were integrated into, validated, and evaluated using CORSIM (Shelby, et al., 2006). Making these enhancements to CORSIM (TSIS 5.2, fall of 2005) makes it possible to select and simulate different strategies to transition between coordinated signal timing plans and to exit preemption control and transition to coordinated operation. The VISSIM microscopic traffic simulation model (release 3.7) was also upgraded in 2005 to provide the ability to use either the best way or hold traffic signal transition strategies (PTV America, 2007).

The development and use of the “software-in-the-loop” simulation tool eliminates the physical need for an actual traffic signal controller to be employed for each signalized intersection to be analyzed, allowing the desired analysis to be performed on a personal computer. This tool has been successfully applied by using the VISSIM microscopic simulation model and Siemens NextPhase Suitcase Tester signal controller software Gardner, 2000). The "software-in-the-loop" simulation tool is presented in Figure 5.

Louisell (2003) developed a method to evaluate the potential safety benefits of preemption control based on conflict analysis. This research also developed an algorithm for potential use in traffic simulation models, incorporating the impacts of automobile driver behavior into the determination of the travel time savings for emergency vehicles operating on roadways with traffic signals. These methods address the current gaps in traffic simulation models, which do not consider unique driver behaviors observed when emergency vehicles are present and operating with lights or a siren.

2.8 Summary

A review of published literature identified a limited number of studies that have evaluated the impacts of different types of vehicles preempting the normal operation of traffic signals. Similarly, there have only been a few studies that evaluated the impacts of using different traffic signal transition strategies to exit from preemption control and return to the coordinated operation of the normal signal timing plan. As a result, little is known about which strategy is the most effective to exit from preemption control and transition to the coordinated operation of the normal signal timing plan.

Only limited technical guidance, recommended practices, or analysis tools are available to transportation professionals to use in developing signal timing plans, evaluating the impacts of preemption control, and assessing the effectiveness of using different strategies to exit preemption control and transition back to coordinated operation of a traffic signal. The majority of available research on preemption control is associated with railroad crossings of highway facilities. The limited research available on traffic signal preemption focused on evaluating the impacts of isolated intersections, assessing the effectiveness of different priority control strategies in support of transit vehicles, using microscopic traffic simulation models, and the "hardware-in-the-loop" simulation tool in performing this analysis.

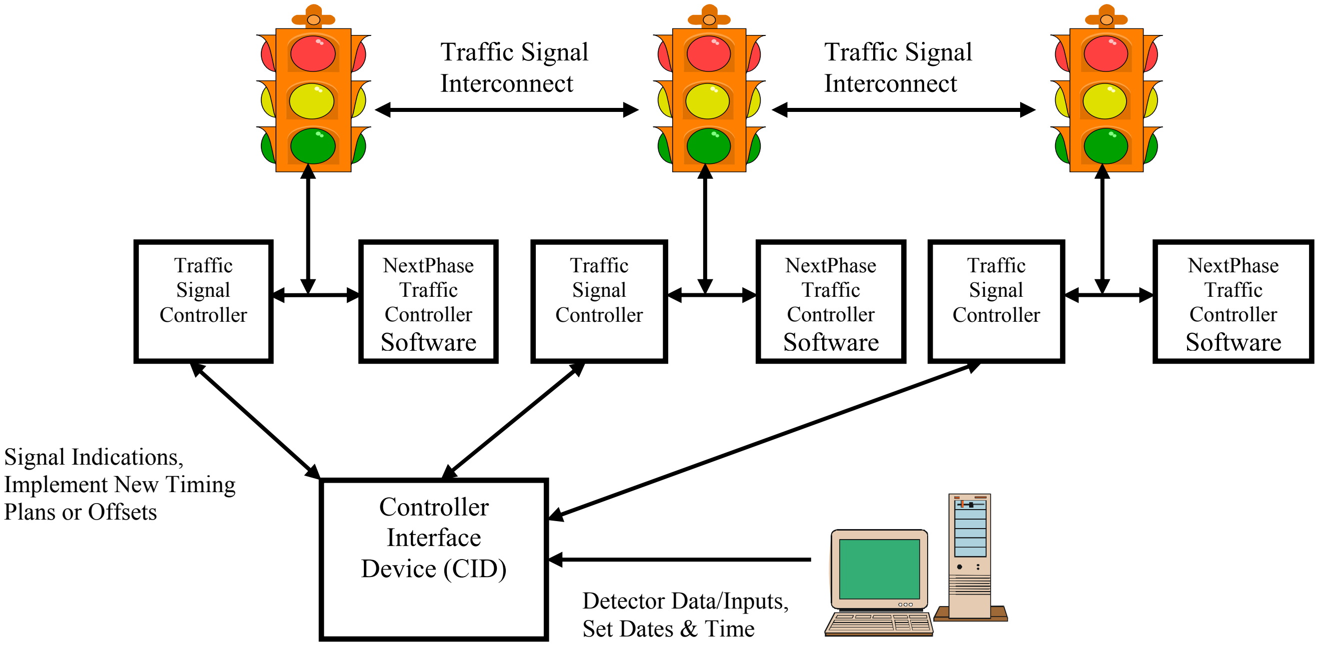


Figure 4. "Hardware-in-the-loop" Traffic Simulation Tool (Urbanik, et al., 1995)

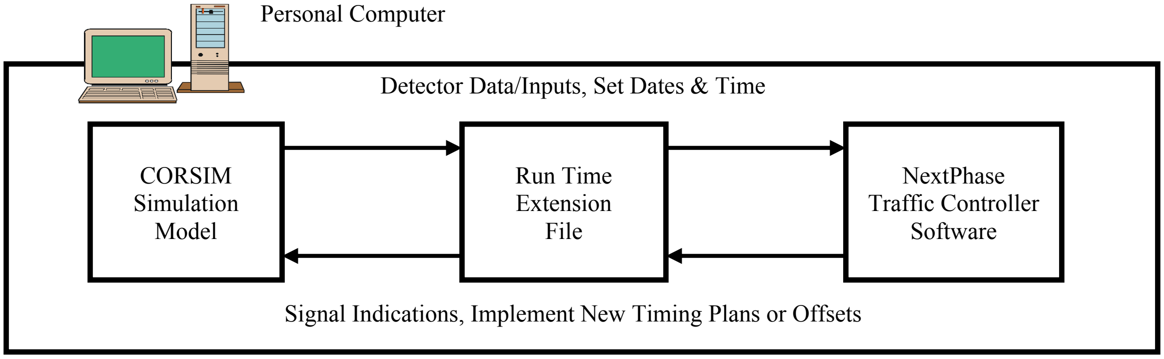


Figure 5. "Software-in-the-loop" Traffic Simulation Tool

This literature review did not identify any studies from the 1990s that evaluated the actual impacts of preemption control or any exit transition strategies. This is important because the standards requiring internal preemption control and exit transition strategies in traffic signal controllers and associated software were first developed in 1992 (NEMA, 1998). As a result, prior research would not have evaluated the capabilities of the traffic signal controllers that are currently available and being used in practice.

The development of the "software-in-the-loop" simulation tool allows for the analysis of preemption control and different traffic signal transition strategies to be performed entirely on a personal computer. Accordingly, it is no longer necessary for a personal computer to be configured, in a laboratory or shop environment, with actual traffic signal controllers for each intersection needing to be evaluated. Prior to the availability of the "software-in-the-loop" simulation tool that was utilized in this dissertation, the literature review identified only one other study where this tool was used to assess preemption control using the actual software of a traffic signal controller (e.g., NEMA 170s).

The literature review did not identify any documented information on the safety implications of the various transition strategies available to exit preemption control. The research performed by Louisell (2003) was the only study identified that addressed any safety implications associated with using preemption control at traffic signals. This research developed a method based on conflict analysis to assess the safety implications of preemption control.

Some authors have suggested that preemption control may improve the safety of emergency vehicles responding with an emergency beacon or siren. However, it is important to note preemption control should not be presented in such a way that it provides emergency vehicle operators with a false sense of security or suggests vehicle operators do not need to obey traffic signals. Nor should preemption control provide emergency vehicle operators with a false sense of safety in operating their vehicles, as discussed in a position paper concerning the use of warning lights and emergency response and patient transport, jointly authored by the National Association on Emergency Medical Services Physicians (NAEMSP) and National Association of State Emergency Medical Services Directors (NASEMSD) (1994).

CHAPTER 3: RESEARCH EVALUATION METHODOLOGY

This chapter presents the research evaluation methodology that was developed and followed in conducting this research. This methodology provides the ability to evaluate and analyze the performance of different traffic signal strategies to exit from preemption control and transition back to the coordinated operation of the normal traffic signal timing plan. This evaluation methodology includes the problem statement, the evaluation plan, alternatives analyzed, the "software-in-the-loop" simulation tool, and the analysis conducted. Following the overview, the remaining sections of this chapter include: 1) problem statement, 2) evaluation of alternatives, 3) alternative traffic signal transition strategies, 4) "software-in-the-loop" simulation tool, and 5) test network description.

3.1 Overview

The purpose of this research is to assess the effectiveness of the commonly available traffic signal transition strategies which are being used in practice to exit from a preemption control plan and transition back to the coordinated operation of the normal signal timing plan. Unique and innovative aspects of this research involved developing the evaluation methodology and analysis tool known as the "software-in-the-loop" traffic simulation tool. The central premise of this research relied on the development and successfully application of this evaluation methodology and enhanced traffic simulation analysis tool to conduct the evaluation performed in this research. The two primary objectives of this research are to:

1. Assess the performance of commonly available traffic signal strategies in exiting from preemption control and transitioning to coordinated operation of the normal signal timing plan; and
2. Quantify the influence increases in traffic volumes may have on the effectiveness pf these strategies in performing this transition.

The evaluation methodology was developed to ensure the analysis conducted would provide the results necessary to validate the central premise, hypotheses and objectives of this research. The "software-in-the-loop" simulation tool was successfully developed as a part of this methodology, providing the capability to simulate and quantify the impacts of preempting the operation of a traffic signal and using different strategies to transition back to the coordinated operation of the normal signal timing plan.

3.2 Problem Statement

This dissertation addresses the need to assess the efficacy and impacts of different strategies available to practitioners to exit from a preemption control plan and transition back to the coordinated operation of the normal signal timing plan. An analysis tool is also needed to provide the ability to perform this analysis directly on a personal computer. This capability will provide the capability to simulate, evaluate, and quantify the potential impacts on traffic resulting from using these different transition strategies.

Agencies have implemented and are operating traffic signals that employ emergency vehicle preemption control throughout the United States. The ITS Joint Program Office inventory of deployed ITS in 2005 indicated that emergency vehicle preemption control was deployed at 20% of the traffic signals in the top 78 metropolitan areas. Preempting the operation of a traffic signal will unconditionally interrupt the normal timing plan by inserting a special plan or phase to accommodate requests for special service received from authorized vehicles. Enabling vehicles to preempt the normal operation of traffic signals has the potential to improve the safety and efficiency of the requesting vehicles, which may be as fire, emergency medical and transit vehicles (FHWA, 2006).

A review of current practice indicates there is limited information available identifying the benefits or impacts of preemption control or of using various traffic signal strategies to exit from preemption control and return to the coordinated operation of the traffic signal. Preempting the operation of a traffic signal and its signal timing plan may also impact the safety, efficiency, and trip reliability of all other vehicles approaching and traveling through this traffic signal. When the preempted signal is located within a coordinated traffic signal system, the potential exists to disrupt the flow of traffic at the preempted traffic signal and other traffic signals within the system. Upon exiting preemption control, to maintain coordinated operation with adjacent traffic signals, the signal's transition strategies are used to perform the necessary adjustments to reach the offset or coordination point in the normal signal timing plan (Obenberger, et al., 2001).

Few studies have evaluated the impacts of preempting the operation of traffic signals. Even fewer studies have evaluated the impacts of using various traffic signal transition strategies to exit from a preemption control plan and return to the coordinated operation of the normal signal timing plan. As a result, little is known about which strategy is the most effective in performing this transition. Neither national standards nor recommended practices currently specify which strategy may be most appropriate to utilize with different types of control (e.g., pre-timed, actuated), factors (e.g., volumes, speeds), and conditions (e.g., uncongested, congested) specific to each intersection or series of coordinated traffic signals.

Previous research has been limited to several microscopic simulation models that have been enhanced to simulate the basic functions associated with traffic signal priority and preemption control. These models are limited, however, by their inability to quantify the potential operational impacts of these strategies on the coordinated signal timing plans. These strategies typically require changes in the signal timing plan involving different cycle lengths or offsets to maintain coordination between traffic signals.

The "hardware-in-the-loop" simulation tool provides the ability to perform this analysis, but requires a laboratory or shop environment to physically accommodate each traffic signal that is being evaluated. Recently FHWA has enhanced CORSIM (TSIS 5.2, fall of 2005) to allow for a variety of different preemption exit strategies currently supported by various traffic controller manufacturers to simulate and analyze their respective transitions between coordinated signal timing plans (Shelby, et al., 2006). These changes were incorporated into CORSIM after the "software-in-the-loop" simulation tool was developed and the simulated runs completed for this research.

With the recent enhancements to CORSIM, an option now exists to perform this desired analysis on a personal computer, in addition to the "software-in-the-loop" simulation tool as developed in this research. It is important to note there are many other microscopic simulation models being used in practice which do not have the capabilities to evaluate priority and preemption control within coordinated signal systems. Over time, the transition strategies that are supported in various traffic controllers will also change from what CORSIM currently supports. As a result, this analysis tool is still needed, providing an option to perform this analysis, eliminating the obstacle of having to use either the CORSIM model or the "hardware-in-the-loop" simulation tool.

3.3 Evaluation Plan

The purpose of the evaluation plan, as a part of the overall research methodology, is to ensure that the analysis performed is able to provide the results necessary to validate the central premise, hypotheses, and objectives of this dissertation. It provides the framework or structure for ensuring the results of the analysis to be performed map to the overall research objectives, more specific evaluation objectives, performance measures, and supporting data. The simulation plan and analysis performed are presented in further detail in Chapter 4. The following elements of this evaluation plan maps the research objectives to each of the supporting evaluation objectives and associated data elements:

Research Hypothesis 1: Motorists will realize benefits from traffic signal transition strategies minimizing the negative impacts associated with exiting from a preemption control plan and transitioning to the coordinated operation of the normal traffic signal timing plan.

Research Objective 1: To assess the performance of commonly available traffic signal transition strategies in exiting from preemption control and transitioning to the coordinated operation of the normal signal timing plan.

Evaluation Objective 1: To identify the most effective transition strategy that minimizes the negative impacts on traffic flow based on a shorter time being required to perform this transition.

Performance Measures (Data Elements):

-Average vehicle delay (Seconds per vehicle) of all vehicles; and

-Average vehicle travel time (Seconds per vehicle) of all vehicles.

Hypothesis 2: Motorists will realize benefits from the selection of the most effective transition strategy, which will minimize negative impacts resulting from changing or varying levels of traffic volume.

Research Objective 2. To quantify the influence increases in traffic volume may have on the effectiveness of these strategies in performing this transition.

Evaluation Objective 2: To identify the most effective transition strategy that minimizes the negative impacts on traffic flow based on a shorter time being required to perform this transition for different levels of traffic volume.

Performance Measures (Data Elements):

-Average delay (Seconds per vehicle) of all vehicles; and
-Average travel time (Seconds per vehicle) of all vehicles.

The above-mentioned performance measures were selected because: 1) they are commonly used to represent traffic flow performance in a manner that is consistent with the traffic flow theory and fundamentals presented in Section 2.7, and 2) the CORSIM model is able to generate these measures. Other potential performance measures that could be used to assess these evaluation objectives include: stops (e.g., number or percentage per travel direction), travel time reliability, speed, vehicle emissions, queue length, and time to transition to coordinated operation. However, several of these measures cannot be generated by CORSIM or the NextPhase Suitcase Tester.

For example, the total number of vehicle stops and stops generated per direction of travel along Columbia Pike were not able to be used due to a problem encountered with the accuracy of the data generated when using the CORSIM software. An attempt was also made to quantify the time required to exit from a preemption control plan and transition to the coordinated operation of the normal signal timing plan. However, the NextPhase Suitcase Tester provides only a visual confirmation on an LCD screen, which appears on the personal computer replicating the screen of an actual NextPhase traffic controller, that the coordinated operation of the signal was established.

The NextPhase Suitcase Tester does not generate an electronic output confirming or indicating when the signal timing plan has returned to coordinated operation. As a result, the RTE file developed for this project was not able to receive the necessary information electronically from the NextPhase Suitcase Tester, to allow CORSIM to identify when the traffic signals completed the transition to coordinated operation.

3.4 Alternative Traffic Signal Transition Strategies

In the assessment presented in Chapter 2 (Literature Review), five commonly available and utilized traffic signal transition strategies were identified. These strategies follow different processes resulting in different lengths of time required to transition to the coordination or offset point in the desired signal timing plan being implemented. The transition strategies available in the NextPhase Suitcase Tester include the hold, max dwell, long, short, and best way strategies (Gardner, 2000).

For the purposes of this research, the transition strategies available in NextPhase that were evaluated as alternatives included the hold, long, short, and best way. The maximum dwell strategy was not selected as an alternative to be analyzed in this research. This was based on its transition process being similar to the hold strategy, along with the variable component of the transition process it follows, which is the time established for the maximum dwell. None of the other strategies have this variable component influencing the process that they follow. The max dwell strategy rests in the coordination phase for a predetermined maximum time until it either reaches coordination or continues cycling through the remaining phases, with the process repeating itself until it reaches the coordination phase.

Several aspects of a signal timing plan or control parameters will influence the amount of time that is required to exit from one signal timing plan and transition to the coordinated operation of the desired plan being implemented. As previously described in Chapter 2 (Literature Review), these aspects and control parameters may include: length of cycle, number and length of signal plan phases, amount of green time beyond the minimum established for each phase, phase to serve first when transitioning, and minimum and maximum phase lengths. For the purposes of this research methodology and the traffic simulation runs to be performed, these aspects and parameters will remain the same for all of the alternatives evaluated.

The return phase identified to be served first upon completing or exiting from the preemption control plan, was selected as the major movement of traffic along the eastbound and westbound direction of travel in the test network. Minimum and maximum phases and overall signal timing plan's cycle length were established to accommodate these different transition strategies. The minimum phase lengths corresponded with the time required by a pedestrian to cross each intersection. The maximum phase length of 105 seconds was established to accommodate the major movement of traffic in the eastbound and westbound directions. This resulted in a minimum cycle length of 55 seconds and a maximum cycle length of 105 seconds.

3.5 "Software-in-the-Loop" Simulation Tool

The "software-in-the-loop" simulation tool has been successfully applied in simulating and analyzing the operation of traffic signals, control strategies, and various operational scenarios and plans. The advantage of this tool is that the desired analysis can be performed on a personal computer, eliminating the need for an actual traffic signal controller and its software to be configured. For the application being evaluated in this research, this tool will require the software from a traffic signal controller to be integrated and operating with a microscopic traffic simulation model.

The application developed in this research consisted of the Gardner NextPhase traffic signal control software (Suitcase Tester, version 1.4B) and the CORSIM (TSIS 5.2 beta version) microscopic traffic simulation model. The Suitcase Tester is the research version that has been modified to operate on a personal computer, as opposed to the NextPhase software that operates in a traffic controller. Gardner Transportation Systems, Inc. furnished a copy of the Suitcase Tester to be used in completing this research.

Zhang, Ghaman, and Juan (2002) demonstrated that CORSIM has the ability to support interfaces with external files or software applications. The CORSIM (FHWA, 2003) and NextPhase (Gardner, 2000) Manuals were used in developing and validating the RTE file operation. The primary information generated from NextPhase and transferred to CORSIM consisted of commands involved with changing the operation of the traffic signal timing plan, implementing new plans, coordinating the operation of the signal timing plans, and changing operation of signal timing plans and status of traffic signal displays at each intersection. CORSIM generated and transmitted to NextPhase the vehicle detector inputs on the test network which were used as inputs in operating the signal timing and preemption control plans.

The RTE developed in this research facilitates the electronic sharing of data between CORSIM and the NextPhase Suitcase Tester. The RTE consists of an electronic file (C++) containing the logic and protocol to facilitate the exchange and conversion of data into the proper formats with an assigned time reference, allowing it to be recognized and used by CORSIM and the NextPhase Suitcase Tester. The RTE file that was used in this research is located in Appendix E. This electronic data exchange included traffic signal indications, signal timing offsets, implementation of new timing plans, detector inputs (e.g., activation), dates, and times.

CORSIM, the NextPhase Suitcase Tester and RTE were successfully installed on a personal computer, their operation successfully tested, and traffic simulation runs conducted for this research. This “software-in-the-loop” simulation tool was used to evaluate the performance of different transition strategies to exit from preemption control and transition to the coordinated operation of the normal signal timing plan.

3.6 Description of Test Network

In order to perform the traffic simulation runs to generate the data identified to be evaluated in this methodology, Columbia Pike in Arlington VA, was selected as the test network for this research. A traffic signal system coordinates the control of traffic along a four-mile segment of the Columbia Pike corridor. Four traffic signals within this signal system were selected based on the presence of coordinated progression of traffic on this network. The Columbia Pike test network and base traffic volumes are presented in Figure 6.

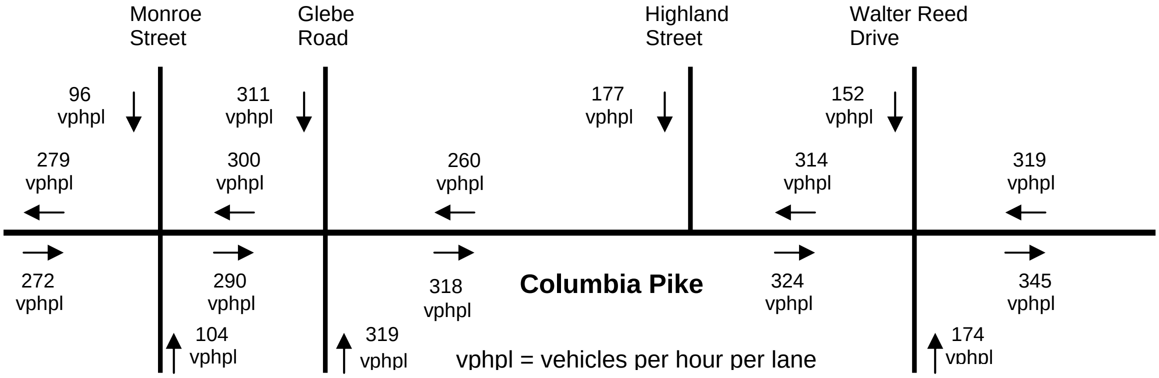


Figure 6. Columbia Pike Test Network

The spacing between the four signalized intersections ranges from 710 to 1095 feet, with the overall test network being 5353 feet (approx. 1 mile) in length, which includes:

- Monroe Street (710' to Glebe Road intersection);
- Glebe Road (1095' to Highland Avenue intersection);
- Highland Street (T-intersection north, 733' to Walter Reed Drive intersection); and
- Walter Reed Drive.

The factors contributing to the selection of these signals as the test network include: traffic signal spacing, progression of traffic between signals, shorter cycle length, limited number of signal phases, and balanced directional flow on Columbia Pike. This network of traffic signals is typical of many urban or suburban arterial roadways where traffic flow is predominantly along the arterial with the operation of traffic signals being coordinated. The progression of traffic between these signals is facilitated by the spacing of these selected intersections, roadway geometry (e.g., turn lanes), uncongested travel conditions, travel speeds maintained between signalized intersections, signal timing plans and coordinated operation of adjacent traffic signals.

The phase in the signal timing plan that contains the coordination or offset point corresponds to the major traffic movements which occur in the eastbound and westbound directions along this test network. The mid-day travel period from 11:00 am to 1:00 pm was selected as the time period to be analyzed. The traffic signal timing plans that were used in developing the simulation model for this test network consisted of a coordinated 75-second fixed cycle length with only two phases. Two lanes of travel exist in each direction of travel along Columbia Pike, with one lane of travel in each direction on the intersecting cross streets, except for two lanes on Glebe Road. Several intersections have dedicated right and left turn lanes. On-street parking is restricted on the test network.

The traffic conditions for this time period, referenced as the base level conditions in this research, can be summarized as uncongested steady state traffic flow with an average speed of 35 miles per hour. Columbia Pike and Glebe Road is the critical intersection in the test network, with relatively balanced traffic volume and equal phase lengths. The traffic simulation model developed for this research was coded and calibrated to replicate these conditions. A summary of the key features of the test network that were included in the coding of the CORSIM model used to perform the simulation runs evaluated for this research are available in Appendix A.

The data for this test network was obtained from a study completed by Virginia Tech, which evaluated the use of transit signal priority along the Columbia Pike corridor in the Washington, D.C. region (Dion, et al., 2001). The roadway, traffic, and traffic signal control data were obtained from the traffic simulation model that was developed and the draft final report of this study. This information and data was used in developing, and validating the CORSIM traffic simulation model for this test network.

The simulation model developed for the test network was calibrated based on a comparison of traffic volumes, average travel speeds, and travel times identified in the draft report of this study. It was determined that the simulation model developed provided a reasonable representation of traffic conditions, and consequently would provide a reasonable basis upon which to perform the simulation runs to generate the data that was evaluated in this dissertation. This determination was based on the comparative analysis performed in this dissertation, which does not require this model to reflect the "ground truth" for the period being evaluated in the test network.

Developing the "software-in-the-loop" simulation model involved verifying that the NextPhase Suitcase Tester and RTE functioned properly with CORSIM. This involved verifying the timing plans functioned properly at each traffic signal; the preempting vehicles were detected at each intersection while traversing the network; and the signal timing plans operated properly upon exiting the preemption control plan. For the NextPhase Suitcase Tester, this validation involved visually verifying for each of the simulation runs that the signal timing plans operated properly at each signalized intersection, as well as the preemption control plan and desired traffic signal transition strategy.

3.7 Evaluation Methodology and "Software-in-the-loop" Simulation Tool

This chapter details the development and application of an innovative evaluation methodology and analytical tool known as the "software-in-the-loop" simulation tool to replicate stochastic characteristics and assess the impacts of preemption control. Specifically, this chapter sets forth how this methodology and "software-in-the-loop" simulation tool can be used to assess the performance of different transition strategies to exit from a preemption control plan and return to the coordinated operation of the normal traffic signal timing plan. The key contributions of this methodology and tool include:

- replicating stochastic characteristics and preemption control impacts on traffic flow;
- replicating and assessing the performance of different traffic signal transition strategies;
- assessing the impacts of varying levels of traffic volume (e.g., 0.40 to 0.60 v/c) on the performance of different traffic signal transition strategies;
- allowing for this simulation tool to be used entirely on a personal computer; and
- providing an enhanced methodology and simulation tool to evaluate traffic control functions and features that are not currently supported by traffic simulation models.

The following is a summary of how this evaluation methodology and simulation tool differs from previously completed research described in Chapter 2.

- McHale (2002) estimated the impacts of preemption control on travel times to be relatively small, ranging from 1.1% to 3.3% travel time increases for a one-hour analysis period, to 0.6% to 1.7% travel time increase for a two-hour period. This research evaluated the impacts of preempting the operation of one uncoordinated traffic signal. The magnitude of these findings is similar in scale to the research results presented in this dissertation. However, due to the methodology used, the results are not directly comparable to the research completed in this dissertation.
- Bullock, et al. (1998), used the "hardware-in-the-loop simulation tool to assess the impacts of preemption control at three coordinated traffic signals. The magnitude of the impacts of preemption control is similar in scale to the research results presented in this dissertation. However, it did not assess transition strategies to exit preemption control and return to coordinated operation.
- Shelby, et al. (2006), evaluated different strategies in transitioning between coordinated traffic signal timing plans. Their research developed the commonly used transition strategies directly into CORSIM to assess these strategies. The magnitude of the performance of the transition strategies tested is similar in scale to the research results presented in this dissertation. However, this study did not address the random nature of when traffic signals were preempted or when transitions occurred between coordinated signals. Further, the methodology utilized in this study did not evaluate other traffic control functions, features, or operational strategies that are not supported in CORSIM.
- Nelson, et al. (2006), assessed preemption control using the "hardware-in-the-loop" simulation tool. The network evaluated consisted of four traffic signals, two of which were at a diamond interchange, with traffic flows and conditions not typical of a suburban arterial roadway. Additionally, their study assessed only the smooth (or best way), add (or long) and dwell (or hold) transition strategies. The magnitude of the impacts of preemption control is similar in scale to the research results presented in this dissertation.

CHAPTER 4: ANALYSIS

This chapter describes the simulation plan and analysis conducted in this research. The traffic simulation model, emergency vehicle preemption control system, simulation plan and runs, data compiled and analysis conducted are described. Following the overview, the remaining sections of this chapter will focus on: 1) preemption control system and scenario; 2) simulation plan and runs; and 3) analysis.

4.1 Overview

The purpose of the simulation plan and runs was to generate the data to be analyzed and evaluated, providing the basis for the conclusions of this research. As presented in Chapter 3, the data compiled and analyzed from the conducted simulation runs involved the average travel time and average delay. The results compiled from these simulation runs are analyzed further in Chapter 5, "Results" of this dissertation.

The traffic simulation runs were conducted using the "software-in-the-loop" simulation tool, rather than through actual field observations, which would have very expensive. Due to experimental design limitations for this research, it was not feasible to perform simulation runs for each possible random event where a vehicle may preempt and disrupt the operation of traffic signals. The time, personnel, and expense associated with compiling that level of detailed data in the test network were also considered to be cost and time prohibitive.

The simulation plan sets forth the approach to that was followed in producing the data required to analyze and draw the conclusions and recommendations required for this research. This plan addresses the number, length and assumptions associated with the simulation runs that were conducted using the simulation model that was developed. These assumptions include: vehicles allowed to preempt traffic signals in the test network, preempting vehicle trip characteristics and performance (e.g., vehicle, driver), and there is a preemption control system. This plan, runs and analysis conducted are presented in the remaining sections of this chapter.

4.2 Preemption Control Scenario and System

The purpose of the preemption control scenario is to describe the key aspects of incorporating preemption control and the requesting vehicle into the "software-in-the-loop" simulation tool that was developed for this research. The preemption control scenario is based on the limitations described in the Literature Review in Chapter 2, i.e., microscopic simulation models have limited ability to simulate vehicles requesting and traffic controllers implementing and exiting from preemption control. The elements of this scenario, for the purposes of this research, consisted of the preempting vehicle, preemption control system and other factors related to the preempting vehicle being incorporated into the developed simulation model for the test network.

Preempting Vehicle:

Current microscopic traffic simulation models are not able to replicate transit or emergency vehicles that may preempt the operation of traffic signals. These models are not able to simulate the operational characteristics (e.g., acceleration, deceleration) and quantify the performance of these vehicles. Further they are unable to simulate or quantify the performance, vehicle-to-vehicle interaction, or influence that vehicles operating with emergency beacons or sirens may have on the behavior and performance of drivers or other vehicles.

Nevertheless, with simplifying assumptions, a microscopic simulation model can be used to simulate and assess the probable impacts of vehicles preempting the operation of coordinated traffic signals. These assumptions apply to the preempting vehicle, as well as other vehicles, traveling at the posted speed limit or prevailing speed, observing motor vehicle laws and traffic rules, and traveling in the normal progression or flow of traffic between traffic signals. If these assumptions are consistently applied in the analysis and evaluation, results can be quantified and conclusions drawn regarding the likely impacts of preemption control and the performance of different transition strategies.

CORSIM does not have the ability to allow the user to select from a range of vehicle types (e.g., fire, light rail) with the operational characteristics (e.g., acceleration, deceleration) that typically issue requests to preempt the operation of traffic signals. The transit vehicle is assumed to have different acceleration and deceleration capabilities than a fire or emergency medical vehicle. However, a transit bus is the closest vehicle available to select from in CORSIM, in comparison to fire trucks or light rail vehicles, which are typically allowed to preempt the operation of traffic signals. Accordingly, a transit bus was selected as the vehicle to generate requests to preempt traffic signals in the simulation runs that were performed. The following assumptions were made concerning how this vehicle issued preemption requests:

- only one preemption request was issued for each simulation run;
- the requesting traveled westbound in the test network;
- the requesting vehicle traveled through each signal in the network; and
- the trip purpose did not allow for any scheduled stops traveling through the network.

In developing the simulation model for the test network, the following additional assumptions were made about the operation of the vehicle that issued requests to preempt the operation of the traffic signals in the simulation runs.

- The preempting vehicle will be either an express-route transit vehicle or emergency vehicle. An express-route transit vehicle typically has a limited number of scheduled stops to board and discharge passengers. For the purposes of the analysis being performed, it is assumed the preempting vehicle will not stop within the network being analyzed.
- The preempting vehicle will not be operating with a flashing beacon or siren. The operation of this vehicle will also not affect other vehicles on its approach to or through signalized intersections. As a result, other vehicles will not pull over to allow the preempting vehicle to pass if a queue of vehicles is encountered on its approach to and through a specific intersection.

- The preempting vehicle will travel within the normal flow of traffic and observe all motor vehicle laws and traffic laws consistent with CORSIM car-following logic.

The path and trip characteristics of the requesting vehicle were coded in the CORSIM simulation model to comply with these assumptions. Scheduled or unscheduled stops to board and alight passengers were not programmed for this vehicle in this model. The path of this vehicle was determined based on the “Path Following” feature in CORSIM. This required establishing a uniquely formatted “path” file that identified the specific order of the nodes in which this vehicle would travel. A corresponding vehicle data file (VEHICLE.DAT) was also required, which specified the type of vehicle and when it would be released into the test network and what path (see PATH.DAT file) it would follow during the simulation run. These two types of files each required a specific name that corresponded to the specific number of the multiple runs that were performed for each alternative being evaluated.

Preemption Control System:

The simulation model that was developed for the test network assumed the signal system had the capability to detect and process preemption requests at each traffic signal within the test network. This assumed the necessary technologies were available in the roadway, in the preempting vehicle, in the traffic signal, as well as in the traffic controller. The components of this assumed preemption control system included:

- emitter (transmitter) on vehicle requesting preemption control;
- detectors (receiver and or loops) at intersection and/or roadside;
- traffic signal controller; and
- traffic signals.

Replicating a preemption control system in the CORSIM model involved coding the system assuming it relied on point-to-point detection. A loop detector was coded in advance of each traffic signal to detect the preemption vehicle and issue a command allowing the preempt command to be sent and processed by the traffic signal controller. Additionally, a loop detector was coded on the far side of each traffic signal in the westbound direction. This check-out detector verified that the preempting vehicle cleared the intersection, allowing the preemption control plan to be terminated and beginning the process to transition back to the coordinated operation of the traffic signal.

Preemption Scenario:

In developing the simulation model, the following additional assumptions were made governing how the preempting vehicle traverses through the test network, how it issues a preemption request, and how the traffic signal controller processes preemption requests.

- Only one vehicle was be allowed to preempt the operation of each traffic signal in the network during each simulation run.
- The preempting vehicle was traveling only in the westbound (WB) direction.
- Pedestrians and pedestrian phases were assumed not to exist or influence the operation of the traffic signals or the strategies used to transition from preemption control to coordinated operation of the traffic signals.
- Major movement (EB-WB through) on Columbia Pike was specified as the phase to return to after exiting from a preemption control plan.

4.3 Simulation Plan and Runs

The purpose of the simulation plan was to identify and perform the series of traffic simulation runs which provided the data which was analyzed and evaluated in this research. The simulation runs performed used the CORSIM simulation model developed for the previously described test network. These runs utilized the “software-in-the-loop” simulation tool, which consists of the CORSIM model along with the NextPhase Suitcase Tester traffic signal controller software. This simulation plan addressed the following:

- arrival of preempting vehicle during the cycle length of traffic signal timing plan;
- number of simulation runs and required sample size per alternative;
- length of traffic simulation runs and time period; and
- simulation scenarios and evaluation performed.

4.3.1 Arrival of Preempting Vehicle

One of the critical factors influencing the results of the simulation runs was the uncertainty associated with the arrival of the vehicle issuing a request to preempt the operation of a traffic signal. When this vehicle approached the signalized intersection and where the traffic signal timing plan was in its cycle length would determine whether a special preemption control plan needed to be implemented. The time required to implement and exit from a preemption control plan depends on when the preempting vehicle issues the request, its proximity to the intersection, its approach speed, and where in the cycle length the signal timing plan may be in its operation.

The potential impact of preempting the normal operation of a traffic signal timing plan is a function of a large number of characteristics and factors. Some of the key characteristics and factors include the current traffic conditions, where in the cycle length this plan is when the request is received, the vehicle's proximity to the intersection, and the time required to return to the coordinated operation of the original signal timing plan after the preemption control plan is terminated. The time to return to the coordination or offset point in the simulation runs that were performed depended on when in the signal phase the preemption request was received, when the preemption control plan was terminated, which strategy was used to perform this transition, and the signal timing plan.

The primary factors influencing the length of time required to perform this transition included the uncertainty of when a preemption request is received, when the plan is implemented and terminated, and which strategy is used to perform this transition. Depending on these factors, the traffic controller may determine that preempting the existing signal timing plan is not needed. The controller will make this decision by evaluating the time required to implement the preemption plan, where the existing timing plan would be when the requesting vehicle would arrive at the signal, and whether the phase currently being served could be extended. The corresponding time to implement a preemption control plan will depend on when the preempting vehicle's request is received in the cycle length, the vehicle's location and approach speed, the type of detection (e.g., point, continuous), the traffic conditions, and any other factors (e.g., pedestrian phases and clearance time) influencing the operation of the signal timing plan.

CORSIM currently does not have the ability to automatically perform a large number of traffic simulation runs (batch runs). When the ability exists to automatically perform a large number of simulation runs, the arrival of the preempting vehicle in the network during cycle length of the traffic signal timing plan will be analyzed once per second over the entire cycle length. Completing these simulation runs every second would account for all possible options for when the preempting vehicle may issue a preemption request within the cycle of the traffic signal timing plan.

Based on an equal probability that a vehicle may issue a preemption request at any time during the cycle of a traffic signal plan, the simulation runs for each alternative needed to replicate this stochastic nature, of when the preempting vehicle may arrive at a traffic signal. Because the capability to perform batch runs in CORSIM did not exist, it was not feasible to perform a simulation run with the vehicle issuing a preemption request at each second during the traffic signal timing plan to quantify this stochastic arrival. The stochastic nature of when a vehicle may issue a preemption request was taken into account by representative runs being performed with the preempting vehicle being released into the simulation run at successive 15-second increments (e.g., 0, 15, 30, 45 and 60 seconds) during the 75 second cycle length for the signal timing plan.

The intervals that were selected and simulation runs conducted will also assist in understanding the impacts of the stochastic nature of when a preemption control request may be initiated during a traffic signal timing plan. A series of 5 different simulation runs, with the results of these runs averaged to develop one value representing the conditions expected for each alternative to be analyzed. The results for each simulation run were averaged to arrive at the performance of each of the alternative transition strategies and three volume alternatives (base, 20% increase in base volume, and 40% increase in base volume) being evaluated in this research.

4.3.2 Sample Size

In order to replicate the stochastic nature of traffic flow and driver behavior using CORSIM, multiple runs were performed for each transition strategy with each volume alternative. To accomplish this, the random number generator in CORSIM generated a different random number seed, which was used for each run performed. The algorithms (e.g., car following, driver behavior) and computational processes in CORSIM rely on random numbers and probability distributions to perform each simulation run.

The number of simulation runs that were determined appropriate for each alternative being analyzed in this research was based on a statistical calculation of the desired sample size that would provide no more than the maximum level of allowable error. The t-distribution formula presented in Equation 6 was used to determine the desired sample size for each simulation run performed to ensure its results corresponded with a 90% level of confidence (ITE, 1999). This formula, which is recommended for sample sizes of typically less than 30 random samples, was used to calculate the sample error (error of the mean) for the simulation runs that were performed for each alternative, ensuring the error of the mean was less than 0.10 (i.e., 10% level of significance or 90% level of confidence).

Equation 6. T-distribution Formula – Sample Size Calculation

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

where:

N = required sample size

t = value of t distribution

σ^2 = sample variance

E = sample error

An iterative process was followed to determine the number of simulation runs which produced the desired sample error of less than 0.10 for each performance measure (average travel time and average delay) being evaluated. Based on the results of the initial simulation runs performed, it was determined that up to 13 runs needed to be performed for each simulation using a different random number seed, to ensure a sample error of less than 0.10. The error of the mean was calculated using the t-test, to ensure that the results contained an error of the mean of less than 0.10 (i.e., 10% level of significance or 90% level of confidence), using the average and standard deviations CORSIM generated for the average delay and average travel times in each simulation run. The results of the runs are available in Appendix B.

4.3.3 Number of Simulation Runs

Simulation runs were performed to analyze the performance of each alternative strategy to exit from preemption control and return to the coordinated operation of the original traffic signal timing plan under varying levels of increasing levels of traffic volume. These alternatives were first analyzed using the traffic volumes existing for the mid-day travel period in the test network, which was considered the “base” traffic volume alternative. Two additional alternatives were analyzed consisting of a 20% and 40% increase to the base traffic volume condition.

In summary, thirteen simulation runs were completed for four different transition strategy alternatives that were analyzed at three different levels of traffic volume in the test network: base level; a 20% increase in traffic volume; and a 40% increase in traffic volume. For each alternative analyzed with each of the three levels of traffic volume, a series of five different simulation runs were performed to represent the stochastic nature of when the preempting vehicle may arrive within the cycle length of a traffic signal timing plan. A summary of the simulation plan and 780 individual simulation runs that were performed to quantify and assess the impacts of the alternative transition strategies for each level of traffic volume evaluated is shown in Table 1. The results for each unique simulation run, verification of statistically valid sample size and averaging of the results for each transition strategy and volume alternative are available in Appendix B.

4.3.4 Length of Simulation Runs

Due to the unsaturated traffic conditions and length of the test network, the impacts of the strategies tested were assumed to be limited to the time period associated with exiting from preemption control and transitioning to the coordinated operation of the normal signal timing plan. The vehicles entering or clearing the network were not expected to encounter any residual effects from either the preemption control plan being implemented or the time required to return to coordinated operation of the traffic signal timing plans. The vehicles entering the test network after coordinated operation was obtained were expected to encounter normal conditions without any adverse delays or further disruption to the progression of traffic between signals.

Table 1. Simulation Plan Summary

Alternative Evaluated	**Simulation Runs**	**Number of Alternatives**
Transition strategies	Hold, long, short & best way	4
Traffic volume & increases (%)	Base, base + 20%, & base + 40%	3
Entry of preempting vehicle into network in 75-second cycle	0, 15, 30, 45 & 60 seconds	5
Multiple runs to obtain desired sample size	13 runs with different random number seed	13
	Total # of Runs:	**780**

The transition to the coordinated operation of traffic signals was expected to require only one to three cycles after each traffic signal exited from the preemption control plan, depending on the strategies being tested and when this preemption occurred during the cycle of the signal timing plan. Due to the relatively limited amount of time required to transition from preemption control to the coordinated operation of the signal, the impacts of each strategy were expected to occur over this time period. This assumption was verified based on visual observations of the simulation runs, which indicated the effects of preemption control did not perpetuate indefinitely. The simulation runs performed accommodated several additional cycle lengths to capture any residual effects these strategies may have had on traffic flow. Three cycle lengths provided more than enough time for any vehicle entering the network, while the signal timing plans were still completing their transition to coordinated operation, to complete its trip through the entire test network.

The length of each simulation run was determined to be 10 minutes, which allowed for eight cycles of the signal timing plan to be completed. One complete cycle of the signal timing plan was completed prior to releasing the preempting vehicle into the simulation run. A five-minute initialization period was also performed to allow equilibrium to be reached in CORSIM prior to initiating each simulation run. This number of cycles provided ample time for the preempting vehicle to travel through the network (less than two cycles), each signal timing plan to transition to the desired coordination or offset point (less than three cycles), and for other vehicles that were in the network when coordinated operation of these signal timing plans was reached (less than two cycles) to complete their trip.

The duration of these simulation runs allowed for the performance data to be collected for a minimum of approximately three cycles after transitioning to coordinated operation. The long and short transition strategies were expected to take the longest amount of time to return to the desired coordination point in the signal timing plan. The short strategy reduced each phase from 7 to 13 seconds, by using the minimum green established for each phase, instead of the actual green times established for each phase. This assessment was based on the amount of time each cycle could be reduced when considering the percentage of the reduction in the cycle length, length of green interval and minimum green time for each phase in the signal timing plan for each signal.

The short strategy would complete this transition within one to three cycles based on the amount of time each phase could be reduced, in addition to when the transition began in the cycle length. The long transition strategy expanded the cycle length of the traffic signal timing plan based on the maximum times established for each phase. The maximum green times for the phases corresponding to the major eastbound and westbound movements were extended from 25 to 30 seconds.

The phases corresponding to the minor or cross street traffic along the network were extended up to five seconds. The long strategy was calculated to complete this transition within one or two cycles. The extension of these maximum phase lengths was determined by placing a priority on the large number of trips occurring along the major movement in the test network where maintaining traffic progression is a priority.

4.4 Analysis

This section presents the analysis conducted using the data generated from the traffic simulation runs performed in this research. Specifically, the data compiled for this analysis provided the basis for the results of this research to be quantified and consequently for conclusions to be drawn. Additional analysis and presentation of these results will follow in Chapter 5, which details conclusions regarding the most effective transition strategies for each of the different levels of traffic volume.

4.4.1. Traffic Volume Alternatives Analyzed

An assessment of the conditions within the test network associated with all three different levels of traffic volume alternatives evaluated revealed relatively uncongested traffic flow conditions. The Columbia Pike and Glebe Road intersection was identified as the critical intersection in the test network, with relatively balanced traffic volume on all approaches and a signal timing plan with equal phase lengths. The volume to capacity ratio (v/c) was calculated to describe the general traffic conditions at this intersection and along the test network. The v/c ratio at this intersection for the base level of traffic volume was estimated to be 0.4 using the formula presented in Equation 7, from the HCM (TRB, 2000).

Equation 7. v/c Ratio

$v/c = v / (s * (g/C))$

Where: v/c = ratio for lane
v = traffic volume for lane group
s = saturation flow rate for lane group
g = effective green time for lane group
C = cycle length of signal timing plan

The v/c ratio for this intersection was calculated based utilizing the traffic volumes on the approach to the intersection with the highest ratio based on the conditions specific to that lane grouping. A review of the traffic volumes identified the eastbound through movement as the most critical movement at this intersection, and for the test network as a whole. The capacity of this approach was based on the effective green time (33 seconds), cycle length (75 seconds), and an assumed saturation flow rate at this intersection of 1,700 vehicles per hour per lane. The actual average traffic volume on this approach is 290 vehicles per hour per lane (see Section 3.6).

As the base level of traffic volume was incrementally increased in this research by 20% and 40%, the traffic flow conditions within the network changed at a similar rate. The v/c ratios representing the traffic conditions in the test network also increased from 0.4 to 0.5, and from 0.5 to 0.6 respectively. Additional increases beyond those analyzed in this research, could provide the basis for further research to assess the performance of the transition strategies when they are used in an unstable or congested flow regime.

If the traffic volumes had been increased beyond the levels addressed in this research, it would have been appropriate to reassess the viability of the signal timing plans at each intersection, along with the corresponding offsets associated with maintaining traffic flow between each signal. These signal timing plans and how they are coordinated need to be revised as traffic volume and congested traffic conditions change, to ensure the most effective timing plan is being utilized for applicable conditions. Due to resource limitations, it was not possible for this research to assess the impacts of subsequent incremental increases in traffic volume.

4.4.2. Simulation Runs and Analysis Conducted

The analysis performed with the CORSIM model made it possible to quantify the performance of the alternative transition strategies for each level of traffic volume that was evaluated. This analysis quantified the performance of the test network in terms of average travel delay and average travel time, as specified in the evaluation and simulation plans, allowing for the influence of each transition strategy to be determined. The results of the simulation runs performed were compiled, evaluated, and summarized. The format that was followed to compile and summarize the results of each simulation run and analysis that was performed in terms of each performance measure (average travel time and average delay) is summarized in Table 2. The results compiled for each simulation run that followed this format are located in Appendix B.

Table 2. Simulation Runs and Analysis Conducted

Alternative	**Hold**	**Long**	**Short**	**Best Way**
Preempting Vehicle (PV) Entry Time	0 15 30 45 60	0 15 30 45 60	0 15 30 45 60	0 15 30 45 60
Traffic Volume Increase (%)	Base, base +20%, & base +40%	Base, base +20%, & base +40%	Base, base +20%, & base +40%	Base, base +20%, & base +40%
Random Number (different seed selected for each simulation run performed)	1 1 1 1 1 2 2 2 2 2 3 3 3 3 3 4 4 4 4 4 5 5 5 5 5 6 6 6 6 6 7 7 7 7 7 8 8 8 8 8 9 9 9 9 9 10 10 10 10 10 11 11 11 11 11 12 12 12 12 12 13 13 13 13 13	1 1 1 1 1 2 2 2 2 2 3 3 3 3 3 4 4 4 4 4 5 5 5 5 5 6 6 6 6 6 7 7 7 7 7 8 8 8 8 8 9 9 9 9 9 10 10 10 10 10 11 11 11 11 11 12 12 12 12 12 13 13 13 13 13	1 1 1 1 1 2 2 2 2 2 3 3 3 3 3 4 4 4 4 4 5 5 5 5 5 6 6 6 6 6 7 7 7 7 7 8 8 8 8 8 9 9 9 9 9 10 10 10 10 10 11 11 11 11 11 12 12 12 12 12 13 13 13 13 13	1 1 1 1 1 2 2 2 2 2 3 3 3 3 3 4 4 4 4 4 5 5 5 5 5 6 6 6 6 6 7 7 7 7 7 8 8 8 8 8 9 9 9 9 9 10 10 10 10 10 11 11 11 11 11 12 12 12 12 12 13 13 13 13 13
MOE Avg. for Each PV By Entry Time	x_1 x_2 x_3 x_4 x_5	x_1 x_2 x_3 x_4 x_5	x_1 x_2 x_3 x_4 x_5	x_1 x_2 x_3 x_4 x_5
MOE Avg. for Each Alternative	X_H	X_{LW}	X_{SW}	X_{BW}
Std. Dev. for Each PV by Entry Time	s_{x1} s_{x2} s_{x3} s_{x4} s_{x5}	s_{x1} s_{x2} s_{x3} s_{x4} s_{x5}	s_{x1} s_{x2} s_{x3} s_{x4} s_{x5}	s_{x1} s_{x2} s_{x3} s_{x4} s_{x5}
Std. Dev. For Each Alt.	S_H	S_{LW}	S_{SW}	S_{BW}

The results generated and compiled for each simulation run performed for each alternative focused on the performance of the entire test network. Individual links or movements within the network were not addressed. Due to resource limitations with this research, it was not possible to quantify and assess the impacts of specific types of movements within the network. This determination was based on the focus and objectives of the research to assess the impacts of using different transition strategies associated with preemption control on the entire test network, rather than a subset of travelers within that network (e.g., side-street, specific turning movements, major movements along arterial street). These issues provide opportunities for future research to assess the potential influence of alternative transition strategies on specific movements within the network, which may be impacted differently by preemption control.

Table 3 summarizes the performance of each alternative transition strategy (hold, long, short, and best way) for each individual level of traffic volume. The average, standard deviation, error of the mean, and range in the error of mean is presented for each performance measure (average delay and average travel time) that was evaluated. The results presented in Table 3 represent the compilation of all the individual simulation runs that were compiled and are summarized in Appendix B. The performance of these alternatives provides the basis for the statistical analysis and comparison that was performed in this research, which is presented in Chapter 5, where the results are quantified and conclusions drawn.

4.4.3. Safety Implications for Alternatives Analyzed

As described in Chapter 2, the review of literature did not identify any documented information on the safety implications using various traffic signal transition strategies to exit from preemption control. Traffic simulation models also do not have the capability to analyze or quantify the potential impacts of preempting the operation of traffic signals or the use of transition strategies on the safety of other non-preempting vehicles traveling through these signals. General conclusions can however be drawn regarding the potential impacts transition strategies may have on vehicle safety at these preempted traffic signals.

Under congested flow conditions, any transition strategy that is selected should consider the impacts that it may have on traffic flow, as well as where vehicle queues or spill back may occur on approaches to signalized intersections, increasing the potential for accidents. The use of the hold or short transition strategies under congested traffic conditions could result in queues forming, with the formation of the queue propagating upstream in a manner motorists may not normally expect to encounter. This could occur at intersections where there is insufficient storage capacity or high turning movements or where vehicles on the through movement blocks the access of other vehicles to turn lanes or side streets.

Table 3: Influence of Alternative Transition Strategies on Traffic Flow: (a) Base Traffic Volume Alternative; (b) 20% Increase in Base Traffic Volume Alternative; and (c) 40% Increase in Base Traffic Volume Alternative.

(a) Base Traffic Volume Alternative – Simulation Run Results				
Transition Strategy	**Hold**	**Long Way**	**Short Way**	**Best Way**
Average Vehicle Delay (Sec./Veh.):				
Avg. Veh. Delay	27.2	26.9	29.1	25.8
Std. Dev. Avg. Delay	1.20	1.24	1.54	1.93
Error of Mean	3.0%	3.1%	3.8%	3.6%
Range in Error of Means	2.2% - 4.7%	2.2% - 4.1%	1.7% - 6.3%	3.0% - 4.8%
Average Vehicle Travel Time (Sec./Veh.):				
Avg. Travel Time	67.9	67.7	70.0	66.8
Std. Dev. Avg. Travel Time	1.76	1.90	2.16	1.95
Error of Mean	1.8%	1.9%	2.2%	2.0%
Range in Error of Means	1.1% - 2.7%	1.2% - 2.3%	0.8% - 3.8%	1.4% - 2.6%

(b) +20% Increase in Base Traffic Volume Alternative – Simulation Run Results				
Transition Strategies	**Hold**	**Long Way**	**Short Way**	**Best Way**
Average Vehicle Delay (Sec./Veh.):				
Avg. Veh. Delay	27.0	27.1	28.5	24.3
Std. Dev. Avg. Delay	1.22	1.27	1.29	1.38
Error of Mean	3.1%	3.3%	3.2%	3.8%
Range in Error of Means	2.1% - 4.1%	2.7% - 4.4%	2.2% - 3.7%	3.3% - 4.9%
Average Vehicle Travel Time (Sec./Veh.):				
Avg. Travel Time	68.0	68.0	69.1	65.2
Std. Dev. Avg. Travel Time	1.79	1.62	1.67	1.72
Error of Mean	1.8%	1.7%	1.7%	1.8%
Range in Error of Means	1.6% - 2.9%	1.2% - 2.3%	1.2% - 2.2%	1.5% - 2.0%

(c) +40% Increase in Base Traffic Volume Alternative – Simulation Run Results				
Transition Strategy	**Hold**	**Long Way**	**Short Way**	**Best Way**
Average Vehicle Delay (Sec./Veh.):				
Avg. Veh. Delay	26.3	26.2	29.0	26.6
Std. Dev. Avg. Delay	1.07	1.06	1.29	1.47
Error of Mean	2.7%	2.6%	2.9%	3.7%
Range in Error of Means	1.6% - 4.0%	1.4% - 3.9%	2.5% - 3.8%	2.4% - 5.0%
Average Vehicle Travel Time (Sec./Veh.):				
Avg. Travel Time	67.3	67.2	70.0	68.2
Std. Dev. Avg. Travel Time	1.40	1.64	1.82	2.27
Error of Mean	1.4%	1.6%	1.8%	2.3%
Range in Error of Means	0.8% - 2.0%	1.1% - 2.4%	1.5% - 2.6%	1.5% - 3.1%

4.4.4. Influence of the Preempting Vehicle Arrival Time

One of the challenges with assessing the impacts of preemption control is the random nature of the time during the cycle that a vehicle may actually issue a request to preempt the operation of a traffic signal. Any analysis of preemption control needs to consider the stochastic characteristics associated with this random event. This assessment needs to assume there is an equal probability of a vehicle issuing a preemption request at any time in the cycle length.

Another factor to consider is the longer a preemption control plan is in operation the longer the signal timing plan is not operating in coordination with the adjacent traffic signals. The longer the preemption control plan is in operation, the longer it may also take to transition or return to the coordinated operation of the normal signal timing plan. The impacts of preemption control will be reduced if the preempting vehicle arrives at the intersection during the green phase corresponding to its approach or direction of travel to the subject traffic signal. This will eliminate any adjustment in the signal timing plan that would be needed to accommodate a preemption control request, thereby limiting its impact on the flow of traffic.

If the requesting vehicle arrives during the green phase in the signal timing plan it will avoid terminating early, extending or skipping another signal phase to implement a special preemption control plan to accommodate the request. If the preempting vehicle arrives during the clearance (yellow or all red intervals) or red phases of the signal timing plan it will require terminating early the current or next phase to be served. This would in turn require early initiation of the green phase, to ensure any queues formed on the approach to the intersection, could be cleared in advance of the requesting vehicle arriving at the intersection.

To estimate the status of the traffic signal timing plan when a preempting vehicle may arrive at each signal, a comparison was made of each traffic signal timing plan, offset or coordination point and average travel speed of the preempting vehicle. The assumed travel time for the preempting vehicle to traverse through the test network was based on its average travel speed divided by the distance between each traffic signal. This total travel time for the vehicle within the network, was compared to the signal timing adjusted to account for its coordinated point, to estimate the status of the signal display on the approach of the preempting vehicle to the traffic signal.

The estimated travel times for the preempting vehicle to reach each signal in the test network were then compared to when the preempting vehicle was incrementally released (e.g., 0, 15, 30, 45 , and 60 seconds) into each traffic simulation run. The details pertaining to the release of the preempting vehicle into each simulation run are described in Section 4.3. A summary of the expected status of each traffic signal based on when the preempting vehicle may be incrementally released into each simulation run is presented in Table 4. Indicated on this table is the expected status of the signal timing plan (green (G), yellow (Y) or red (R)) the requesting vehicle may encounter.

This analysis suggests a vehicle released at either 0 or 60 seconds into the simulation run should encounter the green phase at each intersection in the test network. For the other release times, the vehicle may encounter a clearance or red phase at one to three of the intersections. For example, a preempting vehicle may encounter a red indication at the Glebe Road intersection if it is released at the 15, 30 or 45-second interval. A vehicle released at the 30-second interval in the cycle length may encounter a red or clearance interval at the Monroe, Glebe and Walter Reed intersections.

Table 4. Preempting Vehicle Encountering Green or Clearance Intervals

Traffic Signal Indicated When Preempting Vehicle Arrives at Intersection					
	15-second interval for release of preempting vehicle				
Street	0-second	15-second	30-second	45-second	60-second
Monroe Street	G	G	Y	G	G
Glebe Road	G	R	R	R	G
Highland Ave.	G	G	G	R	G
Walter Reed Drive	G	G	R	R	G

To qualitatively assess the potential impacts associated with the time a request is received to preempt the operation of a signal timing plan, a review was made of the traffic simulation runs performed in this research. A review of these simulation runs, summarized in Appendix B, was performed to determine if there was any difference in performance associated with when the preemption vehicle was released into the run. The average delays and average travel times incurred in each of the five 15-second release intervals (o, 15, 30, 45 and 60) in each simulation run were compared.

The expected status of each traffic signal the preempting vehicle may encounter for each of the 15-second release intervals analyzed, was compared to the results of the simulation runs that were performed, to determine if there were any patterns in performance. This review did not identify any noticeable patterns in the performance of the simulation runs conducted for each 15-second release interval. While the average delay and average travel time may were slightly higher for the 30 and 45-second intervals, there was no noticeable pattern or difference in performance, that would have validated the expected impacts of a preempting vehicle encountering the status of the signal timing plans indicated in Table 4.

The performance of the individual simulation runs was reviewed to identify possible patterns with the impacts of the different 15-second release intervals that were analyzed for each alternative. This review did not identify any patterns or differences in performance (i.e., average delay and average travel time) between the 15-second simulation runs (i.e., 0, 15, 30, 45, 60) conducted for each alternative. This comparison considered the runs that were performed for each of the five 15-second release intervals for each transition strategy that was analyzed at each of the three different levels of traffic volume.

Comparing the results of each 15-second release interval to each transition strategy resulted in an increase in average delay ranging from 1.6 to 5.2 seconds, and an increase in average travel time of 1.6 to 6.2 seconds. Comparing the results of one transition strategy to each 15-second release interval resulted in an increase in average delay ranging from 1.1 to 3.9 seconds, and an increase in average travel time of 1.2 to 4.5 seconds.

CHAPTER 5: RESULTS

This chapter presents the results of the analysis performed on the data from the simulation runs presented in Chapter 4. Following the overview, the remaining sections of this chapter include: 1) impacts of changes in traffic volume; 2) effectiveness of alternative transition strategies analyzed; and 3) overall summary of analysis results.

5.1 Overview

This chapter presents the results of the analysis performed using the data generated from the traffic simulation runs that were performed for the four transition strategies and the three levels of traffic volume evaluated in this research. Specifically, the analysis explores which transition strategies may be the most effective for different levels of traffic volume. The impact changes in traffic volume may have on each transition strategy evaluated is measured in terms of average travel delay and average travel time.

Prior to analyzing the previously compiled results, additional analysis was required to determine if the different transition strategies and changes in traffic volume affected average travel delay and average travel time. This analysis was necessary to determine if either the transition strategies or changes in traffic volume can be isolated to determine what effect they may have on either of these performance measures. This comparative analysis of results relies on statistically-based conclusions to determine what impacts the alternatives may have on each other, along with the resulting performance measures.

5.2 Impacts of Changes in Traffic Volume

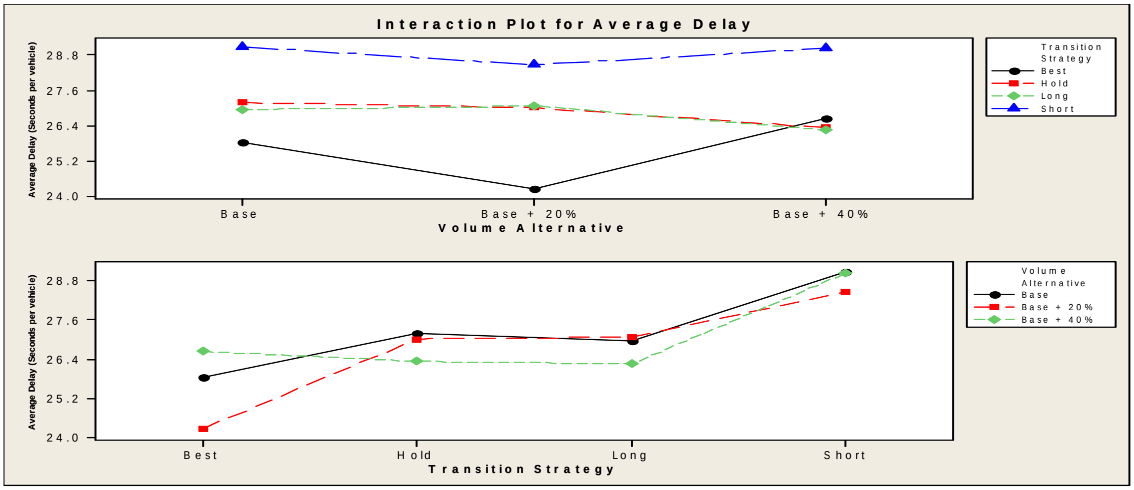
In order to determine if different transition strategies and changes in traffic volume affect average travel delay and average travel time, a two-way analysis of variance (ANOVA) was performed. Table 4 summarizes the numerical and graphic results of this analysis. The analysis indicates that a statistically significant interaction exists between the transition strategies and traffic volume on average travel delay at the 96.4% confidence level. A statistically significant interaction exists between the transition strategies and traffic volume on average travel time at the 99.0% confidence level.

Table 5: Impact of Changes in Traffic Volume on Transition Strategy Performance:

(a) Average Delay - Two-Way ANOVA:

Source	DF	SS	MS	F	P
Volume Alternative	2	3.211	1.6055	1.46	0.242
Transition Strategy	3	83.719	27.9062	25.38	0.000
Interaction	6	16.382	2.7304	2.48	0.036
Error	48	52.768	1.0993		
Total	59	156.080			

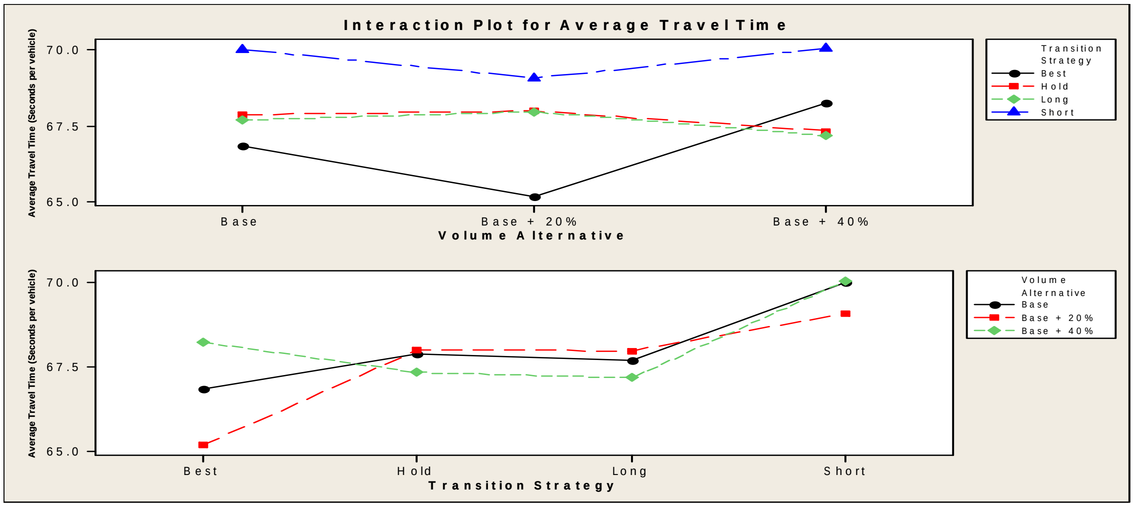
S = 1.048 R-Sq = 66.19% R-Sq(adj) = 58.44%



(b) Average Travel Time - Two-way ANOVA:

Source	DF	SS	MS	F	P
Volume Alternative	2	4.850	2.4252	1.91	0.159
Transition Strategy	3	70.765	23.5882	18.59	0.000
Interaction	6	24.575	4.0958	3.23	0.010
Error	48	60.892	1.2686		
Total	59	161.082			

S = 1.126 R-Sq = 62.20% R-Sq(adj) = 53.54%



These results indicate that neither transition strategies nor traffic volume can be isolated to determine their individual effects on average travel delay or average travel time. Rather, the effects on average travel delay and average travel time resulting from each of the four tested transition strategies depends on the level of traffic volume. However, conclusions can be drawn as to the impacts of the respective transition strategies for each of the three levels of traffic volume tested on these performance measures.

In order to draw statistically-based conclusions about how different transition strategies affected average travel time and average delay, additional analysis was needed specific to each level of traffic volume. This analysis was necessary because the two-way ANOVA statistical test determined that a statistically significant interaction existed between transition strategies and traffic volume.

5.3 Effectiveness of Transition Strategies

In order to determine how each of the four transition strategies affected average travel delay and average travel time for each level of traffic volume that was analyzed, a one-way analysis of variance (ANOVA) was performed. This required a statistical analysis to be completed and conclusions drawn for the base level of traffic volume, 20% increase in volume, and 40% increase in volume. For this research, a statistically significant difference was considered to exist if the resulting “p-value” was less than 0.10 (i.e., 10% level of significance or 90% level of confidence).

5.3.1 Base Level of Traffic Volume

In order to determine if, and if so, which transition strategies affect average travel delay and average travel time for the base level of traffic volume, the t-test was performed on the results of the one-way ANOVA. Table 5 summarizes the results. The resulting statistical analysis indicates that when the base level of traffic volume is present, there are statistically significant differences in the impacts the four respective transition strategies have on: 1) average travel delay at the 98.7% confidence level; and 2) average travel time at the 97.3% confidence level.

Table 6: Transition Strategy Performance – Base Traffic Volume

(a) Average Delay - One-way ANOVA:

Source	DF	SS	MS	F	P
Base Volume Alt.	3	27.47	9.16	4.88	0.013
Error	16	30.00	1.87		
Total	19	57.47			

S = 1.369 R-Sq = 47.81% R-Sq(adj) = 38.02%

Transition Strategies	X_1 Avg. Delay	X_1 Stnd. Dev.	X_2 Avg. Delay	X_2 Stnd. Dev.	% Diff. X_1 - X_2	T-Test	Significant Difference in Means?
Best – Hold	25.820	1.564	27.180	1.314	5.0%	-1.49	No - 1.49 < 1.860
Best – Long	25.820	1.564	26.940	1.442	4.2%	-1.18	No - 1.18 < 1.860
Best – Short	25.820	1.564	29.080	1.117	11.2%	-3.79	Yes - 3.79 > 1.860
Hold – Long	27.180	1.314	26.940	1.442	0.9%	0.28	No - 0.28 < 1.860
Hold – Short	27.180	1.314	29.080	1.117	6.5%	-2.46	Yes - 2.46 > 1.860
Long - Short	26.940	1.442	29.080	1.117	7.4%	-2.62	Yes - 2.62 > 1.860

(b) Average Travel Time - One-way ANOVA:

Source	DF	SS	MS	F	P
Base Volume Alt.	3	27.41	9.14	4.18	0.023
Error	16	35.01	2.19		
Total	19	62.42			

S = 1.479 R-Sq = 43.91% R-Sq(adj) = 33.40%

Transition Strategies	X_1 Avg Travel Time	X_1 Stnd. Dev.	X_2 Avg. Travel Time	X_2 Stnd. Dev.	% Diff. X_1 - X_2	T-Test	Significant Difference in Means?
Best – Hold	66.820	1.711	67.860	1.346	1.5%	-1.07	No - 1.07 < 1.860
Best – Long	66.820	1.711	67.680	1.509	1.3%	-0.84	No - 0.84 < 1.860
Best – Short	66.820	1.711	70.000	1.317	4.5%	-3.29	Yes - 3.29 > 1.860
Hold – Long	67.860	1.346	67.680	1.509	0.3%	0.20	No - 0.20 < 1.860
Hold – Short	67.860	1.346	70.000	1.317	3.1%	-2.54	Yes - 2.54 > 1.860
Long - Short	67.680	1.509	70.000	1.317	3.3%	-2.59	Yes - 2.59 > 1.860

To determine the most effective transition strategy for the base level of traffic volume, the t-test was performed on each combination of the respective transition strategies. There was no statistically significant difference when comparing the best way, long, or hold transition strategies on either average travel delay or average travel time at the 90% confidence level. There was, however, a statistically significant difference when comparing the short and the other three strategies.

The short transition strategy was identified as the least effective, with higher average travel delays and higher average travel times, which were statistically significant at the 90% confidence level. Comparing the results for the best way transition strategy to the long and hold strategies, resulted in a range of 0.9% to 5.0% lower average travel delays, and 0.3% to 1.3% lower average travel times. Comparing the results for the short transition strategy to the best way, long, and hold strategies resulted in a range of 6.5% to 11.2% higher average travel delays, and a 3.1% to 4.5% higher average travel times. Although the short transition strategy was determined to be the least effective, it does not draw any statistically based conclusions as to which transition strategy was the most effective for the base level of traffic volume.

5.3.2 20% Increase in Base Traffic Volume

In order to determine if, and if so, which transition strategies effect average travel delay and average travel time for a 20% increase in the level of traffic volume, the t-test was performed on the results of the one-way ANOVA. Table 6 summarizes the results. The resulting statistical analysis indicates that with a 20% increase in the level of traffic volume, there are statistically significant differences in the impacts the four respective transition strategies have on: 1) average travel delay at slightly less than the 100% confidence level; and 2) average travel time at the 100% confidence level.

To determine the most effective transition strategy with a 20% increase in level of traffic volume, the t-test was performed on each combination of the transition strategies. The best way transition strategy was identified as the most effective, with the lowest average travel delay and lowest average travel time, which was statistically significant at the 90% confidence level. Comparing the results for the best way transition strategy to long, hold and short resulted in a range of 10.1% to 14.8% lower average travel delays, and 4.1% to 5.6% lower average travel times.

There was no statistically significant difference when comparing the short and long transition strategies, or with comparing the hold and long transition strategies, for either average travel delay or average travel time at the 90% confidence level. There was a statistically significant difference when comparing the hold and the short transition strategies, for either average travel delay or average travel time at the 90% confidence level. The short transition strategy was identified as the least effective, with higher average travel delays and higher average travel times, which were statistically significant at the 90% confidence level than for the long transition strategy. Comparing the results for the short to the long and hold transition strategies resulted in a range of 0.2% to 5.1% higher average travel delay and a 0.0% to 1.6% higher average travel time.

Table 7: Transition Strategy Performance – 20% Increase in Base Traffic Volume

(a) Average Delay - One-way ANOVA:

```
Source          DF    SS     MS      F      P
Volume 1 Alt.   3  46.35  15.45  15.42  0.000
Error           16  16.04   1.00
Total           19  62.39
S = 1.001   R-Sq = 74.30%   R-Sq(adj) = 69.48%
```

Transition Strategies	X_1 Avg. Delay	X_1 Stnd. Dev.	X_2 Avg. Delay	X_2 Stnd. Dev.	% Diff. X_1 - X_2	T-Test	Significant Difference in Means?
Best – Hold	24.260	0.940	27.000	0.458	10.1%	-5.86	Yes – 5.86 > 1.860
Best - Long	24.260	0.940	27.060	1.655	10.3%	-3.29	Yes – 3.29 > 1.860
Best - Short	24.260	0.940	28.460	0.422	14.8%	-9.11	Yes – 9.11 > 1.860
Hold - Long	27.000	0.458	27.060	1.655	0.2%	-0.08	No – 0.08 < 1.860
Hold - Short	27.000	0.458	28.460	0.422	5.1%	-5.24	Yes – 5.24 > 1.860
Long - Short	27.060	1.655	28.460	0.422	4.9%	-1.83	No – 1.83 < 1.860

(b) Average Travel Time - One-way ANOVA:

```
Source          DF    SS     MS      F      P
Volume 1 Alt.   3  41.72  13.91  13.48  0.000
Error           16  16.50   1.03
Total           19  58.23
S = 1.016   R-Sq = 71.66%   R-Sq(adj) = 66.34%
```

Transition Strategies	X_1 Avg. Travel Time	X_1 Stnd. Dev.	X_2 Avg. Travel Time	X_2 Stnd. Dev.	% Diff. X_1 - X_2	T-Test	Significant Difference in Means?
Best – Hold	65.160	0.817	67.980	0.559	4.1%	-6.37	Yes – 6.37 > 1.860
Best - Long	65.160	0.817	67.960	1.677	4.1%	-3.36	Yes – 3.36 > 1.860
Best - Short	65.160	0.817	69.060	0.577	5.6%	-8.72	Yes – 8.72 > 1.860
Hold - Long	67.980	0.559	67.960	1.677	0.0%	0.03	No – 0.03 < 1.860
Hold - Short	67.980	0.559	69.060	0.577	1.6%	-3.01	Yes – 3.01 > 1.860
Long - Short	67.960	1.677	69.060	0.577	1.6%	-1.39	No – 1.38 < 1.860

5.3.3. 40% Increase in Base Traffic Volume

In order to determine if, and if so which transition strategies effect average travel delay and average travel time for a 40% increase in the level of traffic volume, the t-test was performed on the results of the one-way ANOVA. Table 7 summarizes the results. The resulting statistical analysis indicates that with a 40% increase in the level of traffic volume, there are statistically significant differences in the impacts the four respective transition strategies have on: 1) average travel delay at slightly less than the 100% confidence level; and 2) average travel time at the 100% confidence level.

Table 8: Transition Strategy Performance – 40% Increase in Base Traffic Volume

Average Delay - One-way ANOVA:

```
Source          DF     SS     MS     F      P
Volume 2 Alt.    3  26.274  8.758  20.80  0.000
Error           16   6.736  0.421
Total           19  33.010
S = 0.6488   R-Sq = 79.59%   R-Sq(adj) = 75.77%
```

Transition Strategies	X_1 Avg. Delay	X_1 Stnd. Dev.	X_2 Avg. Delay	X_2 Stnd. Dev.	% Diff. X_1 - X_2	T-Test	Significant Difference in Means?
Best – Hold	26.620	0.887	26.320	0.526	1.1%	0.65	No - 0.65 < 1.860
Best - Long	26.620	0.887	26.240	0.391	1.4%	0.88	No - 0.88 < 1.860
Best - Short	26.620	0.887	29.020	0.683	8.3%	-4.79	Yes - 4.79 > 1.860
Hold - Long	26.320	0.526	26.240	0.391	0.3%	0.27	No - 0.27 < 1.860
Hold - Short	26.320	0.526	29.020	0.683	9.3%	-7.00	Yes - 7.00 > 1.860
Long - Short	26.240	0.391	29.020	0.683	9.6%	-7.90	Yes - 7.90 > 1.860

Average Travel Time - One-way ANOVA:

```
Source          DF     SS     MS     F      P
Volume 2 Alt.    3  26.206  8.735  14.90  0.000
Error           16   9.380  0.586
Total           19  35.586
S = 0.7657   R-Sq = 73.64%   R-Sq(adj) = 68.70%
```

Transition Strategies	X_1 Avg. Travel Time	X_1 Stnd. Dev.	X_2 Avg. Travel Time	X_2 Stnd. Dev.	% Diff. X_1 - X_2	T-Test	Significant Difference in Means?
Best – Hold	68.220	0.829	67.320	0.733	1.3%	1.82	No - 1.82 < 1.860
Best - Long	68.220	0.829	67.160	0.498	1.6%	2.45	Yes - 2.45 > 1.860
Best - Short	68.220	0.829	70.040	0.934	2.6%	-3.26	Yes - 3.26 > 1.860
Hold - Long	67.320	0.733	67.160	0.498	0.2%	0.40	No - 0.40 < 1.860
Hold - Short	67.320	0.733	70.040	0.934	3.9%	-5.12	Yes - 5.12 > 1.860
Long - Short	67.160	0.498	70.040	0.934	4.1%	-6.08	Yes - 6.08 > 1.860

To determine the most effective transition strategy when a 40% increase in the level of traffic volume is present, the t-test was performed on each combination of the respective transition strategies. There was no statistically significant difference when comparing the best way to the hold transition strategy, or with comparing the hold to the long transition strategy, for either average travel delay or average travel time at the 90% confidence level. There was, however, no statistically significant difference when comparing the best way and the long transition strategies for average travel time at the 90% confidence level. There was a statistically significant difference when comparing the best way to the long transition strategy, and the short to the hold, long or best way transition strategies for either average travel delay or average travel time at the 90% confidence level.

The short transition strategy was identified as the least effective, with higher average travel delays and higher average travel times, which were statistically significant at the 90% confidence level. Comparing the results of the long transition strategy to the best way and hold strategies resulted in 0.3% to 1.4% lower average travel delays, and 0.2% to 1.6% lower average travel times, which were not statistically significant at the 90% confidence level. Comparing the results of the short transition strategy to the long, best way, and hold strategies resulted in an average travel delay ranging from 8.3% to 9.6% higher and average travel time ranging from 2.6% to 4.1% higher than the best way. Although the short transition strategy was determined to be the least effective, it does not draw any statistically based conclusions as to which transition strategy is the most effective for a 40% increase in the level of traffic volume.

5.4 Summary of Analysis Results

A graphical comparison of the impacts associated with changes in traffic volume on the performance of different transition strategies is presented in Figure 6. The graphic results of this comparison previously summarized in Tables 5, 6 and 7, reinforces the statistically based conclusions drawn from the test results. It is important to note the transition strategies' performance had a similar effect on both average travel delay and average travel time for each level of traffic volume tested.

Several conclusions, set forth below, can be drawn based upon an evaluation of the results of the analysis that was performed on the strategies to transition from a preemption control plan back to the coordinated operation of the normal traffic signal timing plan.

- Statistically significant interaction exists between traffic volume and transition strategies, eliminating the ability to determine the isolated effects of either transition strategies on average travel delay and average travel time, or changes in traffic volume on average travel delay and average travel time. Conclusions, however, can be drawn about the most efficient transition strategy to use for a specific level of traffic volume.
- Selecting the most effective transition strategy needs to be based on traffic volume and conditions specific to each traffic signal or series of coordinated traffic signals.
- When the base traffic volume (~ 0.40 v/c) is present, the most efficient strategies are the best way, long and hold, and the most inefficient strategy is the short. Comparing the short to the best way, long or hold strategies resulted in a 6.5% to 11.2% higher average travel delay, and a 3.1% to 4.5% higher average travel time. Comparing the best way to the long or hold strategies resulted in a 0.9% to 5.0% lower average travel delay, and a 0.3% to 1.3% lower average travel time.
- When a 20% increase in base traffic volume (~ 0.50 v/c) is present, the most efficient strategy is the long, and the most inefficient strategy is the short and long. Comparing the best way to the long, short or hold strategies resulted in a 10.1% to 14.8% lower average travel delay, and a 4.1% to 5.6% lower average travel time. Comparing the short to the long or hold strategies resulted in 0.2% to 5.1% higher average travel delay, and up to a 1.6% higher average travel time.
- When a 40% increase in base traffic volume (~ 0.60 v/c) is present, the most efficient strategies are the best way, long and hold, and the most inefficient strategy is the short. Comparing the short to the long, best way or hold strategies resulted in a 8.3% to 9.6% higher average travel delay, and a 2.6% to 4.1% higher average travel time. Comparing the long to the best way or hold strategies resulted in a 0.3% to 1.4% lower average travel delay, and a 0.2% to 1.6% lower average travel time.

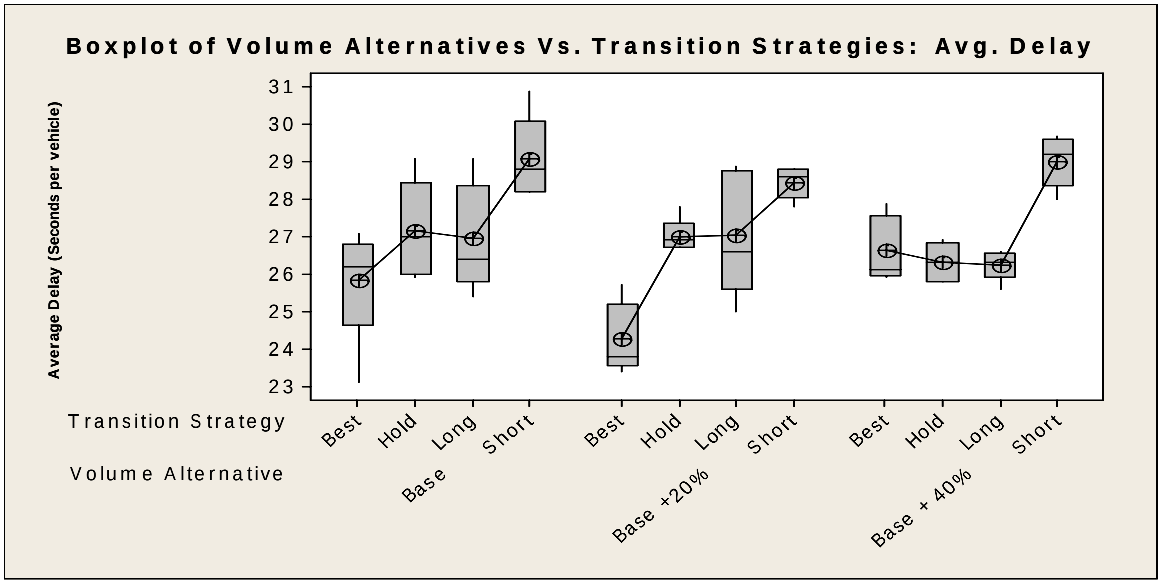
- Conclusions can be drawn about the impacts the respective transition strategies may have on each of the three different levels of traffic volume tested, as measured in terms of average travel delay and average travel time.
- Traffic volume is the primary variable that continuously changes and has the potential to significantly influence which transition strategy is most effective.
- Additional research is needed to evaluate the impacts of: higher levels of traffic volume that approach and exceed traffic congestion (e.g., v/c 0.8 to over 1.0), unbalanced directional flow of traffic (e.g., a.m. inbound, p.m. outbound), varying levels of turning movements at intersections, changing levels of traffic volume on cross streets, and different volumes of pedestrian traffic.
- Other variables or factors will also determine which transition strategy is the most effective based on conditions specific to each signalized intersection or series of coordinated traffic signals. These may include: spacing of intersections, progression of traffic between signals with coordinated operation, signal timing plan (e.g., cycle length, number of phases, green time available within each phase); pedestrian phases; geometric configuration (e.g., turn lanes and adequate storage); and capability of traffic signal controllers and ITS devices.
- For all of the traffic volumes that were analyzed, the best way strategy was the most efficient strategy for the base traffic volume and 20% increase in the base traffic volume, and the short was the statistically significant most inefficient strategy for all traffic volumes. However, only the best way was statistically significant for a 20% increase in the base traffic volume. Comparing the best way to short strategy resulted in lower average travel times ranging from 6.5 % to 14.8%, and lower average delay ranging from 2.6% to 5.6%. The short cycle length (75 seconds) and green phases in the signal timing plan for the side streets, provided limited time or opportunity to reduce these phases, contributing to why the short was the most inefficient strategy.
- In summary, the above conclusions generally support the research hypothesis and objectives presented in the evaluation plan in chapter 3.

5.5 Summary of Evaluation Methodology and Analysis Performed

The primary contribution of this research is the enhancement and demonstration of an evaluation methodology that can be used to replicate the stochastic nature and assess the impacts of preemption control. A critical component of this methodology is the "software-in-the-loop" traffic simulation tool with the capability to analyze the impacts of preemption control and the use of different traffic signal transition strategies to exit from preemption control and return to the coordinated operation of the normal signal timing plan. Researchers and practitioners desiring to assess the impacts of preemption control and performance of transition strategies to exit from preemption control and return to coordinated operation would need to consider the following critical components of this evaluation methodology in performing this analysis:

- develop evaluation plan including research hypothesis and objectives, evaluation objectives and performance measures (see Section 3.3);
- select test network and collect data necessary to perform analysis (see Section 3.6);
- select traffic simulation software considering its ability to (see Sections 2.7 & 3.5):
    1. replicate transition strategies (see Sections 2.3 & 2.4)?
       -build the "hardware-in-the-loop" simulation tool; or
       -develop the "software-in-the-loop" simulation tool;
    2. replicate preempting vehicle (see Sections 3.4 & 3.5)?
       -build RTE with software to replicate vehicles' operational characteristics; or
       -build RTE with software to replicate the stochastic nature of when vehicle issues requests to preempt traffic signal operation;
- build traffic simulation model for test network see Sections 3.5, 3.6 & 4.2);
- prepare traffic simulation plan and experimental design (see Section 4.3); and
- conduct simulation runs, compile and analyze results (see Section 4.4).

(a) Average Delay:



(b) Average Travel Time:

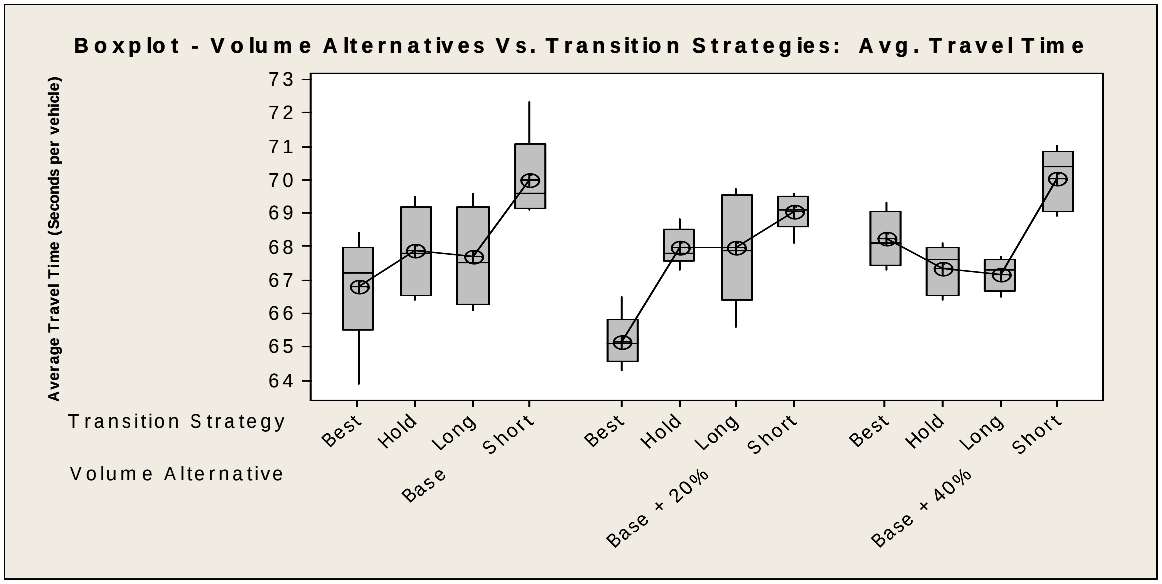


Figure 7: Impact of Changes in Traffic Volume on Transition Strategy Performance

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

This chapter draws conclusions from the results of the analysis performed for this dissertation, and makes recommendations for future research. Following the overview, the remaining sections of this chapter include: 1) assessment of the "software-in-the-loop" simulation tool; 2) assessment of strategies to transition to coordinated operation; 3) recommendations for future research; and 4) final summary.

6.1 Research Contributions

A review of published literature identified only a few studies that have evaluated the impacts of preemption control and the performance of different transition strategies to exit from preemption control and return to coordinated operation of the traffic signal's normal signal timing plan. As a result, little is known about which transition strategy is the most effective to exit from preemption control and transition back to coordinated operation. This research expands upon previously completed research that relied on the use of the "hardware-in-the-loop" simulation tool to assess the impacts of preemption control and the performance of different transition strategies to exit from a preemption control plan.

The primary contribution of this research is the enhancement to and application of an innovative evaluation methodology and "software-in-the-loop" simulation tool to replicate the stochastic characteristics and assess the impacts of preemption control. This research also presents how this methodology and tool can be used to assess the performance of different transition strategies to exit preemption control and return to the coordinated operation of the normal signal timing plan entirely on a personal computer. In addition, this research demonstrates the potential of the evaluation methodology and simulation tool to assess other traffic control functions, features and operational strategies not currently supported by microscopic traffic simulation tools. This methodology and analysis was previously summarized in Section 5.5.

The results of this research should be of interest to traffic engineers and researchers involved in developing or operating coordinated traffic signal control systems. This research adds to the greater body of knowledge and advances the state-of-the-art in developing traffic signal control systems, operating traffic signals, selecting traffic signal transition strategies, analyzing traffic signal priority control, and preemption control. Several conclusions were drawn from this research, validating the importance and need for the capabilities that this enhanced evaluation methodology and simulation tool provides for practitioners and researchers. The contributions of this research include:

- enhancing an evaluation methodology and "software-in-the-loop" simulation tool to replicate stochastic characteristics and assess the impacts of preemption control;
- evaluating the effectiveness of the most commonly available transition strategies to exit from preemption control and transition to the coordinated operation of the normal traffic signal timing plan including the best way, long, short, and hold strategies;
- assessing the impacts of varying levels of traffic volume (e.g., 0.40 to 0.60 v/c) on the performance of different transition strategies to exit from preemption control and in transitioning to coordinated operation of the traffic signal; and
- enhancing the methodology and "software-in-the-loop" simulation tool to evaluate preemption control, traffic signal transition strategies, traffic control functions, and other features not currently supported by microscopic traffic simulation models which can operate entirely on a personal computer.

6.2 Assessment of Strategies to Transition to Coordinated Operation

The research demonstrates that the traffic signal transition strategy determined to be the most effective for each transit signal within a coordinated signal system depends upon the traffic volume and conditions specific to each traffic signal or system. The transition strategies determined appropriate for the test network evaluated were the best way strategy, along with the long or hold strategy, depending on the level of traffic volume in the test network that was evaluated. Several conclusions listed below, were drawn based on the evaluation of these strategies to exit from a preemption control plan and transition back to coordinated operation of the signal timing plan.

- Statistically significant interaction exists between traffic volume and transition strategies, eliminating the ability to determine the isolated effects of either transition strategies on average travel delay and average travel time, or the effects of changes in traffic volume on average travel delay and average travel time.

- Conclusions can be drawn about the performance of different transition strategies during this transition for specific levels of traffic volumes.
- Selecting the most effective transition strategy needs to be based on the traffic volume and conditions specific to each traffic signal or series of coordinated traffic signals.
- Traffic volume is the primary variable that continuously changes and has the potential to significantly influence which transition strategy is most effective.
- Other variables or factors will also determine which transition strategy is the most effective based on conditions specific to each signalized intersection or coordinated traffic signals. These may include: spacing of intersection; progression of traffic between signals; signal timing plan (e.g., cycle length, number of phases, green time available within each phase); pedestrian phases; geometric configuration (e.g., turn lanes, adequate storage); and capability of traffic signal controllers and devices.
- For all of the traffic volumes that were analyzed, the best way strategy was the most efficient strategy for the base traffic volume and 20% increase in the base traffic volume, and the short was the statistically significant most inefficient strategy for all traffic volumes. However, only the best way was statistically significant for a 20% increase in the base traffic volume. Comparing the best way to short strategy resulted in lower average travel times ranging from 6.5 % to 14.8%, and lower average delay ranging from 2.6% to 5.6%. The short cycle length (75 seconds) and green phases in the signal timing plan for the side streets, provided limited time or opportunity to reduce these phases, contributing to why the short was the most inefficient strategy.

6.3 Recommendations for Future Research

Further research is needed to assess the performance of different transition strategies and the time required to return to coordinated operation of the signal timing plan under higher levels of traffic volume, different traffic characteristics, cycle lengths, signal timing plans, and roadway geometric configurations. Topics identified for further research to assess the performance and implications of using different traffic signal strategies to exit from preemption control and transition to the coordinated operation of the normal signal timing plan include:

- evaluate the impacts of higher levels of traffic volume that approach and exceed traffic congestion (e.g., v/c 0.8 to over 1.0), unbalanced directional flow of traffic (e.g., a.m. inbound, p.m. outbound), varying levels of turning movements at intersections, changing levels of traffic volume on cross streets, and different pedestrian volumes; at higher levels approaching and exceeding traffic congestion (e.g., v/c 0.8 to over 1.0), unbalanced directional flow of traffic (e.g., a.m. inbound, p.m. outbound), varying levels of turning movements at intersections, changing levels of traffic volume on cross streets, and different pedestrian volumes;
- assess the influence of various roadway geometric features (e.g., intersection spacing, turn lanes, length of turn lanes);
- quantify the influence of different signal plan features (e.g., cycle length, number of phases, left turn phases, ranges in maximum and minimum green times);
- compare the impacts of different numbers, time in between, types of requests (e.g., pedestrian, light rail) to preempt normal operation of a traffic signal;
- assess the influence of different factors on preemption control (e.g., frequency, direction), technology capabilities (e.g., continuous, zone, or point detection);
- develop the traffic simulation model capabilities, features (e.g., transition time to coordinated operation) and performance measures (e.g., requesting vehicle, time required to transition to coordinated operation, travel time reliability, vehicle stops) to evaluate the performance and impacts of preemption and priority control;
- examine general patterns of performance under different levels of traffic volume associated with exiting from preemption control and transitioning to the coordinated operation of the normal traffic signal timing plan; and
- develop a recommended data dictionary, protocol and requirements to allow preemption and priority control to be analyzed using the “software-in-the-loop” simulation tool.

6.4 Final Summary

The findings and conclusions of this research are consistent with and build upon the results of other previously completed research efforts focusing on the performance of traffic signal transition strategies applied with preemption control. A comparison of the methodology, tool, analysis and performance of using traffic signal transition strategies to exit from preemption control and return to the coordinated operation of the normal signal timing plan suggests the following (Shelby, et al., 2006 and Nelson, et al., 2000):

- performance of transition strategies is impacted by changes in traffic volume levels;
- significant differences exist in comparing performance of different transition strategies;
- transition strategies may have a limited impact on travel time and delay in comparison to the overall performance of the traffic signal network;
- magnitude of the findings of these two research efforts are similar in scale to the research results presented in this dissertation;
- best way transition strategy appears to be the most effective strategy for uncongested traffic conditions, however, methodological differences among these three research efforts prohibit identification of:
  -least effective strategy for uncongested traffic conditions; and
  -most effective strategy for uncongested traffic conditions.

The central premise of this research as presented in Chapter 1 - Introduction, is as follows:

> Motorists will benefit from strategies that minimize the adverse impacts associated with exiting from a preemption control plan and transitioning to the coordinated operation of the normal traffic signal timing plan. The degree of these benefits and impacts is dependent on each transition strategy and a function of the effects resulting from the interaction of the key factors of its environment. These key factors include the vehicle issuing a preemption request, traffic volume (e.g., number of vehicles, direction of travel), roadway geometry (e.g., spacing between traffic signals, turn lane storage capacity), traffic signal timing plan, progression of traffic and coordinated traffic signal operation.

This central premise and its hypothesis as presented in chapter 3 have been validated in this research, where motorists appear to realize benefits from selecting the most effective traffic signal strategy to exit from preemption control and transition to the coordinated operation of the normal signal timing plan. This selection needs to be based on the traffic volume, signal timing plan and conditions specific to each traffic signal and series of coordinated traffic signals. This research demonstrated that by increasing only the level of traffic volume, different transition strategies were more effective for each specific volume level.

This research also confirmed previously completed research on preemption control regarding where analysis is needed in addition to varying traffic volume, to assess the impacts of other factors that will influence which transition strategy may be the most effective for a specific application. These factors may include signal cycle length, signal timing plan phases, spacing of traffic signals, queue length, and other roadway geometric features. The key contributions of this research include:

- demonstrating the application of an innovative analytical approach known as the “software-in-the-loop” simulation tool, to evaluate entirely on a personal computer, the performance of different traffic signal transition strategies in exiting from preemption control;
- validating that a statistically significant interaction exists between traffic volume and transition strategies, eliminating the ability to determine the isolated effects of the transition strategies on the effects of changing levels of traffic volume;
- selecting the most effective transition strategy needs to be based on the traffic volume and conditions specific to each traffic signal or series of coordinated signals; and
- providing insights into which transition strategy may be the most effective for the specific set of conditions tested along with the influence increases in traffic volume may have with performing this transition.

It is important to note that these results should not be considered a basis for establishing a recommended practice or policy for how an agency selects a transition strategy. Rather, the results should provide insights into the issues that should be considered when selecting or evaluating the potential impacts varying conditions might have on the impacts different transition strategies may have on the performance of each signal timing plan or series of coordinated traffic signals. The evaluation methodology, analysis tool, and issues addressed in this research provide a useful framework or structure for state and local agencies to analyze and provide the basis to select which transition strategies may be appropriate for a given range of conditions specific to each signal timing plan, traffic signal, preemption or priority control plans, or series of coordinated signals.

REFERENCES

Bullock, D. and A. Catarella, *A Real-Time Simulation Environment for Evaluating Traffic Signal Systems*, Transportation Research Record No. 1634, TRB, National Research Council, Washington, DC, pp 130-135, 1998.

Bullock, D., J. Morales, and B. Sanderson, *Evaluation of Emergency Vehicle Preemption on the Route 7 Virginia Corridor*, USDOT, FHWA, Oct. 1998.

Dion, F., Rakha, H., and Zhang, Y., *A Modeling Evaluation of Transit Signal Priority and Adaptive Signal Control Along the Columbia Pike in the Washington, D.C. Region*, Draft Report, Virginia Tech Transportation Institute, 2001.

Eagle Traffic Control Systems, *EPAC300 Intersection Controller Unit Manual*, June 1996.

Econolite Control Products, Inc., *Cermak Road Bus Preemption*, March 1997.

Econolite Control Products, Inc., *Preemption to Coordination, Application Note 1002A*, March 1995.

Federal Highway Administration (FHWA), CORSIM Reference Manual, Washington, D.C., February 2003.

FHWA, Manual on Uniform Traffic Control Devices, 2001 Edition, USDOT, Washington, D.C., Jan. 17, 2001.

FHWA, Traffic Analysis Tools Primer, Decision Support Methodology for Selecting Traffic Analysis Tools, and Guidelines for Applying Traffic Microsimulation Modeling Software, Washington, D.C., 2004.

FHWA, Traffic Signal Preemption for Emergency Vehicles, A Cross-cutting Study, USDOT, Washington, D.C., January 2006.

Gardner Transportation Systems Inc., *NextPhase Intersection Management Software Operations Manual*, Version 1.4. Concord, Calif., 1999.

Gardner Transportation Systems, Inc., *VISSIM, NextPhase, and the Software Suitcase Tester,* Concord, Calif., 2000.

Gkritza K., J. Collura, D. Teodorovic and S. Tignor. *An Analysis of the Characteristics of Emergency Vehicle Operations,* Transport Science and Technology, pp. 327-341, 2007, Elsevier Ltd., Oxford, U.K.

Institute of Transportation Engineers, Traffic Engineering Handbook, 5th Edition, Prentice – Hall, Inc., 1999.

Intelligent Transportation Society (ITS) of America, An Overview of Transit Signal Priority, Washington, D.C., 2002.

ITS America, Transit Signal Priority: A Planning and Implementation Handbook, May 2005.

Louisell, W. C., *A Framework and Analysis Methods for Evaluation of Preferential Treatment for Emergency and Transit Vehicles at Signalized Intersections*, Virginia Tech, April 8, 2003.

MacGowan, J. C., *Bus Priority and Bus Preemption in the Urban Traffic Control System*, 1975 Compendium of Technical Papers, pp 1-11, ITE.

McHale, G. M., *An Assessment Methodology for Emergency Vehicle Traffic Signal Priority Systems*, Virginia Tech, February 26, 2002.

Marshall, P., and Berg, W., *Evaluation of Railroad Preemption Capabilities of Traffic Signal Controllers*, Transportation Research Record No. 1254, Transportation Research Board, Washington, D.C., pp. 44-49, 1990.

National Association on Emergency Medical Services Physicians (NAEMSP) and the National Association of State Emergency Medical Services Directors (NASEMSD), Use of Warning Lights and Emergency Medical Vehicle Response and Patient Transport, Prehospital and Disaster Medicine, Volume 9, Number 2, April-June 1994.

National Cooperative Highway Research Program (NCHRP), Traffic Signal State Transition Logic Using Enhanced Sensor Information, Project 3-66 Interim Report. TRB, National Research Council, Washington, D.C., Dec. 2003.

National Electrical Manufacturers Association (NEMA), Standard TS 2–1998: Traffic Controller Assemblies, 1998.

Nelson, E. J., and D. Bullock, *Impact Evaluation of Emergency Vehicle Preemption on Signalized Corridor Operation: An Evaluation.* Transportation Research Record No. 1727, TRB, National Research Council, Washington, D.C., pp. 1-11, 2000.

North Carolina DOT, *Guidelines for the Application of Emergency Vehicles Initiated Preemption*, September 1, 1997.

Noyce, D., *Barriers to Implementation of Signal Priority Systems for Transit Operations: Lessons Learned from Advanced Traffic Management Systems*, Texas A&M, CVEN Course Notes, August 1996.

Obenberger, J., and J. Collura, *Transition Strategies to Exit Preemption Control: State-of-the-Practice Assessment*, Transportation Research Record No. 1748, TRB, National Research Council, Washington, D.C., pp. 72-79, 2001.

Obenberger, J., and Rupert, R., *Issues to Consider in Operating HOV Lanes*, Transportation Research Record No 1711, TRB, National Research Council, Washington, DC, pp 6-12, 2000.

Oregon DOT, *Preemption, Section VIII, Traffic Signal Policies and Guidelines*, Nov. 1999.

PTV America, http://www.english.ptv.edu, January 2007.

Shelby, S. J., D. Bullock, and D. Gettman, *Transition Methods in Traffic Signal Control*, TRB 85th Annual Meeting, TRB, National Research Council, Washington, D.C., 2006.

Skarbardonis, A., *Assessment of Traffic Simulation Models*, Washington State DOT, Seattle, WA, May 1999.

Transit Cooperative Research Program (TCRP), Improved Traffic Signal Priority for Transit, Project A-16 Interim Report, National Research Council, Washington, D.C., Dec. 1998.

Transportation Research Board, Highway Capacity Manual, National Research Council Washington, D.C., 2000.

Urbanik, T. II, and S. Venglar, *Advanced Technology Applications: The "Smart Diamond"*. 65th ITE Annual Meeting. In Compendium of Technical Papers, Washington, D.C., pp 164-168, 1995.

Wapiti Software Users Group, *Recovery Methods From Full Preemption*, July 2000. http://www.odot.state.or.us/signals/wapiti.html. Accessed July 25, 2000.

Zhang, L., R. Ghaman, and M. Juan, *An Application of Client/Server Architecture in Interfacing Virtual Traffic Signal Controller with CORSIM*. Proceedings 7th International Conference on Application of Advanced Technology in Transportation Studies, American Society of Civil Engineers, Reston, VA, pp. 836-843, 2002.

APPENDIX A: CORSIM INPUT FILE - TEST NETWORK SIMULATION MODEL

This appendix contains a CORSIM input file associated with one of the traffic simulation runs that were conducted in this research. A description and diagram of this test network appears in Section 3.6. The following is a typical input file representative of what was used in the simulation runs that were conducted in this research associated with the traffic volume, conditions and geometric configuration of the test network.

```
Created by TSIS Mon Jun 28 14:54:48 2004 from TNO Version 64
Columbia Pike Calibrated Base Network                                          0
12345678 1 2345678 2 2345678 3 2345678 4 2345678 5 2345678 6 2345678 7 234567
Jon Obenberger                         3  252004                           0   1
       1   0   1   6 97165909 1000  1              31200    6799963041456717   2
 600                                                                           3
                  75                                                           4
   1      75  75  75   0   0   0   0   0   0   1                               5
   4  18SWalterReed                                                           10
   1  12Monroe South                                                          10
   1  11Monroe North                                                          10
   5  20Edgewood Sth                                                          10
   2  13Glebe North                                                           10
   3  16NB Highland                                                           10
   2  14Glebe South                                                           10
   4  17NWalterReed                                                           10
  18   4NBWalterReed                                                          10
  19   5WB Edgewood                                                           10
   4   5EB Edgewood                                                           10
  20   5NB Edgewood                                                           10
   2   3EB Highland                                                           10
   3   2WB Glebe                                                              10
  16   3NBHighland                                                            10
   1   2EB Glebe                                                              10
   2   1WB Monroe                                                             10
  10   1EB Monroe                                                             10
  11   1SB Monroe                                                             10
  12   1NB Monroe                                                             10
  13   2SB Glebe                                                              10
  14   2NB Glebe                                                              10
  15   3SB Highland                                                           10
   4   3WB Highland                                                           10
  17   4SBWalterReed                                                          10
   5   4WB Edgewood                                                           10
   3   4EBWalterReed                                                          10
   1  101700         2     01           8001              20  19  38 10       11
   4  18 300         2     01           8009              20  19  33 10       11
   1  12 300         1     01           8004              20  19  33  0       11
   1  11 300         1     01           8003              20  19  33 10       11
   5  20 300         1     01           8010              20  19  33  0       11
   2  13 300         2     01           8005              20  18  33 10       11
   3  16 300         1     01           8011              20  19  33  0       11
```

```
   5  19 800         2     01           8002              20  18  38 10       11
   2  14 300         2     01           8006              20  19  33 10       11
   3  15 300         1     01           8007              20  19  33 10       11
   4  17 300         2     01           8008              20  19  33 10       11
  18   4 300 120     2 1   01          3  17   5      17  20  19  33  0       11
  19   5 800 100     2 1   11         20   4           4  20  19  38 10       11
   4   5 265         2    -11             19  20          20  19  38 10       11
  20   5 300         1     01          4      19          20  19  33 10       11
   2   31095         2    -11         15   4  16       4  20  19  38  0       11
   3   21095 210 210 2 1 1 11         14   1  13       1  20  19  38  0       11
  16   3 300     100 1   1 01          2  15   4      15  20  19  33  0       11
   1   2 710     150 2   1 21         13   3  14       3  20  19  38  0       11
   2   1 700         2    -21         12  10  11      10  20  19  38  0       11
  10   11700         2     21         11   2  12       2  20  19  38  0       11
  11   1 300         1     01          2  12  10      12  20  19  33  0       11
  12   1 300         1     01         10  11   2      11  20  19  33  0       11
  13   2 300     140 2   1 01          3  14   1      14  20  19  33  0       11
  14   2 300         2     01          1  13   3      13  20  19  33  0       11
  15   3 300      80 1   1 01          4  16   2      16  20  19  33  0       11
   4   3 733         2     21         16   2  15       2  20  19  38  0       11
  17   4 300 120     2 1   01          5  18   3      18  20  19  33  0       11
   5   4 265 235     2 1   11         18   3  17       3  20  19  38  0       11
   3   4 733 332     2 1  -21         17   5  18       5  20  19  38  0       11
8001  10             2     21              1              20  19      0       11
8004  12             1     01              1              20  19     10       11
8003  11             1     01              1              20  19     10       11
8005  13             3     01              2              20  19     10       11
8006  14             2     01              2              20  19     10       11
8007  15             1     01              3              20  19     10       11
8008  17             3     01              4              20  19      0       11
8009  18             3     01              4              20  19     10       11
8010  20             1     01              5              20  19     10       11
8002  19             2     11              5              20  19      0       11
8011  16             1     01              3              20  19      0       11
  18   4   4  17   1 1                                                        14
  18   4   4  17   2  1                                                       14
  18   4   4   5   1 1                                                        14
  18   4   4   3   7  1                                                       14
  19   5   5  20   2 1                                                        14
  19   5   5   4   1 1                                                        14
  19   5   5   4   2  1                                                       14
   4   5   5  20   1 1                                                        14
   4   5   5  19   1 1                                                        14
   4   5   5  19   2  1                                                       14
  20   5   5  19   1 1                                                        14
  20   5   5   4   1  1                                                       14
   2   3   3  16   1 1                                                        14
   2   3   3  15   2 1                                                        14
   2   3   3   4   1 1                                                        14
   2   3   3   4   2  1                                                       14
   3   2   2  13   6 1                                                        14
   3   2   2  14   7  1                                                       14
   3   2   2   1   1 1                                                        14
   3   2   2   1   2  1                                                       14
  16   3   3  15   1 1                                                        14
  16   3   3   2   1  1                                                       14
  16   3   3   4   7 1                                                        14
```

```
 1   2   2  14   7 1                                                        14
 1   2   2   3   1 1                                                        14
 1   2   2   3   2  1                                                       14
 2   1   1  10   1 1                                                        14
 2   1   1  10   2  1                                                       14
 2   1   1  12   2 1                                                        14
 2   1   1  11   1 1                                                        14
10   1   1  12   1 1                                                        14
10   1   1  11   2 1                                                        14
10   1   1   2   1 1                                                        14
10   1   1   2   2  1                                                       14
11   1   1  10   1 1                                                        14
11   1   1  12   1 1                                                        14
11   1   1   2   1  1                                                       14
12   1   1  10   1  1                                                       14
12   1   1  11   1 1                                                        14
12   1   1   2   1 1                                                        14
13   2   2  14   1 1                                                        14
13   2   2  14   2  1                                                       14
13   2   2   1   7 1                                                        14
14   2   2  13   1 1                                                        14
14   2   2  13   2  1                                                       14
14   2   2   3   1 1                                                        14
15   3   3  16   1 1                                                        14
15   3   3   2   7 1                                                        14
15   3   3   4   1  1                                                       14
 4   3   3  16   2 1                                                        14
 4   3   3  15   1 1                                                        14
 4   3   3   2   1 1                                                        14
 4   3   3   2   2  1                                                       14
17   4   4  18   1 1                                                        14
17   4   4  18   2  1                                                       14
17   4   4   5   7  1                                                       14
17   4   4   3   1 1                                                        14
 5   4   4  18   7  1                                                       14
 5   4   4  17   1 1                                                        14
 5   4   4   3   1 1                                                        14
 5   4   4   3   2  1                                                       14
 3   4   4  18   1 1                                                        14
 3   4   4  17   7  1                                                       14
 3   4   4   5   1 1                                                        14
 3   4   4   5   2  1                                                       14
 1  10     100                                                              21
 4  18     100                                                              21
 1  12     100                                                              21
 1  11     100                                                              21
 5  20     100                                                              21
 2  13     100                                                              21
 3  16     100                                                              21
 5  19     100                                                              21
 2  14     100                                                              21
 3  15     100                                                              21
 4  17     100                                                              21
18   4  52 186 109    0                                                     21
19   5  13 629   0    0                                                     21
 4   5   0 690  20    0                                                     21
20   5  20   0  38    0                                                     21
```

```
   2   3   0 599  37   0                                                      21
   3   2  46 519 112   0                                                      21
  16   3  10  32  28   0                                                      21
   1   2   0 508  72   0                                                      21
   2   1  50 499  50   0                                                      21
  10   1  29 484  30   0                                                      21
  11   1  47  23  26   0                                                      21
  12   1  32  23  49   0                                                      21
  13   2   0 542  80   0                                                      21
  14   2   0 585  53   0                                                      21
  15   3  68  10  99   0                                                      21
   4   3   0 599  37   0                                                      21
  17   4  61 164  78   0                                                      21
   5   4  75 505  48   0                                                      21
   3   4  61 519  48   0                                                      21
8001  10     100                                                              21
8004  12     100                                                              21
8003  11     100                                                              21
8005  13     100                                                              21
8006  14     100                                                              21
8007  15     100                                                              21
8008  17     100                                                              21
8009  18     100                                                              21
8010  20     100                                                              21
8002  19     100                                                              21
8011  16     100                                                              21
   1   0  10  12   2  11       45   3   2  20   3   2                          35
   2  64   1  14   3  13       34   4   1  31   4   1                          35
   3  12   2  16   4  15       47   4   1  18   4   1                          35
   4  22   3  18   5  17       42   4   1  23   4   1                          35
   5      19   4  20                                                          35
  10       18001                                                              35
  11       18003                                                              35
  12       18004                                                              35
  13       28005                                                              35
  14       28006                                                              35
  15       38007                                                              35
  16       38011                                                              35
  17       48008                                                              35
  18       48009                                                              35
  19       58002                                                              35
  20       58010                                                              35
   1 1212 0202 2222 2121 2020 2222                                     1    2 36
   2 9212 0202 2222 2929 2020 2222                                     2    2 36
   3 9292 0202 2222 2121 2020 2222                                     3    2 36
   4 1212 0202 2222 2121 2020 2222                                     4    2 36
   5 111                                                                      36
  10 11                                                                       36
  11 11                                                                       36
  12 11                                                                       36
  13 11                                                                       36
  14 11                                                                       36
  15 11                                                                       36
  16 11                                                                       36
  17 11                                                                       36
  18 11                                                                       36
  19 11                                                                       36
```

```
  20 11                                                                       36
  10   1   12  13200   121    60  0                             1   1         42
   2   1   12      0   106    60  0                                           42
  10   1   12      0   102    60  0                                           42
  11   1   1       0   104    60  0                                           42
  12   1   1       0   108    60  0                                           42
   1   2   12   6650   162    60  0                             1   1         42
   1   2   12   6550   223   120  0                             1   2         42
   1   2   12      0   202    60  0                                           42
  13   2   12      0   204    60  0                                           42
   3   2   12      0   206    60  0                                           42
  14   2   12      0   208    60  0                                           42
   2   3   12  10050   264   120  0                             1   2         42
   2   3   12   9950   325   120  0                             1   3         42
   2   3   12      0   302    60  0                                           42
  16   3   1       0   308    60  0                                           42
  15   3   1       0   304    60  0                                           42
   4   3   12      0   306    60  0                                           42
  17   4   12      0   404    60  0                                           42
   5   4   12      0   406    60  0                                           42
   3   4   12      0   402    60  0                                           42
  18   4   12      0   408    60  0                                           42
   3   4   12   6550   366   120  0                             1   3         42
   3   4   12   6550   427   120  0                             1   4         42
   4   5   12   1900   468   120  0                             1   4         42
8001  10 557   0   0  100                                                     50
8009  18 347   0   0  100                                                     50
8004  12 104   0   0  100                                                     50
8003  11 102   0   0  100                                                     50
8010  20  58   0   0  100                                                     50
8005  13 622   0   0  100                                                     50
8011  16  70   0   0  100                                                     50
8002  19 642   0   0  100                                                     50
8006  14 638   0   0  100                                                     50
8007  15 177   0   0  100                                                     50
8008  17 295   0   0  100                                                     50
  16  40          100                     100   0 100   0  00             250  58
   4  18        14  14                                                        80
   1  12        15                                                            80
   1  11        15                                                            80
   5  20        14                                                            80
   2  13        14  14                                                        80
   3  16        14                                                            80
   5  19        14  14                                                        80
   2  14        14  14                                                        80
   3  15        14                                                            80
   4  17        14  14                                                        80
  18   4        14  14                  14                                    80
  19   5        14  14                  14                                    80
   4   5        14  14                                                        80
  20   5        14                                                            80
   2   3        14  14                                                        80
   3   2        14  14              14  14                                    80
  16   3        14                      14                                    80
   1   2        14  14                  14                                    80
   2   1        14  14                                                        80
  11   1        15                                                            80
```

```
  12   1      15                                                              80
  13   2      14  14                  14                                      80
  14   2      14  14                                                          80
  15   3      14                      14                                      80
   4   3      14  14                                                          80
  17   4      14  14                  14                                      80
   5   4      14  14                  14                                      80
   3   4      14  14                  14                                      80
   1  10   1   1   2   2   3   3   4   4   5   5  19                          90
   2  19   5   5   4   4   3   3   2   2   1   1  10                          90
   0                                                                         170
   18001  10   1   2   3   4   5  198002                                     187
   13600   0                                                                 189
8001       0     500                                                         195
8009    4500       0                                                         195
8004    2000       0                                                         195
8003    2000    1000                                                         195
8010    4800       0                                                         195
8005    2700    1000                                                         195
8011    3800       0                                                         195
8002    5800     500                                                         195
8006    2700       0                                                         195
8007    3800    1000                                                         195
8008    4500    1000                                                         195
   1    2000     500                                                         195
   2    2700     500                                                         195
   3    3800     500                                                         195
   4    4500     500                                                         195
   5    4800     500                                                         195
  10     300     500                                                         195
  11    2000     800                                                         195
  12    2000     200                                                         195
  13    2700     800                                                         195
  14    2700     200                                                         195
  15    3800     800                                                         195
  16    3800     200                                                         195
  17    4500     800                                                         195
  18    4500     200                                                         195
  19    5600     500                                                         195
  20    4800     200                                                         195
   1   0   3                                                                 210
```

APPENDIX B: SUMMARY OF TRAFFIC SIMULATION RUN RESULTS

The following is a list of the tables included in Appendix B which contain the results of the simulation runs performed in support of each transition strategy and traffic volume alternative that was analyzed in this research:

Table B.1.: Summary of Transition Strategies' Impacts - Base Traffic Volume

Alternative Strategy	Average Delay Sec./Veh.	Average Delay Std. Dev.	Average Delay Error of Mean	Average Delay Range in Error of Mean	Average Travel Time Sec./Veh.	Average Travel Time Std. Dev.	Average Travel Time Error of Mean	Average Travel Time Range in Error of Mean
Hold								
EB Travel	6.88	0.53	5.2%	4.7% - 6.0%	22.1	0.61	1.8%	1.6% - 2.4%
WB Travel	9.12	0.66	4.8%	3.1% - 8.9%	23.2	1.22	3.6%	1.3% - 3.6%
Network Avg.	27.2	1.20	3.0%	2.2% - 4.7%	67.9	1.76	1.8%	1.1% - 2.7%
Long								
EB Travel	6.63	0.51	5.1%	2.6% - 8.4%	21.9	0.56	1.7%	0.8% - 2.8%
WB Travel	9.09	0.79	5.7%	4.7% - 8.7%	24.1	0.76	2.1%	1.3% - 4.4%
Network Avg.	26.9	1.24	3.1%	2.2% - 4.1%	67.7	1.90	1.9%	1.2% - 2.3%
Short								
EB Travel	7.25	0.52	5.2%	4.0% - 6.3%	22.5	0.53	1.7%	1.4% - 2.0%
WB Travel	9.24	0.77	6.0%	3.1% - 8.7%	24.9	0.80	2.3%	1.1% - 3.6%
Network Avg.	29.1	1.54	3.8%	1.7% - 6.3%	70.0	2.16	2.2%	0.8% - 3.8%
Best Way								
EB Travel	6.21	0.61	6.7%	4.8% - 8.3%	21.4	0.66	2.1%	1.6% - 2.7%
WB Travel	7.64	0.67	6.0%	4.9% - 6.7%	23.3	0.71	2.1%	1.7% - 2.8%
Network Avg.	25.8	1.93	3.6%	3.0% - 4.8%	66.8	1.95	2.0%	1.4% - 2.6%

Notes:

1. Table summarizes the *impacts of the alternative strategies* to exit from preemption control on *base level* of traffic flow in *test network.*
2. The path of vehicle issuing the preemption request traveled in the eastbound direction.
3. The major movement of traffic in the test network is in the eastbound and westbound directions.
4. *Base* volumes were used in performing the simulation runs for these alternatives.
5. Error (E) calculated with respect to the mean MOE is based on a 90% confidence level.

Table B.2.: Impacts of Hold Strategy - Base Traffic Volume

Preemption Vehicle Release (Seconds into Signal Plan)	# Simulation Runs	Average Delay Sec./Veh.	Average Delay Std.Dev.	Average Delay Error of Mean	Average Travel Time Sec./Veh.	Average Travel Time Std. Dev.	Average Travel Time Error of Mean
EB:							
0 Seconds	10	6.31	0.52	5.1%	21.5	0.62	1.8%
15 Seconds	8	6.63	0.47	4.9%	21.9	0.49	1.6%
30 Seconds	8	6.53	0.44	4.7%	21.7	0.51	1.6%
45 Seconds	9	7.42	0.58	5.1%	22.7	0.64	1.8%
60 Seconds	8	7.51	0.65	6.0%	22.7	0.77	2.4%
Avg. EB	8.6	6.88	0.53	5.2%	22.1	0.61	1.8%
WB:							
0 Seconds	10	9.33	0.46	3.1%	24.9	0.53	1.3%
15 Seconds	8	9.48	0.50	3.7%	25.0	0.56	1.6%
30 Seconds	8	8.16	0.59	5.0%	23.7	0.60	1.8%
45 Seconds	9	10.88	0.74	4.4%	26.4	0.82	2.0%
60 Seconds	8	7.75	1.00	8.9%	23.2	1.22	3.6%
Avg. WB	8.6	9.12	0.66	4.8%	24.6	0.75	2.0%
Network Average:							
0 Seconds	10	27.0	1.06	2.4%	67.8	1.83	1.7%
15 Seconds	8	27.8	1.22	3.0%	68.9	1.54	1.5%
30 Seconds	8	26.1	0.82	2.2%	66.7	1.07	1.1%
45 Seconds	9	29.1	1.28	2.9%	69.5	1.93	1.8%
60 Seconds	7	25.9	1.63	4.7%	66.4	2.45	2.7%
Network Avg.:	8.4	27.2	1.20	3.0%	67.9	1.76	1.8%

Notes:

1. Table summarizes the impacts of *hold strategy* to exit from preemption control on *base level* of traffic flow within *test network*.
2. The path of vehicle issuing the preemption request traveled in the eastbound direction.
3. The major movement of traffic in the test network is in the eastbound and westbound directions.
4. *Base* volumes were used in performing the simulation runs.
5. Error (E) calculated with respect to the mean MOE is based on a 90% confidence level.

Table B.3.: Impacts of Long Strategy - Base Traffic Volume

Preemption Vehicle Release (Seconds into Signal Plan)	# Simulation Runs	**Average Delay** Sec./Veh.	**Average Delay** Std. Dev.	**Average Delay** Error of Mean	**Average Travel Time** Sec./Veh.	**Average Travel Time** Std. Dev.	**Average Travel Time** Error of Mean
EB:							
0 Seconds	8	6.47	0.78	8.4%	21.7	0.88	2.8%
15 Seconds	9	6.33	0.25	2.6%	21.7	0.25	0.8%
30 Seconds	9	6.66	0.57	5.6%	21.9	0.61	1.8%
45 Seconds	10	6.79	0.50	4.6%	22.0	0.55	1.5%
60 Seconds	8	6.89	0.46	4.6%	22.3	0.52	1.6%
Avg. EB	8.8	6.63	0.51	5.1%	21.9	0.56	1.7%
WB:							
0 Seconds	8	8.84	0.72	5.6%	21.6	0.77	2.5%
15 Seconds	9	8.86	0.58	4.3%	24.5	0.61	1.6%
30 Seconds	9	7.58	0.65	5.6%	23.1	0.46	1.3%
45 Seconds	10	9.39	0.64	4.2%	24.9	0.64	1.6%
60 Seconds	8	10.8	1.35	8.7%	26.2	1.32	3.5%
Avg. WB	8.8	9.09	0.79	5.7%	24.1	0.76	2.1%
Network Average:							
0 Seconds	8	26.4	1.44	3.8%	67.5	2.23	2.3%
15 Seconds	9	26.2	0.89	2.2%	66.1	1.21	1.2%
30 Seconds	9	25.4	0.96	2.5%	66.4	1.80	1.8%
45 Seconds	10	27.6	1.20	2.7%	68.8	2.03	1.8%
60 Seconds	8	29.1	1.73	4.1%	69.6	2.22	2.2%
Network Avg.:	8.8	26.9	1.24	3.1%	67.7	1.90	1.9%

Notes:

1. Table summarizes the impacts of *long way strategy* to exit from preemption control on b*ase level* of traffic flow in *test network* .
2. The path of vehicle issuing the preemption request traveled in the eastbound direction.
3. The major movement of traffic in the test network is in the eastbound and westbound directions.
4. *Base* volumes were used in performing the simulation runs.
5. Error (E) calculated with respect to the mean MOE is based on a 90% confidence level.

Table B.4.: Impacts of Short Strategy - Base Traffic Volume

Preemption Vehicle Release (Seconds into Signal Plan)	# Simulation Runs	Average Delay			Average Travel Time		
		Sec./Veh.	Std. Dev.	Error of Mean	Sec./Veh.	Std. Dev.	Error of Mean
EB:							
0 Seconds	7	7.71	0.54	5.2%	23.0	0.53	1.7%
15 Seconds	8	7.23	0.42	4.0%	22.5	0.44	1.4%
30 Seconds	8	7.03	0.47	4.6%	22.2	0.55	1.7%
45 Seconds	7	7.03	0.60	6.3%	22.3	0.60	2.0%
60 Seconds	7	7.23	0.58	5.9%	22.4	0.53	1.8%
Avg. EB	7.4	7.25	0.52	5.2%	22.5	0.53	1.7%
WB:							
0 Seconds	7	9.86	0.89	6.7%	25.4	0.74	2.2%
15 Seconds	8	8.94	0.74	5.7%	24.6	0.79	2.2%
30 Seconds	8	9.07	0.41	3.1%	24.7	0.40	1.1%
45 Seconds	7	8.81	1.03	8.7%	24.4	1.20	3.6%
60 Seconds	7	9.52	0.79	6.1%	25.2	0.87	2.6%
Avg. WB	7.4	9.24	0.77	6.0%	24.9	0.80	2.3%
Network Average:							
0 Seconds	7	29.3	1.46	3.7%	69.8	2.34	2.5%
15 Seconds	8	30.9	1.34	3.0%	72.3	1.84	1.8%
30 Seconds	8	28.2	0.70	1.7%	69.1	0.77	0.8%
45 Seconds	7	28.8	2.44	6.3%	69.6	3.53	3.8%
60 Seconds	7	28.2	1.76	4.6%	69.2	2.32	2.5%
Network Avg.:	7.4	29.1	1.54	3.8%	70.0	2.16	2.2%

Notes:

1. Table summarizes impacts of the *short way strategy* to exit from preemption control on *base level* of traffic flow in *test network*.
2. The path of vehicle issuing the preemption request traveled in the eastbound direction.
3. The major movement of traffic in the test network is in the eastbound and westbound directions.
4. *Base* volumes were used in performing the simulation runs.
5. Error (E) calculated with respect to the mean MOE is based on a 90% confidence level.

Table B.5.: Impacts of Best Way Strategy - Base Traffic Volume

Preemption Vehicle Release (Seconds into Signal Plan)	# Simulation Runs	**Average Delay** Sec./Veh.	Std. Dev.	Error of Mean	**Average Travel Time** Sec./Veh.	Std. Dev.	Error of Mean
EB:							
0 Seconds	8	6.63	0.46	4.8%	21.9	0.52	1.6%
15 Seconds	9	6.40	0.53	5.4%	21.6	0.54	1.6%
30 Seconds	9	5.40	0.61	7.4%	20.6	0.63	2.0%
45 Seconds	8	5.59	0.67	8.3%	20.4	0.79	2.7%
60 Seconds	7	7.01	0.78	8.2%	22.3	0.81	2.7%
Avg. EB	8.2	6.21	0.61	6.7%	21.4	0.66	2.1%
WB:							
0 Seconds	8	7.94	0.77	6.7%	23.5	0.86	2.5%
15 Seconds	9	7.11	0.63	5.8%	22.8	0.61	1.7%
30 Seconds	9	6.83	0.57	5.5%	22.5	0.59	1.7%
45 Seconds	8	8.56	0.88	7.1%	24.1	0.98	2.8%
60 Seconds	7	7.78	0.51	4.9%	23.5	0.53	1.7%
Avg. WB	8.2	7.64	0.67	6.0%	23.3	0.71	2.1%
Network Average:							
0 Seconds	8	26.2	1.80	4.8%	67.1	2.51	2.6%
15 Seconds	9	27.1	1.43	3.4%	68.4	2.11	2.0%
30 Seconds	9	23.1	1.05	3.0%	63.9	1.36	1.4%
45 Seconds	9	26.2	1.39	3.5%	67.2	1.87	1.8%
60 Seconds	7	26.5	1.26	3.5%	67.5	1.88	2.1%
Network Avg.:	8.4	25.8	1.39	3.6%	66.8	1.95	2.0%

Notes:

1. Table summarizes impacts of the *best way strategy* to exit from preemption control on *base level* of traffic flow in *base network*.
2. The path of vehicle issuing the preemption request traveled in the eastbound direction.
3. The major movement of traffic in the test network is in the eastbound and westbound directions.
4. *Base* volumes were used in performing the simulation runs.
5. Error (E) calculated with respect to the mean MOE is based on a 90% confidence level.

Table B.6.: Summary of Transition Strategies' Impacts - 20% Increase Base Traffic Volume

Alternative	**Average Delay**			Range in	**Average Travel Time**			Range in
Strategy	Sec./Veh.	Std. Dev.	Error of Mean	Error of Mean	Sec./Veh.	Std. Dev.	Error of Mean	Error of Mean
Hold								
EB	6.43	0.48	5.1%	2.8% - 8.7%	21.7	0.56	1.8%	1.1% - 2.6%
WB	9.13	0.71	5.3%	3.7% - 8.3%	24.6	0.72	2.0%	1.7% - 3.2%
Total	27.0	1.22	3.1%	2.1% - 4.1%	68.0	1.72	1.8%	1.6% - 2.9%
Long								
EB	6.69	0.51	5.3%	3.3% - 8.3%	21.9	0.51	1.6%	0.8% - 2.7%
WB	9.11	0.78	6.0%	5.5% - 7.5%	24.6	0.85	2.4%	1.9% - 4.0%
Total	27.1	1.27	3.3%	2.7% - 4.4%	68.0	1.62	1.7%	1.2% - 2.3%
Short								
EB	7.24	0.55	5.3%	2.6% - 6.6%	22.4	0.65	2.0%	1.1% - 2.6%
WB	9.03	0.65	5.1%	3.5% - 7.0%	24.6	0.70	2.0%	1.1% - 3.0%
Total	28.5	1.29	3.2%	2.2% - 3.7%	69.1	1.67	1.7%	1.2% - 2.2%
Best Way								
EB	5.92	0.53	6.1%	4.2% - 8.1%	21.2	0.54	1.7%	1.3% - 2.4%
WB	7.30	0.59	5.0%	4.8% - 7.0%	22.9	0.67	2.0%	1.6% - 2.5%
Total	24.3	1.38	3.8%	3.3% - 4.9%	65.2	1.72	1.8%	1.5% - 2.0%

Notes:

1. Table summarizes the impacts of 20*% increase in base level of traffic volume* on the influence *alternative strategies* to exit from preemption control have on the flow of traffic in the test network.
2. The path of vehicle issuing the preemption request traveled in the eastbound direction.
3. The major movement of traffic in the test network is in the eastbound and westbound directions.
4. 20*% increase* base volumes were used in performing the simulation runs for these alternatives.
5. Error (E) calculated with respect to the mean MOE is based on a 90% confidence level.

Table B.7.: Impacts of Hold Strategy - 20% Increase Base Traffic Volume

Preemption Vehicle Release (Seconds into Signal Plan)	# Simulation Runs	**Average Delay** Sec./Veh.	**Average Delay** Std. Dev.	**Average Delay** Error of Mean	**Average Travel Time** Sec./Veh.	**Average Travel Time** Std. Dev.	**Average Travel Time** Error of Mean
EB:							
0 Seconds	7	7.03	0.60	6.3%	22.3	0.77	2.6%
15 Seconds	8	6.63	0.47	4.9%	21.9	0.49	1.6%
30 Seconds	9	5.87	0.78	8.7%	21.1	0.75	2.3%
45 Seconds	8	5.96	0.25	2.9%	21.1	0.39	1.3%
60 Seconds	9	6.62	0.28	2.8%	21.9	0.38	1.1%
Avg. EB	8.2	6.42	0.48	5.1%	21.7	0.56	1.8%
WB:							
0 Seconds	7	8.25	0.56	5.0%	23.8	0.54	1.7%
15 Seconds	8	9.48	0.5	3.7%	25.0	0.57	1.6%
30 Seconds	9	9.63	1.22	8.3%	25.0	1.12	2.9%
45 Seconds	8	9.43	0.62	4.6%	25.0	0.70	1.9%
60 Seconds	9	8.88	0.64	4.7%	24.4	0.68	1.8%
Avg. WB	8.2	9.13	0.71	5.3%	24.6	0.72	2.0%
Network Average:							
0 Seconds	7	26.7	1.45	4.0%	67.8	1.63	1.8%
15 Seconds	8	27.8	1.22	3.0%	68.8	1.54	1.6%
30 Seconds	9	26.7	1.66	4.1%	67.3	2.59	2.5%
45 Seconds	8	26.9	1.12	2.9%	68.2	1.65	1.7%
60 Seconds	9	26.9	0.86	2.1%	67.8	1.37	1.3%
Network Avg.:	8.2	27.1	1.22	3.1%	68.0	1.79	1.8%

Notes:

1. Table summarizes the impacts of 20*% increase in the base level of traffic volume* on the influence the *hold strategy* to exit from preemption control has on the flow of traffic in the test network.
2. The path of vehicle issuing the preemption request traveled in the eastbound direction.
3. The major movement of traffic in the test network is in the eastbound and westbound directions.
4. 20*% increase* in base volumes were used in performing the simulation runs and analysis.
5. Error (E) calculated with respect to the mean MOE is based on a 90% confidence level.

Table B.8.: Influence of Long Strategy - 20% Increase Base Traffic Volume

Preemption Vehicle Release (Seconds into Signal Plan)	# Simulation Runs	**Average Delay** Sec./Veh.	Std. Dev.	Error of Mean	**Average Travel Time** Sec./Veh.	Std. Dev.	Error of Mean
EB:							
0 Seconds	7	6.19	0.28	3.4%	21.5	0.23	0.8%
15 Seconds	8	6.34	0.30	3.3%	21.6	0.27	0.9%
30 Seconds	7	6.98	0.78	8.3%	22.1	0.82	2.7%
45 Seconds	8	7.27	0.49	4.7%	22.5	0.51	1.6%
60 Seconds	9	6.66	0.68	6.7%	21.8	0.72	2.2%
Avg. EB	7.8	6.69	0.51	5.3%	21.9	0.51	1.6%
WB:							
0 Seconds	7	7.97	0.59	5.5%	23.5	0.59	1.9%
15 Seconds	8	8.54	0.92	7.5%	24.1	0.94	2.7%
30 Seconds	7	10.5	0.79	5.6%	25.8	1.06	3.0%
45 Seconds	8	9.89	0.86	6.0%	25.4	0.84	2.3%
60 Seconds	9	8.64	0.74	5.6%	24.3	0.81	2.2%
Avg. WB	7.8	9.11	0.78	6.0%	24.6	0.85	2.4%
Network Average:							
0 Seconds	7	25.0	1.01	3.0%	65.6	1.58	1.8%
15 Seconds	8	26.2	1.12	3.0%	67.2	1.35	1.4%
30 Seconds	7	28.9	1.28	3.3%	69.7	1.52	1.6%
45 Seconds	8	28.6	1.12	2.7%	69.4	1.23	1.2%
60 Seconds	9	26.6	1.81	4.4%	67.9	2.44	2.3%
Network Avg.:	7.8	27.1	1.27	3.3%	68.0	1.62	1.7%

Notes:

1. Table summarizes the impacts of 20*% increase in the base level of traffic volume* on the influence the *long strategy* to exit from preemption control has on the flow of traffic in the test network.
2. The path of vehicle issuing the preemption request traveled in the eastbound direction.
3. The major movement of traffic in the test network is in the eastbound and westbound directions.
4. 20*% increase* in base volumes were used in performing the simulation runs and analysis.
5. Error (E) calculated with respect to the mean MOE is based on a 90% confidence level.

Table B.9.: Impact of Short Strategy - 20% Increase Base Traffic Volume

Preemption Vehicle Release (Seconds into Signal Plan)	# Simulation Runs	**Average Delay** Sec./Veh.	Std. Dev.	Error of Mean	**Average Travel Time** Sec./Veh.	Std. Dev.	Error of Mean
EB:							
0 Seconds	8	7.05	0.59	5.8%	22.3	0.69	2.1%
15 Seconds	7	7.30	0.26	2.6%	22.5	0.32	1.1%
30 Seconds	8	7.34	0.68	6.4%	22.6	0.68	2.1%
45 Seconds	9	7.21	0.57	5.2%	22.2	0.89	2.6%
60 Seconds	7	7.31	0.65	6.6%	22.5	0.65	2.1%
Avg. EB	7.8	7.24	0.55	5.3%	22.4	0.65	2.0%
WB:							
0 Seconds	8	9.05	0.60	4.6%	24.7	0.66	1.9%
15 Seconds	7	9.19	0.80	6.4%	24.8	0.99	3.0%
30 Seconds	8	9.27	0.52	3.9%	24.8	0.54	1.5%
45 Seconds	9	8.62	0.93	7.0%	24.1	0.95	2.6%
60 Seconds	7	9.00	0.42	3.5%	24.6	0.37	1.1%
Avg. WB	7.8	9.03	0.65	5.1%	24.6	0.70	2.0%
Network Average							
0 Seconds	8	28.3	0.89	2.2%	69.1	1.24	1.2%
15 Seconds	7	28.8	1.38	3.5%	69.4	2.05	2.2%
30 Seconds	8	28.8	1.37	3.3%	69.6	1.46	1.5%
45 Seconds	9	27.8	1.38	3.2%	68.1	1.81	1.7%
60 Seconds	7	28.6	1.42	3.7%	69.1	1.81	1.9%
Network Avg.:	7.8	28.5	1.29	3.2%	69.1	1.67	1.7%

Notes:

1. Table summarizes the impacts of 20*% increase in base level of traffic volume* on the influence the *short way strategy* to exit from preemption control has on the flow of traffic in the test network.
2. The path of vehicle issuing the preemption request traveled in the eastbound direction.
3. The major movement of traffic in the test network is in the eastbound and westbound directions.
4. 20*% increase* in base volumes were used in performing the simulation runs and analysis performed.
5. Error (E) calculated with respect to the mean MOE is based on a 90% confidence level.

Table B.10.: Impacts of Best Way Strategy - 20% Increase Base Traffic Volume

Preemption Vehicle Release (Seconds into Signal Plan)	# Simulation Runs	**Average Delay** Sec./Veh.	Std. Dev.	Error of Mean	**Average Travel Time** Sec./Veh.	Std. Dev.	Error of Mean
EB:							
0 Seconds	7	5.74	0.63	8.13%	21.0	0.69	2.43%
15 Seconds	8	6.89	0.42	4.22%	22.1	0.48	1.51%
30 Seconds	10	5.55	0.50	5.58%	20.7	0.50	1.50%
45 Seconds	9	5.98	0.66	7.21%	21.3	0.66	2.02%
60 Seconds	8	5.46	0.46	5.84%	20.7	0.39	1.31%
Avg. EB	8.4	5.92	0.53	6.10%	21.2	0.54	1.74%
WB:							
0 Seconds	7	7.88	0.58	5.45%	23.4	0.66	2.09%
15 Seconds	8	7.67	0.77	6.96%	23.3	0.83	2.47%
30 Seconds	10	6.80	0.53	4.83%	22.3	0.59	1.64%
45 Seconds	9	7.30	0.58	5.19%	22.9	0.63	1.80%
60 Seconds	8	6.86	0.51	5.15%	22.5	0.62	1.91%
Avg. WB	8.4	7.30	0.59	5.50%	22.9	0.67	1.97%
Network Average:							
0 Seconds	7	24.7	1.15	3.45%	65.1	1.53	1.74%
15 Seconds	8	25.7	1.24	3.34%	66.5	1.90	1.98%
30 Seconds	10	23.8	1.46	3.80%	64.3	1.59	1.53%
45 Seconds	9	23.4	1.36	3.80%	65.1	1.74	1.75%
60 Seconds	8	23.7	1.68	4.91%	64.8	1.84	1.97%
Network Totals	8.4	24.3	1.38	3.84%	65.2	1.72	1.79%

Notes:

1. Table summarizes the impacts of 20*% increase in base level of traffic volume* on the influence the *best way strategy* to exit from preemption control has on the flow of traffic in the test network.
2. The path of vehicle issuing the preemption request traveled in the eastbound direction.
3. The major movement of traffic in the test network is in the eastbound and westbound directions.
4. 20*% increase* in base volumes were used in performing the simulation runs and analysis performed.
5. Error (E) calculated with respect to the mean MOE is based on a 90% confidence level.

Table B.11.: Summary of Transition Strategies' Impacts - 40% Increase Base Traffic Volume

Alternative	**Average Delay**			Range in	**Average Travel Time**			Range in
Strategy	Sec./Veh.	Std. Dev.	Error of Mean	Error of Mean	Sec./Veh.	Std. Dev.	Error of Mean	Error of Mean
Hold								
EB	6.24	0.52	5.6%	3.6% - 8.5%	21.5	0.51	1.6%	0.9% - 2.5%
WB	8.97	0.73	5.5%	3.6% - 8.7%	24.6	0.95	2.6%	1.1% - 5.0%
Total	26.3	1.07	2.7%	1.6% - 4.0%	67.3	1.40	1.4%	0.8% - 2.0%
Long								
EB	6.33	0.53	5.5%	3.1% - 7.8%	21.6	0.56	1.7%	0.9% - 2.3%
WB	8.81	0.63	4.7%	2.7% - 7.4%	24.4	0.60	1.6%	1.0% - 2.7%
Total	26.2	1.06	2.6%	1.4% - 3.9%	67.2	1.64	1.6%	1.1% - 2.4%
Short								
EB	7.50	0.50	4.4%	2.6% - 5.7%	22.8	0.55	1.6%	0.8% - 2.4%
WB	9.91	0.66	4.4%	1.7% - 5.6%	25.6	0.69	1.7%	0.5% - 2.4%
Total	29.0	1.29	2.9%	2.5% - 3.8%	70.0	1.82	1.8%	1.5% - 2.6%
Best Way								
EB	6.51	0.52	5.4%	3.0% - 8.4%	21.6	0.61	1.9%	1.4% - 2.5%
WB	8.02	0.64	5.4%	3.3% - 7.1%	23.7	0.66	1.9%	1.1% - 2.4%
Total	26.6	1.47	3.7%	2.4% - 5.0%	68.2	2.27	2.3%	1.5% - 3.1%

Notes:

1. Table summarizes the impacts of *40% increase in base level of traffic volume* on the influence *alternative strategies* to exit from preemption control have on the flow of traffic in the test network.
2. The path of vehicle issuing the preemption request traveled in the eastbound direction.
3. The major movement of traffic in the test network is in the eastbound and westbound directions.
4. *40% increase base volumes* were used in performing the simulation runs for these alternatives.
5. Error (E) calculated with respect to the mean MOE is based on a 90% confidence level.

Table B.12.: Impacts of Hold Strategy - 40% Increase Base Traffic Volume

Preemption Vehicle Release			**Average Delay**			**Average Travel Time**	
(Seconds into Signal Plan)	# Simulation Runs	Sec./Veh.	Std. Dev.	Error of Mean	Sec./Veh.	Std. Dev.	Error of Mean
EB:							
0 Seconds	7	5.16	0.59	8.5%	20.3	0.58	2.1%
15 Seconds	10	6.44	0.42	4.0%	22.3	0.34	0.9%
30 Seconds	7	6.62	0.45	5.0%	21.7	0.47	1.6%
45 Seconds	8	6.59	0.76	8.0%	21.8	0.80	2.5%
60 Seconds	10	6.38	0.37	3.6%	21.6	0.36	1.0%
Avg. EB	8.4	6.24	0.52	5.6%	21.5	0.51	1.6%
WB:							
0 Seconds	7	9.91	1.17	8.7%	25.0	1.68	5.0%
15 Seconds	10	9.25	0.39	2.6%	25.0	0.43	1.1%
30 Seconds	7	8.25	0.51	4.6%	24.6	0.99	3.0%
45 Seconds	8	8.23	0.94	7.9%	23.8	0.92	2.7%
60 Seconds	10	9.19	0.65	4.4%	24.8	0.72	1.8%
Avg. WB	8.4	8.97	0.73	5.5%	24.6	0.95	2.6%
Network Average:							
0 Seconds	7	26.3	1.12	3.2%	67.6	1.61	1.8%
15 Seconds	10	26.8	0.96	2.2%	68.1	1.43	1.3%
30 Seconds	7	25.8	1.06	3.0%	66.4	1.22	1.4%
45 Seconds	8	25.8	1.48	4.0%	66.7	1.91	2.0%
60 Seconds	10	26.9	0.71	1.6%	67.8	0.83	0.8%
Network Avg.:	8.4	26.3	1.07	2.7%	67.3	1.40	1.4%

Notes:

1. Table summarizes the impacts of *40% increase in base level of traffic volume* on the influence of the *hold strategy* to exit from preemption control has on the flow of traffic in the test network.
2. The path of vehicle issuing the preemption request traveled in the eastbound direction.
3. The major movement of traffic in the test network is in the eastbound and westbound directions.
4. 40*% increase* in base volumes were used in performing the simulation runs and analysis.
5. Error (E) calculated with respect to the mean MOE is based on a 90% confidence level.

Table B.13.: Impacts of Long Strategy - 40% Increase Base Traffic Volume

Preemption Vehicle Release (Seconds into Signal Plan)	# Simulation Runs	**Average Delay** Sec./Veh.	Std. Dev.	Error of Mean	**Average Travel Time** Sec./Veh.	Std. Dev.	Error of Mean
EB:							
0 Seconds	8	6.21	0.63	7.0%	21.5	0.71	2.3%
15 Seconds	9	6.16	0.74	7.8%	21.4	0.75	2.3%
30 Seconds	9	6.50	0.54	5.4%	21.7	0.51	1.5%
45 Seconds	9	6.39	0.30	3.1%	21.6	0.31	0.9%
60 Seconds	10	6.37	0.44	4.3%	21.7	0.53	1.5%
Avg. EB	9	6.33	0.53	5.5%	21.6	0.56	1.7%
WB:							
0 Seconds	8	8.83	0.51	4.0%	24.5	0.36	1.0%
15 Seconds	9	9.20	0.60	4.3%	24.9	0.56	1.5%
30 Seconds	9	8.28	0.94	7.4%	23.9	0.97	2.7%
45 Seconds	9	8.61	0.69	5.2%	24.1	0.71	1.9%
60 Seconds	10	9.12	0.40	2.7%	24.7	0.41	1.0%
Avg. WB	9	8.81	0.63	4.7%	24.4	0.60	1.6%
Network Totals							
0 Seconds	8	26.3	0.85	2.2%	67.7	1.32	1.4%
15 Seconds	9	26.5	1.06	2.6%	67.3	1.50	1.5%
30 Seconds	9	25.6	1.27	3.2%	66.5	1.93	1.9%
45 Seconds	9	26.2	1.55	3.9%	66.8	2.48	2.4%
60 Seconds	10	26.6	0.58	1.4%	67.5	1.22	1.1%
Network Avg.:	9	26.2	1.06	2.6%	67.2	1.69	1.6%

Notes:

1. Table summarizes the impacts of 40*% increase in base level of traffic volume* on the influence of the *long way strategy* to exit from preemption control has on the flow of traffic in the test network.
2. The path of vehicle issuing the preemption request traveled in the eastbound direction.
3. The major movement of traffic in the test network is in the eastbound and westbound directions.
4. 40*% increase* in base volumes were used in performing the simulation runs and analysis.
5. Error (E) calculated with respect to the mean MOE is based on a 90% confidence level.

Table B.13.: Impacts of Short Strategy - 40% Increase Base Traffic Volume

Preemption Vehicle Release (Seconds into Signal Plan)	# Simulation Runs	Average Delay Sec./Veh.	Average Delay Std. Dev.	Average Delay Error of Mean	Average Travel Time Sec./Veh.	Average Travel Time Std. Dev.	Average Travel Time Error of Mean
EB:							
0 Seconds	10	7.63	0.48	3.9%	23.0	0.52	1.4%
15 Seconds	9	7.48	0.63	5.5%	22.7	0.82	2.4%
30 Seconds	9	7.75	0.31	2.6%	23.3	0.28	0.8%
45 Seconds	9	7.23	0.63	5.7%	22.5	0.61	1.8%
60 Seconds	7	7.42	0.47	4.7%	22.6	0.51	1.7%
Totals EB	8.8	7.50	0.50	4.4%	22.8	0.55	1.6%
WB:							
0 Seconds	10	9.93	0.77	4.8%	25.6	0.81	2.0%
15 Seconds	9	10.1	0.76	4.9%	25.7	0.82	2.1%
30 Seconds	9	10.2	0.80	5.1%	25.9	0.80	2.0%
45 Seconds	9	9.34	0.24	1.7%	24.9	0.20	0.5%
60 Seconds	7	10.0	0.75	5.6%	25.7	0.83	2.4%
Totals WB	8.8	9.91	0.66	4.4%	25.6	0.69	1.8%
Network Average:							
0 Seconds	10	28.7	1.17	2.5%	69.2	1.54	1.4%
15 Seconds	9	29.5	1.15	2.5%	70.7	1.46	1.3%
30 Seconds	9	29.7	1.50	3.3%	71.0	2.10	1.9%
45 Seconds	9	28.0	1.15	2.7%	68.9	1.49	1.4%
60 Seconds	7	29.2	1.49	3.8%	70.4	2.50	2.6%
Network Avg.:	8.8	29.0	1.29	2.9%	70.0	1.82	1.7%

Notes:

1. Table summarizes the impacts of 40*% increase in base level of traffic volume* on the influence of the *short way strategy* to exit from preemption control has on the flow of traffic in the test network.
2. The path of vehicle issuing the preemption request traveled in the eastbound direction.
3. The major movement of traffic in the test network is in the eastbound and westbound directions.
4. 40*% increase* in base volumes were used in performing the simulation runs and analysis performed.
5. Error (E) calculated with respect to the mean MOE is based on a 90% confidence level.

Table B.15.: Impacts of Best Way Strategy - 40% Increase Base Traffic Volume

Preemption Vehicle Release (Seconds into Signal Plan)	# Simulation Runs	**Average Delay** Sec./Veh.	Std. Dev.	Error of Mean	**Average Travel Time** Sec./Veh.	Std. Dev.	Error of Mean
EB:							
0 Seconds	7	6.58	0.43	4.8%	21.8	0.52	1.8%
15 Seconds	8	6.88	0.45	4.5%	22.1	0.46	1.4%
30 Seconds	9	6.37	0.66	6.8%	21.6	0.64	1.9%
45 Seconds	8	5.84	0.71	8.4%	21.0	0.76	2.5%
60 Seconds	10	6.90	0.33	3.0%	21.7	0.69	2.0%
Avg. EB	8.4	6.51	0.52	5.4%	21.6	0.61	1.9%
WB:							
0 Seconds	7	8.00	0.77	7.1%	23.7	0.77	2.4%
15 Seconds	8	7.08	0.57	5.6%	22.7	0.59	1.8%
30 Seconds	9	8.03	0.54	4.4%	23.7	0.69	1.9%
45 Seconds	8	9.03	0.88	6.8%	24.7	0.84	2.4%
60 Seconds	10	7.94	0.42	3.3%	23.5	0.42	1.1%
Avg. WB	8.4	8.02	0.64	5.4%	23.7	0.66	1.9%
Network Average:							
0 Seconds	7	26.0	1.74	5.0%	67.6	2.45	2.7%
15 Seconds	8	27.9	1.54	3.8%	68.8	2.16	2.2%
30 Seconds	9	25.9	1.31	3.3%	68.1	3.25	3.1%
45 Seconds	8	27.2	1.74	4.4%	69.3	1.86	1.9%
60 Seconds	10	26.1	1.00	2.4%	67.3	1.65	1.5%
Network Avg.:	8.4	26.6	1.47	3.7%	68.2	2.27	2.3%

Notes:

1. Table summarizes the impacts of 40*% increase in base level of traffic volume* on the influence the *best way strategy* to exit from preemption control has on the flow of traffic in the test network.
2. The path of vehicle issuing the preemption request traveled in the eastbound direction.
3. The major movement of traffic in the test network is in the eastbound and westbound directions.
4. 40*% increase* in base volumes were used in performing the simulation runs and analysis performed.
5. Error (E) calculated with respect to the mean MOE is based on a 90% confidence level.

Table B.16.: Comparison of Increases to Traffic Volume on Transition Strategies

Alternative Strategies	**Hold**		**Long**		**Short**		**Best Way**	
	Avg. Delay Sec./Veh	Avg. Travel Time Sec./Veh.	Avg. Delay Sec./Veh	Avg. Travel Time Sec./Veh.	Avg. Delay Sec./Veh	Avg. Travel Time Sec./Veh.	Avg. Delay Sec./Veh	Avg. Travel Time Sec./Veh.
Numerical Results								
Base volumes	27.2	67.9	26.9	67.7	29.1	70.0	25.8	66.8
Base +20% increase	27.0	68.0	27.1	68.0	28.5	69.1	24.3	65.2
Base +40% increase	26.3	67.6	26.2	67.2	29.0	70.0	26.6	68.2
Standard Deviation								
Base volumes	1.20	1.76	1.24	1.90	1.54	2.16	1.93	1.95
Base +20% increase	1.22	1.79	1.27	1.62	1.29	1.67	1.38	1.72
Base +40% increase	1.07	1.40	1.06	1.64	1.29	1.82	1.47	2.27

Notes:

1. Table compares the impact of *varying levels of traffic volumes* on the influence of each *alternative strategy*
2. The path of vehicle issuing the preemption request traveled in the eastbound direction.
3. The major movement of traffic in the test network is in the eastbound and westbound directions.
4. *Base, 20% and 40% Increases* in volumes were used in performing the simulation runs for these alternatives.

APPENDIX C: IMPACTS OF TRANSITION STRATEGIES

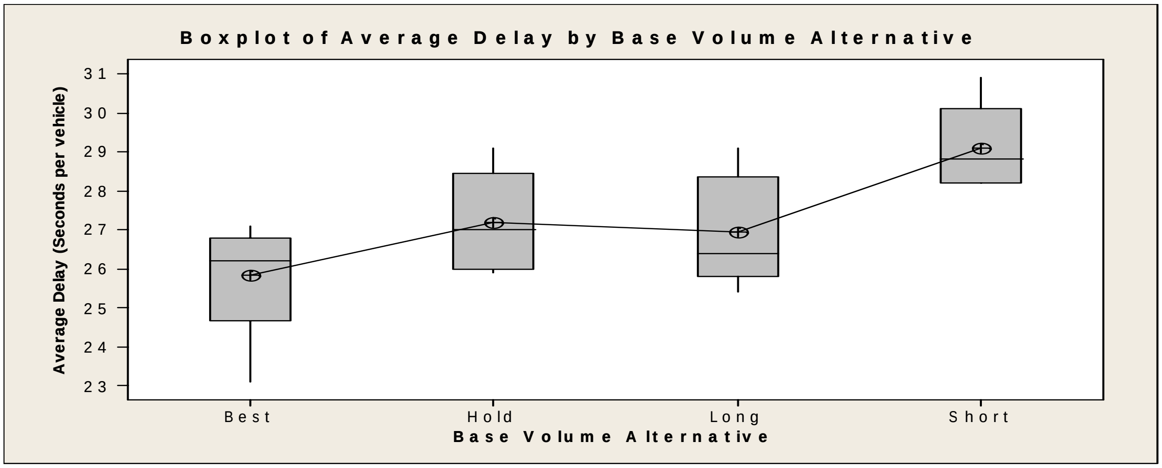
The following is a list of the tables included in Appendix C which contain the results of the simulation runs, one-way statistical analysis, and comparison performed in support of assessing the impacts of each transition strategy on the flow of traffic in the test network for each traffic volume alternative analyzed in this research:

Table C.1. Base Volume Alternative - Average Delay: One-way ANOVA

```
Source            DF     SS    MS      F      P
Base Volume Alte   3  27.47  9.16  4.88  0.013
Error             16  30.00  1.87
Total             19  57.47
S = 1.369   R-Sq = 47.81%   R-Sq(adj) = 38.02%
                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level  N    Mean  StDev  -------+---------+---------+---------+--
Best   5  25.820  1.564  (--------*--------)
Hold   5  27.180  1.314            (-------*--------)
Long   5  26.940  1.442          (--------*-------)
Short  5  29.080  1.117                        (--------*--------)
                         -------+---------+---------+---------+--
                             25.5      27.0      28.5      30.0

Pooled StDev = 1.369
```

Average Delay MOE

Comparison of Alternative Transition Strategies	X_1 Avg. Delay	X_1 Stnd. Dev.	X_2 Avg. Delay	X_2 Stnd. Dev.	T – Test	Is There a Significant Difference in Means?
Best - Hold	25.820	1.564	27.180	1.314	-1.49	No - 1.49 < 1.860
Best - Long	25.820	1.564	26.940	1.442	-1.18	No - 1.18 < 1.860
Best - Short	25.820	1.564	29.080	1.117	-3.79	Yes - 3.79 > 1.860
Hold - Long	27.180	1.314	26.940	1.442	0.28	No - 0.28 < 1.860
Hold - Short	27.180	1.314	29.080	1.117	-2.46	Yes - 2.46 > 1.860
Long - Short	26.940	1.442	29.080	1.117	-2.62	Yes - 2.62 > 1.860



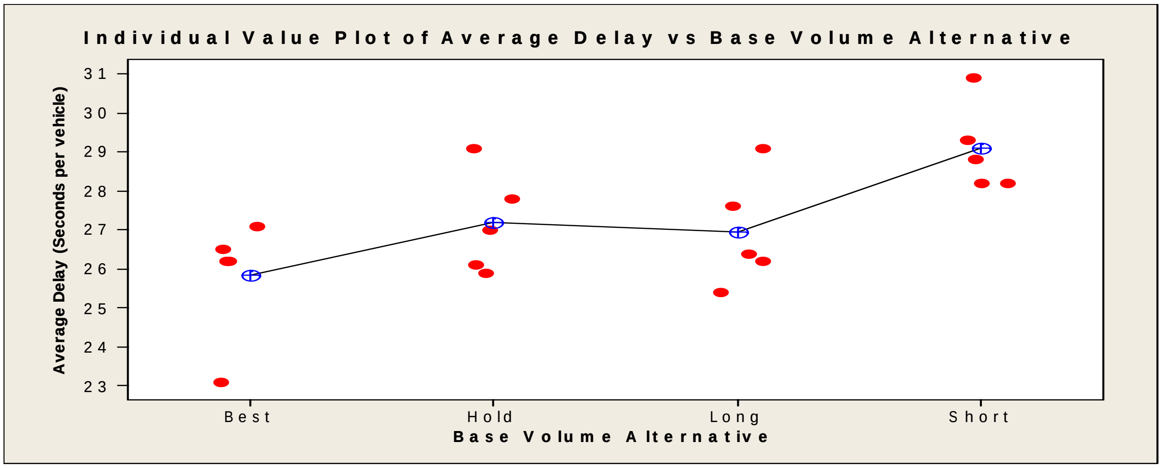
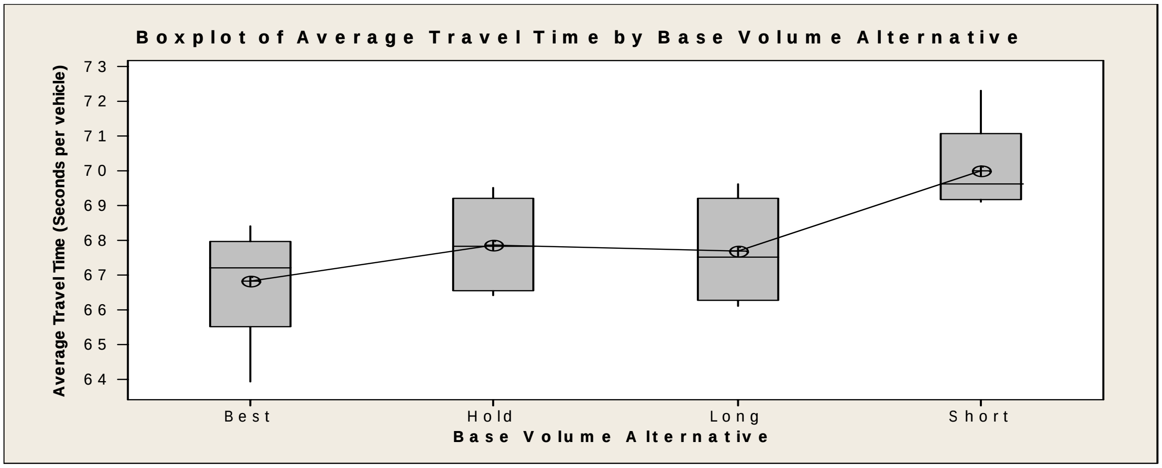


Table C.2. Base Volume Alternative - Average Travel Time: One-way ANOVA

```
Source            DF     SS    MS     F      P
Base Volume Alte   3  27.41  9.14  4.18  0.023
Error             16  35.01  2.19
Total             19  62.42
S = 1.479   R-Sq = 43.91%   R-Sq(adj) = 33.40%

                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level  N    Mean  StDev  ----+---------+---------+---------+-----
Best   5  66.820  1.711  (--------*---------)
Hold   5  67.860  1.346         (--------*---------)
Long   5  67.680  1.509        (--------*---------)
Short  5  70.000  1.317                       (---------*--------)
                         ----+---------+---------+---------+-----
                          66.0      67.5      69.0      70.5

Pooled StDev = 1.479
```

Comparison of Alternative Transition Strategies	X_1 Avg. Travel Time	X_1 Stnd. Dev.	X_2 Avg. Travel Time	X_2 Stnd. Dev.	T - Test	Is There a Significant Difference in Means?
Best - Hold	66.820	1.711	67.860	1.346	-1.07	No - 1.07 < 1.860
Best - Long	66.820	1.711	67.680	1.509	-0.84	No - 0.84 < 1.860
Best - Short	66.820	1.711	70.000	1.317	-3.29	Yes - 3.29 > 1.860
Hold - Long	67.860	1.346	67.680	1.509	0.20	No - 0.20 < 1.860
Hold - Short	67.860	1.346	70.000	1.317	-2.54	Yes - 2.54 > 1.860
Long - Short	67.680	1.509	70.000	1.317	-2.59	Yes - 2.59 > 1.860



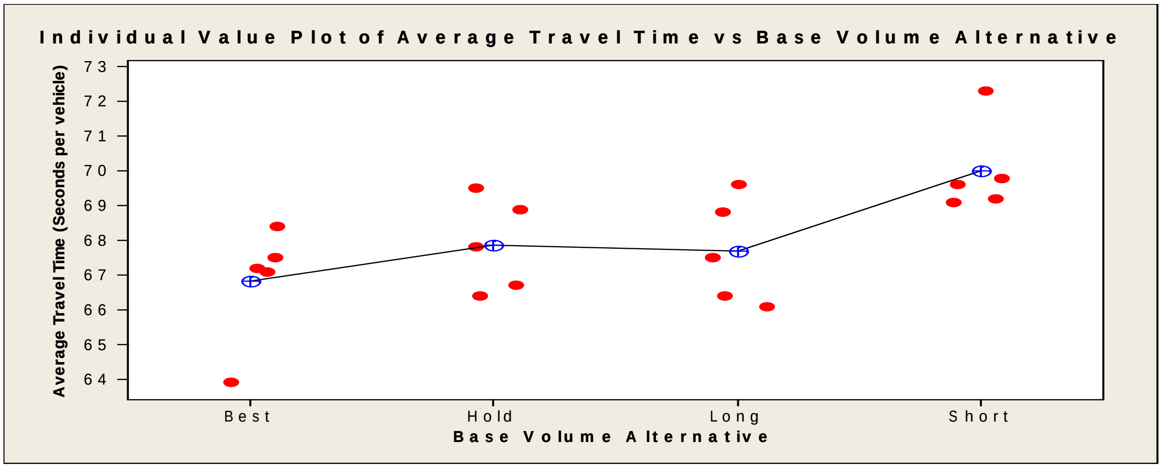
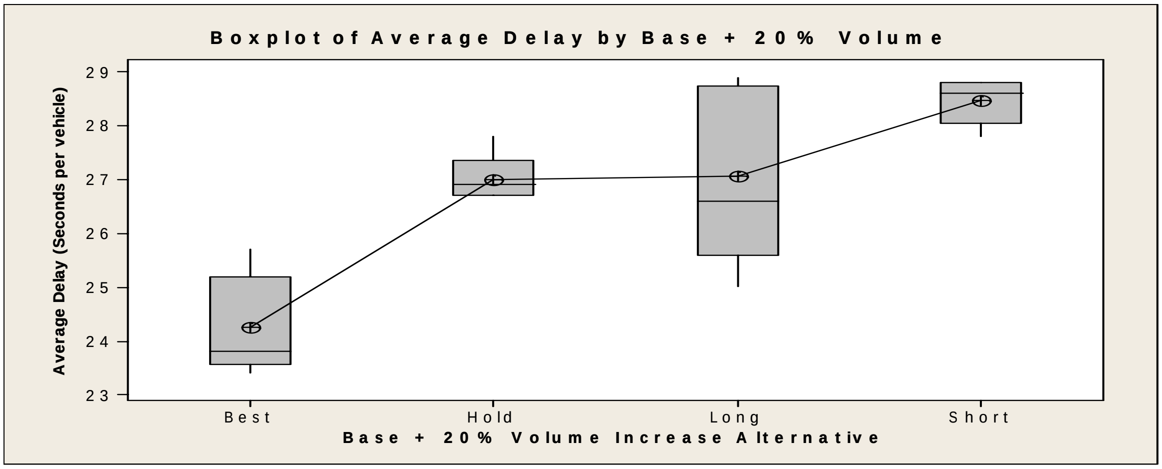


Table C.3. 20% Increase in Base Volume Alternative - Avg. Delay: One-way ANOVA

```
Source              DF      SS      MS       F       P
Base + 20% Alt.      3   46.35   15.45   15.42   0.000
Error               16   16.04    1.00
Total               19   62.39
S = 1.001   R-Sq = 74.30%   R-Sq(adj) = 69.48%

                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level   N    Mean  StDev  ----+---------+---------+---------+-----
Best    5  24.260  0.940  (-----*-----)
Hold    5  27.000  0.458                  (-----*-----)
Long    5  27.060  1.655                  (-----*-----)
Short   5  28.460  0.422                           (-----*-----)
                          ----+---------+---------+---------+-----
                            24.0      25.6      27.2      28.8

Pooled StDev = 1.001
```

Comparison of Alternative Transition Strategies	X_1 Avg. Delay	X_1 Stnd. Dev.	X_2 Avg. Delay	X_2 Stnd. Dev.	T - Test	Is There a Significant Difference in Means?
Best - Hold	24.260	0.940	27.000	0.458	-5.86	Yes - 5.86 > 1.860
Best - Long	24.260	0.940	27.060	1.655	-3.29	Yes - 3.29 > 1.860
Best - Short	24.260	0.940	28.460	0.422	-9.11	Yes - 9.11 > 1.860
Hold - Long	27.000	0.458	27.060	1.655	-0.08	No - 0.08 < 1.860
Hold - Short	27.000	0.458	28.460	0.422	-5.24	Yes - 5.24 > 1.860
Long - Short	27.060	1.655	28.460	0.422	-1.83	No - 1.83 < 1.860



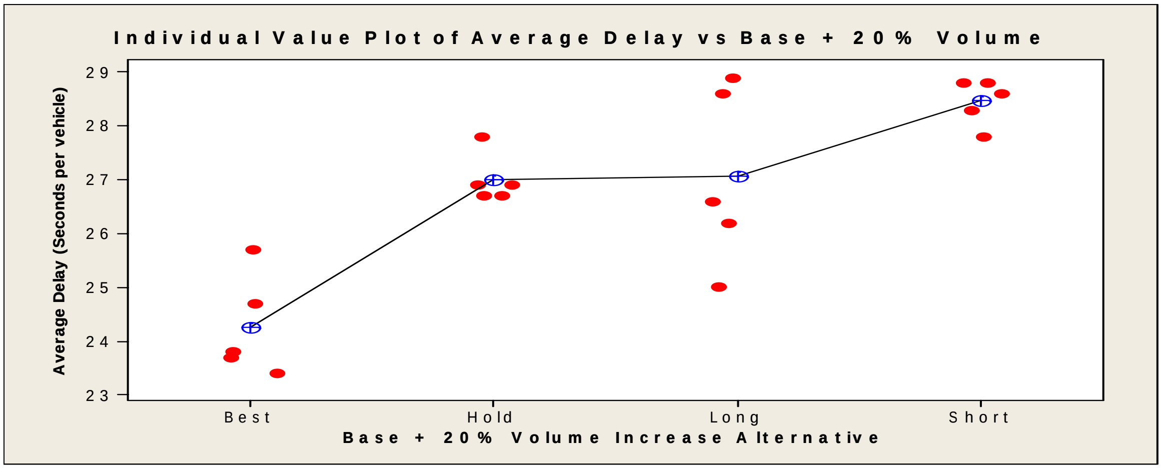
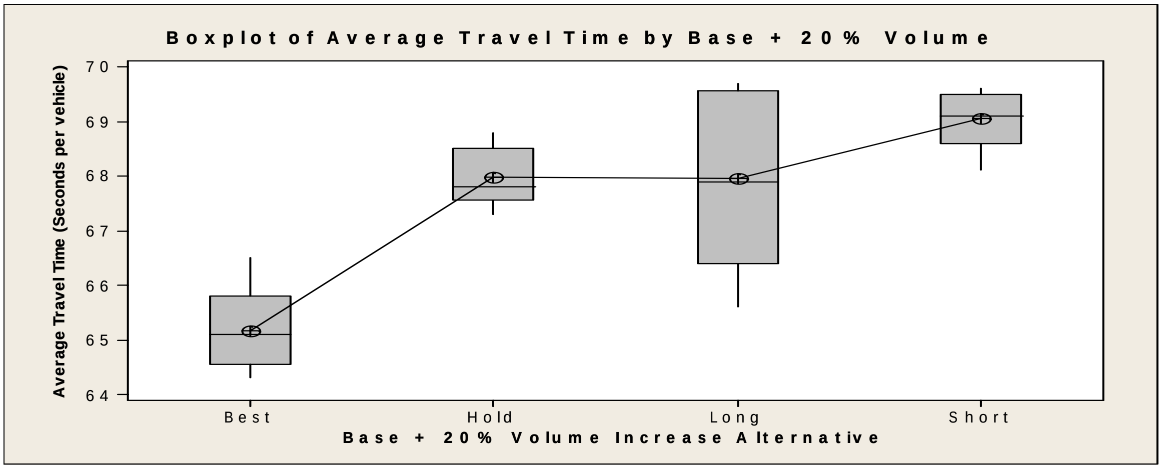


Table C.4. 20% Increase in Base Volume Alternative – Avg. Travel Time: One-way ANOVA

```
Source            DF     SS     MS      F      P
Base + 2-% Alt.    3  41.72  13.91  13.48  0.000
Error             16  16.50   1.03
Total             19  58.23
S = 1.016   R-Sq = 71.66%   R-Sq(adj) = 66.34%
                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level  N    Mean  StDev   --+---------+---------+---------+-------
Best   5  65.160  0.817   (-----*------)
Hold   5  67.980  0.559                      (-----*------)
Long   5  67.960  1.677                      (-----*-----)
Short  5  69.060  0.577                             (-----*------)
                          --+---------+---------+---------+-------
                         64.5      66.0      67.5      69.0
Pooled StDev = 1.016
```

Comparison of Alternative Transition Strategies	X_1 Avg. Travel Time	X_1 Stnd. Dev.	X_2 Avg. Travel Time	X_2 Stnd. Dev.	T - Test	Is There a Significant Difference in Means?
Best – Hold	65.160	0.817	67.980	0.559	-6.37	Yes - 6.37 > 1.860
Best – Long	65.160	0.817	67.960	1.677	-3.36	Yes - 3.36 > 1.860
Best – Short	65.160	0.817	69.060	0.577	-8.72	Yes - 8.72 > 1.860
Hold – Long	67.980	0.559	67.960	1.677	0.03	No - 0.03 < 1.860
Hold – Short	67.980	0.559	69.060	0.577	-3.01	Yes - 3.01 > 1.860
Long - Short	67.960	1.677	69.060	0.577	-1.39	No - 1.38 < 1.860



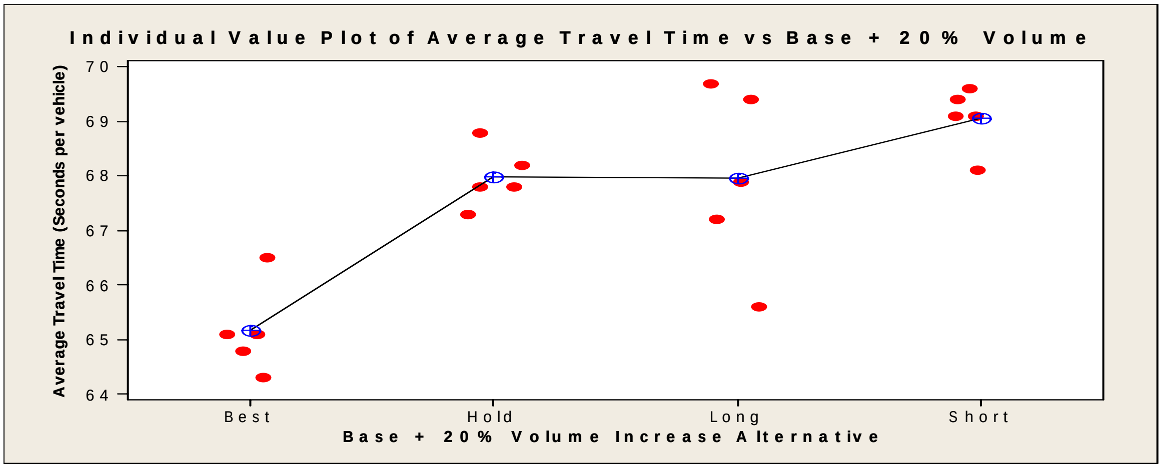
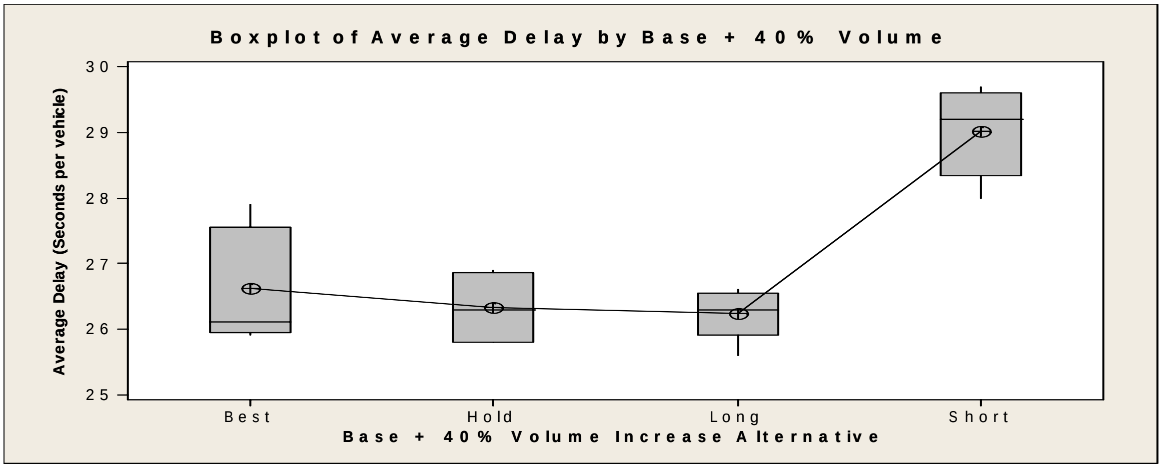


Table C.5. 40% Increase in Base Volume Alternative - Avg. Delay: One-way ANOVA

```
Source            DF      SS     MS      F      P
Base + 40% Alt.    3  26.274  8.758  20.80  0.000
Error             16   6.736  0.421
Total             19  33.010
S = 0.6488   R-Sq = 79.59%   R-Sq(adj) = 75.77%

                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level  N    Mean  StDev  ------+---------+---------+---------+---
Best   5  26.620  0.887     (----*----)
Hold   5  26.320  0.526  (----*----)
Long   5  26.240  0.391  (----*----)
Short  5  29.020  0.683                         (----*----)
                         ------+---------+---------+---------+---
                            26.4      27.6      28.8      30.0

Pooled StDev = 0.649
```

Average Delay MOE

Comparison of Alternative Transition Strategies	X_1 Avg. Delay	X_1 Stnd. Dev.	X_2 Avg. Delay	X_2 Stnd. Dev.	T - Test	Is There a Significant Difference in Means?
Best – Hold	26.620	0.887	26.320	0.526	0.65	No - 0.65 < 1.860
Best – Long	26.620	0.887	26.240	0.391	0.88	No - 0.88 < 1.860
Best – Short	26.620	0.887	29.020	0.683	-4.79	Yes - 4.79 > 1.860
Hold – Long	26.320	0.526	26.240	0.391	0.27	No - 0.27 < 1.860
Hold – Short	26.320	0.526	29.020	0.683	-7.00	Yes - 7.00 > 1.860
Long - Short	26.240	0.391	29.020	0.683	-7.90	Yes - 7.90 > 1.860



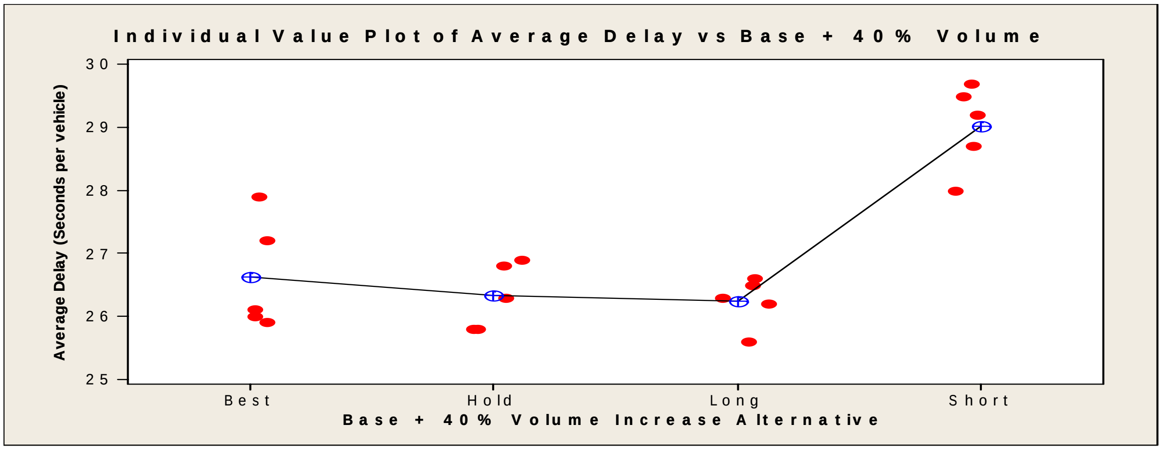
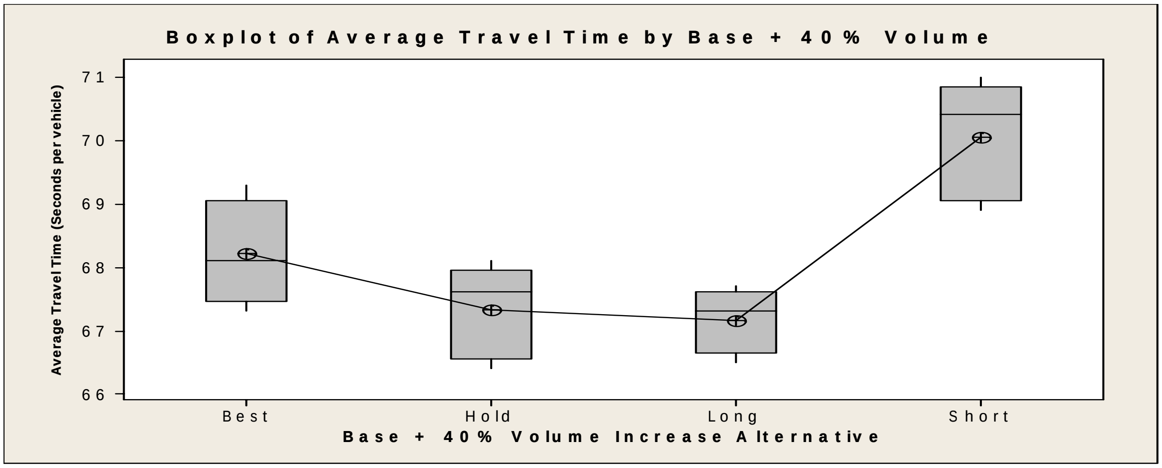


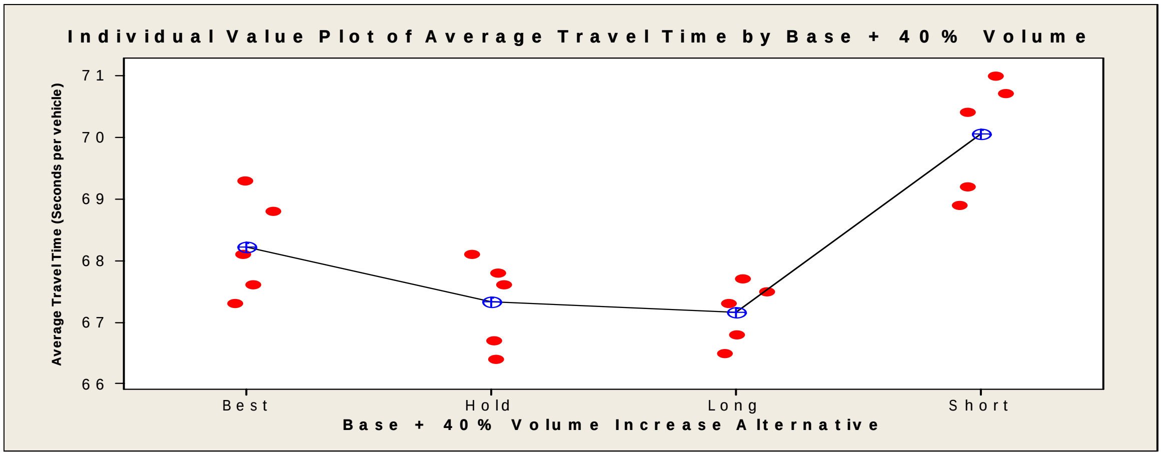
Table C.6. 40% Increase in Base Volume Alternative - Avg. Travel Time: One-way ANOVA

```
Source            DF      SS     MS      F      P
Base +40% Alt.     3  26.206  8.735  14.90  0.000
Error             16   9.380  0.586
Total             19  35.586
S = 0.7657   R-Sq = 73.64%   R-Sq(adj) = 68.70%

                                 Individual 95% CIs For Mean Based on
                                 Pooled StDev
Level   N    Mean  StDev  ------+---------+---------+---------+---
Best    5  68.220  0.829          (-----*------)
Hold    5  67.320  0.733   (-----*-----)
Long    5  67.160  0.498  (-----*-----)
Short   5  70.040  0.934                        (-----*-----)
                          ------+---------+---------+---------+---
                             67.2      68.4      69.6      70.8
Pooled StDev = 0.766
```

Average Travel Time MOE

Comparison of Alternative Transition Strategies	X_1 Avg. Travel Time	X_1 Stnd. Dev.	X_2 Avg. Travel Time	X_2 Stnd. Dev.	T - Test	Is There a Significant Difference in Means?
Best – Hold	68.220	0.829	67.320	0.733	1.82	No - 1.82 < 1.860
Best – Long	68.220	0.829	67.160	0.498	2.45	Yes - 2.45 > 1.860
Best – Short	68.220	0.829	70.040	0.934	-3.26	Yes - 3.26 > 1.860
Hold – Long	67.320	0.733	67.160	0.498	0.40	No - 0.40 < 1.860
Hold – Short	67.320	0.733	70.040	0.934	-5.12	Yes - 5.12 > 1.860
Long - Short	67.160	0.498	70.040	0.934	-6.08	Yes - 6.08 > 1.860





APPENDIX D: INFLUENCE OF TRAFFIC VOLUME ALTERNATIVES

The following is a list of the tables included in Appendix D which contain the results of the simulation runs, one-way statistical analysis, and comparison performed in support of assessing the influence of different levels of traffic volumes on how each transition strategy impacts the flow of traffic in the test network analyzed in this research:

Table D.1. Hold Strategy Compared to Volume Alternatives - Average Delay

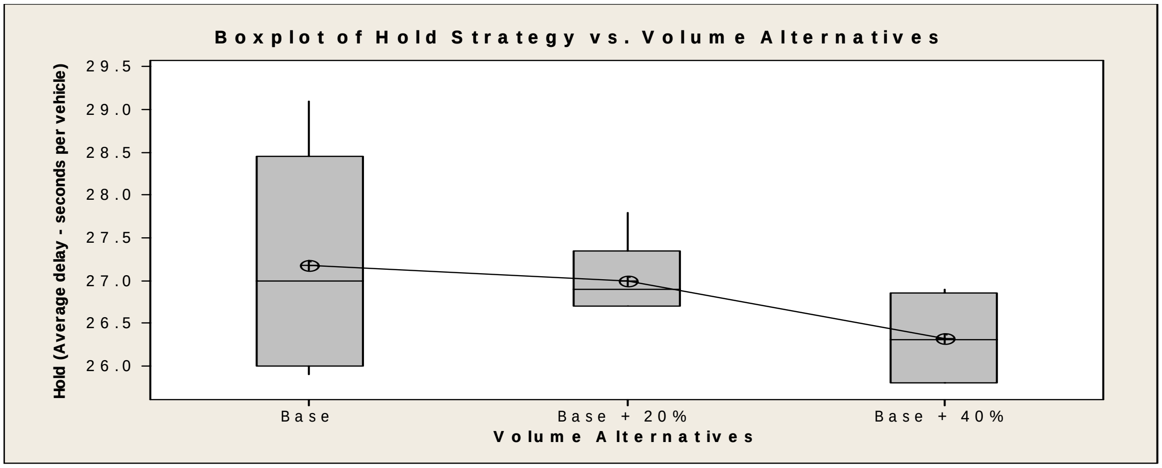
One-way ANOVA:

```
Source            DF      SS     MS     F      P
Volume Alt’s.      2   2.057  1.029  1.39  0.286
Error             12   8.856  0.738
Total             14  10.913
S = 0.8591   R-Sq = 18.85%   R-Sq(adj) = 5.33%

                            Individual 95% CIs For Mean Based on
                            Pooled StDev
Level     N    Mean  StDev  ------+---------+---------+---------+---
Base      5  27.180  1.314              (-----------*-----------)
Base +20% 5  27.000  0.458            (-----------*-----------)
Base +40% 5  26.320  0.526  (-----------*-----------)
                            ------+---------+---------+---------+---
                               25.90     26.60     27.30     28.00
Pooled StDev = 0.859
```

Comparison of Volume Alternatives	X_1 Avg. Delay	X_1 Stnd. Dev.	X_2 Avg. Delay	X_2 Stnd. Dev.	T - Test	Is There a Significant Difference in Means?
Base – Base + 20 %	27.18	1.314	27.000	0.458	0.29	No - 0.29 < 1.860
Base - Base + 40%	27.18	1.314	26.320	0.526	1.36	No - 1.36 < 1.860
Base + 20% - Base + 40%	27.00	0.458	26.320	0.526	2.18	Yes - 2.18 > 1.860

Tukey 95% Simultaneous Confidence Intervals:

```
All Pairwise Comparisons among Volume Alternative
Individual confidence level = 97.94%
Volume Alternative = Base subtracted from:
Volume
Alternative    Lower   Center   Upper  ---------+---------+---------+---------+
Base + 20%   -1.6284  -0.1800  1.2684       (------------*-----------)
Base + 40%   -2.3084  -0.8600  0.5884  (-----------*-----------)
                                       ---------+---------+---------+---------+
                                             -1.2       0.0       1.2       2.4
Volume Alternative = Volume 1 subtracted from:
Volume
Alternative    Lower   Center   Upper  ---------+---------+---------+---------+
Base + 40%   -2.1284  -0.6800  0.7684   (-----------*-----------)
                                       ---------+---------+---------+---------+
                                             -1.2       0.0       1.2       2.4
```



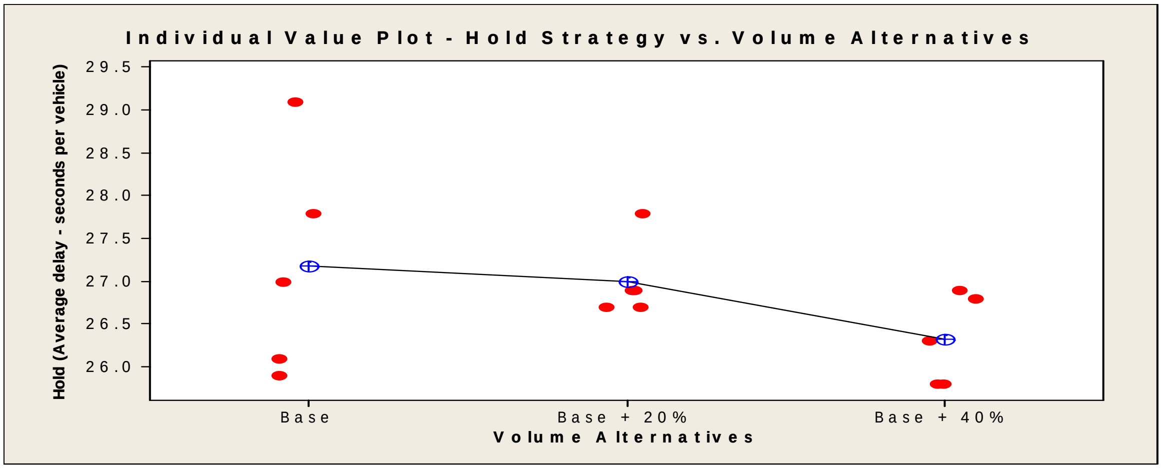


Table D.2. Hold Strategy Compared to Volume Alternatives - Average Travel Time

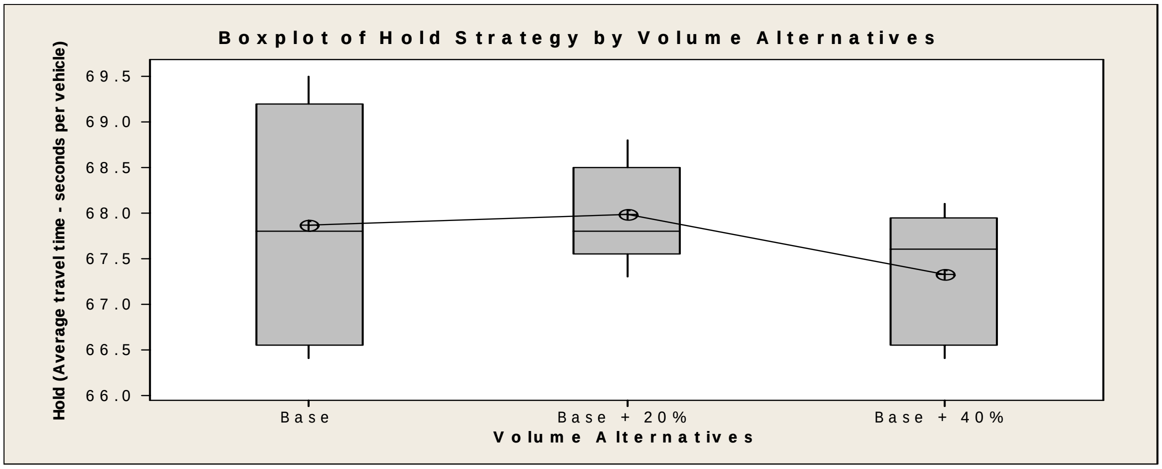
One-way ANOVA:

```
Source            DF      SS     MS      F      P
Volume Alternati   2   1.236  0.618   0.70  0.517
Error             12  10.648  0.887
Total             14  11.884
S = 0.9420   R-Sq = 10.40%   R-Sq(adj) = 0.00%
                            Individual 95% CIs For Mean Based on
                            Pooled StDev
Level     N    Mean  StDev    -+---------+---------+---------+--------
Base      5  67.860  1.346           (------------*-------------)
Base +20% 5  67.980  0.559             (------------*------------)
Base +40% 5  67.320  0.733    (------------*------------)
                              -+---------+---------+---------+--------
                            66.50     67.20     67.90     68.60
Pooled StDev = 0.942
```

Comparison of Volume Alternatives	X_2 Avg. Travel Time	X_1 Stnd. Dev.	X_2 Avg. Travel Time	X_2 Stnd. Dev.	T - Test	Is There a Significant Difference in Means?
Base – Base + 20%	67.860	1.346	67.980	0.559	-0.18	No - 0.18 < 1.860
Base - Base + 40%	67.860	1.346	67.320	0.733	0.79	No - 0.79 < 1.860
Base + 20% - Base + 40%	67.980	0.559	67.320	0.733	1.60	No - 1.60 < 1.860

Tukey's 95% Simultaneous Confidence Intervals:

```
All Pairwise Comparisons among Levels of Volume Alternative
Individual confidence level = 97.94%
Volume Alternative = Base subtracted from:
Volume
Alternative    Lower  Center   Upper  ---------+---------+---------+---------+
Base + 20%   -1.4682  0.1200  1.7082        (------------*------------)
Base + 40%   -2.1282 -0.5400  1.0482   (------------*-------------)
                                      ---------+---------+---------+---------+
                                            -1.2       0.0       1.2       2.4
Volume Alternative = Volume 1 subtracted from:
Volume
Alternative    Lower  Center   Upper  ---------+---------+---------+---------+
Base + 40%   -2.2482 -0.6600  0.9282  (------------*-------------)
                                      ---------+---------+---------+---------+
                                            -1.2       0.0       1.2       2.4
```



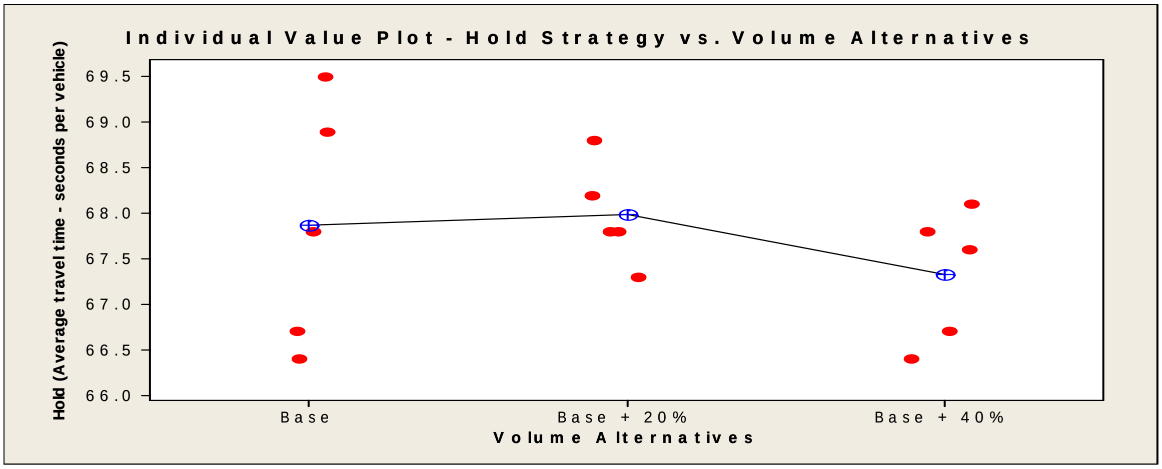


Table D.3. Long Strategy Compared to Volume Alternatives - Average Delay

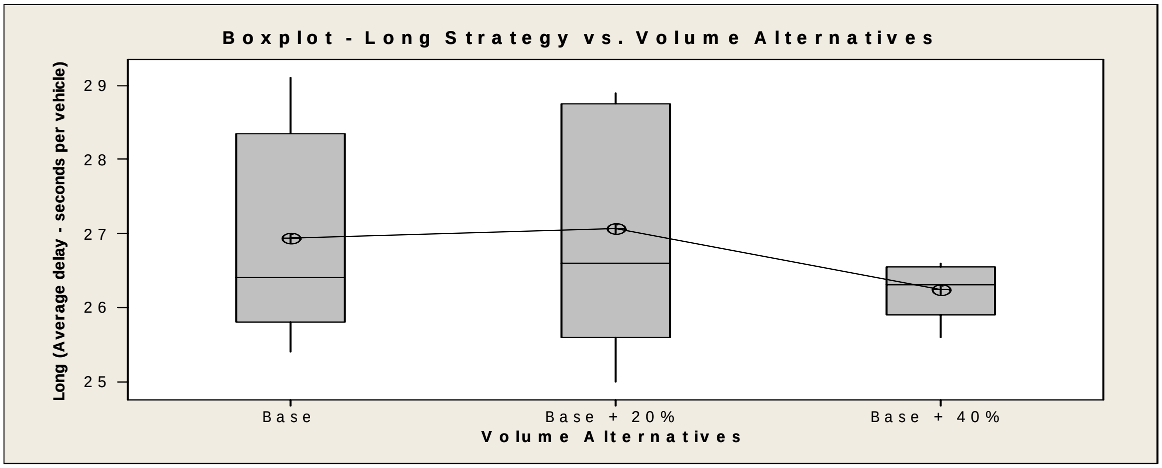
One-way ANOVA:

```
Source             DF     SS    MS     F      P
Volume Alternati    2   1.96  0.98  0.59  0.569
Error              12  19.88  1.66
Total              14  21.84
S = 1.287   R-Sq = 8.98%   R-Sq(adj) = 0.00%
                                Individual 95% CIs For Mean Based on Pooled
                                StDev
Level      N    Mean  StDev       +---------+---------+---------+---------
Base       5  26.940  1.442              (-----------*------------)
Base +20%  5  27.060  1.655               (------------*-----------)
Base +40%  5  26.240  0.391       (-----------*------------)
                                  +---------+---------+---------+---------
                                25.0      26.0      27.0      28.0
Pooled StDev = 1.287
```

Comparison of Volume Alternatives	X_1 Avg. Delay	X_1 Stnd. Dev.	X_2 Avg. Delay	X_2 Stnd. Dev.	T - Test	Is There a Significant Difference in Means?
Base – Base + 20%	26.940	1.442	27.060	1.655	-0.12	No - 0.12 < 1.860
Base - Base + 40%	26.940	1.442	26.240	0.391	1.05	No - 1.05 < 1.860
Base + 20% - Base +40%	27.060	1.655	26.240	0.391	1.08	No - 1.08 < 1.860

Tukey 95% Simultaneous Confidence Intervals:

```
All Pairwise Comparisons among Levels of Volume Alternative
Individual confidence level = 97.94%
Volume Alternative = Base subtracted from:
Volume
Alternative   Lower  Center  Upper     +---------+---------+---------+---------
Base + 20%   -2.050   0.120  2.290           (--------------*-------------)
Base + 40%   -2.870  -0.700  1.470      (-------------*--------------)
                                       +---------+---------+---------+---------
                                    -3.0      -1.5       0.0       1.5
Volume Alternative = Volume 1 subtracted from:
Volume
Alternative   Lower  Center  Upper     +---------+---------+---------+---------
Base + 40%   -2.990  -0.820  1.350     (--------------*-------------)
                                       +---------+---------+---------+---------
                                    -3.0      -1.5       0.0       1.5
```



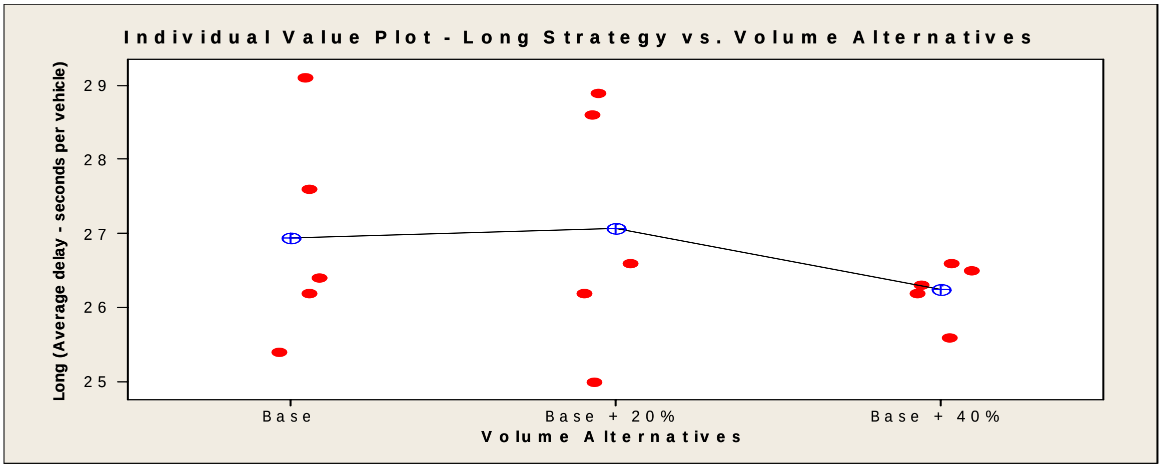


Table D.4. Long Strategy Compared to Volume Alternative - Average Travel Time

One-way ANOVA:

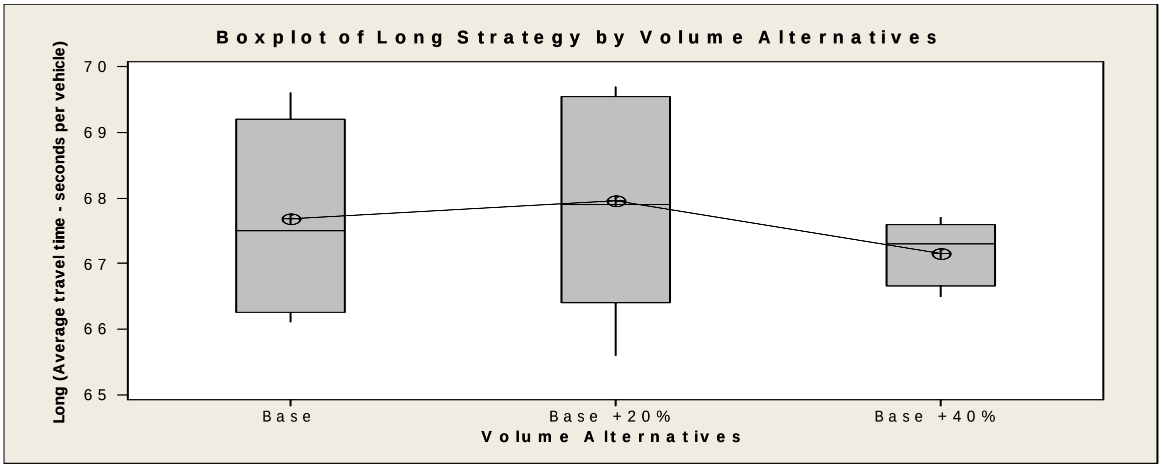
```
Source            DF     SS    MS     F      P
Volume Alternati   2   1.65  0.82  0.46  0.640
Error             12  21.35  1.78
Total             14  23.00
S = 1.334   R-Sq = 7.17%   R-Sq(adj) = 0.00%
```

```
                            Individual 95% CIs For Mean Based on Pooled St Dev
Level     N    Mean  StDev    -+---------+---------+---------+--------
Base      5  67.680  1.509         (------------*------------)
Base +20% 5  67.960  1.677            (------------*------------)
Base +40% 5  67.160  0.498    (------------*------------)
                              -+---------+---------+---------+--------
                            66.0      67.0      68.0      69.0
Pooled StDev = 1.334
```

Comparison of Volume Alternatives	X_1 Avg. Travel Time	X_1 Stnd. Dev.	X_2 Avg. Travel Time	X_2 Stnd. Dev.	T - Test	Is There a Significant Difference in Means?
Base – Base + 20%	67.680	1.509	67.960	1.677	-0.28	No - 0.28 < 1.860
Base - Base + 40%	67.680	1.509	67.160	0.498	0.73	No - 0.73 < 1.860
Base + 20% - Base + 40%	67.960	1.677	67.160	0.498	1.02	No - 1.02 < 1.860

Tukey 95% Simultaneous Confidence Intervals:

```
All Pairwise Comparisons among Levels of Volume Alternative
Individual confidence level = 97.94%
Volume Alternative = Base subtracted from:
Vol. Alt.     Lower  Center  Upper  ---------+---------+---------+---------+
Base +20%    -1.969   0.280  2.529         (-------------*-------------)
Base +40%    -2.769  -0.520  1.729    (-------------*-------------)
                                    ---------+---------+---------+---------+
                                          -1.6       0.0       1.6       3.2
Volume Alternative = Volume 1 subtracted from:
Vol. Alt.     Lower  Center  Upper  ---------+---------+---------+---------+
Base +40%    -3.049  -0.800  1.449  (-------------*-------------)
                                    ---------+---------+---------+---------+
                                          -1.6       0.0       1.6       3.2
```



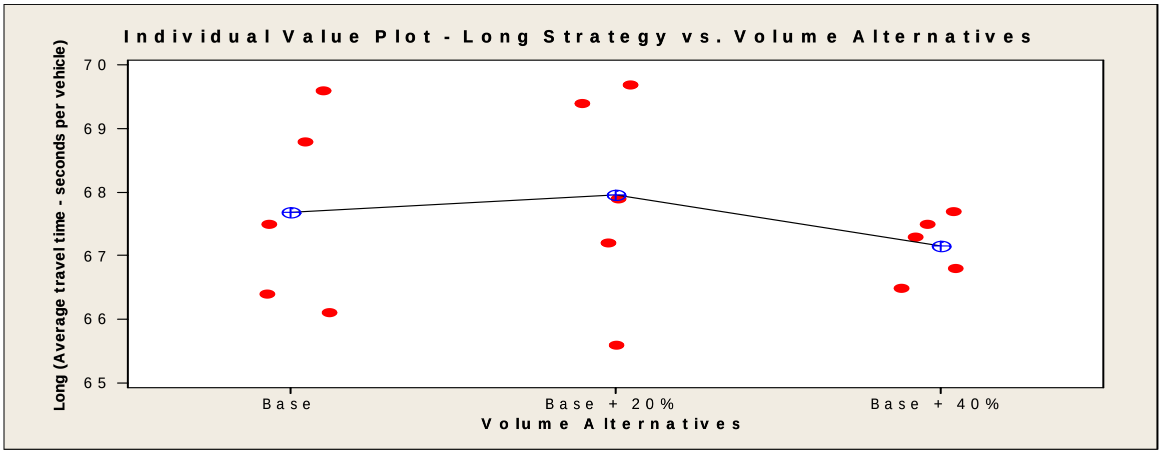


Table D.5. Short Strategy Compared to Volume Alternatives - Average Delay

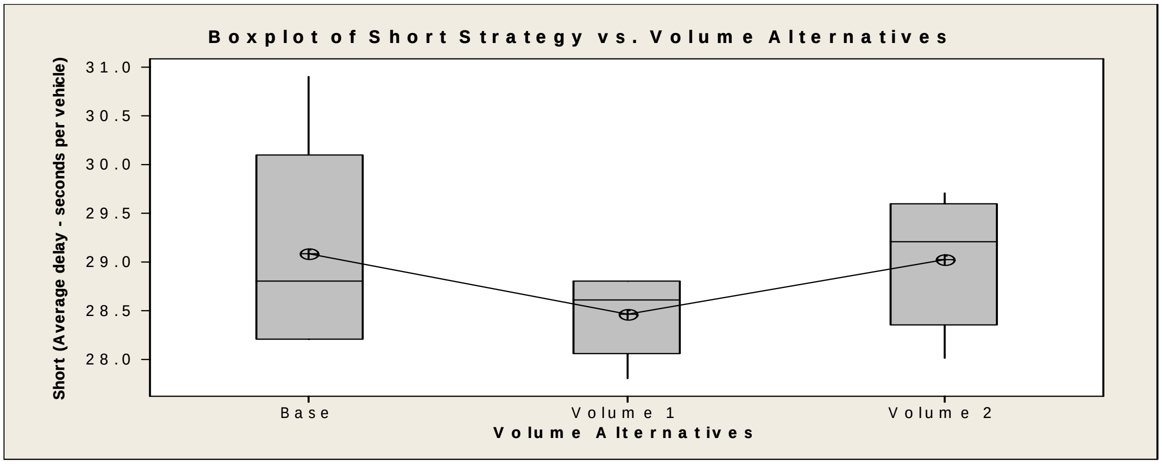
One-way ANOVA:

```
Source           DF     SS     MS     F      P
Volume Alternati  2  1.169  0.585  0.93  0.422
Error            12  7.568  0.631
Total            14  8.737
S = 0.7941   R-Sq = 13.38%   R-Sq(adj) = 0.00%

                            Individual 95% CIs For Mean Based on
                            Pooled StDev
Level     N    Mean  StDev  ---------+---------+---------+---------+
Base      5  29.080  1.117           (------------*------------)
Base +20% 5  28.460  0.422  (------------*------------)
Base +40% 5  29.020  0.683          (------------*------------)
                            ---------+---------+---------+---------+
                                 28.20     28.80     29.40     30.00

Pooled StDev = 0.794
```

Comparison of Volume Alternatives	X_1 Avg. Delay	X_1 Stnd. Dev.	X_2 Avg. Delay	X_2 Stnd. Dev.	T - Test	Is There a Significant Difference in Means?
Base – Base +20%	29.080	1.117	28.460	0.422	1.16	No - 1.16 < 1.860
Base – Base +40%	29.080	1.117	29.020	0.683	0.10	No - 0.10 < 1.860
Base + 20% - Base + 40%	28.460	0.422	29.020	0.683	-1.56	No - 1.56 < 1.860

Tukey 95% Simultaneous Confidence Intervals:

```
All Pairwise Comparisons among Levels of Volume Alternative
Individual confidence level = 97.94%  Volume Alternative = Base subtracted from:
Alternative    Lower   Center   Upper
Base +20%    -1.9589  -0.6200  0.7189
Base +40%    -1.3989  -0.0600  1.2789

Alternative     +---------+---------+---------+---------
Base +20%       (-------------*------------)
Base +40%             (------------*-------------)
                +---------+---------+---------+---------
             -2.0      -1.0       0.0       1.0
Volume Alternative = Volume 1 subtracted from:
Volume
Alternative    Lower  Center   Upper
Base +40%    -0.7789  0.5600  1.8989
                +---------+---------+---------+---------
                            (-------------*------------)
                +---------+---------+---------+---------
             -2.0      -1.0       0.0       1.0
```



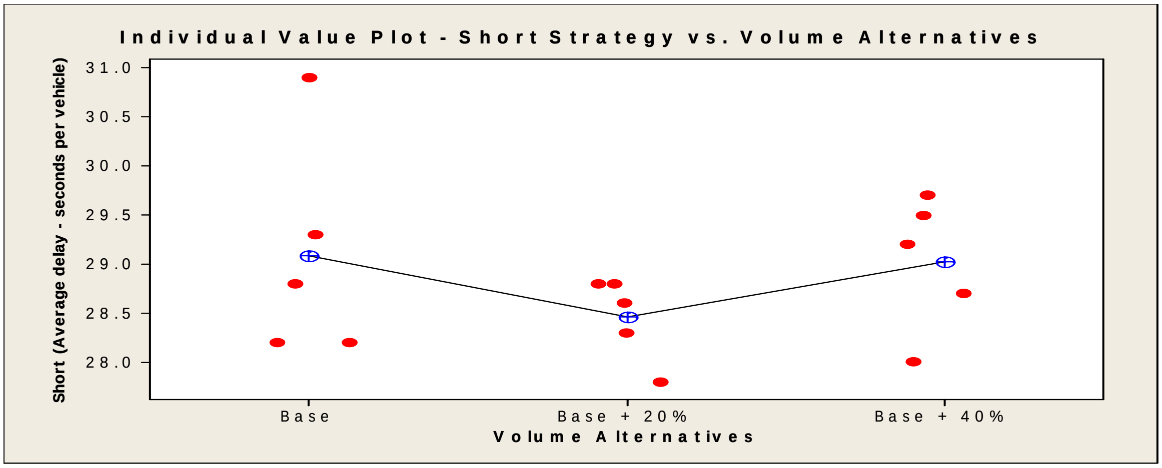


Table D.6. Short Strategy Compared to Volume Alternative - Average Travel Time

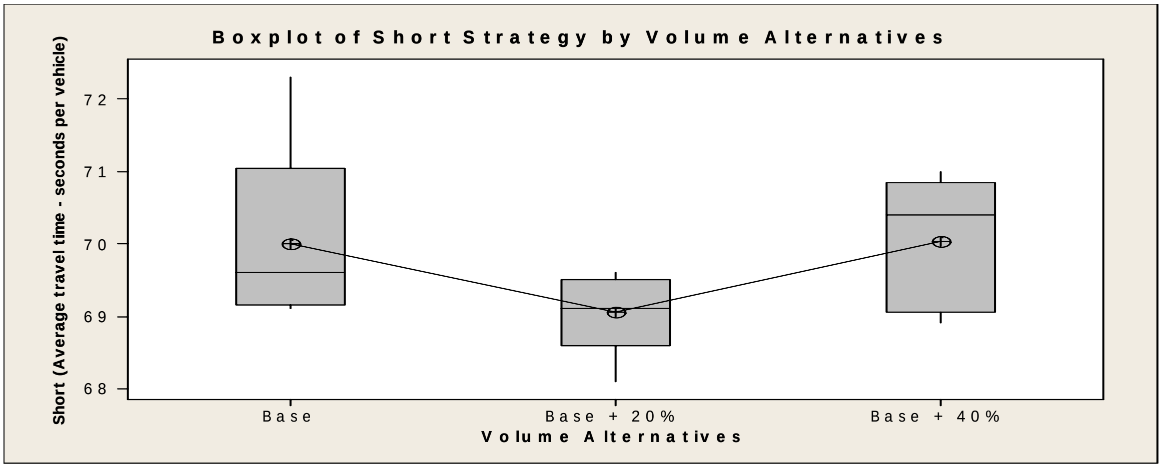
One-way ANOVA:

```
Source            DF      SS     MS     F      P
Volume Alternati   2   3.076  1.538  1.57  0.248
Error             12  11.764  0.980
Total             14  14.840
S = 0.9901   R-Sq = 20.73%   R-Sq(adj) = 7.52%
                            Individual 95% CIs For Mean Based on Pooled St Dev
Level      N    Mean  StDev  ---------+---------+---------+---------+
Base       5  70.000  1.317              (-----------*-----------)
Base +20%  5  69.060  0.577  (-----------*-----------)
Base +40%  5  70.040  0.934              (------------*-----------)
                             ---------+---------+---------+---------+
                                  68.80     69.60     70.40     71.20
Pooled StDev = 0.990
```

Comparison of Volume Alternatives	X_1 Avg. Travel Time	X_1 Stnd. Dev.	X_2 Avg. Travel Time	X_2 Stnd. Dev.	T - Test	Is There a Significant Difference in Means?
Base – + Base 20%	70.000	1.317	69.060	0.577	1.46	No - 1.46 < 1.860
Base - + Base 40%	70.000	1.317	70.040	0.934	-0.06	No - 0.06 < 1.860
+ Base 20% - + Base 40%	69.060	0.577	70.040	0.934	-2.00	Yes - 2.00 > 1.860

Tukey 95% Simultaneous Confidence Intervals:

```
All Pairwise Comparisons among Levels of Volume Alternative
Individual confidence level = 97.94%
Volume Alternative = Base subtracted from:
Volume
Alternative     Lower   Center   Upper   --------+---------+---------+---------+-
Base +20%     -2.6093  -0.9400  0.7293    (----------*----------)
Base +40%     -1.6293   0.0400  1.7093          (----------*----------)
                                         --------+---------+---------+---------+-
                                              -1.5       0.0       1.5       3.0
Volume Alternative = Volume 1 subtracted from:
Volume
Alternative     Lower  Center   Upper   --------+---------+---------+---------+-
Base +40%     -0.6893  0.9800  2.6493               (-----------*----------)
                                        --------+---------+---------+---------+-
                                             -1.5       0.0       1.5       3.0
```



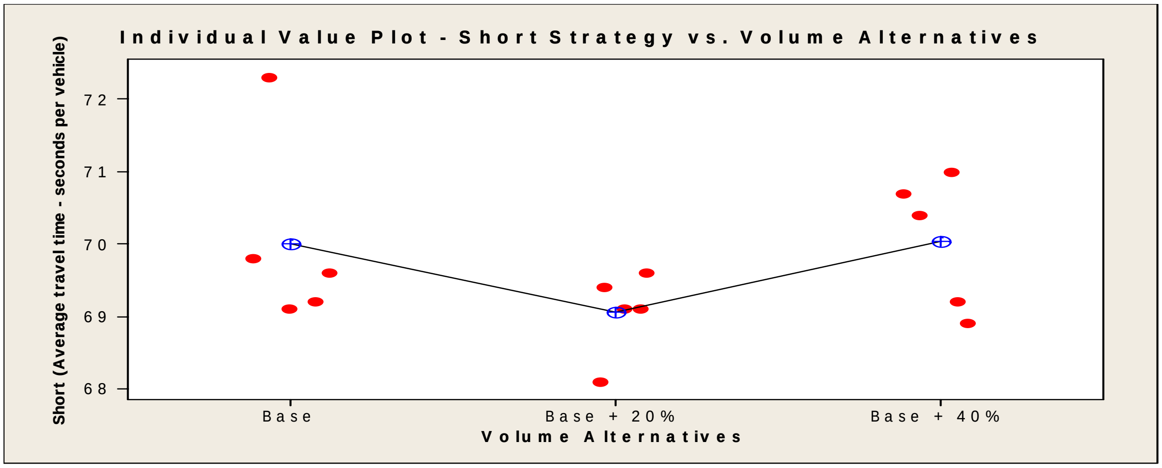


Table D.7. Best Strategy Compared to Volume Alternatives - Average Delay

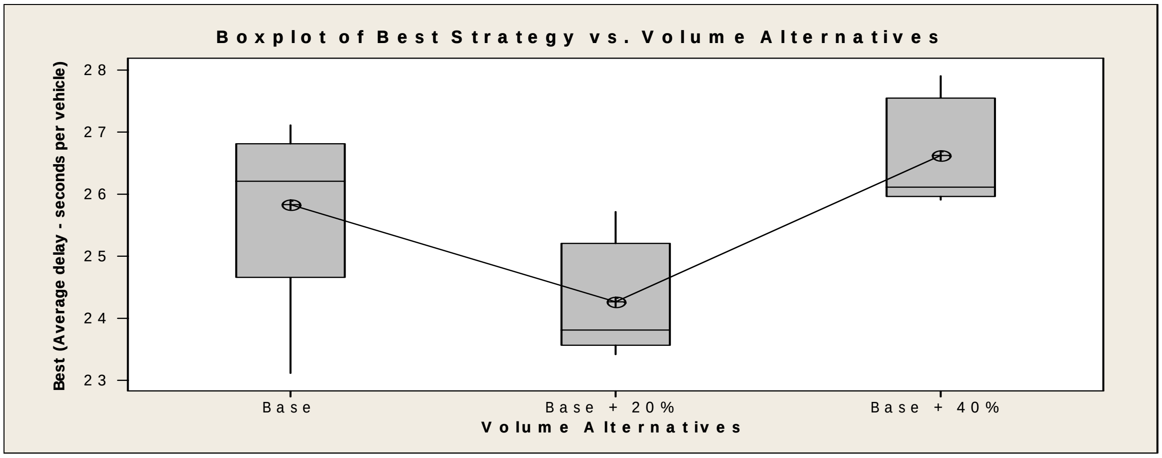
One-way ANOVA:

```
Source            DF     SS    MS     F      P
Volume Alternati   2  14.41  7.20  5.25  0.023
Error             12  16.47  1.37
Total             14  30.87
S = 1.171   R-Sq = 46.66%   R-Sq(adj) = 37.77%
                            Individual 95% CIs For Mean Based on Pooled St Dev
Level      N    Mean  StDev  -------+---------+---------+---------+--
Base       5  25.820  1.564               (--------*---------)
Base +20%  5  24.260  0.940  (--------*---------)
Base +40%  5  26.620  0.887                    (---------*--------)
                             -------+---------+---------+---------+--
                                 24.0      25.2      26.4      27.6

Pooled StDev = 1.171
```

Comparison of Volume Alternatives	X_1 Avg. Delay	X_1 Stnd. Dev.	X_2 Avg. Delay	X_2 Stnd. Dev.	T - Test	Is There a Significant Difference in Means?
Base – Base +20%	25.820	1.564	24.260	0.940	1.91	Yes – 1.91 > 1.860
Base - Base +40%	25.820	1.564	26.620	0.887	-0.99	No - 0.99 < 1.860
Base +20% - Base +40%	24.260	0.940	26.620	0.887	-4.08	Yes - 4.08 > 1.860

Tukey 95% Simultaneous Confidence Intervals:

```
All Pairwise Comparisons among Levels of Volume Alternative
Individual confidence level = 97.94%
Volume Alternative = Base subtracted from:

Vol. Alt.    Lower  Center  Upper  -------+---------+---------+---------+--
Base +20%    -3.535  -1.560  0.415     (-------*-------)
Base +40%    -1.175   0.800  2.775              (-------*-------)
                                    -------+---------+---------+---------+--
                                        -2.5       0.0       2.5       5.0
Volume Alternative = Volume 1 subtracted from:
Vol. Alt.    Lower  Center  Upper  -------+---------+---------+---------+--
Base +40%    0.385   2.360  4.335                     (------*-------)
                                   -------+---------+---------+---------+--
                                       -2.5       0.0       2.5       5.0
```



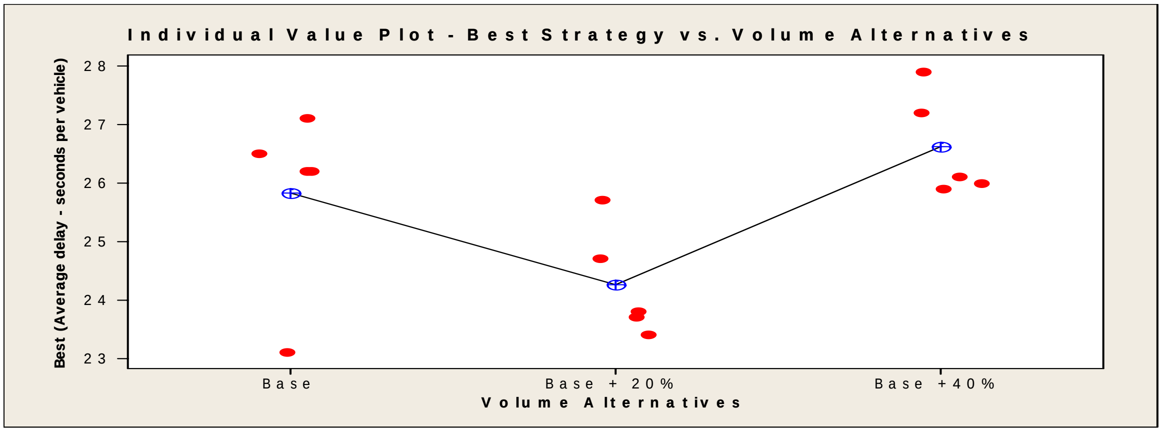


Table D.8. Best Strategy Compared to Volume Alternative - Average Travel Time

One-way ANOVA:

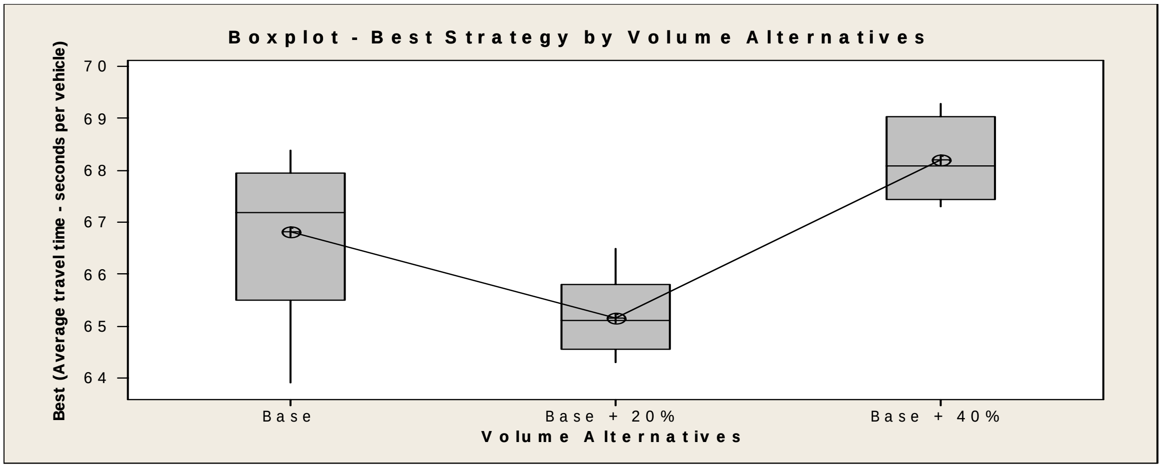
```
Source            DF     SS     MS     F      P
Volume Alternati   2  23.47  11.73  8.22  0.006
Error             12  17.13   1.43
Total             14  40.59
S = 1.195   R-Sq = 57.81%   R-Sq(adj) = 50.77%
                            Individual 95% CIs For Mean Based on Pooled St Dev

Level      N    Mean  StDev  ---+---------+---------+---------+------
Base       5  66.820  1.711            (------*-------)
Base +20%  5  65.160  0.817  (------*-------)
Base +40%  5  68.220  0.829                     (-------*-------)
                             ---+---------+---------+---------+------
                             64.5      66.0      67.5      69.0
```

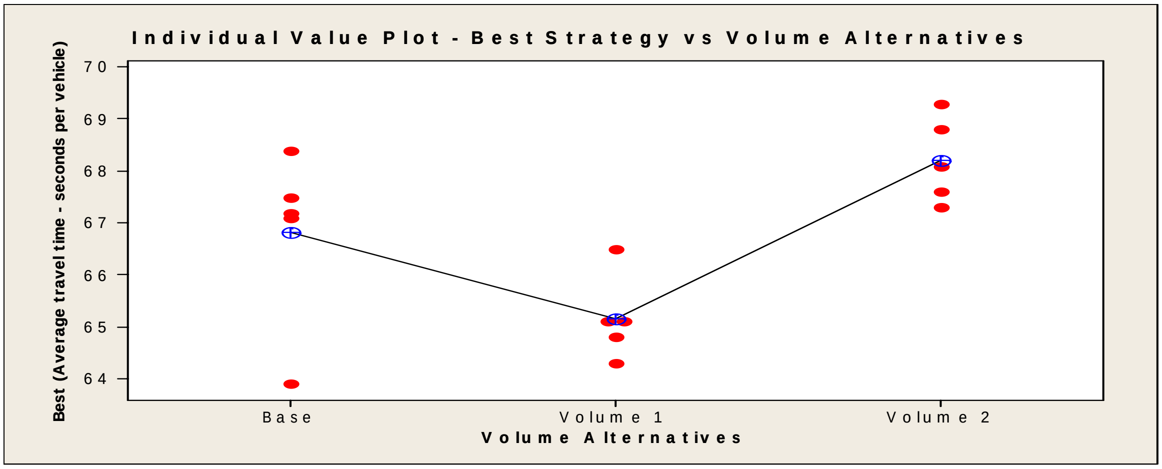
```
Pooled StDev = 1.195
```

Comparison of Volume Alternatives	X_1 Avg. Travel Time	X_1 Stnd. Dev.	X_2 Avg. Travel Time	X_2 Stnd. Dev.	T - Test	Is There a Significant Difference in Means?
Base - Base +20%	66.820	1.711	65.160	0.817	1.96	Yes – 1.96 > 1.860
Base - Base +40%	66.820	1.711	68.220	0.829	-1.65	No - 1.65 < 1.860
Base + 20% – Base +40%	65.160	0.817	68.220	0.829	-5.88	Yes - 5.88 > 1.860

Tukey 95% Simultaneous Confidence Intervals:

```
All Pairwise Comparisons among Levels of Volume Alternative
Individual confidence level = 97.94%

Volume Alternative = Base subtracted from:
Volume
Alternative   Lower   Center   Upper  -------+---------+---------+---------+--
Base +20%    -3.674   -1.660   0.354       (-----*------)
Base +40%    -0.614    1.400   3.414                 (------*-----)
                                      -------+---------+---------+---------+--
                                          -3.0       0.0       3.0       6.0
Volume Alternative = Volume 1 subtracted from:
Volume
Alternative  Lower  Center  Upper  -------+---------+---------+---------+--
Base +20%    1.046   3.060  5.074                    (------*------)
                                   -------+---------+---------+---------+--
                                       -3.0       0.0       3.0       6.0
```





APPENDIX E: Run Time Extension Files

Developing the “software-in-the-loop” simulation model involved developing a run time extension (RTE) file to interface the NextPhase Suitcase Tester and personal computer functioning with CORSIM. This RTE file (C++) was developed to provide the basis for developing the interface and facilitate the sharing of data between the appropriate interests. The RTE was developed with the logic and protocol to facilitate the exchange of date electronically between NextPhase Suitcase Tester and personal computer functioning with CORSIM. The following is the run time extension file that was used in this dissertation:

ITT Industries, Systems Division, All rights reserved. This software is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government and ITT Industries assume no liability for its contents or use.

```
***********************************************************************
#include <stdio.h>
#include "stdafx.h"
// Include to provide access to the OutputString function.
#include "corwin.h"
#include "link.h"
#include "netsim.h"
#include "network.h"
#include "upcntrl.h"
// Initialize global variables declared in upcntrl.h.
char gsOutput[132] = { '\0' };
int giEndOfInit = 0;
int giPrevInit = 0;
int giPrevTime = 0;
// Initialize a pointer to the network object used by the functions
// in this file.
CNetwork* pNetwork = NULL;
// ***********************************************************************
// Implementation of the exported RTE interface intialization function.
// CORSIM calls this function once at the beginning of the simulation.
// ***********************************************************************
DLL_EXPORT void __stdcall INIT()
{
  // Set global variables.
  giEndOfInit = 0;
  giPrevInit = 0;
  // Copy the CORSIM input file name from the imported string to a CString.
  // Use the imported string length just in case the string is not null
  // terminated.
  CString strInputFileName( inputFileName, inputFileNameLength );
  // Create the network object.
  pNetwork = new CNetwork( strInputFileName );
```

```
  // Read the traf file.
  pNetwork->ReadTrafFile();
  // Display a message in the CORSIM Driver interface.  Note that the size
  // passed to OuputString does not include the null terminator.  The last
  // argument specifies the color of the message.
  sprintf( gsOutput, "\nRTE initialization complete\n" );
  OutputString( gsOutput, strlen(gsOutput), SIM_COLOR_RGB, RTE_MESSAGE_RGB );
}
// ************************************************************************
// Implementation of the exported RTE interface main function.
// CORSIM calls this function at each time step in the simulation.
// ************************************************************************
DLL_EXPORT void __stdcall JMAIN()
{
  // Initialize the simulation time.
  int nTime = 0;
  // Initialization flag.  CORSIM sets yinit to TRUE during initialization
  // and to FALSE after initialization has been completed.
  bool init = yinit == 0 ? false : true;
  // The algorithm that controls the signal states at the intersections
  // assumes time is always increasing, but the CORSIM clock starts over
  // after initialization; so the time at which initialization is over must
  // be recorded.
  if( (!init) && (giPrevInit) )
  {
    // End of initialization.
    giEndOfInit = giPrevTime + 1;
  }
  // Adjust the time by adding the end of initialization.
  nTime = sclock + giEndOfInit;
  // Get signal state for the node under corsim control.
  pNetwork->UpdateNodeSignalStates();
  // Process any detector information.
  pNetwork->ProcessDetectors();
  // Record whether the simulation has reached equilibrium or not, so the
  // time at which initialization can be recorded.
  giPrevInit = init;
  giPrevTime = nTime;
}
// ************************************************************************
// Implementation of the exported RTE interface exit function.
// CORSIM calls this function once at the end of the simulation.
// ****************************************************************************
DLL_EXPORT void __stdcall JEXIT()
{// Clean up -- delete all objects that were created.
  delete pNetwork;
  sprintf( gsOutput, "RTE exit function - complete\n" );
  OutputString( gsOutput, strlen(gsOutput), SIM_COLOR_RGB, RTE_MESSAGE_RGB );
}
```

VITA

Jon T. Obenberger was born in 1963 in Wausau, Wisconsin and grew up in Green Bay, Wisconsin. He attended the University of Wisconsin in Madison, graduating with a Bachelor of Science degree in Civil and Environmental Engineering in 1986 and a Master of Science degree in Civil and Environmental Engineering in 1995. Jon lives in Arlington, Virginia with his wife and two children.

Following his graduation in 1986, Jon served for three and a half years as the city traffic engineer and metropolitan planning organization (MPO) coordinator for the City of Beloit (WI) where he was responsible for managing the City's traffic engineering program, in addition to managing the MPO for the Beloit (WI-IL) urbanized area. In 1990, Jon joined the Wisconsin Department of Transportation (WisDOT) in the Madison District Office where he served for four years as a design team leader. In this position he was responsible for: managing activities of the team; conducting special studies, developing and designing complex roadway improvement projects that included: rural and urban freeways and expressways; freeway interchanges; rural two-lane highways; and urban arterial surface streets. In 1994, he served for two and a half years as the technical lead for the statewide WisDOT Intelligent Transportation System (ITS) program. In this position he was responsible for: directing technical activities of the program, managing special studies (e.g., ITS studies, operational tests), developing and managing program initiatives and project budgets, and providing technical leadership and assistance.

In 1996 he accepted a position with the Federal Highway Administration (FHWA) and moved to Washington, D.C. He served for eight years as the agency's national authority on freeway management and traffic operations while managing the freeway management program in the Office of Operations. In this position he was responsible for: advocating and advancing the state-of-the-practice for freeway management and traffic operations, traffic management systems (TMCs), HOV facilities, and managed lane strategies. Since 2004, he has served as the preconstruction group team leader in the Office of Infrastructure, where he directs and manages FHWA's Preconstruction Program. In this position he is responsible for: geometric design, Interstate Highway System design standards and access control, context sensitive solutions, value engineering, employing engineering services, and utility accommodations.

Jon is a licensed professional engineer in Wisconsin and serves in a leadership capacity on several committees of the American Association of State Highway and Transportation Officials (Secretary of the AASHTO Technical Committee on Preconstruction Engineering Management) and the Transportation Research Board (Secretary of the TRB Freeway Operations Committee).