MULTI-PERSPECTIVE SYSTEM-WIDE ANALYSES OF ADAPTIVE TRAFFIC SIGNAL CONTROL SYSTEMS USING MICROSIMULATION AND CONTEMPORARY DATA SOURCES

by

ABHAY D. LIDBE

ALEXANDER M. HAINEN, COMMITTEE CHAIR
STEVEN L. JONES
JAY K. LINDLY
RANDY K. SMITH
SHARIF H. MELOUK

A DISSERTATION

Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy
in the Department of Civil, Construction and Environmental Engineering
in the Graduate School of
The University of Alabama

TUSCALOOSA, ALABAMA

2016

Copyright Abhay D. Lidbe 2016
ALL RIGHTS RESERVED

ABSTRACT

The primary function of traffic signals is to assign the right of way to vehicular and pedestrian traffic at intersections. Effective traffic signal system reduces congestion, increases intersection capacity, and improves other traffic related performance measures such as safety and mobility. To ensure these goals are met, traffic signals require updated timings to maintain proper operation. These updated signal timings impact not only traffic performance, but overall transportation system efficiency.

Because traditional signal timing plans may not accommodate variable and unpredictable traffic demands, a more proactive approach is necessary to ensure properly timed and maintained traffic signals. Adaptive traffic control systems (ATCS) continually collect data and optimize signal timing on a real time basis thereby reducing the aforementioned drawbacks of traditional signal retiming. Understanding and characterizing how these systems are working is important to transportation engineers, and evaluating these systems can provide useful insights.

The objective of this dissertation is to develop evaluation methodologies (both operational and economical) for adaptive traffic signal control that go beyond the traditional assessments that use traffic measures of effectiveness (MOEs). Case studies are conducted for Sydney Coordinated Adaptive Traffic System (SCATS) implementations in Alabama, which are useful in objective evaluations of ATCS (in general) for both their current and future operational environments by using microsimulation techniques and/or field data from contemporary data sources. The study contains detailed comparative analyses of traffic operations of the study

corridors for existing peak hour traffic conditions under the previous time-of-day (TOD) plan and similar peak hour conditions after SCATS implementation. Although simulation analysis using VISSIM traffic microsimulation software is the primary methodological technique used for evaluating comparative performances, arterial data from other sources (Bluetooth MAC Address Matching and crowdsourced travel data) are also used to perform the evaluations, which is a novel application for this context. While past studies have considered either the arterial or its side-streets performances in their evaluations, this work explored a system-wide approach looking at the composite performance of both dimensions together.

Finally, for transportation agencies which operate within budget constraints, it is important to know the real worth of attaining the benefits from ATCS implementations. The last chapter of this dissertation extends the evaluation methodology to include benefit-cost analysis (BCA) by evaluating the ATCS performance for both current and future traffic conditions. This information will be helpful for transportation agencies, planners, and practitioners to understand and justify their ATCS investment and also serve as a guideline for their future ITS projects.

DEDICATION

To my parents, who have been there for me from day one. Thank you for all of the love and support.

To my elder brother and younger sister, who have always encouraged and appreciated me. Thank you for all of the inspiration.

To my wife, who has been there for me for the last eleven years and who has the patience of a saint. Thank you for all of your love, support, help, sacrifices and encouragement.

Finally, to my two little adorable angels, who have compromised on so many expectations without any complaints. Thank you for all your tolerance.

This is a tribute to these seven rainbow colors of my life.

LIST OF ABBREVIATIONS AND SYMBOLS

ACS Lite	Adaptive Control Software Lite
ATCS	Adaptive Traffic Signal Control Systems
BCA	Benefit-Cost Analysis
BCR	Benefits-Costs Ratio
DOT	Department of Transportation
FHWA	Federal Highway Administration
GA	Genetic Algorithm
ITS	Intelligent Transportation System
LCCA	Life Cycle Cost Analysis
MOE	Measures of Effectiveness
OPAC	Optimization Policies for Adaptive Control
RHODES	Real-Time Hierarchical Optimized Distributed and Effective System
SA	Simulated Annealing
SCATS	Sydney Coordinated Adaptive Traffic system
SCOOT	Split Cycle Offset Optimization Technique
TOD	Time-of-day
TS	Tabu Search

ACKNOWLEDGMENTS

I am pleased to have this opportunity to thank the many colleagues, friends, and faculty members who have helped me on my path to the doctoral degree. I would like to express my deep appreciation and gratitude to my advisor and committee chair, Dr. Alexander Hainen, for the patient guidance and mentorship he provided to me, all the way from when I was still envisaging the research topic for my doctorate in Transportation through to completion of this degree. Dr. Steven Jones' intellectual immensity is matched only by his genuinely good nature and pragmatic modesty, and I am truly fortunate to have had the opportunity to work with him.

I also thank my committee members, Drs. Jay Lindly, Randy Smith, and Sharif Melouk for the friendly guidance and thought-provoking suggestions that each of them offered to me over the years. I would also like to acknowledge and thanks, Dr. Yingyan Lou for offering me this doctoral opportunity in the Civil Engineering department. In a similar vein, I would like to recognize Drs. Burcu Keskin, Charles Schmidt, John Mittenthal, Charles Sox, David Miller and Michael Adams for the contributions that each of them made to my intellectual growth during my years of study at the Culverhouse College of Commerce and Business Administration at The University of Alabama.

I am especially indebted to Elsa Tedla, my colleague, and friend, who has always been there from the very beginning until the end of the research project that eventually turned into my dissertation. I am also thankful to Alabama Department of Transportation for granting UTCA this SCATS project. I should not forget to mention the efforts taken by Ms. Connie Harris to put all administrative procedures and requirements in place that has led to the smooth completion of my degree. I would also like to thank my fellow doctoral students and post-doc researchers in UTCA – Gaurav Mehta, Kofi Adanu, Samwel Zephaniah, Jing Li and Luana Ozelim for their support, feedback, and friendly conversations.

Finally, I would be culpable if I didn’t acknowledge the innumerable sacrifices made by my wife, Pallavi, in shouldering more than her fair share of the parenting and household responsibilities while I pursued this final degree.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 Introduction

The primary function of traffic signals is to assign right of way to vehicular and pedestrian traffic at an intersection. Effective traffic signal system reduces congestion, increases intersection capacity, and improves other traffic related performance measures such as safety and mobility. Traffic signals are often retimed every 3-5 years to keep updated with changing traffic demand and to prevent aging or outdated timing plans.

Because traditional signal timing plans may not accommodate variable and unpredictable traffic demands, a more proactive approach is necessary to ensure properly timed and maintained traffic signals. Adaptive traffic control systems (ATCS) are becoming more widely used throughout the traffic engineering industry. ATCS continuously detect vehicular traffic data and then compute and implement optimal signal timings in real time (Martin, Stevanovic, & Stevanovic, 2005). ATCS reduces the aforementioned drawbacks of traditional signal retiming aging and deprecated timings. Benefits typically attributed to ATCS include:

(1) Reduced congestion and fuel consumption

(2) Improved travel time reliability

(3) Prolonged effectiveness of traffic signal timing

(4) Proactive traffic signal adjustments from monitoring and responding to real-time traffic demands.

1.2 ATCS Technologies

Various ATCS technologies are implemented at different places. Different ATCSs have different characteristics, and they work on different principles. While some ATCS are more suitable for arterial traffic operations, some others are more effective for urban grid networks (with a wide variety there within). The following section provides a brief discussion of each of the different ATCS technologies.

1.2.1 SCATS

The Sydney Coordinated Adaptive Traffic System (SCATS) gathers the real-time traffic data using detectors at stop-bars. It controls the traffic at two levels – strategic and tactical. At strategic control, SCATS determines the three signal timing parameters – cycle length, phase splits and offsets. The tactical control provides local flexibility within the constraints of strategic control, e.g., omission of a phase in case of no demand or early termination of green phase in case of low demand. The combination of strategic and tactical control offers SCATS significant flexibility to adjust to the varying traffic conditions (Lowrie, 1982; RTA (Roads and Traffic Authority) & TYCO, n.d.). In addition, SCATS can be configured by local traffic engineers to achieve desired policy outcomes such as congestion management and mainline progression (Chong-White, Millar, & Aydos, 2014; Roads and Maritime Services, n.d.).

1.2.2 SCOOT

Split Cycle Offset Optimization Technique (SCOOT) works on the principle of making small but continuous adjustments to the signal timings to minimize the vehicle delays throughout the network. It uses three optimization procedures – the split optimizer, the offset optimizer, and the cycle optimizer. The optimizers estimate the impact of incremental changes on the performance of a regional network which consists of several intersections operating on a common cycle length.

1.2.3 RHODES

Real-Time Hierarchical Optimized Distributed Effective System (RHODES) is a traffic adaptive signal system that optimizes the real-time performance of a corridor or a network. It operates on a proactive predictive strategy where the real-time demand is taken from the detectors to predict the future traffic conditions in the network and then proactively set the signal phases to respond to the stochastic variations in traffic.

1.2.4 InSync

InSync is an adaptive traffic signal developed by Rhythm Engineering that uses advanced technologies such as sensor technology, image processing, and artificial intelligence to automate the coordination of signals in real-time along arterials. The signal optimization attempts to improve the platoon progression along the mainline arterial and clear the traffic along the secondary traffic movements. This is attained by turning the signal light green at an intersection at the expected arrival time of the platoon from the upstream intersections (Stevanovic, 2010).

1.2.5 OPAC

Optimized Policies for Adaptive Control (OPAC) is a distributed control system based on a dynamic optimization algorithm which determines the signal timings to minimize overall intersection performance measures, such as delays and stops. The signal timings are only constrained by the minimum and maximum phase lengths. In addition, OPAC determines the optimal offsets and also synchronizes the network-wide (or groups of intersections) cycle lengths.

1.2.6 ACS Lite

Adaptive Control Software Lite (ACS Lite) was developed by the Federal Highway Administration (FHWA) as a lower cost, less monitoring-intensive, and easier to manage adaptive system. ACS Lite operates on the normal, coordinated timing plans and adjusts the phase splits and offsets incrementally every 5-10 minutes. The split adjustments are based on the utilization of each phase. ACS Lite offset adjustment decisions are based on maximizing the percentage arrivals on green. ACS Lite is designed to operate on a linear arterial network of 8 to 10 signals (Shelby & Bullock, 2008).

NCHRP 403 provides detailed discussions of the working principles, architecture, and hardware and software requirements of the different ATCSs (Stevanovic, 2010). This work, however, is focused only on the SCATS operations.

1.3 Research Problem

This study is motivated by the fact that although ATCSs are expensive in terms of time and money, there is a feeling that these systems are not well understood by the traffic signal community, and inadequate considerations are often given for their installations (Stevanovic, 2010). Such concerns are documented in NCHRP 403, which is perhaps the most comprehensive document on ATCS so far. The concerns and views in that document are based on literature reviews, surveys of ATCS vendors, and ATCS users. Following these concerns, the research problem is divided into three different sections as follows in the sections below.

1.3.1 ATCS performance evaluations

Although ATCSs are promising, they are expensive systems. The costs of any ATCS installation can vary between $29,000 and over $100,000 per intersection (Hatcher et al., 2014) and the ATCS installations can take between 3 months and 3 years (Stevanovic, 2010). Considering the resource intensiveness of the ATCS installations and even the greater impact this may have on the other stakeholder's of the transportation system, it is very important for the transportation agencies to give a serious and a detailed deliberation for an ATCS implementation before making their final decision. It is recommended that a detailed pre-installation evaluation of estimated operational benefits of the ATCS be performed before deciding to implement the system.

However, literature studies show that such studies are often conducted after ATCS has been installed. Past post-installation evaluation studies show mixed performances of ATCS implementations. Several studies have shown improvements in traffic performance measures with ATCS implementations (Gord & Associates, 2007; Hutton, Bokenkroger, & Meyer, 2010; Schrank, Eisele, Lomax, & Bak, 2015; SRF Consulting Group Inc., 2000). Additionally, a report on ITS evaluation program shows a wide range of reported post-install benefits across several measures from ATCS implementations (Hatcher et al., 2014). However, some studies have reported non-optimal performance of ATCS (Jayakrishnan, Mattingly, & McNally, 2000; Taale, Fransen, & Dibbits, 1998). Regarding SCATS control, although none of the studies reported underperformance, a few indicated only limited improvements with regard to travel time on the study corridor (Hunter, Wu, Kim, & Suh, 2012; Martin & Stevanovic, 2008; Tian, Ohene, & Hu, 2011). This implies that while benefits from ATCS implementation can be expected, they are not guaranteed. This further establishes the need for a very careful and comprehensive evaluation of any ATCS implementation.

1.3.2 Techniques

The ATCS performance is usually evaluated in two different ways. The first is by collecting and analyzing before-and-after ATCS field data (Eghtedari, 2006; Hunter et al., 2012; Hutton et al., 2010; Peters, McCoy, & Bertini, 2007; Wang, Robinson, Shelby, Cox, & Townsend, 2010). In some cases, when the before-ATCS data was not available, ATCS were turned off for a brief period to collect without-ATCS data and then used for ATCS performance evaluations (Dutta, McAvoy, Lynch, & Vandeputte, 2008; Martin & Stevanovic, 2008). Comparison between before-and-after versus off-on studies indicates reasonably consistent results (Kergaye, Stevanovic, & Martin, 2010b). However, conducting evaluation studies using field data pose some shortcomings, which are as follows:

(1) Traffic conditions before-and-after ATCS can vary and are difficult to control.

(2) Field data collection is expensive

(3) Field data collection may address limited sets of traffic conditions (only for the period during data collection)

(4) Most importantly, "ATCS deployment is an exacting science and something of an art" (Kergaye, Stevanovic, & Martin, 2008). Hence, any deviation from the requirements may result in an unfair comparison of ATCS's performance.

Thus, the second method for conducting ATCS performance evaluations which overcome these shortcomings involves using microsimulation techniques (Day et al., 2012; Hansen, Martin, & Perrin ., 2007; Kergaye et al., 2008; Shelby & Bullock, 2008; Stevanovic, Kergaye, & Stevanoic, 2012). Microsimulation can be an effective tool for evaluating arterial performance if the microsimulation model is well calibrated and validated (Kergaye, Stevanovic, & Martin, 2010a). SCATSIM is a software package used to replicate the SCATS adaptive control by linking it to a microsimulation tool (Kergaye et al., 2010a; Nguyen, 1996). This allows SCATS algorithms to be applied to a wide variety of conditions and situations, including before and after scenarios. This indicates that although field data can be useful to conduct performance evaluation studies, microsimulation techniques can be an even better approach and can provide more insights to supplement the findings from field data.

1.3.3 Type of evaluations

According to NCHRP 403, pre-installation evaluation of ATCS can prove to be very useful for deciding to implement ATCS. And if the capital costs and other infrastructural changes required to successfully implement an ATCS are extensive, it should be ensured that ATCS performs better over a longer period (Stevanovic, 2010). However, it is difficult to define what constitutes a longer period. The second aspect of decision making is that transportation agencies often face budget constraints. Thus, they need to justify the magnitude of their investments in ATCS implementation before deciding to implement ATCS.

A very useful tool that can solve both the purposes is the benefit-cost analysis (BCA). However, an accurate BCA requires an accurate, if not precise, estimate of the life of ATCS. The hindrance to estimating the life of an ATCS is, the ATCS performance may change in future period as traffic demand changes (usually an increase). Thus, it is also imperative to derive an estimate of ATCS performance in future period for an accurate BCA.

1.4 Research Objectives

The objective of this dissertation is to develop evaluation methodologies (both operational and economical) for adaptive traffic signal control that goes beyond the traditional assessments that use traffic measures of effectiveness (MOEs). Case studies are conducted for Sydney Coordinated Adaptive Traffic System (SCATS) implementations in Alabama, which is useful in objective evaluations of ATCS (in general) for both their current and future operational environments by using microsimulation techniques and/or field data from contemporary data sources. The study contains detailed comparative analyses of traffic operations of the study corridors for existing peak hour traffic conditions under the previous time-of-day (TOD) plan and similar peak hour conditions after SCATS implementation. Although simulation analysis using VISSIM traffic microsimulation software is the primary methodological technique used for evaluating comparative performances, arterial data from other sources (Bluetooth MAC Address Matching and crowdsourced travel data) are also used to perform the evaluations, which is a novel application for this context. While past studies have considered either the arterial or its side-streets performances in their evaluations, this work explored a system-wide approach looking at the composite performance of both dimensions together. Each specific objective of this dissertation comprises an individual journal article. The specific objectives are discussed in the following paragraphs.

The first objective of the work (CHAPTER 2) is to establish a more robust procedure for calibrating microsimulation models. This work leverages modern operational research techniques to compare the performance of different heuristics algorithms when used for calibrating a microsimulation model (specifically the VISSIM model). It is important to both calibrate and validate microsimulation models to ensure accurate performance that reflects (or will reflect) actual field performance. VISSIM microsimulation traffic models can be manually calibrated by using a trial-and-error approach in which the user-adjustable parameters are varied and the model output evaluated. However, the number of user-adjustable parameters is so large that evaluating all possible combinations of these parameters in a reasonable time is infeasible. The use of heuristics methods for calibrating microsimulation traffic models has been utilized in past studies independently without evaluating which performs better. This paper, therefore, addresses the need to examine which of the three (Genetic Algorithm, Simulated Annealing and Tabu Search) heuristics perform better for calibrating microsimulation models. The same microsimulation model is calibrated using these three heuristic algorithms, and their performances are evaluated.

The second objective (CHAPTER 3) is to establish the use of unconventional performance evaluation measures of different scales that best assess the potential changes in system operation. This is achieved by analyzing and comparing ATCS performance against the TOD performance on three different arterial corridors with differing physical and operational characteristics. Since the three corridors greatly differ in their traffic saturation levels, this study also gives insights regarding how well SCATS performs with varying corridor saturation levels. Finally, it also shows how looking at just traditional ways of performance evaluations such as corridor travel time and delays can be misleading and how examining a range of other performance measures at various scales helps in fully assessing the potential network improvements.

The objective of CHAPTER 4 is to develop a range of analyses techniques to compare the arterial performance for before, during, and after ATCS implementations through the use of different data sources at different points of implementation. The analyses are based on both field-collected data and microsimulation results. The study examines two data sources from the field – crowdsourced data and Bluetooth MAC address matching data. Different methodologies are discussed to understand different analyses to be conducted at the different points of ATCS deployment to better monitor the system performance. Additionally, this study shows how a well-calibrated and validated simulation model can provide results close to the field conditions and also how simulation can be put to use to gain detailed insights to supplement the information gained from field data.

The fourth and final objective presented in CHAPTER 5 is to develop a newer and more accurate approach to calculating the BCA of adaptive traffic control implementation. This study demonstrates how by using microsimulation techniques, SCATS performance can be assessed under current and future traffic demand conditions and how the techniques can be further used to determine a more accurate effective life of any ATCS defined as the period during which the ATCS delivers higher benefits over other existing signal systems. This study further demonstrates BCA conducted based on the effective life of ATCS. It also shows how more benefits can be gained from ATCS for an extended period beyond its effective life.

CHAPTER 2

COMPARATIVE STUDY OF SIMULATED ANNEALING, TABU SEARCH AND GENETIC ALGORITHM FOR CALIBRATION OF MICROSIMULATION MODEL

2.1 Introduction

Microscopic simulation techniques provide researchers and practitioners with an environment to perform detailed analysis of transportation systems in a fast, safe, and cost effective manner. However, to be effective, microsimulation models must be well calibrated and validated to ensure that the simulated traffic model reproduces the local field conditions and behavior. The Traffic Analysis Toolbox Volume III developed by the U.S Federal Highway Administration (FHWA) (Dowling et al. 2004) provides a recommended process for using traffic simulation software in transportation analyses including the calibration process. Many traffic simulation software packages are commercially available such as: CORSIM, VISSIM, Paramics, AIMSUN, and SIMTRAFFIC. The FHWA Office of Safety Research and Development offers a comprehensive, detailed comparison of these and other simulation software packages (Gettman and Head 2003). A calibrated microsimulation model can accurately replicate field conditions (Kergaye et al. 2010). A not so well calibrated model can often yield erroneous results on which significant engineering and investments systems can be unfortunately based. The daunting part of calibration is that microsimulation consists of various sub-models with each sub-model containing several user-adjustable parameters resulting in excessive parameters to be handled by the modeler (Hollander and Liu 2008a). Often, with limited data availability and/or familiarity with the field conditions, the best judgment of the parameter values can be used to calibrate the model manually (Hourdakis et al. 2003; Jayakrishnan et al. 2001; Lianyu Chu et al. 2004; Shaaban and Radwan 2005; Suh et al. 2013). However, since each parameter impacts the simulation results differently (Dowling et al. 2004), manual model calibration typically involves an iterative trial-and-error process of using intuitive discrete values of each parameter and feasible combinations of multiple parameters each time till the desired results are obtained (Hourdakis et al. 2003). Additionally, due to the correlated nature of the simulation results with multiple parameters of the model, it is possible to easily get caught in a circular process of fixing one problem only to generate another (Dowling et al. 2004). This can make manual calibration an inefficient and even ineffective process and is suggested only when the number of parameters is small (Hollander and Liu 2008a).

The literature suggests that researchers have discussed and proposed a variety of other calibration approaches in the past. For example, Gao (2008) emphasized the importance of comprehending the underlying logic of the car-following model of the traffic simulating software for accurate calibration (Gao 2008). Oketch and Carrick (2005) emphasize the importance of detailed data such as link traffic volumes, turning movement counts, travel times and approach queues for successful calibration and validation (Oketch and Carrick 2005). It was concluded that while target benchmarks can be achieved with moderate calibration efforts, greater efforts are required to achieve marginal improvements in the accuracy of the model outputs. Another viewpoint is that higher efforts in a powerful calibration methodology can still bring only marginal gains if the most influencing parameters are excluded from the calibration efforts (Hollander and Liu 2008a). Other researchers have addressed the data requirements for calibrating simulation models are detailed in many other studies (Dowling et al. 2004; Oregon DOT 2011; Park and Won 2006).

Significant differences are seen among past studies in terms of the methodologies adopted for calibrating microsimulation models. Typical calibration techniques include manual methods, formulation of mathematical optimization programs, heuristics approaches, and other techniques. Manual methods are an iterative trial-and-error process of using judgmental values of each parameter and a feasible combination of multiple parameters each time until the desired results are obtained from the simulation (Hourdakis et al. 2003). Manual methods discussed in the literature follow stepwise procedures to calibrate simulation models (Hellinga 1998; Merritt 2004; Miller 2009; Park and Schneeberger 2003; Shaaban and Radwan 2005). Several mathematical optimization based methods are also used in literature. For example, Toledo et al. (2003) apply an optimization-based calibration approach that seeks to minimize a measure of the deviation between observed and simulated parameters (Toledo et al. 2003). Another study presents a methodology based on the sequential simplex algorithm that uses ITS data to calibrate microsimulation models (Kim and Rilett 2003). Yet, there are other studies that use optimization techniques in some form to calibrate the simulation models (Gomes et al. 2004; Hollander and Liu 2008b; Peng et al. 2016; Toledo et al. 2004; Zou and Kulkarni 2014).

It is suggested that when a large number of parameters are to be calibrated, automated procedures using heuristics algorithms can be quite effective (Hollander and Liu 2008a; Jayakrishnan et al. 2001). With a large number of user-adjustable parameters, evaluating many different combinations of parameter sets becomes infeasible unless automated methods are used to efficiently search for suitably calibrated parameters. One such study concludes that the VISSIM calibrated model using genetic algorithm (GA) meta-heuristics reasonably reproduces the observed traffic operations (Wu et al. 2005). The same authors later presented the application of simulated annealing (SA) for finding a suitable combination of VISSIM parameters for calibrating the model (Sun et al. 2011). GA optimized calibration has even larger potential. For example, it was found that in contrast to the default and best-guess parameters, the distribution of simulation outputs by a calibrated model using GA was able to correctly match the field travel times for multiple days (Park and Qi 2005). With the availability of more traffic-related data by ITS deployments, GA was also used to calibrate a VISSIM traffic model to match the simulation results with the observed distributions obtained from the field (Kim et al. 2005). GA based calibration approach is used in many other studies (Li et al. 2009; Manjunatha et al. 2013; Mathew and Radhakrishnan 2010; Omrani and Kattan 2013; Yu et al. 2006).

In addition to GA and SA techniques, the literature also suggests the use of other novel techniques for microsimulation model calibration. For example, speed-flow graphs from the field and simulation were used to match and thus calibrate the microsimulation model (Menneni et al. 2008). In one other study, a hybrid algorithm was developed to calibrate the simulation model. This algorithm combined the advantages of GA and SA to increase the efficiency of convergence (Liu et al. 2006). Some researchers have used the simultaneous perturbation stochastic approximation (SPSA) optimization technique (Paz et al. 2012; Zhang et al. 2008b). Many other studies exist that uses various other approaches for calibrating microsimulation models (Ciuffo and Punzo 2014; Errampalli et al. 2012; Hu and Chiu 2011; Ma et al. 2007; Sahraoui and Jayakrishnan 2005; Song and Sun 2016; Zhang and Chang 2014).

As mentioned, microsimulation models comprise several sub-models with each sub-model consisting of several parameters, making the total number of parameters to be calibrated large. Calibrating parameters for each sub-model separately is simpler but it might lead to biased estimates; whereas procedures to simultaneously calibrate multiple parameter subsets results in better calibration but the use of automated algorithms for efficient calibration is suggested (Hollander and Liu 2008a; Jayakrishnan et al. 2000). Our review of literature, as well as other studies (Hollander and Liu 2008a) on the use of meta-heuristics for calibration of microsimulation models, suggests that GA is the most preferred optimization method. One possible reason for its preference among meta-heuristic methods is its relatively easy implementation (Zhang et al. 2008a). However, only one other study was found that used SA (Sun et al. 2011). Hence, the question of GA being the best choice for calibrating microsimulation remains unanswered. Comparisons of various meta-heuristics performance applied to different problems from Operational Research literature (Arostegui et al. 2006; Ghazanfari et al. 2007; Habib Youssef, Sadiq M. Sait 2001; Levin and Lieven 1998; Sexton et al. 1999) show mixed results. For example, SA found better solutions when applied on fuzzy cognitive map (Ghazanfari et al. 2007) whereas, Tabu Search (TS) algorithm exhibited the best performance when tested on five different VLSI circuits (Habib Youssef, Sadiq M. Sait 2001). In another study, GA obtained superior solutions compared to SA for optimizing neural networks (Sexton et al. 1999). This raises a question as to which meta-heuristics would be more suitable for calibrating microsimulation model. According to the “No Free Lunch” theorem, for both static and time-dependent optimization problems, average performance of any pair of problems across all possible problems is identical or in other words, choice of most appropriate algorithm depends on the problem under study and the algorithm (Ciuffo and Punzo 2014; Ho and Pepyne 2001; Wolpert and Macready 1997). Hence the question that which meta-heuristics suits more for the problem of calibration of microsimulation model still remains open (Abdalhaq and Baker 2014).

2.2 Purpose and Scope

The objective of this paper is to evaluate and compare procedures for calibration of microsimulation models. The literature review suggests that suitability of meta-heuristics for calibrating microsimulation model still remains unanswered. Also, no single study was found in the literature which compares the performances of meta-heuristics against the manually calibrated model. We apply manual calibration and automated techniques using three meta-heuristics (GA, SA and TS) to a case study (simulation/calibration) of an actual arterial. This paper, therefore, addresses the need to examine and identify the suitability of a particular meta-heuristics for calibrating microsimulation models. As such the contribution of this research is the addition of knowledge to the existing body of literature on the calibration of microsimulation models in order to offer insights into improved calibration techniques for others to follow.

2.3 Methodological Approach

The test corridor selected in this paper is a four-lane principal arterial corridor in Alabama, USA comprising 11 intersections as illustrated in Figure 2.1. The corridor travel time was measured using the floating car method. Weekday traffic volumes for this corridor and the traffic signal timing parameters were obtained from the local traffic agency. The geometric data was collected from field observations and aerial imagery. This data was used to develop a simulation model in VISSIM. VISSIM is a typical (time step and behavior-based) microscopic traffic simulation software package capable of accurately modeling complex traffic operations (Planung Transport Verkehr (PTV) AG 2011). It analyzes traffic operations within the constraints of lane configuration, vehicle composition, signal timings, etc. The traffic simulator in VISSIM uses different car following and lane changing sub-models. VISSIM uses the psycho-physical driver behavior that closely mimics the real driver behavior. This enhances the accuracy of VISSIM models. The Wiedemann car-following model is the heart of VISSIM. The stochastic nature of traffic is introduced by incorporating several parameters with stochastic distributions in the Wiedemann model. Under the Wiedemann model, at any given moment, the driver is either in free driving mode, in approaching mode, in the following mode, or in the braking mode. And the acceleration at that particular instance is a result of speed, speed difference, distance and driver characteristics. As VISSIM user manual recommends Wiedemann 74 car-following model was chosen for the arterial model (Planung Transport Verkehr (PTV) AG 2011). The Wiedemann 74 car following model is shown in Equation (2.1).

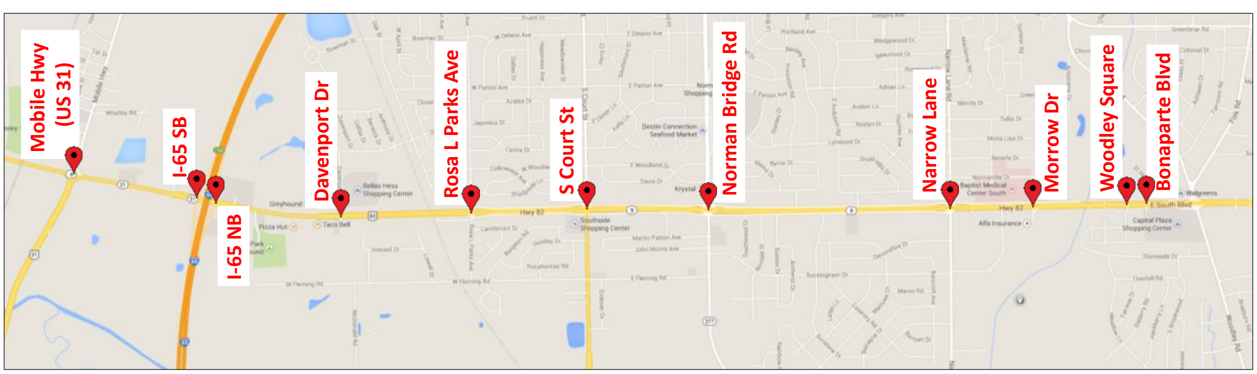


Figure 2.1 Network Diagram

$$\textit{Safety Distance} = ax + bx \qquad \textbf{Equation (2.1)}$$

where, $bx = (bx_{add} + bx_{mult} * z)\sqrt{v}$

v is the vehicle speed

z ranges between 0 and 1, normally distributed with mean = 0.5 and std. dev. 0.15

The term ax defines the average standstill distance between stopped cars, while bx adds stochastic variation to the safety distance. These three car following parameters (ax, bx_{add}, and bx_{mult}) are user defined and must ultimately then be calibrated. Similarly, there are several lane change parameters that have to be set by the modeler.

The VISSIM model was first calibrated manually using a trial-and-error approach. Volume balancing was performed using Synchro (a macroscopic analysis and optimization traffic software) to avoid any directional data inconsistencies. Various VISSIM parameters such as driving behavior, lane change parameters, speed distributions and the routing decisions combined were used to match the link volumes, turning movement counts and queues at each intersection. Speed distributions and speed decisions were based on posted speed limits and travel times. In the absence of specific data for the local parameters, our judgment based on field observations and the suggested ranges from the literature (Miller 2009; Oregon DOT 2011; Park and Won 2006; Planung Transport Verkehr (PTV) AG 2011) were used. Table 2.1 shows these user-adjustable parameters and their ranges.

Table 2.1 Wiedemann 74 Parameters

	Parameters	*Units*	*Min. Value*	*Max. Value*
Car Following Parameters	*Standstill Distance (Ax)*	ft	2	8
	Additive Part (Bx_{add})	--	0	3
	Multiplicative Part (Bx_{mult})	--	0	3
Lane Change Parameters	*Maximum Deceleration (own)*	ft/s^2	-20	-3
	Maximum Deceleration (trailing vehicle)	ft/s^2	-20	-3
	-1 ft/s^2 per distance (own)	ft	50	200
	-1 ft/s^2 per distance (trailing vehicle)	ft	50	200
	Accepted Deceleration (own)	ft/s^2	-6	-0.33
	Accepted Deceleration (trailing vehicle)	ft/s^2	-6	-0.33
	Waiting time before diffusion	sec	40	80
	Min. headway	ft	1.64	25
	Safety Distance Reduction factor	--	0	1
	Maximum Deceleration for Coop Braking	ft/s^2	-35	-3

In the next step, the three meta-heuristics (GA, SA and TS) were coded with Visual Basic (VB). The VB script accesses the parameters in VISSIM through a COM interface. The COM interface allows the use of generic programming environments to export objects, methods, and properties and thus automates the task of running multiple simulation runs while changing the required different parameters during each run. The schematic representation of the workflow is shown in Figure 2.2.

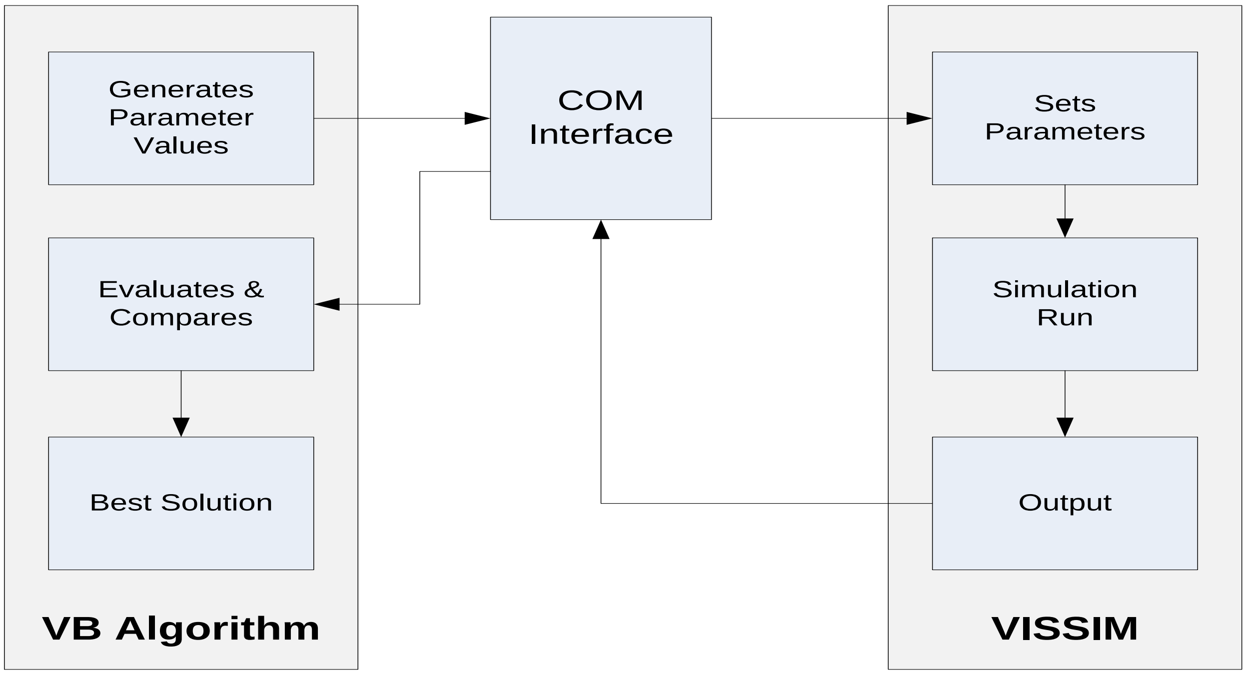


Figure 2.2 Schematic Diagram of the Simulation Controls and Evaluation

For the Weidemann 74 car-following model, only the three car-following parameters can be accessed by COM interface. The lane change parameters cannot be changed using COM interface, which was essential for the heuristics algorithm to be effective. As a result, multiple VISSIM models (files) were created with each file containing different combinations of lane change parameters. To ensure that no combination of parameter values is left out within the set parameter ranges, 100 different samples were generated using the Latin Hypercube Space Filling (LHSF) design in JMP statistical software. Latin Hypercube (LH) sampling is a method that generates random samples that effectively reduces the number of samples to a reasonable level, while still covering the entire parameter surface (Miller 2009; Park and Qi 2005; Park and Schneeberger 2003). Each parameter takes many levels that are spaced evenly from its minimum value to maximum value while maximizing the minimum difference between any two consecutive levels. For this study, each sample consisted of the 10 lane change parameters listed in Table 2.1. An example of LHSF design for two variables (x1 and x2) with 10 samples is shown in Figure 2.3. Eventually, 100 VISSIM models were generated using the 100 samples of lane change parameters that were generated using the LHSF design. Thus, each VISSIM model differed only in the combination of the ten lane changing parameters used in the model. Table 2.2 shows the sample parameter values.

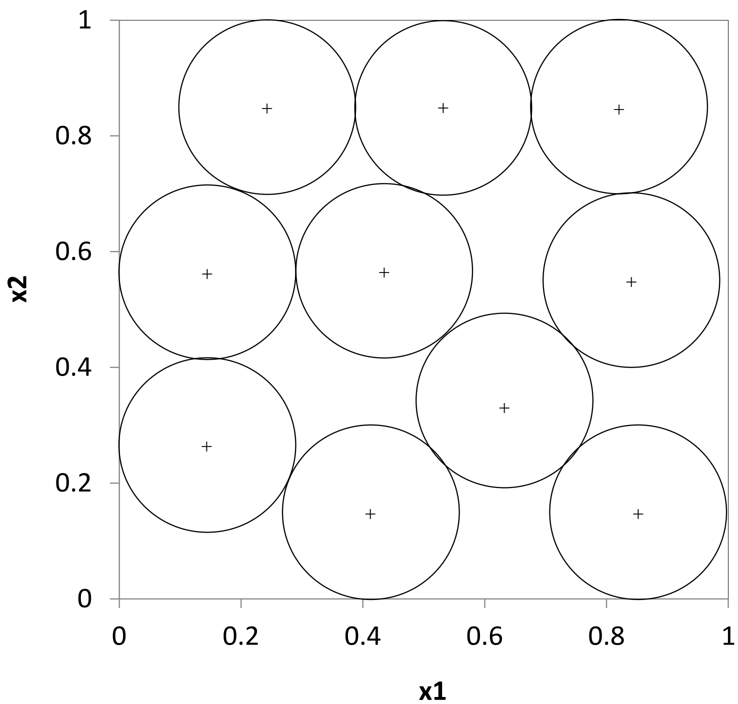


Figure 2.3 Example of Latin Hypercube Space Filling Sample (Source: www.jmp.com)

Table 2.2 Sample of Lane Change Parameter Values generated by Latin Hypercube for the 100 VISSIM models

Model #	Maximum Deceleration	Maximum Deceleration	-1 ft/s^2 per distance	-1 ft/s^2 per distance	Accepted Deceleration	Accepted Deceleration	Waiting time before diffusion	Min. headway	Safety Distance Reduction factor
Model 1	-16.39	-9.52	115.15	103.03	-0.73	-1.64	56.16	13.20	0.07
Model 2	-8.15	-5.57	178.78	150.00	-0.67	-4.62	65.05	13.43	0.21
Model 3	-17.93	-10.04	63.63	166.66	-1.70	-1.47	43.63	2.34	0.55
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
Model 98	-9.01	-16.91	198.48	125.75	-3.59	-0.78	62.22	11.07	0.98
Model 99	-16.90	-16.05	157.57	190.90	-2.04	-4.56	59.79	23.34	0.54
Model 100	-19.82	-10.55	119.69	118.18	-5.31	-3.99	52.12	24.76	0.03

It is worth noting that each lane change parameter can practically be assigned any real number value within its acceptable range. However, it then becomes a case of either linear or non-linear optimization problem. By generating the 100 discrete combinations of the 10 parameter values, this problem is transformed into a combinatorial optimization problem which can be effectively be solved using heuristics search algorithms. Although a higher number of samples could have been generated, 100 samples is a random number that was selected. The number of samples is a trade-off between the solution quality and the computing time required to search the solution space. Selecting any random model from the 100 models implies selecting a random combination of lane change parameters. Thus, for the meta-heuristics, random selection of 13 parameters of VISSIM model listed in Table 2.1 was narrowed down to a selection of four parameters - three car-following parameters and one VISSIM model from 100 generated using LHSF design. The manually calibrated model was not used for meta-heuristics. Instead, a non-calibrated model using the default parameter values of VISSIM was used as starting point for all meta-heuristics.

Traffic volumes and travel times were primarily used as measures of effectiveness (MOEs) for both manual and automated calibration approaches. A total of 118 different link volume counts and 20 travel times from different travel time sections for the eleven-intersection network were collected for each simulation run. Each simulation run comprised multiple replications with different random seed numbers (Dowling et al. 2004; Hollander and Liu 2008a). The MOEs were averaged over these replications (Hollander and Liu 2008a) as is standard practice with traffic simulation. Although three replications were used in this study, the minimum number of replications is typically determined by the standard deviation of the MOE (Dowling et al. 2004; Hollander and Liu 2008a) and overcomes the limitations of many other past studies (Hollander and Liu 2008a). Nevertheless, the random seed numbers were uniformly varied from the lowest to the highest number so that the complete range of possible stochastic behavior of the traffic characteristics gets captured in the results. As a result, the difference between the averages of former and the later approach if any is expected to be insignificantly small. GEH statistic as given by Equation (2.2) was used to measure the goodness of fit for volumes.

$$GEH = \sqrt{\frac{2(M-O)^2}{(M+O)}} \qquad \textbf{Equation (2.2)}$$

where; M: simulated flows O: observed flows

Various GEH values give an indication of a goodness of fit as outlined below:

GEH < 5	Flows can be considered a good fit
5 < GEH < 10	Flows may require further investigation
10 > GEH	Flows cannot be considered to be a good fit

Percentage error as given in Equation (2.3) was used to measure goodness of fit for travel time.

$$tt_{error} = \frac{\left|Travel\ Time_{field} - Travel\ Time_{simulation}\right|}{Travel\ Time_{field}}$$ **Equation (2.3)**

It is suggested that, when multiple performance measures are used to assess simulation model, a combination of these measures is preferred (Park and Won 2006). However, meta-heuristics performance can be compared by using only a single measure. Additionally, use of two measures also triggers a scale issue due to the difference in magnitude as well as the unit. To overcome this problem, a single comprehensive score was used for each run based on the two measures (volume and travel time). The score was calculated as the sum of percentage travel time error and a product of a normalizing weight (*K*) and GEH as shown in Equation (2.4).

$$Score = K.\sum_{i=1}^{n} GEH_i + \sum_{j=1}^{m} tt_{error}(j)$$ **Equation (2.4)**

The results from the manual calibration process were used to decide the normalizing weight *K* using a trial-and-error approach. *K* was set (to 30) such that, both MOEs are weighed equally. Lower scores mean a relatively smaller difference between the field data and simulated model results. Hence, the model with the lowest score is considered to perform the best. GA, SA and TS share many similarities, but they also possess distinctive features, mainly in their strategies for searching the solution state space. In this study GA with (ax, bx_{add}, bx_{mult}, *Model #)* as chromosome, calculated scores such as the fitness value, tournament selection of parents, one-point crossover, variable small probability mutation and generational replacement is employed. The GA is terminated when the fixed number of generations has lapsed. The conceptual diagram of GA is shown in Figure 2.4. For SA, the neighborhood structures are the same as the GA chromosomes i.e. (ax, bx_{add}, bx_{mult}, *Model #).* A fixed number random neighborhood searches, current solution replacement by a better solution, probabilistic non-improving solution acceptance for avoiding local optimum traps, temperature control using cooling rate is employed in this study. The SA flow chart is shown in Figure 2.5. Similarly, in TS, fixed number random neighborhood searches, better solution acceptance, acceptance of non-Tabu non-improving solution is employed. The TS flow chart is shown in Figure 2.6. Since this study seeks to compare the performances of the three meta-heuristics, parameters such as the number of iterations (generations in GA), the number of neighborhoods (population size in GA) were chosen in way that the total solution space searches were approximately the same in all three for the true assessment of their performance. The tuning of heuristics parameters such as tabu list size, cooling rate, initial temperature, mutation rate, and population size was performed by referring to literature on similar topics and repeated trials. The possible ranges of results were already known from the manual calibration that was performed before the automated approach. This greatly helped in tuning the meta-heuristics parameters. The user-defined parameters, ax, bx_{add}, *and* bx_{mult} were randomly generated numbers in steps of 0.5 within the range shown in Table 2.1 whereas; *Model #* was a randomly generated integer between 1 and 100. Parameters used for the three meta-heuristics are shown in Table 2.3. It should be noted that the performance and the results of the algorithms significantly depends on these parameters and hence should be decided very meticulously.

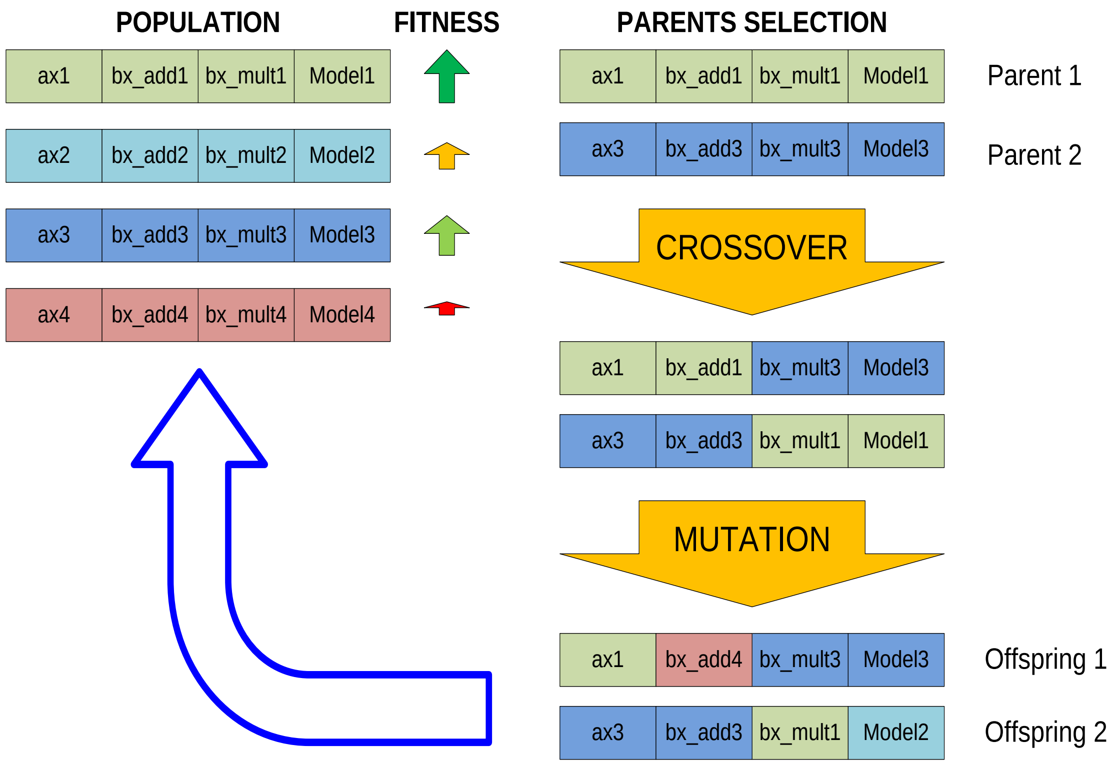


Figure 2.4 Conceptual Diagram of Genetic Algorithm

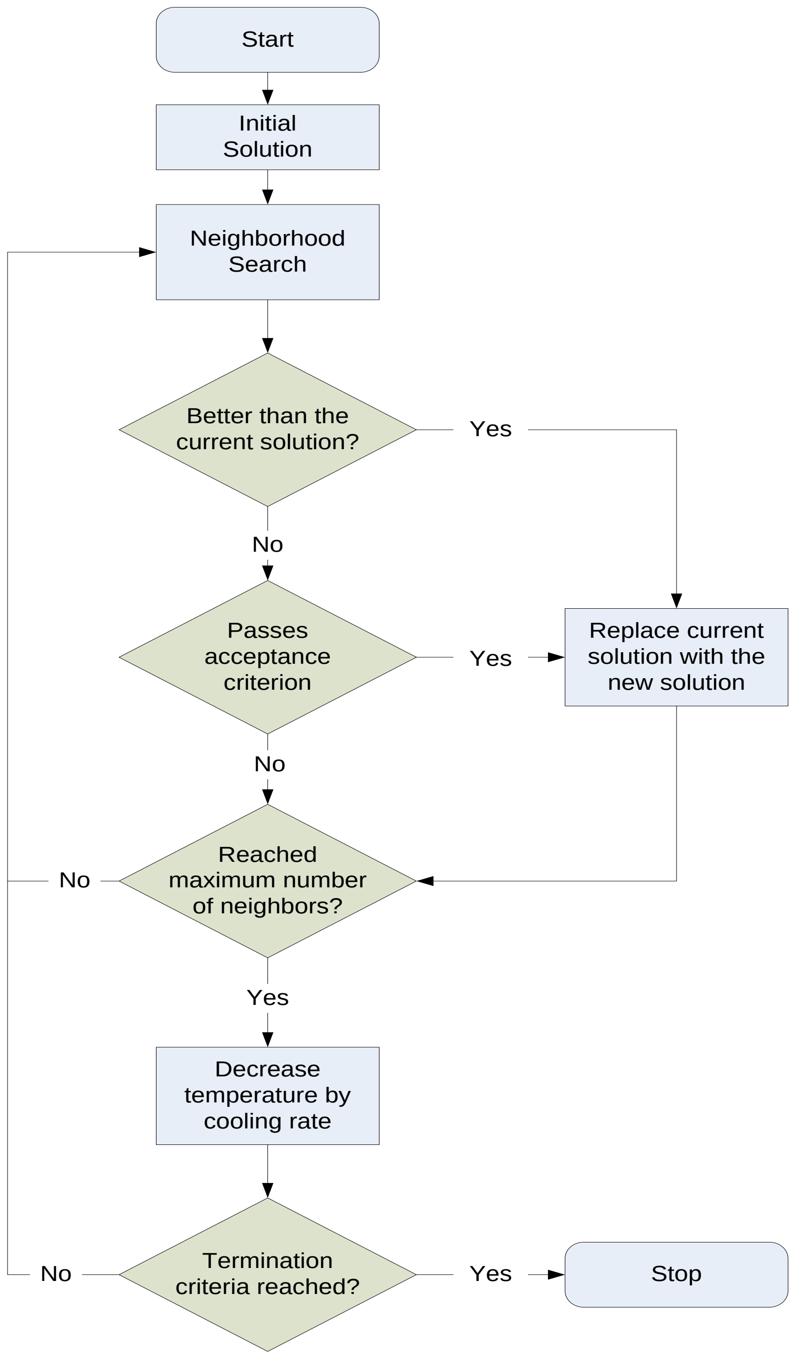


Figure 2.5 Simulated Annealing Flow Chart

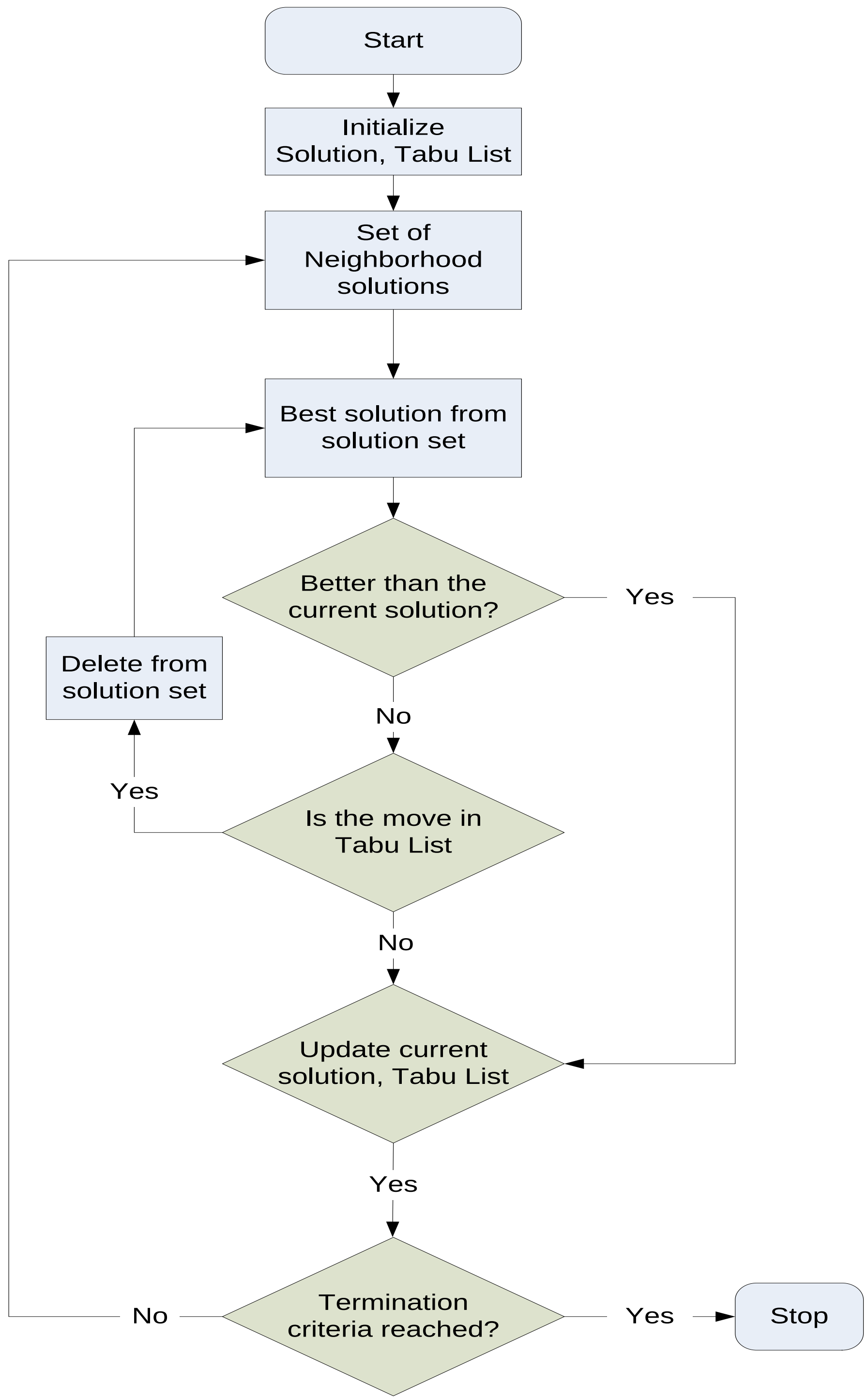


Figure 2.6 Tabu Search Flow Chart

Table 2.3 Algorithm Parameters

Genetic	Algorithm	Simulated	Annealing	Tabu	Search
Population size	10	*Maximum no of iterations*	100	*Maximum no of iterations*	50
No of generations	25	*Maximum no of neighbors searched*	5	*Maximum no of neighbors searched*	5
Crossover	at random point between first and last chromosome	*Initial temperature (T_0)*	70000	*Tabu List size*	10
Maximum Mutation rate	0.3	*Cooling rate*	0.9		
Fitness function	Score calculated based on 1) GEH statistics for difference in volume 2) % difference between field travel time and simulated travel time	*Objective Function value*	Score calculated based on 1) GEH statistics for difference in volume 2) % difference between field travel time and simulated travel time	*Objective Function value*	Score calculated based on 1) GEH statistics for difference in volume 2) % difference between field travel time and simulated travel time
		Acceptance probability of non-optimal solution	$exp\,[(score_{best} - score) / T]$		

2.4 Results

Ten runs of each meta-heuristics were repeated. The results of the runs are presented in Table 2.4. For the GA case, 10 populations were simulated for 25 generations. Hence, the total number of solution searches for all runs was 260. Similarly, in the case of TS, starting with an initial random solution and 50 iterations thereafter and 5 neighborhood searches in each iteration, the total number of solution searches are 255 for all 10 runs. For SA, however, the maximum possible number of simulation runs is 500 (100 iterations x maximum 5 neighbors). However, the acceptance probability introduces an element of randomness and there are fewer runs since not all five neighboring solutions are searched if a better solution is found before searching for a new neighboring solution. Thus, the number of simulations for SA varies for each run. The number of better solutions represents the number of those solutions found by the heuristic, which were better than the solution of the manually calibrated simulation model. As discussed in the previous section, the score calculated for each simulation model is used for comparing the performances of the three heuristic algorithms and the best model is the one with the least score.

The comparative results show that GA found 15 better solutions compared to the manually calibrated solution, SA was able to find 19 better solutions and TS found 23 better solutions. In three runs, GA failed to find any better solution whereas SA and TS failed to find a better solution only once. With the manually calibrated simulation model, the best score found was 4801.The best solution found by GA in all runs is 4767, by SA is 4753 and best solution found by TS has a score of 4745. In all both, SA and TS found four better solutions than GA's best solution. But TS found two solutions either equal or better than SA. Also, convergence of TS is found to be best amongst the three heuristics with an average of 80 runs to search for the best solution, followed by GA as the second best at 118 and lastly the SA at 143. These results imply that TS tends to perform better as compared to GA and SA. In terms of time performance, TS took an average of about 98 hours for each run, computation time for SA is about 94 hours and that of GA is best at about 80 hours per run. But considering the fact that manual calibration efforts can last for a couple of months, the computational times for the meta-heuristics is almost insignificant. Figure 2.7 is a scatter plot showing the comparison between the solutions explored by GA, SA and TS. This figure shows the spread and pattern of the solution spaces explored by the meta-heuristics. The orange shaded area is the convergence zone over the 10 runs. The convergence region for GA is much flatter and takes an average of 118 iterations to converge to

Table 2.4 GA, SA and TS Comparative Results

	GA				**SA**				**TS**			
Total Solutions Explored	260				*Min:* 275 *Avg: 303* *Max: 333*				255			
Run #	*# Better Solutions*	*Run # of Best Solution*	*Best Score*	*Run Time (hrs)*	*# Better Solutions*	*Run # of Best Solution*	*Best Score*	*Run Time (hrs)*	*# Better Solutions*	*Run # of Best Solution*	*Best Score*	*Run Time (hrs)*
Run 1	1	46	4796	79.4	2	19	4777	92.3	6	21	4753	93.9
Run 2	0	33	(4806)	77.6	0	87	(4807)	95.8	1	161	4787	104.6
Run 3	1	104	4783	77.2	2	124	4766	88.3	0	41	(4805)	103
Run 4	1	185	4788	77.4	1	75	4760	91.1	1	6	4771	94.4
Run 5	5	258	4768	80.9	2	278	4780	90.6	1	71	4798	99.2
Run 6	0	198	(4801)	91.5	2	275	4789	97	4	26	4774	97.2
Run 7	2	56	4767**	78.6	4	189	4758	94.3	4	26	4759	95.2
Run 8	4	30	4789	78.9	2	84	4784	92.9	1	201	4745**	99.9
Run 9	1	121	4789	77.3	3	85	4776	93.7	2	186	4760	97.5
Run 10	0	147	(4802)	80.4	1	210	4753**	102	3	56	4775	94.6
Average	1.5	118	4789	79.9	1.9	143	4775	93.8	2.3	80	4773	97.9

Score for manually calibrated model: 4801
(…) results are not better than the manual calibration solution
***** best solution***

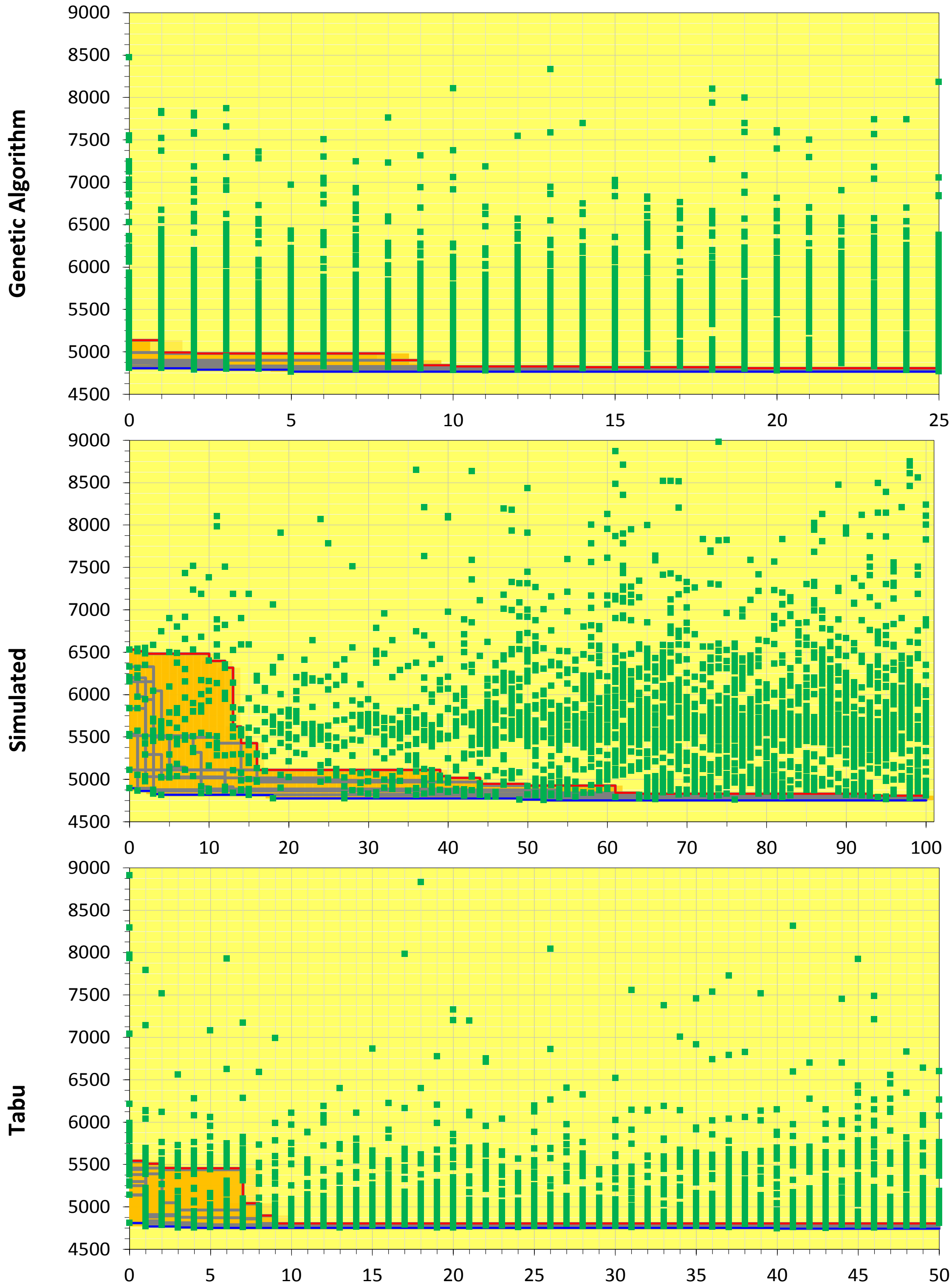


Figure 2.7 Comparison between GA, SA and TS Solutions

the best solution. The convergence zone for SA is broader at an average of 143 iterations and is the longest among three. The convergence for TS is the best at an average of 80 iterations.

2.5 Summary and Conclusion

Microsimulation modeling offers many benefits over the field data based traffic studies. However, microsimulation models should be well calibrated before it is used for meaningful analysis. It is expected to accurately reproduce field traffic conditions so that the results of simulation studies can be more reliably used for making right decisions. However, calibration of a microsimulation model poses a challenge due to numerous user-defined parameters included in the model that needs to attuned to correct levels. The manual calibration process is a trial-and-error approach of iteratively trying different parameter values in each step till desired results are obtained. However, manual calibration has its own limitations and can only be adopted when the number of parameters to be calibrated is small enough. But, when the calibration parameters set is large, literature suggests the use of automated techniques such as mathematical optimization, meta-heuristics or any other algorithms which try to find the best combination of parameters such that the simulation model closely follows the field conditions. It was also found that amongst the meta-heuristics, GA has been widely used in the past and SA has been used only once. We did not find any adoption of TS for calibrating microsimulation model in the literature. In addition, the literature also lacks any study that compares the manual and automated technique using meta-heuristics. Thus, the objective of this paper is to fill this research gap and examine the suitability of meta-heuristics for such application. This study can be differentiated to similar other studies in the past because:

(1) Multiple replications is being implemented overcoming the limitations many such past studies (Hollander and Liu 2008a)
(2) The approach of converting the real number ranges of the parameter values to discrete number ranges using LHSD is adopted. This approach gives modeler flexibility to select his own tradeoff between solution quality and computational time.
(3) Performances of GA, SA and TS meta-heuristics for calibration of microsimulation model are compared with each other and also with the manual calibration.

The comparison of manual, GA, SA and TS meta-heuristics shows that TS gives better calibration results compared to GA and SA. This study helps us to conclude that

(1) An automated approach using meta-heuristics can be relied upon to calibrate simulation models very effectively.
(2) Based on the results, the three meta-heuristics GA, SA and TS have the ability to perform better calibration than the manual process.
(3) TS perform better than GA and SA for calibration of microsimulation models. The number of better solutions, as well as the best solution found by TS, is better than those found by GA and SA.
(4) TS also have faster convergence to best solution compared to GA and SA.
(5) A significant amount of time can be saved by using meta-heuristics for calibrating micro-simulation models. However, time for developing the code, testing the code, tuning the parameters, setting up the COM interface, etc should be given due consideration. Lack of experience with any of these elements might result in spending more time. Despite this,

efforts on such automated procedures are still worth spending and intellectually satisfying.

The conclusion is however limited to the parameter settings used in meta-heuristics. Since for this study the manually calibrated microsimulation model was already available before starting with the comparisons of the meta-heuristics performances, the meta-heuristics parameters were relaxed in the interest of time. However, in practice, Latin Hypercube sample size, possible incremental steps of car following parameters *(ax, bx_{add}, and bx_{mult})* can all be varied to get a better solution; although that would be achieved only at the expense of computational time. Of particular interest is the tuning of meta-heuristics parameters. For this study, manual calibration was performed before the automated approach. Thus the possible ranges of results were already known beforehand. This greatly helped in the tuning of meta-heuristics parameters. However, in absence of this prior knowledge, greater efforts need to be directed in tuning the parameters correctly. Sensitivity analysis of these parameters would be of great value to other researchers but is considered as beyond the scope of this study and should be considered for future research. There are many other algorithms that still need to be tested for calibration of microsimulation models. This is still another potential area for future study. With the advent of 'Big Data', the calibration process in the future is likely to become more complex. Use of meta-heuristics can prove to be a more useful method to help engineers and planners achieve better model results.

2.6 References

Abdalhaq, B. K., and Baker, M. I. A. (2014). "Using Meta Heuristic Algorithms to Improve Traffic Simulation." Journal of Algorithms and Optimization, 2(4), 110–128.

Arostegui, M. a., Kadipasaoglu, S. N., and Khumawala, B. M. (2006). "An empirical comparison of Tabu Search, Simulated Annealing, and Genetic Algorithms for facilities location problems." International Journal of Production Economics, 103(2), 742–754.

Ciuffo, B., and Punzo, V. (2014). "'No free lunch' Theorems applied to the calibration of traffic simulation models." IEEE Transactions on Intelligent Transportation Systems, 15(2), 553–562.

Dowling, R., Skabardonis, A., and Alexiadis, V. (2004). Traffic Analysis Toolbox Volume III : Guidelines for Applying Traffic Microsimulation Modeling Software.

Errampalli, M., Okushima, M., and Akiyama, T. (2012). "Development of the Microscopic Traffic Simulation Model with the Fuzzy Logic Technique." Simulation, 89(1), 87–101.

Gao, Y. (2008). "Calibration and Comparison of the VISSIM and INTEGRATION Microscopic Traffic Simulation Models." Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

Gettman, D., and Head, L. (2003). Surrogate Safety Measures From Traffic Simulation Models. FHWA-RD-03-050.

Ghazanfari, M., Alizadeh, S., Fathian, M., and Koulouriotis, D. E. (2007). "Comparing simulated annealing and genetic algorithm in learning FCM." Applied Mathematics and Computation, 192(1), 56–68.

Gomes, G., May, A., and Horowitz, R. (2004). "Congested Freeway Microsimulation Model Using VISSIM." Transportation Research Record: Journal of the Transportation Research Board, 1876(1), 71–81.

Habib Youssef, Sadiq M. Sait, H. A. (2001). "Evolutionary algorithms, simulated annealing and tabu search: a comparative study." Engineering Applications of Artificial Intelligence, 14(2), 167–181.

Hellinga, B. R. (1998). "Requirements for the Calibration of Traffic Simulation Models." Canadian Society for Civil Engineering, Halifax, Nova Scotia, 211–222.

Ho, Y.-C. H. Y.-C., and Pepyne, D. L. (2001). "Simple explanation of the no free lunch theorem of optimization." 40th IEEE Conference on Decision and Control, Orlando, Florida, 4409–4414.

Hollander, Y., and Liu, R. (2008a). “The principles of calibrating traffic microsimulation models.” Transportation, 35(3), 347–362.

Hollander, Y., and Liu, R. (2008b). “Estimation of the distribution of travel times by repeated simulation.” Transportation Research Part C: Emerging Technologies, 16(2), 212–231.

Hourdakis, J., Michalopoulos, P., and Kottommannil, J. (2003). “Practical Procedure for Calibrating Microscopic Traffic Simulation Models.” Transportation Research Record, 1852, 130–139.

Hu, X., and Chiu, Y.-C. (2011). “A new approach to calibrating time-dependent origin-destination departure profile for traffic simulation models.” 14th IEEE Conference on Intelligent Transportation Systems, Washington, DC, 139–144.

Jayakrishnan, R., Mattingly, S. P., and McNally, M. G. (2000). Performance Study of SCOOT Traffic Control System with Non-Ideal Detectorization etectorization : Field Operational Test in the City of Anaheim. Report UC Irvine, California.

Jayakrishnan, R., Oh, J.-S., and Sahraoui, A. (2001). “Calibration and path dynamics issues in microscopic simulation for advanced traffic management and information systems.” Transport Research Record, 1771, 9–17.

Kergaye, C., Stevanovic, A., and Martin, P. (2010). “Comparative Evaluation of Adaptive Traffic Control System Assessments Through Field and Microsimulation.” Journal of Intelligent Transportation Systems, 14(2), 109–124.

Kim, K.-O., and Rilett, L. (2003). “Simplex-Based Calibration of Traffic Microsimulation Models with Intelligent Transportation Systems Data.” Transportation Research Record, 1855, 80–89.

Kim, S.-J., Kim, W., and Rilett, L. R. (2005). “Calibration of Microsimulation Models Using Nonparametric Statistical Techniques.” Transportation Research Record, 1935, 111–119.

Levin, R. I., and Lieven, N. a. J. (1998). “Dynamic Finite Element Model Updating Using Simulated Annealing and Genetic Algorithms.” Mechanical Systems and Signal Processing, 12(1), 91–120.

Li, Z., Liu, H., and Zhang, K. (2009). “Calibration and validation of PARAMICS for freeway using toll data.” 12th International IEEE Conference on Intelligent Transportation Systems, St. Louis, MO, 172–177.

Lianyu Chu, Liu, H. X., Oh, J.-S., and Recker, W. (2004). “A calibration procedure for microscopic traffic simulation.” 83rd TRB Annual Meeting, Washington, DC.

Liu, H., Yang, X., and Sun, J. (2006). “Parameter Calibration for VISSIM using a Hybrid Heuristic Algorithm: A case study of a congested traffic network in China.” Applications of Advanced Technology in Transportation, American Society of Civil Engineers (ASCE), Chicago, Illinois, 522–527.

Ma, J., Dong, H., and Zhang, H. M. (2007). “Calibration of Microsimulation with Heuristic Optimization Methods.” Transportation Research Record: Journal of the Transportation Research Board, 1999(1), 208–217.

Manjunatha, P., Vortisch, P., and Mathew, T. (2013). “Methodology for the Calibration of VISSIM in Mixed Traffic.” 92nd TRB Annual Meeting, Washington, DC, 11.

Mathew, T. V., and Radhakrishnan, P. (2010). “Calibration of Microsimulation Models for Nonlane-Based Heterogeneous Traffic at Signalized Intersections.” Journal of Urban Planning and Development, 136(1), 59–66.

Menneni, S., Sun, C., and Vortisch, P. (2008). “Microsimulation Calibration Using Speed Flow Relationships.” Transportation Research Record: Journal of the Transportation Research Board, 2088, 1–9.

Merritt, E. (2004). “Calibration and Validation of CORSIM for Swedish Road Traffic Conditions.” 83rd TRB Annual MeetingAnnual Meeting, Washington, DC.

Miller, D. M. (2009). “Developing a Procedure To Identify Parameters for Calibration of a VISSIM Model.” (May), 169.

Oketch, T., and Carrick, M. (2005). “Calibration and Validation of a Micro-Simulation Model in Network Analysis.” 84th TRB Annual Meeting, Washington, D.C., 1–17.

Omrani, R., and Kattan, L. (2013). “Simultaneous Calibration of Microscopic Traffic Simulation Model and Estimation of Origin / Destination (OD) Flows based on Genetic Algorithms in a High-Performance Computer * I N ’ iN exs _ XO) 2.” 16th International IEEE Annual Conference on Intelligent Transportation Systems, Hague, Netherlands, 2316–2321.

Oregon DOT. (2011). Protocol for VISSIM Simulation.

Park, B. (Brian), and Qi, H. (Maggie). (2005). “Development and Evaluation of a Procedure for the Calibration of Simulation Models.” Transportation Research Record: Journal of the Transportation Research Board, 1934(1), 208–217.

Park, B. (Brian), and Won, J. (2006). Microscopic Simulation Model Calibration and Validation Handbook. Virginia Transportation Research Council, Richmond, Virginia.

Park, B., and Schneeberger, J. (2003). “Microscopic Simulation Model Calibration and Validation: Case Study of VISSIM Simulation Model for a Coordinated Actuated Signal System.” Transportation Research Record, 1856(1), 185–192.

Paz, A., Molano, V., and Gaviria, C. (2012). “Calibration of CORSIM models considering all model parameters simultaneously.” IEEE Conference on Intelligent Transportation Systems, Anchorage, Alaska, 1417–1422.

Peng, Z., Guan, F., Wang, K., Li, T., and Yao, B. (2016). “Simulation-optimization model for one-way traffic reconfiguration.” Simulation, 92(7), 627–635.

Planung Transport Verkehr (PTV) AG. (2011). VISSIM 5.40-01 - User Manual. Karlsruhe, Germany.

Sahraoui, A.-E.-K., and Jayakrishnan, R. (2005). “Microscopic-macroscopic Models Systems Integration: A Simulation Case Study for ATMIS.” Simulation, 81(5), 353–363.

Sexton, R. S., Dorsey, R. E., and Johnson, J. D. (1999). “Optimization of neural networks: A comparative analysis of the genetic algorithm and simulated annealing.” European Journal of Operational Research, 114(3), 589–601.

Shaaban, K. S., and Radwan, E. (2005). “A Calibration and Validation Procedure for Microscopic Simulation Model : A Case Study of SimTraffic for Arterial Streets.” 84rd Annual Meeting, Washington, DC.

Song, R., and Sun, J. (2016). “Calibration of a micro-traffic simulation model with respect to the spatial-temporal evolution of expressway on-ramp bottlenecks.” Simulation, 92(6), 535–546.

Suh, W., Henclewood, D., Greenwood, a., Guin, a., Guensler, R., Hunter, M. P., and Fujimoto, R. (2013). “Modeling pedestrian crossing activities in an urban environment using microscopic traffic simulation.” Simulation, 89(2), 213–224.

Sun, J., Wu, Z., and Yang, X. (2011). “Calibration of VISSIM for Shanghai Expressway Weaving Sections Using Simulated Annealing Algorithm.” Computing in Civil Engineering (2005), American Society of Civil Engineers (ASCE), Cancun, Mexico, 693–700.

Toledo, T., Ben-Akiva, M., Darda, D., Jha, M., and Koutsopoulos, H. (2004). “Calibration of Microscopic Traffic Simulation Models with Aggregate Data.” Transportation Research Record, 1876, 10–19.

Toledo, T., Koutsopoulos, H. N., Davol, A., Ben-Akiva, M. E., Burghout, W., Andréasson, I., Johansson, T., and Lundin, C. (2003). “Calibration and validation of microscopic traffic simulation tools: Stockholm case study.” Transportation Research Record: Journal of the Transportation Research Board, 1831, 65–75.

Wolpert, D. H., and Macready, W. G. (1997). “No Free Lunch Theorems for Optimization.” IEEE Transactions on Evolutionary Computation, 1(1), 67–82.

Wu, Z., Sun, J., and Yang, X. (2005). "Calibration of VISSIM for Shanghai Expressway using Genetic Algorithm." 2005 Winter Simulation Conference, Fujimoto, 2645–2648.

Yu, L., Yu, L., Chen, X., Wan, T., and Guo, J. (2006). "Calibration of VISSIM for bus rapid transit systems in Beijing using GPS data." Journal of Public Transportation, (BRT Special Edition), 239–257.

Zhang, M., Ma, J., and Dong, H. (2008a). Developing Calibration Tools for Microscopic Traffic Simulation Final Report Part II: Calibration Framework and Calibration of Local/Global Driving Behavior and Departure/Route Choice Model Parameters. California PATH Research Report UCB-ITS-PRR-2008-7, California.

Zhang, M., Ma, J., Singh, S. P., and Chu, L. (2008b). Developing Calibration Tools for Microscopic Traffic Simulation Final Report Part III: Global Calibration - O-D Estimation, Traffic Signal Enhancements and a Case Study. California PATH Research Report UCB-ITS-PRR-2008-8.

Zhang, X., and Chang, G.-L. (2014). "A mixed-flow simulation model for congested intersections with high pedestrian-vehicle traffic flows." Simulation, 90(5), 570–590.

Zou, G., and Kulkarni, R. (2014). "Simulation-based adaptive calibration and optimization of intelligent transportation systems for highway congestion management." Simulation, 90(12), 1360–1374.

CHAPTER 3

COMPARING THE PERFORMANCES OF DIFFERENT ARTERIAL CORRIDORS WITH VARYING TRAFFIC CHARACTERISTICS UNDER TOD AND SCATS TRAFFIC CONTROL USING MICROSIMULATION TECHNIQUE

3.1 Introduction

Traffic signals are used to assign right of way to vehicular and pedestrian traffic at an intersection. Proper traffic signal timing and operations reduce congestion, improve mobility, and enhance safety. Although signal operations impact several individual performance measures, one of the most positive potential benefits is the overall improvement of system efficiency. The process of developing and maintaining traffic signal timing plans can be extremely resource intensive. Furthermore, traditional time-of-day (TOD) plans do not accommodate variable and unpredictable traffic demands and cannot adjust to changing travel demand over time. As such, adaptive traffic signal control (ATCS) systems are becoming more widely used throughout the traffic engineering industry.

ATCS systems continuously detect vehicular traffic data and then compute and implement optimal signal timings in real time (Martin, Stevanovic, and Stevanovic 2005). Benefits typically attributed to ATCS systems include:

(1) Reduced congestion and fuel consumption

(2) Improved travel time reliability

(3) Prolonged effectiveness of traffic signal timing

(4) Proactive traffic signal adjustments from monitoring and responding to real-time traffic demands.

ATCSs are widely used in the United Kingdom, Asia, and Australia. In the United States, ATCS technologies are currently used on less than one percent of all signalized intersections. Commonly cited barriers to ATCS deployment include high hardware and software costs, lack of local expertise necessary to configure and maintain the system, the uncertainty about the benefits of adaptive signal control technology, and the lack of active performance measurement (Day et al. 2012). Various ATCSs available in the market include the Sydney Coordinated Adaptive Traffic System (SCATS), Split Cycle Offset Optimization Technique (SCOOT), Optimization Policies for Adaptive Control (OPAC), Adaptive Control Software Lite (ACS Lite), Real-Time Hierarchical Optimized Distributed and Effective System (RHODES), InSync and others. The underlying algorithms in each system vary in approach and structure but essentially optimize operational efficiency by maximizing throughput, minimizing delay, or some combination of both (Stevanovic 2010).

SCATS is one of the most widely used ATCS. It controls traffic at two levels (strategic and tactical) by determining the three signal timing parameters, namely; phase splits, cycle lengths and offset. The strategic control uses data collected from the lane-by-lane stop bar zones by the local controllers to determine the three signal timing parameters. SCATS uses degree of saturation (DS) as the basic measure for traffic control. DS is defined as the ratio of efficiently used phase time to the total available phase time at each intersection. SCATS constantly make changes to the cycle length to maintain the DS at the level of around 0.9. The phase splits are varied each cycle to maintain equal DS on competing approaches to minimize delays. SCATS do not optimize offsets. However, offset scheme based on the balance of traffic and the cycle length are selected such that better flow movements are achieved between the intersections. Tactical control is undertaken by the local controllers at each intersection to provide flexibility to meet the cyclic variation in demand. Tactical control consists of operations such as early termination of green phase in case of lower demand and omission of a certain phase in case of no demand. The combination of strategic and tactical control helps SCATS respond to both gradual and rapid but smaller changes in traffic demand and hence, resulting in very efficient operation of the signals (Lowrie 1982; RTA (Roads and Traffic Authority) and TYCO, n.d.). In addition, SCATS is customizable in the sense that the local traffic engineers can configure SCATS to achieve desired policy outcome e.g. congestion management, mainline progression (Chong-White, Millar, and Aydos 2014; Roads and Maritime Services, n.d.).

3.2 Literature Review

The 2012 National Traffic Signal Report Card emphasizes the greater need for better signal management and operations (National Transportation Operations Coalition 2012). On average, poor signal timings contribute up to five percent of total traffic congestion. Other studies have shown ATCS systems to perform better (in certain performance measures) than fixed-time and actuated control. The 2012 Urban Mobility Report published by Texas A&M Transportation Institute reports ATCS systems as performing some three times better than actuated control with regard to delay reduction (Schrank et al. 2015). Another study on evaluation of ATCS shows that InSync was able to reduce travel times over an arterial study corridor (Hutton, Bokenkroger, and Meyer 2010). The improvements, however, were directionally specific and limited to a specific time-of-day. Another study in Minneapolis showed that SCOOTS significantly improved travel times during special events. Overall peak hour travel times, however, showed no significant change under ATCS (SRF Consulting Group Inc. 2000). An evaluation of OPAC in Florida showed significant improvements to arterial operations but reported that these were at the expense of side-street efficiency (Gord & Associates 2007). Taale et al. (1998) show that the proper functioning of SCOOT system relies on the parameter settings that can influence the results of any assessment (Taale, Fransen, and Dibbits 1998). In addition to this, there are other studies of investigation of suboptimal deployment of ATCS (Jayakrishnan, Mattingly, and McNally 2000).

Previous evaluations of SCATS have reported mixed results. Peters et al. (2007) reported that SCATS reduced travel times during the AM peak period in one direction but an increase in the opposite direction on the Burnside corridor in Gresham, Oregon. The before-after SCATS comparison, however, might have been biased as the original timing plans explicitly favored one direction during the AM peak period (Peters, McCoy, and Bertini 2007). Although none of the studies showed worsening operations under SCATS control, several showed only limited improvements with regard to travel time Tian, Ohene, and Hu (2011), Hunter et al. (2012) and Martin and Stevanovic (2008) reported that a SCATS deployment in UTAH resulted in improved travel times in addition to reduced stopped delay and number of stops (Martin and Stevanovic 2008). This review suggests the need for careful evaluation of the ATCS performances.

3.3 Purpose and Scope

The purpose of this paper is to compare three principal arterial corridors with different physical and operational characteristics under both conventional and adaptive traffic signal control by examining various performance measures, including travel time, delay, average speed, and queue lengths. The comparison is conducted through microsimulation analysis of each corridor under their latest TOD signal operations compared with the same field conditions (i.e., traffic volumes, geometry, access management) operating under SCATS control. The three corridors greatly differ in the traffic saturation levels. Thus, the objective of this paper is to analyze and compare the performance of SCATS under varying saturation conditions.

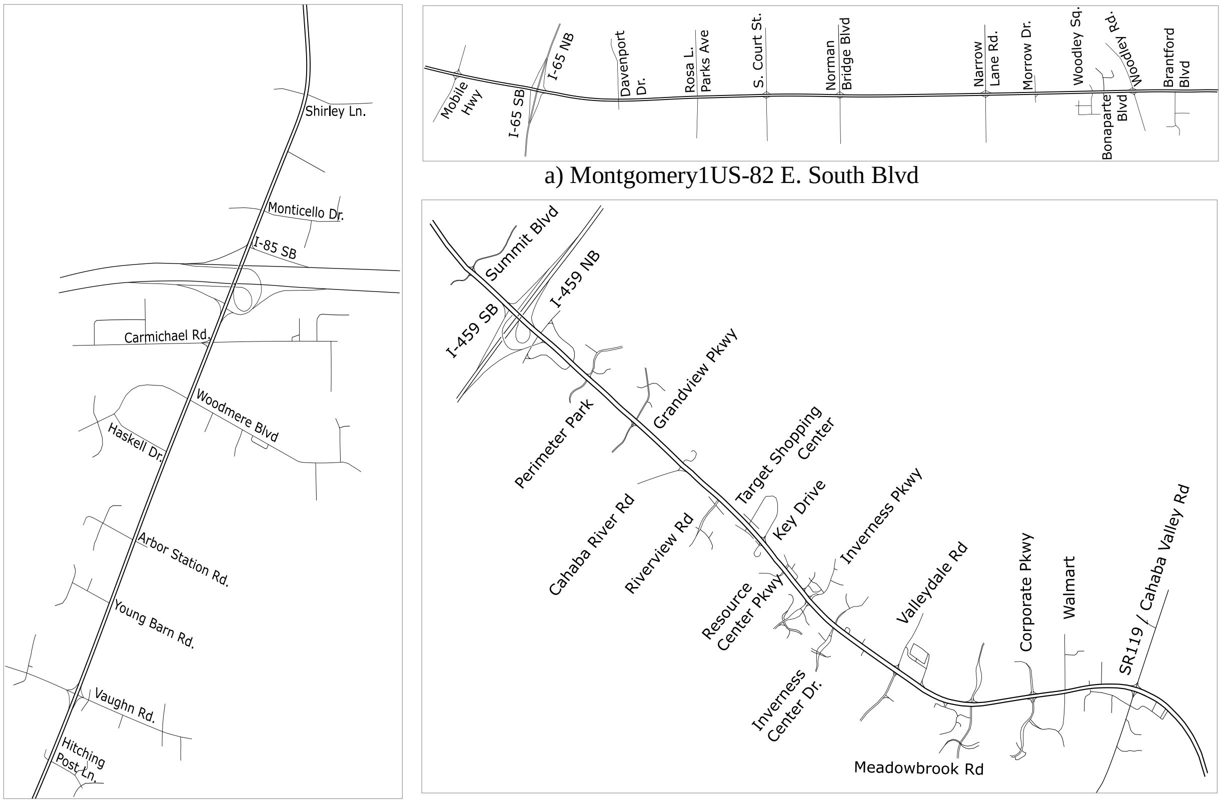
3.4 Methodology

Three separate arterial corridors were studied using a variety of performance metrics. The corridors differ in prevailing operational speeds, volume characteristics (mainline vs. side-street, turning movements, etc.), as well as in terms of geometric and access management conditions. Montgomery1 has the least traffic among the three corridors with AADT of 38,000, Montgomery2 has 43,000 and Birmingham has the highest of about 70,000. Hence based on the field condition and traffic volumes, the congestion levels are subjectively assessed as low, medium and high respectively. This allows a comparison of SCATS performance across very different conditions as all three operated under independent SCATS configurations (i.e. subsystems). Schematic layouts of the corridors are shown in Figure 3.1and relevant details are summarized in Table 3.1.

Table 3.1 Corridor Characteristics

Corridor	Montgomery US-82/ E. South Blvd *(Montgomery1)*	Montgomery US-231/ Eastern Blvd *(Montgomery2)*	Birmingham US-280 *(Birmingham)*
Characteristics	Low volume; Irregular-spaced intersections	Moderate volume; Closely spaced intersections	High volume; Many closely-spaced intersections
# lanes	4	6	6
# Intersections (Interchanges)	13	10	17
Total Corridor Length (miles)	4.9	2.3	4.6
Average Spacing between Intersections (miles)	0.4	0.26	0.27
Average Traffic Volume (vph) per Intersection	1250	1900	2850
Average Cross Street Traffic Volume (vph) per Intersection	200	150	150
Congestion levels	Low	Medium	High
Peak traffic periods	16:30 – 17:30	16:30 – 17:30	16:30 – 17:30

Weekday volumes, turning movement counts at each intersection, vehicle compositions were collected between 14:00 – 18:00 for the study corridor. The travel time data was collected using multiple floating cars that made multiple runs over multiple days. The saturation flow data for intersections which was initially collected for the separate study was also used (Majeed et al. 2014). The before-SCATS optimized field TOD signal timing parameters and the with-SCATS fine-tuned field signal configurations were retained from the Traffic Engineering Department. Relevant geometric data was collected from field observations and aerial imagery. The existing operational data was used to develop VISSIM (version 5.4) microsimulation model. Detector locations (for both TOD and with-SCATS), signal phases, and other geometric conditions in the simulation models were adjusted to match those in the field.



a) Montgomery1US-82 E. South Blvd

b) Montgomery2 US-231 Eastern Blvd

c) Birmingham US-280

Figure 3.1 SCATS Corridor Network Diagrams

The TOD model was calibrated manually using a trial-and-error approach. Volume balancing was performed using Synchro to avoid any directional data inconsistencies. Various VISSIM parameters such as driving behavior, lane change parameters, speed distributions and the routing decisions combined were used to match the link volumes, turning movement counts and queues at each intersection. Speed distributions and speed decisions were based on posted speed limits and travel times.

Both networks TOD and with-SCATS were simulated for 10 replications of 90 minutes each (Dowling, Skabardonis, and Alexiadis 2004). Different random seeds were used across the

10 replications to capture the stochastic variation in traffic characteristics. Warm-up periods of initial 30 minutes were used to fill the network corridor to the given traffic conditions prior to recording performance measures. The remaining 60 minutes were used to evaluate the network performance. The model was validated by comparing the modeled and field volumes, turn movement counts at each signalized intersection, travel times between the signalized intersections and end-to-end corridor travel times.

Kergaye et al. (2010) reported that microsimulation is an effective tool for evaluating ATCS systems (Kergaye, Stevanovic, and Martin 2010a). SCATSIM software allows for the replication of SCATS adaptive control (detection via Simhub and control via WinTraff) directly within the VISSIM simulation environment (Kergaye, Stevanovic, and Martin 2010b; Nguyen 1996). Figure 3.2 shows the elements of the microsimulation process. SCATSIM was used to run the three simulation models under SCATS control. The fine-tuned field SCATS signal configurations were used in the SCATSIM. Validation of the SCATS models was done by comparing phase splits, cycle length, and volumes from the Strategic Monitor against VISSIM outputs. The SCATS controlled simulation models were similar to the TOD models in all respects except for the signal control. This allowed for the comparison of same baseline conditions under different signal control systems and hence objective evaluation of SCATS performance.

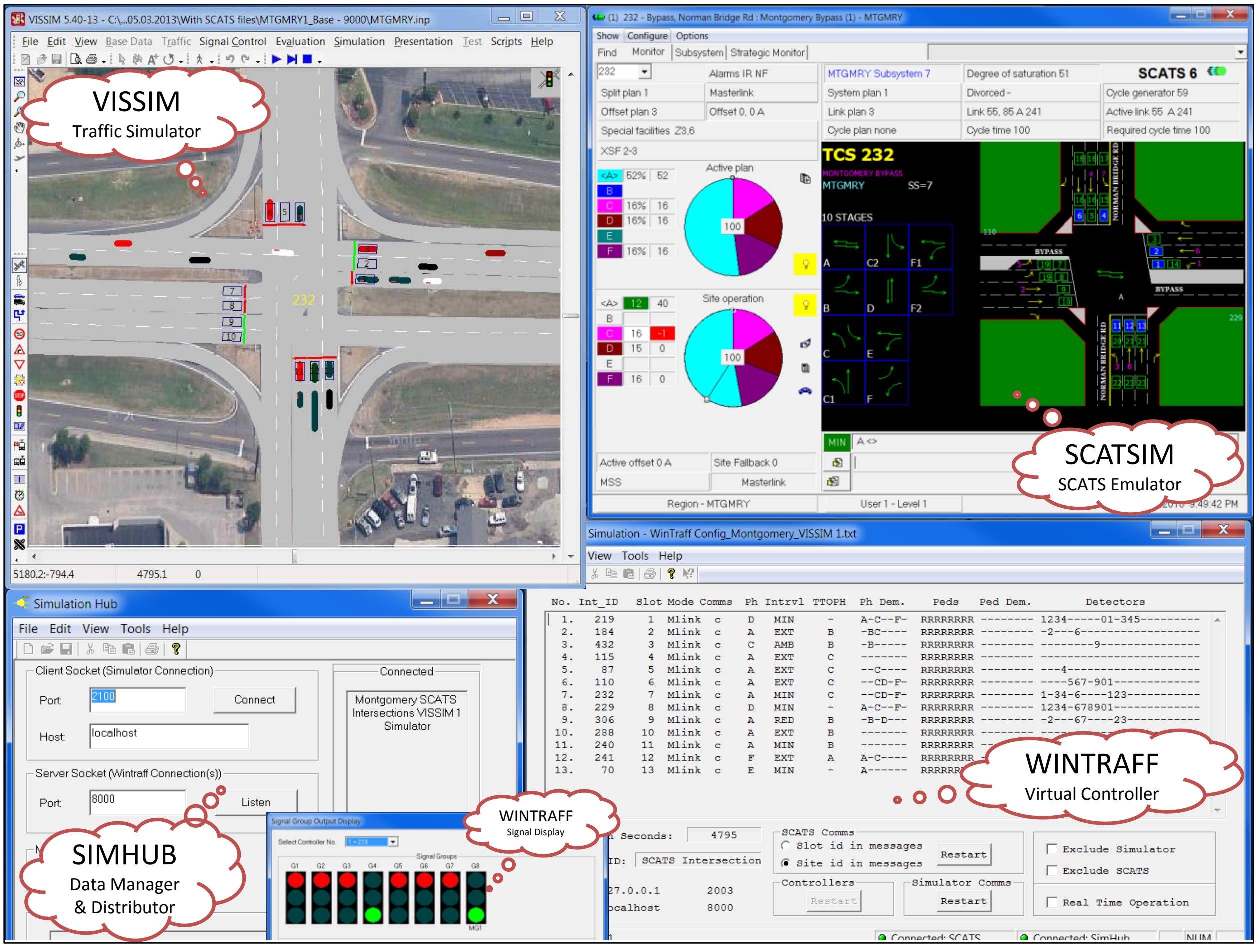


Figure 3.2 Components of SCATS Microsimulation

3.5 Findings and Results

There are numerous performance measures available for comparative evaluation of ATCS vs. non-ATCS operations. Overall, corridor travel time (or delay) is most common followed by number of stops, intersection delays, average speed and queue lengths in that order (Stevanovic 2010). All three study corridors were evaluated on the basis of overall corridor travel time as well as network-wide average delay, average queue lengths, and average speed.

Additional analyses were conducted at the sub-corridor level to identify specific points that illustrate detailed operational differences between SCATS and the latest TOD plans.

3.5.1 Travel Time Assessment

The first assessment looks at travel time, but a major finding in this paper is that travel time does not accurately characterize the entire performance of adaptive control systems and subsequent sections show a more comprehensive picture. The results of the end-to-end corridor travel times and delays for each corridor are shown in Figure 3.3 and Figure 3.4 respectively. By end-to-end corridor, it means starting from the first intersection and ending at the last intersection of the corridor in the mainline direction. The end-to-end corridor travel time sections start from the mainline stop line at the first intersection to the stop line at the last intersection. While the Major 1 is the traffic movement in the mainline peak direction, Major 2 is the traffic movement in the mainline non-peak direction.

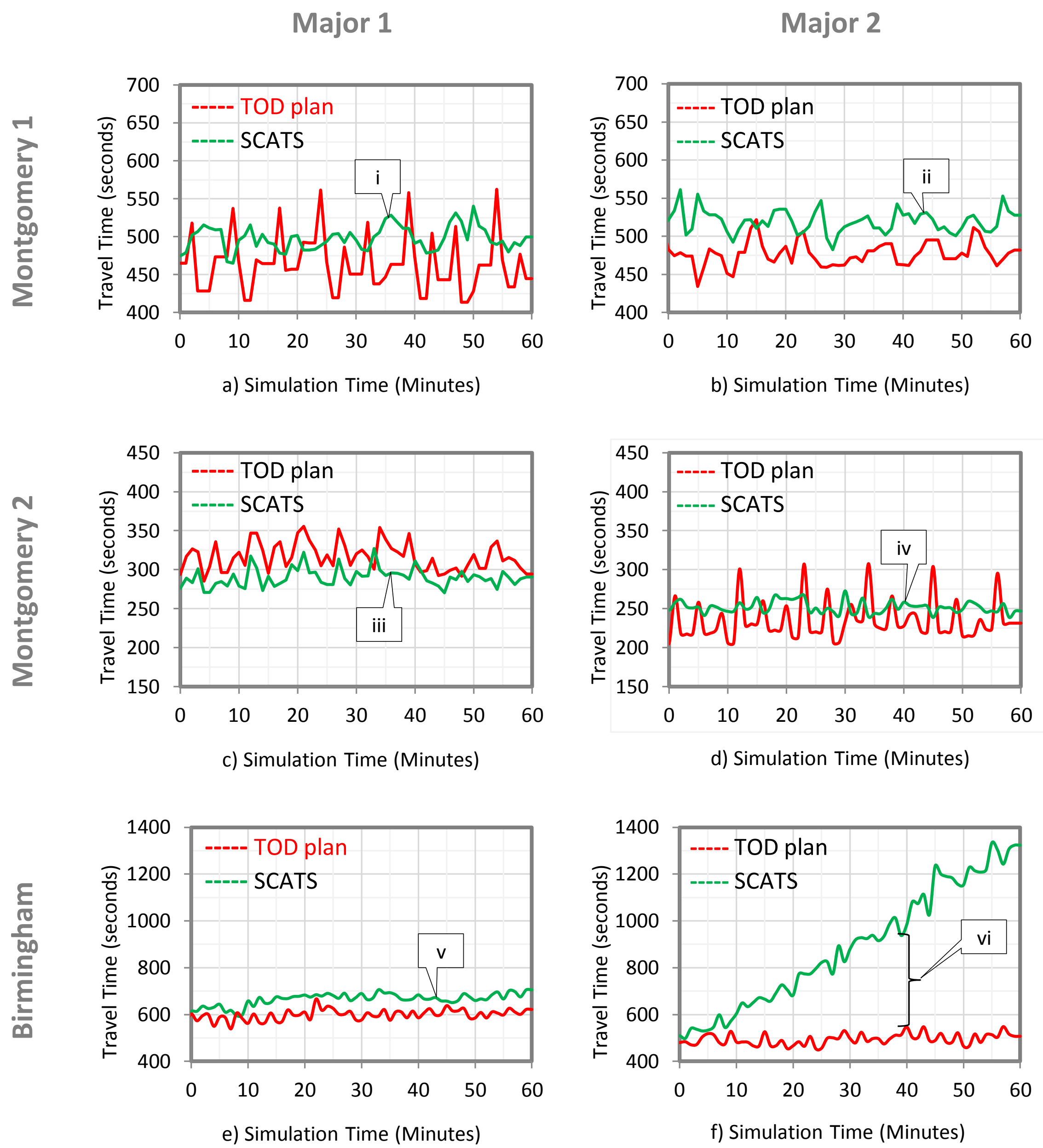


Figure 3.3 End-to-End Corridor Level Travel Times

As can be seen from Figure 3.3, the travel time for the Montgomery1 in the Major 1 direction with SCATS is little higher as compared to the TOD plan and little lower for Montgomery2 (callouts “3.3.i” and “3.3.iii”, where “3.3.i” refers to callout “i" in Figure 3.3 and so on). However, the travel time with SCATS in Major 2 direction is higher as compared to the TOD plan (callouts "3.3.ii" and "3.3.iv").

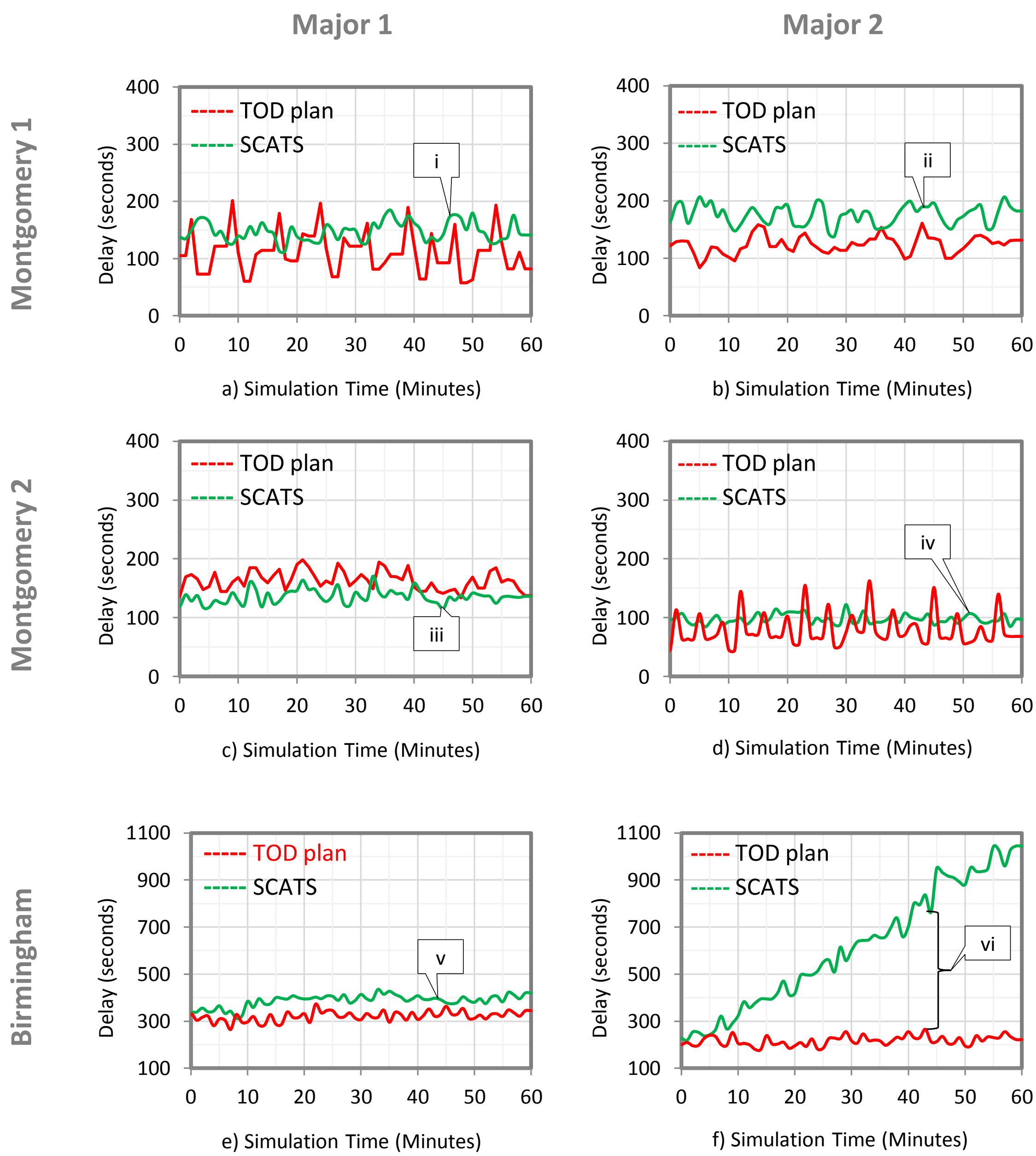


Figure 3.4 End-to-End Corridor Level Delays

The delay with SCATS for these two corridors in both directions shows the same trend as shown by callouts “3.4.i”, “3.4.ii”, “3.4.iii” and “3.4.iv”. In the case of the Birmingham corridor, the travel time in the Major 1 direction with SCATS is higher than with the TOD plan (callout “3.3.v”). In Major 2 direction, the travel time with SCATS starts initially on the lower side, but eventually shifts to being higher than the TOD plan (callout “3.3.vi”). The same phenomenon can be seen with the delay for the Birmingham corridor (callouts “3.4.v” and “3.4.vi”). This might be the case because Major 1 is the peak direction of travel, and thus takes priority over Major 2 traffic. To summarize the results, both travel time and delay follow the same pattern. Across all three study corridors, travel time and delay with SCATS are either equal or slightly higher than the TOD plan. As discussed in the literature review section, ATCS may not always show improvement at corridor level. However, the end-to-end corridor is only one way among many other possible ways that could be further analyzed as needed. In the next section, other network-wide and intersection level performance measures are further examined.

3.5.2 Average Delay and Speed

Going beyond just the traditional analysis of using travel time and delay, Figure 3.5 shows the comparison between network-wide travel time, average delay and average speed for the three study corridors. These three performance measures are available as part of Network Performance in VISSIM. Network-wide travel time is the cumulative sum of travel times of all vehicles that entered the network. Average speed is the total distance traveled by all vehicles divided by the network-wide travel time and average delay is cumulative sum of the delay time of individual vehicles divided by total vehicles that entered the network (Planung Transport

Verkehr (PTV) AG 2011). Each symbol (circle, triangle or square) represents one of the 10 replications.

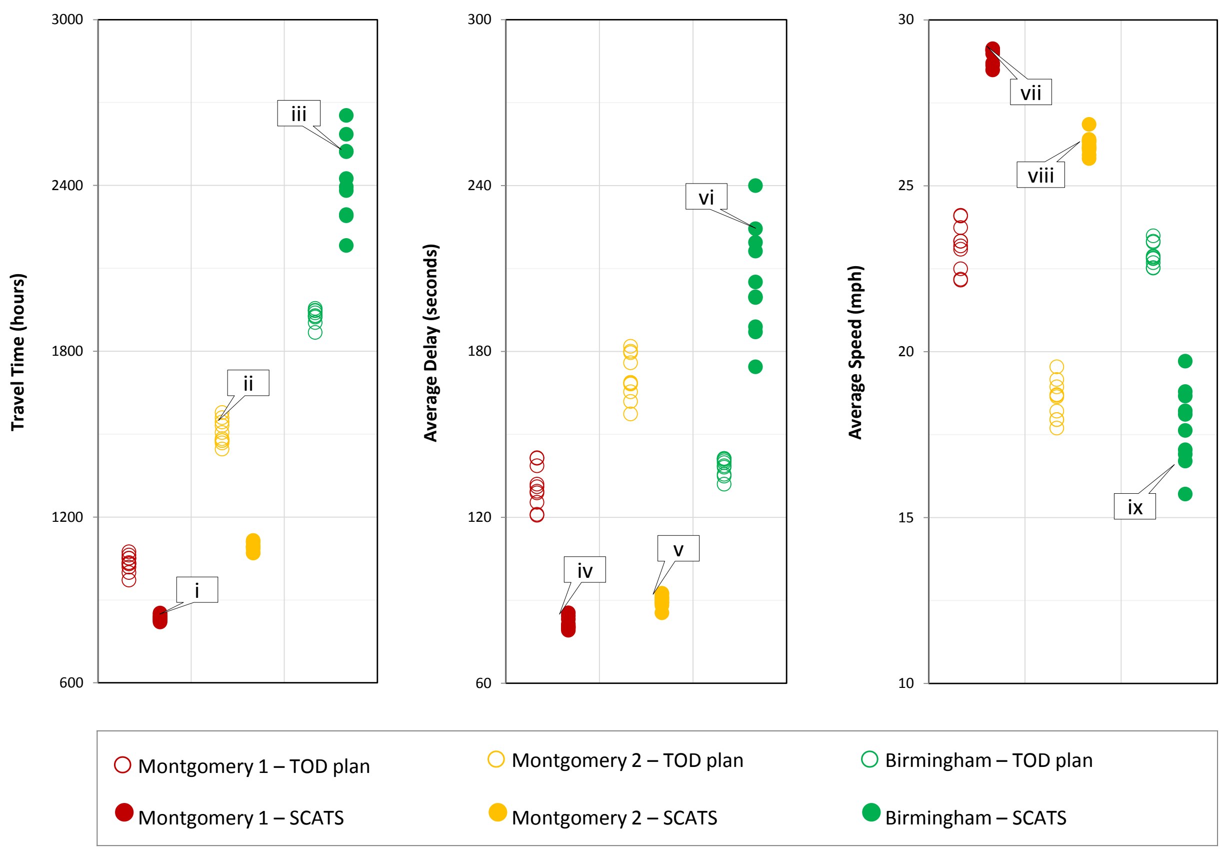


Figure 3.5 Network-wide Performances

Montgomery1 (the most uncongested network with least traffic volume) and Montgomery2 (an average level corridor with average saturation level) clearly show SCATS performing better over TOD on all network-wide performance measures. In contrast to the end-to-end travel time, the network-wide travel time for Montgomery1 and Montgomery2 shows a decrease with SCATS when compared to the TOD plan (callouts "3.5.i" and "3.5.ii"). Similarly, the network-wide average delay shows significant improvements (callouts "3.5.iv" and "3.5.v").

The network-wide average speed for these two corridors is higher with SCATS compared to the TOD (callouts “3.5.vii” and “3.5.viii”).

The results for the Birmingham corridor, the oversaturated network, indicate no real operational improvements are attributable to SCATS. Figure 3.5 (callout “3.5.iii”) shows that the network-wide travel time for the Birmingham corridor with SCATS is slightly higher than that achieved under TOD control. Similarly, the network-wide average delay and network-wide average speed (callouts “3.5.vi” and “3.5.ix”) fail to show improvements. Such findings are not entirely unexpected as it can be quite difficult to achieve improvements for oversaturated corridors (Stevanovic 2010). NCHRP Synthesis 403 cites several other reasons for poor performance of ATCSs such as systems not fine-tuned or customized as needed (Stevanovic 2010).

ATCS improves the traffic condition by continuously monitoring the demand and then intelligently distributing the signal cycle time over different traffic movements at each intersection as well as over an entire network. In the congested condition where continuous queues are formed and are never cleared, the extent of real traffic demand is difficult to be measured. It is documented that SCATS can be configured with congestion management techniques which can be more efficiently used to manage the congested condition, provided it is configured for that purpose (Chong-White, Millar, and Aydos 2014). Under such circumstances, SCATS follows the policy for which it is configured. Thus, the results might be the outcome of the use of an inefficient policy. This explains the reason why SCATS fails to yield any benefits in the Birmingham corridor. This result is consistent with other ATCS evaluation study (Gord &

Associates 2007) which state that the effectiveness of ATCS is constrained where demand exceeds available

It is interesting to see that while the end-to-end corridor travel time does not improve, the network-wide travel time (and other performance measures) shows significant improvements. This contrasting finding is investigated further by looking at three movements separately. ‘Major’ movement is the traffic along the arterial mainline corridor and ‘Minor’ movement is the both side- streets traffic combined. For each study corridor, the Major 1 is the movement in the peak direction and Major 2 is the movement in the non-peak direction.

3.5.3 Queue Length Assessment

Figure 3.6 shows the queue lengths for the Major 1, Major 2 and Minor directions for the three corridors plotted over one hour of simulation period (excluding warm-up period). These plots show that the queue lengths with SCATS for the two major directions are either almost same as TOD or slightly longer than those with TOD. In the case of Montgomery1 and Montgomery2, the average queue lengths with SCATS in the Major 1 and Major 2 directions maintain almost same levels (callouts “3.6.i”, “3.6.iii” and “3.6.iv”) as TOD. However, the queue lengths for the minor direction significantly improve (shortens) with SCATS for the Montgomery1 and Montgomery2 corridors (callouts “3.6.vi” and “3.6.vii”). For Birmingham, the SCATS queue lengths are little longer than with TOD (callouts “3.6.ii” and “3.6.v”) in the Major 1 and Major 2 directions. In fact, the average queue length with SCATS for the Major 2 direction initially starts at a lower level, but eventually grows to exceed the queue length level with the TOD plan (callout “3.6.v”). This phenomenon was earlier seen in the case of the travel time and delay for the Birmingham corridor for the Major 2 direction (callouts “3.3.vi” and “3.4.vi”).

There is no significant change in queue lengths between the TOD and SCATS for the Birmingham minor movement (callout “3.6.viii”).

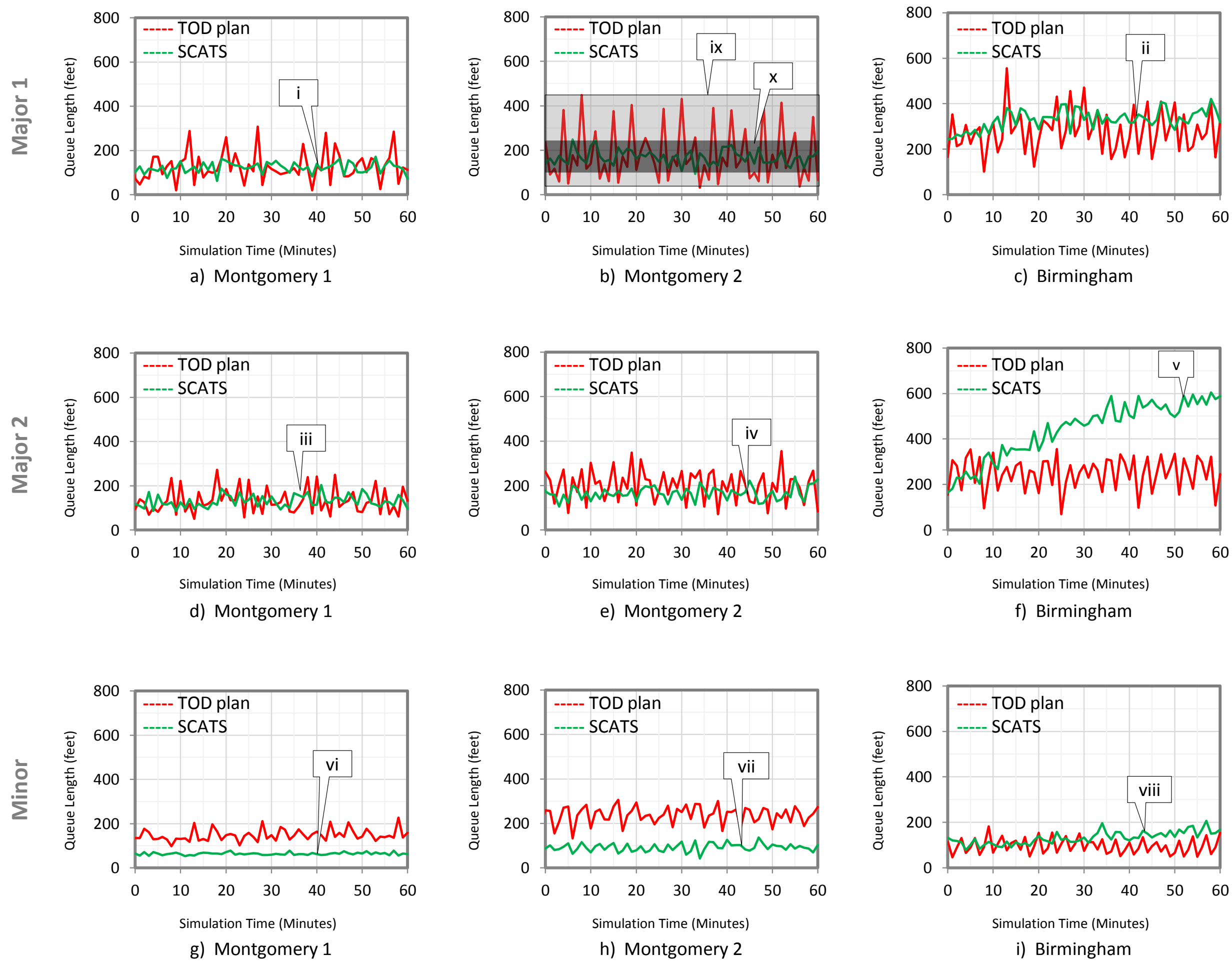


Figure 3.6 Average Queue Lengths

Another interesting observation is that although the average queue lengths over the entire simulation run either show no gains (in the case of major directions but some gains in minor directions), significant improvements can consistently be seen in the cycle-to-cycle queue lengths. According to Figure 3.6, the queue lengths resulted from the TOD plan of Major 1 and Major 2 directions on both Montgomery1 and Montgomery2 corridors experienced significant fluctuations during the simulation period (callout “3.6.ix”), the largest wave range is approximately 400 feet. On the other hand, the queue length under the SCATS control (callout “3.6.x”) is relatively stable with a wave range of about 100 feet for these two corridors. This result is consistent for all corridors and for all three movements. Thus, based on the results, it can be concluded that SCATS generates relatively shorter cycle to cycle queue lengths. This is an important finding as shorter queue lengths may have considerable benefits such as increased opposed turning capacity, increased shared lane capacities, and reduced chance of downstream queue interference which would lead to additional performance gains (Akcelik, Besley, and Chung 1998).

To summarize, significant improvements in the queue lengths were only observed for the minor movement of an unsaturated corridor. Because the network-wide performance measures show improvements while the end-to-end corridor performance measures do not, the shorter queue lengths on the minor streets and the shorter cycle-to-cycle queue lengths under SCATS control can be attributed towards the overall network performance improvement. More explanation on this follows in later paragraphs when the distribution of signal timings is discussed. The added capacity caused by shorter queue lengths on each directional movement over the entire network can even have significant implications for the city transportation planners.

3.5.4 Delay Assessment

In addition to the queue length, delays are also analyzed for the Major 1, Major 2 and Minor directions, separated by left-turn and through movements. Figure 3.7 shows the improvement in delay with SCATS for each of the intersections/nodes for Montgomery1 corridor, Figure 3.8 shows the same for Montgomery2 corridor, and Figure 3.9 for Birmingham corridor. Green bars indicate that the delays with SCATS are lower than with the TOD plan (hence negative difference). The red bars indicate ineffectiveness of SCATS to reduce delays.

The major through movements do not show any improvements for Montgomery1 and Montgomery2 as shown by callouts “3.7.i” and “3.7.iii” in Figure 3.7 and callout “3.8.i” and “3.8.iii” in Figure 3.8. In contrast, significant improvements can be seen with SCATS on the major left movements on some of the intersections for these two corridors (callouts “3.7.ii”, “3.7.iv”, “3.8.ii”and “3.8.iv”). Significant improvements are seen for all minor movements of Montgomery1 and Montgomery2 corridors (callouts “3.7.v”, “3.7.vi”, “3.8.v” and “3.8.vi”).

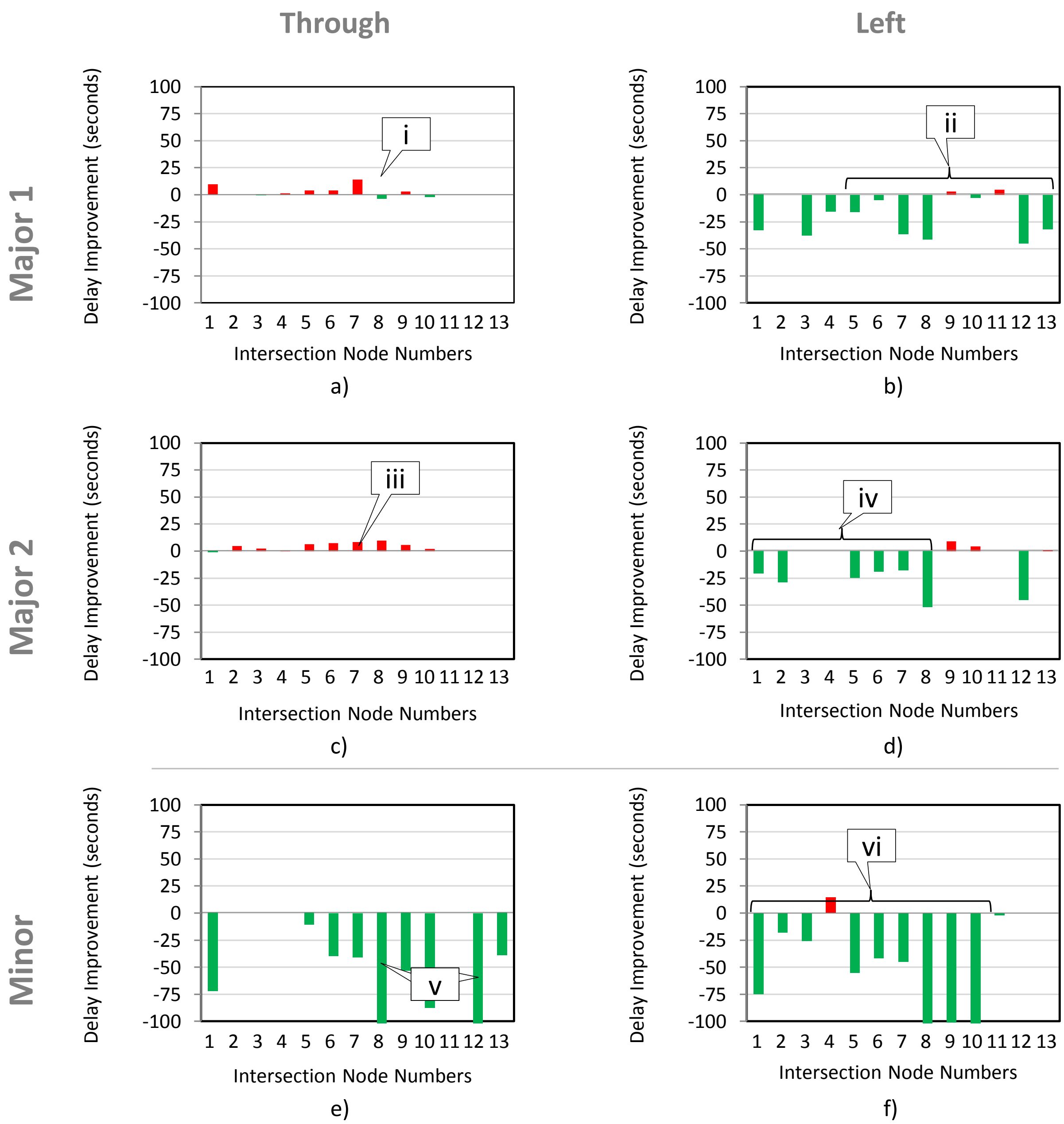


Figure 3.7 Individual Intersection Delay Improvements by Movements (Montgomery1)

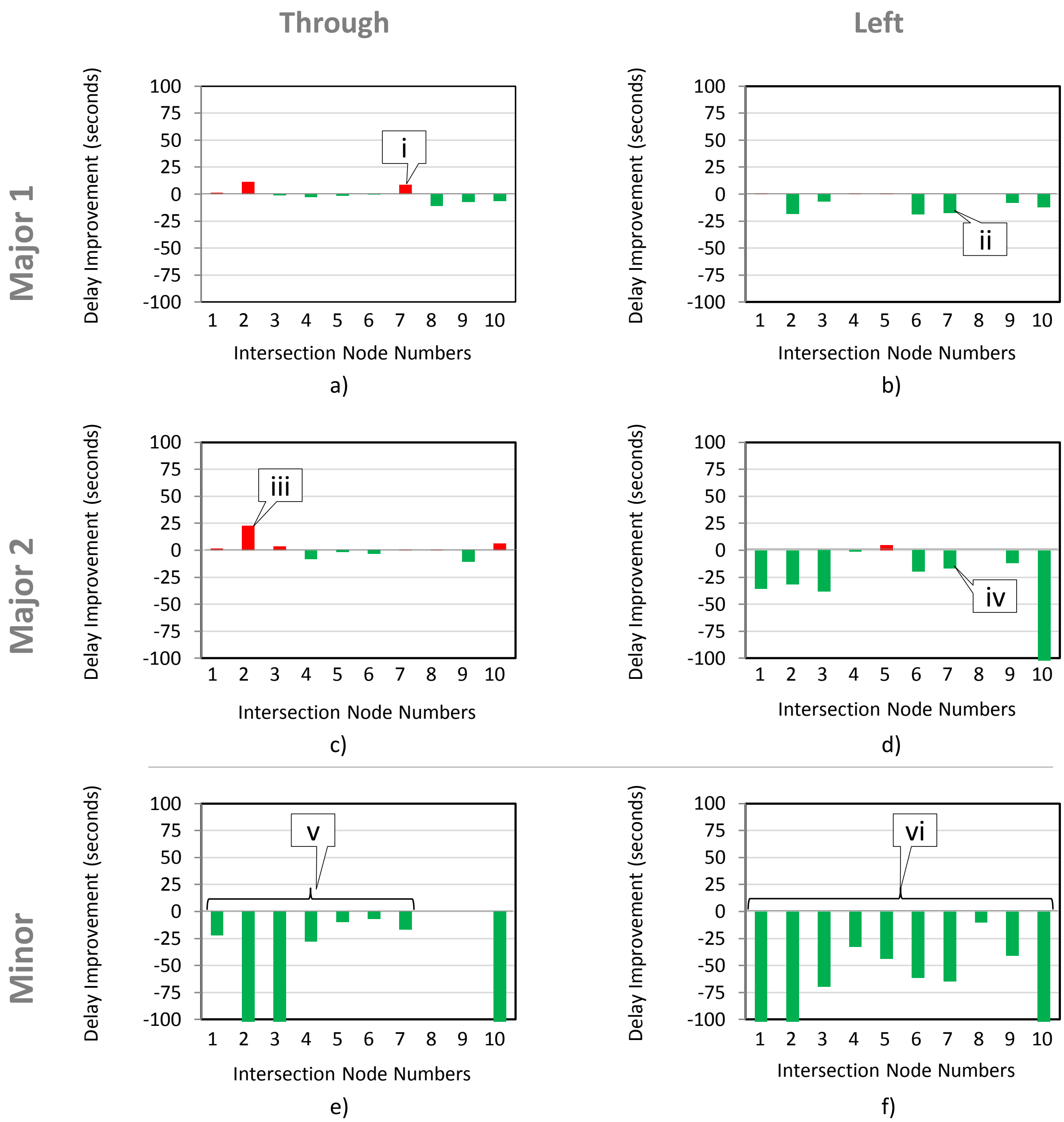


Figure 3.8 Individual Intersection Delay Improvements by Movements (Montgomery2)

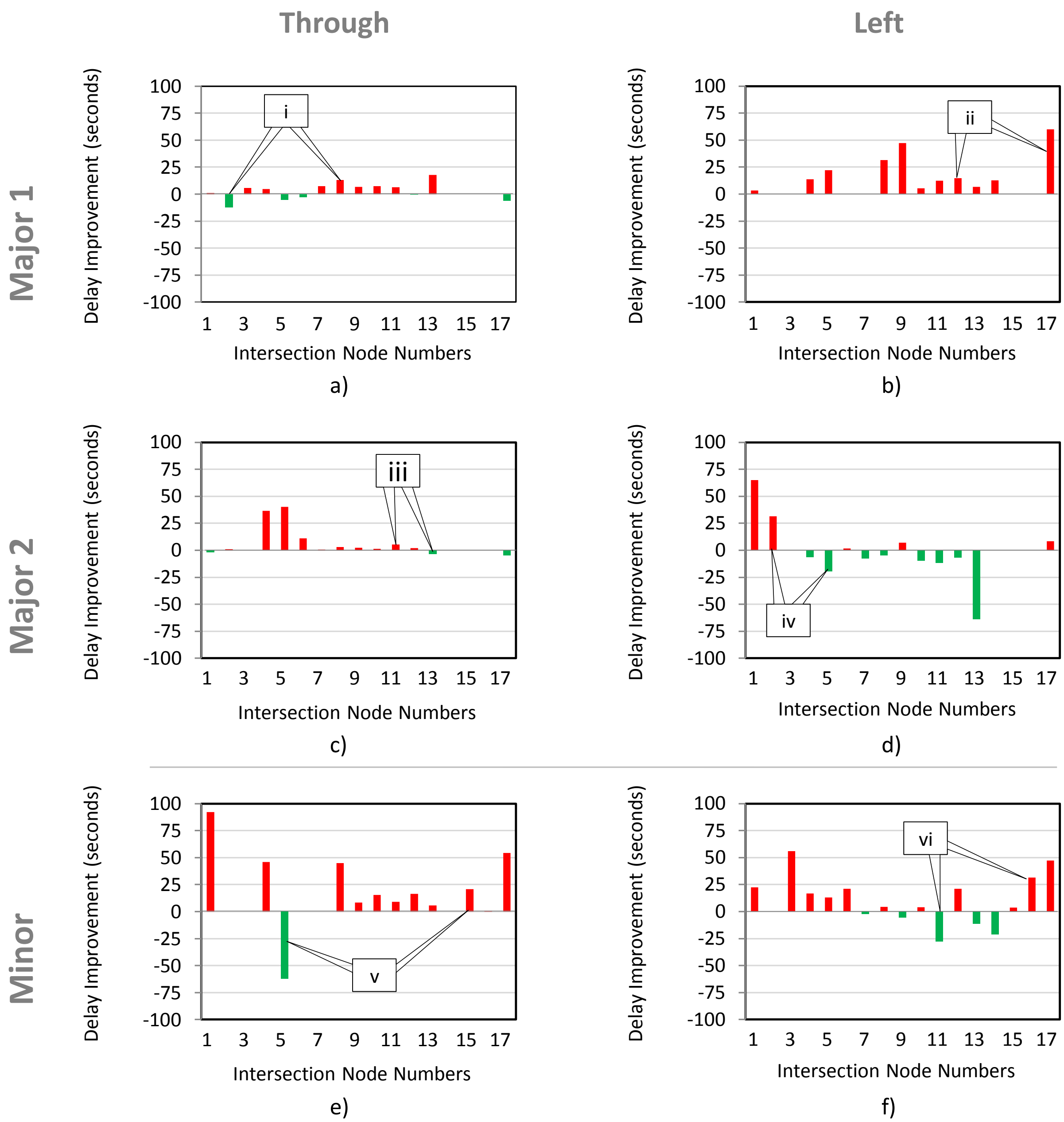


Figure 3.9 Individual Intersection Delay Improvements by Movements (Birmingham)

For Birmingham, both major through and major left movements show mixed results. While there are reductions in delays on some intersections, a few others show an increase in delays and the remaining fail to show either. These are indicated by callouts “3.9.i”, “3.9.ii”, “3.9.iii” and “3.9.iv” in Figure 3.9. Similar to the major movements for Birmingham corridor, the minor movements show mixed results. Some intersections show improvements in delay, some show deterioration in delay, and some are neutral (callouts “3.9.v” and “3.9.vi”). The delay results reiterate the findings from queue lengths where the minor streets show significant improvements in performance while the major movement shows either little or no improvements. However, one distinguishing finding from the analysis of delays is that only the major through movements fail to gain. The major left movements do show improvements. It appears that in all three corridors, SCATS balances the network performance rather than favoring only mainline performance.

The results so far can be explained best by analyzing the SCATS behavior. SCATS tries to achieve two things simultaneously; i) maintain the DS at the level of around 0.9 on the lane with greatest DS and ii) vary the phase splits to maintain equal DS on competing approaches (RTA (Roads and Traffic Authority) and TYCO, n.d.). To further elaborate on this, an analysis on the comparison of the distribution of signal time is performed. Figure 3.10 shows the typical distribution of the green time and the cycle lengths over one hour of simulation period for any given intersection (with very few exceptions) on the three networks.

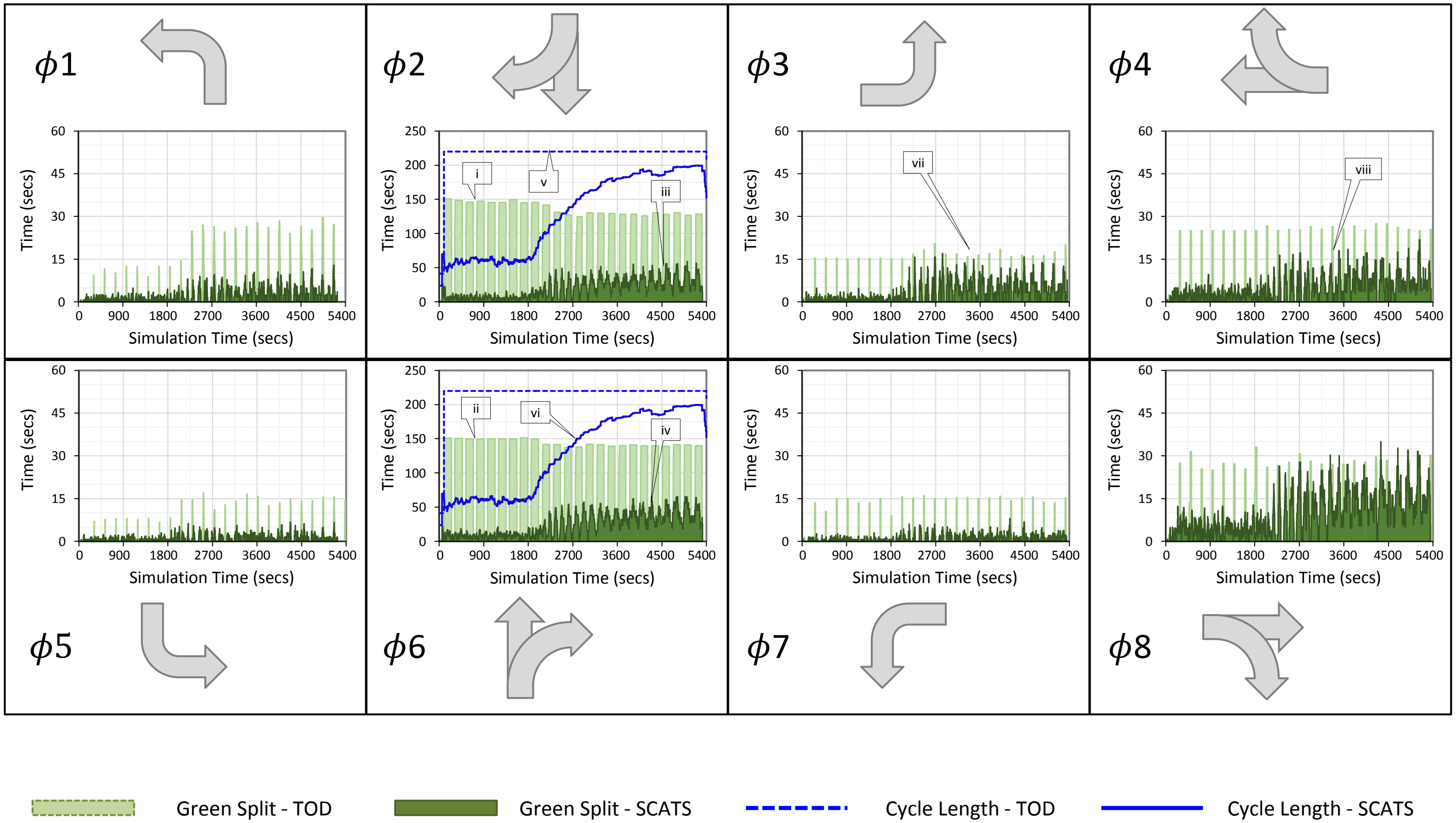


Figure 3.10 Typical Signal Green Times and Cycle Lengths

The figure shows that, under the TOD plan, excessive green times are given for ϕ2 and ϕ6, which are the major through movements (callouts “3.10.i” and “3.10.ii”). As a result, traffic on the side-street suffers and has to wait longer causing longer queues and delays. This was also observed during the visual assessment of the simulation runs. As a result, huge imparity is caused in the DS levels of the mainline and the side-streets. SCATS overcomes this problem by offering smaller green time to the mainline traffic improving its DS (callouts “3.10.iii” and “3.10.iv”). Cycle length decreases as a result of shorter ϕ2 and ϕ6. Callout “3.10.v” shows the cycle length for the TOD plan, which remains at a constant level throughout the span of the simulation run. Callout “3.10.vi” shows the cycle length, which although builds up over the simulation run, but still remains lower than the TOD cycle length. Shorter cycle length helps in clearing the side-street traffic at a higher frequency resulting in shorter queues (callouts “3.6.vi” and “3.6.vii”). The occurrence of this phenomenon at every intersection on the network results in overall improvement in the network performance as can be seen in Figure 3.5. However, travel time for the mainline traffic suffers due to shorter green times, as seen in Figure 3.3. One interesting observation is that side-street traffic condition improves despite getting lesser percentage green time (callouts “3.7.v”, “3.7.vi”, “3.8.v” and “3.8.vi”).

Birmingham corridor differentiates from the other two corridors because of its overly congested nature. As a result, there is a very little flexibility for manipulating the cycle time and phase splits to improve traffic efficiency. Even if it was possible, an improvement in one movement can only be achieved at the expense of performance of other competing movements. As a result, the overall performance of the entire network may still fail to see any improvements. As a result, the Birmingham corridor shows no improvement for any MOEs. This result is consistent with other similar studies on ATCS performance on oversaturated networks (Stevanovic 2010). In another study that examined the impact of a locally adaptive traffic signal on network stability, it was found that adaptive signals appear to have little or no effect on network stability in heavily congested networks due to more constrained vehicle movements (Gayah, Gao, and Nagle 2014).

3.6 Conclusions

ATCS systems are a useful tool in the continuing quest for more efficient traffic operations. Although largely positive towards ATCS, literature reports somewhat mixed results on ATCS performance. Most of the literature, however, reports the results from a single corridor where network-wide or corridor level travel times/speeds are the primary performance measures. This study was performed with the aim of comparing three different network corridors with different physical and operational characteristics under TOD and SCATS signal control. The study yielded the following general conclusions/recommendations:

(1) Corridor travel time and delay are the traditional way to assess the improvements of an adaptive system. There are other measures available to evaluate ATCS depending on overall policy goals (e.g. optimizing mainline progression or an overall congestion management strategy). As such, it is recommended that traffic engineers and other stakeholders examine a range of performance measures at various scales (i.e., network, corridor, sub-corridor, intersection) to fully assess potential improvements and changes in system operation according to policy preferences (Chong-White, Millar, and Aydos 2014).

(2) SCATS showed significant network-wide performance improvements over the TOD plans, in terms of travel time, average delays, and average speed, on the unsaturated networks studied herein.

(3) With SCATS, the shorter side-street queue lengths and the shorter cycle-to-cycle queue lengths on the unsaturated networks can be attributed to the network-wide performance improvements over the TOD. The added capacity created by shorter queue lengths on each directional movement over the entire network is a potential benefit of the systems that can be leveraged for additional operational enhancements within the system.

(4) The analyses of delays show that major network-wide performance improvements for the unsaturated networks come from the side-streets movement and left-turn movements.

(5) On the oversaturated study corridor, however, the higher volumes (and saturated conditions) constrain the potential vehicle movements limiting the ability of SCATS to meaningfully manipulate timing parameters.

While considering these conclusions, it is worthwhile to note that the real potential of any ATCS is not easy to assess. Similar to what other studies have shown, SCATS (and any other ATCS in general) is found to have a minimal effect on oversaturated conditions. The other, systematic advantages of ATCS such as real-time monitoring of traffic demand and adapting to the changing traffic conditions must still be counted in the complete evaluation. It is recommended that the potential benefits of ATCS be assessed through scenario-based (e.g.: incidents, lane closure, traffic increase, etc.) sensitivity analyses.

3.7 References

Akcelik, R., Besley, M., & Chung, E. (1998). *An Evaluation of SCATS Master Isolated Control. In* 19th ARRB Transport Research Conference (Transport 98) (pp. 1–24). Vermont South, Australia.

Chong-White, C., Millar, G., & Aydos, J. C. (2014). *Scenarios Demonstrating Congestion Management Policies using SCATS : Stage 2*. In 26th ARRB Conference – Research driving efficiency (pp. 1–17). Sydney, Australia.

Day, C. M., Ernst, J. M., Brennan, T. M., Chou, C.-S., Hainen, A. M., Remias, S. M., … Bullock, D. M. (2012). *Adaptive Signal Control Performance Measures : A System-in-the-Loop Simulation Case Study*. Transportation Research Record, 2311, 1–15.

Dowling, R., Skabardonis, A., & Alexiadis, V. (2004). *Traffic Analysis Toolbox Volume III : Guidelines for Applying Traffic Microsimulation Modeling Software* (Vol. FHWA-HRT-0).

Gayah, V. V, Gao, X. S., & Nagle, A. S. (2014). *On the impacts of locally adaptive signal control on urban network stability and the Macroscopic Fundamental Diagram*. Transportation Research Part B, 70, 255–268.

Gord & Associates, I. (2007). *Adaptive versus Traditional Traffic Control Systems - A field-based comparative assessment.* Retrieved from https://www.pinellascounty.org/mpo/ITS/Final-Evaluation-Paper-Field-Studies-040907.pdf.

Hunter, M., Wu, S. K., Kim, H. K., & Suh, W. (2012). *A Probe-vehicle-based Evaluation Of Adaptive Traffic Signal Control*. IEEE Transactions on Intelligent Transportation Systems, 13(2), 704–713.

Hutton, J., Bokenkroger, C., & Meyer, M. (2010). *Evaluation of an Adaptive Traffic Signal System: Route 291 in Lee's Summit, Missouri*. Jefferson City, Missouri. Retrieved from http://trid.trb.org/view.aspx?id=916407

Jayakrishnan, R., Mattingly, S. P., & McNally, M. G. (2000). *Performance Study of SCOOT Traffic Control System with Non-Ideal Detectorization : Field Operational Test in the City of Anaheim.* Report UCI-ITS-WP-00-27. Irvine, California.

Kergaye, C., Stevanovic, A., & Martin, P. (2010a). Comparative Evaluation of Adaptive Traffic Control System Assessments Through Field and Microsimulation. Journal of Intelligent Transportation Systems, 14(2), 109–124.

Kergaye, C., Stevanovic, A., & Martin, P. T. (2010b). *Comparison of Before-After Versus Off-On Adaptive Traffic Control Evaluations.* Transportation Research Record: Journal of the Transportation Research Board, 2128, 192–201.

Lowrie, P. R. (1982). *Sydney Co-ordinated Adaptive Traffic System - Principles, Methodology, Algorithms.* IEEE Conference Publication, (207), 67–70.

Majeed, A. A., Zephaniah, S. O., Mehta, G., & Jones, S. (2014). *Field-Based Saturation Headway Model for Planning Level Applications*. International Journal of Traffic and Transportation Engineering, 3(5), 207–215.

Martin, P. T., & Stevanovic, A. (2008). *Adaptive Signal Control V - SCATS Evaluation in Park City, Utah.* Retrieved from http://www.mountain-plains.org/pubs/pdf/MPC08-200.pdf.

Martin, P. T., Stevanovic, A., & Stevanovic, I. (2005). *Adaptive Signal Control IV - Evaluation of Adaptive Traffic Control System in Park City* (Vol. UT – 05.16).

National Transportation Operations Coalition. (2012). *2012 National Traffic Signal Report Card.* National Transportation Operations Coalition. Retrieved from http://www.ite.org/reportcard/TechnicalReport.pdf

Nguyen, V. N. (1996). *Evaluation of SCATSIM – RTA Adaptive Traffic Network Simulation Model*. Transportation Research Record, 1566, 8–19.

Peters, J. M., McCoy, J., & Bertini, R. (2007). *Evaluating an Adaptive Signal Control System in Gresham.* ITE Western District Annual Meeting.

Planung Transport Verkehr (PTV) AG. (2011). *VISSIM 5.40-01 - User Manual.* Karlsruhe, Germany.

Roads and Maritime Services. (n.d.). *An Introduction to SCATS 6.* South Wales, Australia: Roads and Maritime Services. Retrieved from http://www.scats.com.au/files/an_introduction_to_scats_6.pdf.

RTA (Roads and Traffic Authority), & TYCO. (n.d.). *SCATS Booklet*. Retrieved from http://www.traffic-tech.com/pdf/scatsbooklet.pdf

Schrank, D., Eisele, B., Lomax, T., & Bak, J. (2015). *2015 Urban Mobility Scorecard*.

SRF Consulting Group Inc. (2000). *Adaptive Urban Signal Control and Integration*. October.

Stevanovic, A. (2010). *NCHRP Synthesis 403 Adaptive Traffic Control Systems : Domestic and Foreign State of Practice*. Washington, D.C.

Taale, H., Fransen, W. C. M., & Dibbits, J. (1998). *The second assessment of the SCOOT sytem in Nijmegen*. In IEEE Road Transport Information and Control (pp. 109–113). London, United Kingdom.

Tian, Z., Ohene, F., & Hu, P. (2011). *Arterial performance evaluation on an adaptive Traffic Signal control system.* Procedia - Social and Behavioral Sciences, 16, 230–239. http://doi.org/10.1016/j.sbspro.2011.04.445

CHAPTER 4

ANALYSIS TECHNIQUES FOR EVALUATING THE IMPLEMENTATION OF ADAPTIVE TRAFFIC SIGNAL CONTROL SYSTEMS

4.1 Introduction & Background

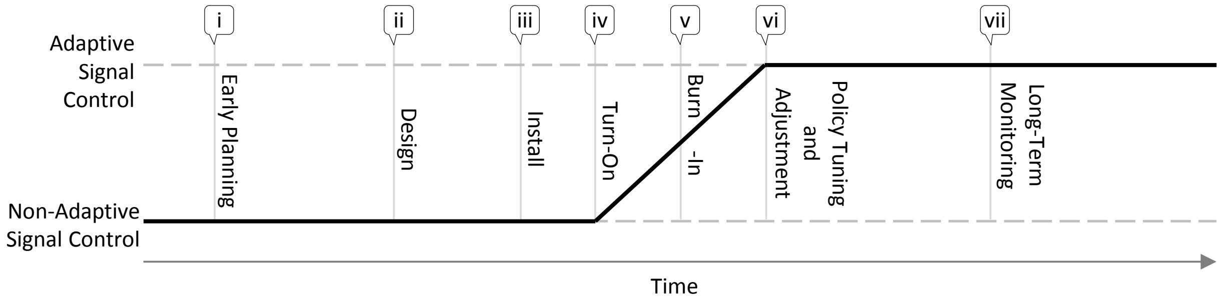
According to the Federal Highway Administration, traffic congestion costs Americans approximately 6 billion hours and poor signal timing contributes about five percent of total congestion (Grant, Bauer, Plaskon, & Mason, 2010). The National Traffic Signal Report Card emphasizes a greater need for better signal management and operations (National Transportation Operations Coalition, 2012). Traffic signal operation is a critical component of efficient traffic management. Proper traffic signal timing and operations reduce congestion, improve mobility, and enhance safety. The 2015 Urban Mobility Scorecard (Schrank, Eisele, Lomax, & Bak, 2015) suggests simple actions such as retiming of traffic signals as a means for congestion relief. This signal retiming is often effective for a while, but will eventually require subsequent review and periodic updating. To avoid this repetitive process, an alternate option is to use adaptive traffic control systems (ATCS) to automate the retiming process. ATCS systems are becoming more widely used throughout the traffic engineering industry.

ATCSs continuously detect the vehicular traffic on the roadways. These systems then adjust the signal timing plan in real-time to adapt to the changing traffic conditions. ATCSs are believed to benefit the users by reducing the congestion and fuel consumption and improving travel time reliability. The 2012 Urban Mobility Report published by Texas A&M Transportation Institute reports ATCS systems as performing some three times better than actuated control with regard to delay reduction (Schrank, Eisele, & Lomax, 2012). Previous evaluations of ATCS implementation at different locations have corroborated such benefits (Martin & Stevanovic, 2008; Shelby & Bullock, 2008; Tian, Ohene, & Hu, 2011). According to another study gains in travel time was achieved by ATCS over an arterial corridor (Hutton, Bokenkroger, & Meyer, 2010). However, the improvements were directionally specific and were also time specific. According to SRF Consulting Group Inc., (2000) there were no significant changes in the travel times between before and after ATCS deployment under certain conditions. In an evaluation of ATCS deployment in Florida, arterial performance improved but at the expense of side-street efficiency (Gord & Associates, 2007). Another study simulated the semiactuated, coordinated, time-of-day (TOD) using hardware-in-the-loop simulation (HILS) and SCATS on an 11-intersection arterial of Cobb Parkway in Cobb County, Georgia (Hunter, Roe, & Wu, 2010). The initial findings from the comparative results indicate that during peak conditions both control strategies provide similar performance. However, during the shoulder peak periods ATCS provides better traffic control suitable to the current conditions. In one such before-after ATCS comparative study, the authors are of the view that biased TOD plan can influence the ATCS performance results (Peters, McCoy, & Bertini, 2007). The literature review shows mixed results for ATCS deployments. Thus, careful consideration needs to be taken evaluating ATCS performance at any point in time.

Deployments of newer technologies such as ATCSs are often expensive, complex and require a lengthy implementation period that can be difficult for engineers to assess improvements over time. ATCS installation can take about 18 months (Stevanovic, 2010) and may even go longer. Failure to configure the ATCS systems for the possible changes in either traffic conditions or geometrical features or transportation policies during this period can lead to loss of ATCS performance. Additionally, it is often misperceived that once installed, ATCS systems can be left to operate with little maintenance. However, an ATCS may underperform if it is not customized or not fine-tuned to the policy requirements. Stevanovic (2010) notes that there is a need for comprehensive evaluation study in order to understand the true costs and benefits of ATCSs both during the deployment and post-deployment. Such evaluations and continuous monitoring help transportation planners to better understand the effectiveness of their investment strategies, fine-tune the operations of implemented projects, and calibrate and refine their planning tools and models (Grant et al., 2010). Further, it is recommended multiple data sources be considered depending on the analysis performed and the level of detail required (Tahmasseby, 2015). With these considerations, this paper compares the arterial performance and demonstrates how to use data from different sources with different techniques and methods to evaluate ATCS performance at different stages of its implementation.

4.2 Purpose & Scope

Figure 4.1 shows a typical timeline for implementation of an ATCS system. It is important to monitor and assess ATCS performance and benefits at any point during the implementation process in order to fully understand its importance.



TIME INTERVAL	i	Ii	iii	iv	v	vi	vii
ATCS PHASE	Early Planning	Design	Install	Turn-On	Burn-In	Policy Tuning and Adjustment	Long-Term Monitoring
DESCRIPTION	Need for corridor improvements identified at a high-level	Work with adaptive vendor to plan and design the ATCS system	Vendor upgrading cabinet hardware, install central-system software	ATCS is turned on and assumes operational control	Vendor identifies major hardware and timing issues	Vendor and operator modify ATCS parameters for operator-desired policy and performance	Operator monitors the adaptive system for seasonal and long term changes
DATA REQUIRE-MENTS	Corridor Volumes, Turning Movement Counts	Design Traffic Volumes, Turning Movements, Travel Time Observations	Existing signal timings, Travel Time Observations	Travel time Data, ATCS Performance Data	Signal controller event-data, Travel time Data, ATCS Performance Data	Signal controller event-data, Travel time Data, ATCS Performance Data	Signal controller event-data, Travel time Data, ATCS Performance Data, Corridor Volumes, Turning Movement Counts
ANALYSIS	Project programming -level analysis	Simulation of the before conditions	Before-condition travel time observations	Short-term travel time assessment, field observation	Medium-term travel time analysis, ATCS reporting analysis	Long-term travel time observation, ATCS reporting analysis	Simulation of the non-ATCS control under current conditions

Figure 4.1 Adaptive Traffic Signal Control Implementation Process and Practices

Typically, ATCS will be identified as a suitable solution for a corridor improvement project at the project programming level (i). This is often based on preliminary volumetric data and other information from the traffic operations department. After the project has been selected, the design phase begins to start planning and designing the ATCS (ii). Design traffic observations and preliminary performance measures can be collected and simulation of the ATCS can be conducted for these “before” conditions. After the design is finalized, the ATCS hardware and software will be installed and detailed “before” observations should be collected (iii). After all the components are in place, the system can be turned on and short-term comparisons can be conducted for preliminary assessment and adjustment (iv). A burn-in period for the hardware and software will follow to examine weekdays, weekends, different time-of-day (TOD) settings, and other hardware and software configuration groups (v). Following this burn-in period, additional policy changes, tunings, and adjustments are made both before and after the vendor hands operation of the ATCS over to the local operator (vi). Finally, long-term monitoring can be conducted (vii). Throughout all of these periods, Figure 4.1 discusses different analyses that may be performed.

The objective of this paper is to demonstrate the use of different data sources and analyses techniques to compare the arterial performance for before, during, and after ATCS implementation. This paper presents several analyses using field-collected travel time data and simulation or modeling techniques. The methodologies discussed will help transportation engineers, planners, and policy makers to understand what analysis can be conducted at any point of an ATCS deployment to understand how the system is performing. As policies and timings are adjusted, this feedback is an effective way to continuously monitor the ATCS.

4.3 Study Corridor

The study corridor shown in Figure 4.2 is US-231/Eastern Blvd in Montgomery, Alabama. The corridor is a 2.3 miles long 6 lane arterial road having 10 intersections over its span. The average spacing between adjacent intersections is 0.26 miles. The corridor experiences average traffic volumes of 1900 vph per intersection on the main line and approximately 150 vph on cross streets. The traffic saturation level can be considered to be moderate. Three time periods - AM-peak (7:00 to 10:00), PM-peak (16:00 to 19:00), and off-peak (13:00 to 16:00) are considered for the study purpose. The ATCS system installed on the corridor is the Sydney Co-ordinated Adaptive Traffic Control System (SCATS). The traffic signal system on this corridor underwent the following changes since 2011:

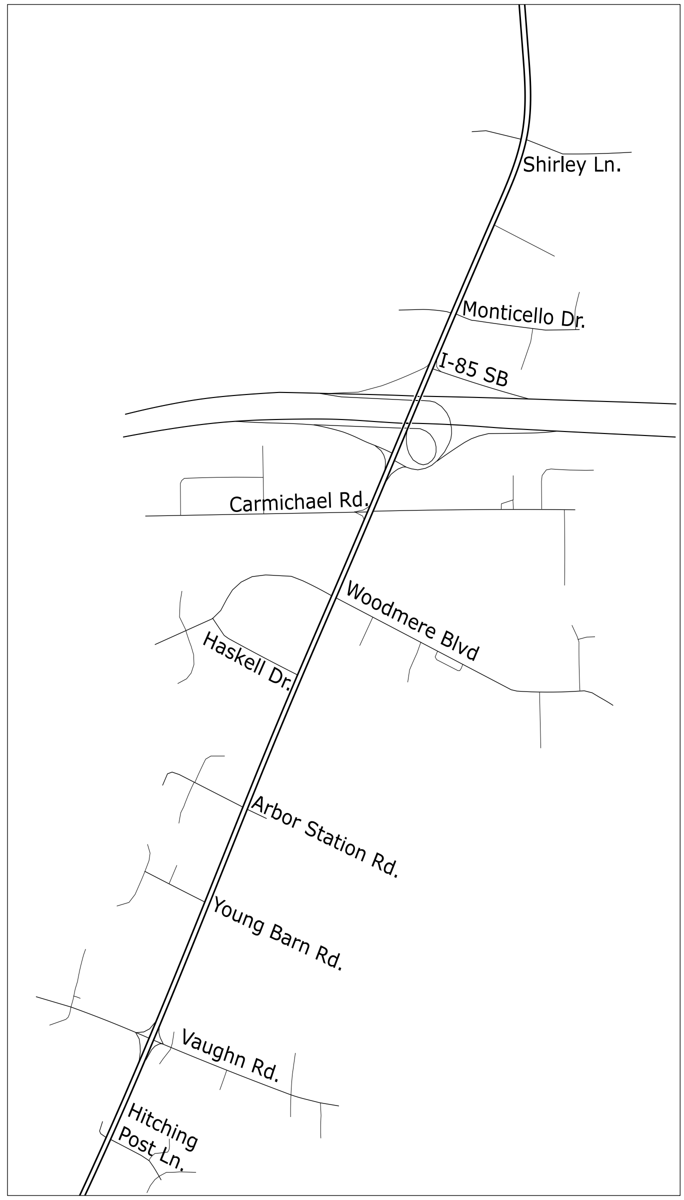


Figure 4.1 Corridor Map

(1) October 2012 – The adaptive system was turned on. Prior to the system turned on, traditional TOD plans were used with actuated coordinated systems.

(2) November 5th, 2012 – The adaptive system was turned off temporarily for one week for data collection purpose. This period was important to gather travel time data after all the data collection equipment was in place and configured.

(3) October 2013 – Camera detection upgrades were made to the system on the side-streets. The local traffic engineers decided to make a policy change and reduce the delay on the side-streets after feedback and field observation. Also, the City Traffic Engineering Department takes control of the adaptive system from the vendor.

(4) June 2014 – The City Traffic Engineering Department removed the ATCS vendor-recommended Lead / Lag sequencing. This operational change is important to note as the vendor had configured the ATCS for their own policy, but now this change adds another element to consider when evaluating long-term before/after comparison of the old traffic signal control and the new ATCS system.

(5) Oct 2014 – The City Traffic Engineering Department decided to make adjustments to the Marriage/Divorce settings in the ATCS system. This potentially has a large effect on the system adaptability and is another change that should be considered when evaluating the after-performance of the ATCS.

4.4 Field Data Collection

Data collection for ATCS implementation (or other corridor signal projects) can vary from turning movement counts, link volumes, floating car travel times, and many other different sources. The types of studies depend on the policies and goals that need to be examined before and after the installation of the ATCS. Typically, delay and LOS are used to evaluate the performance of movements along the corridor.

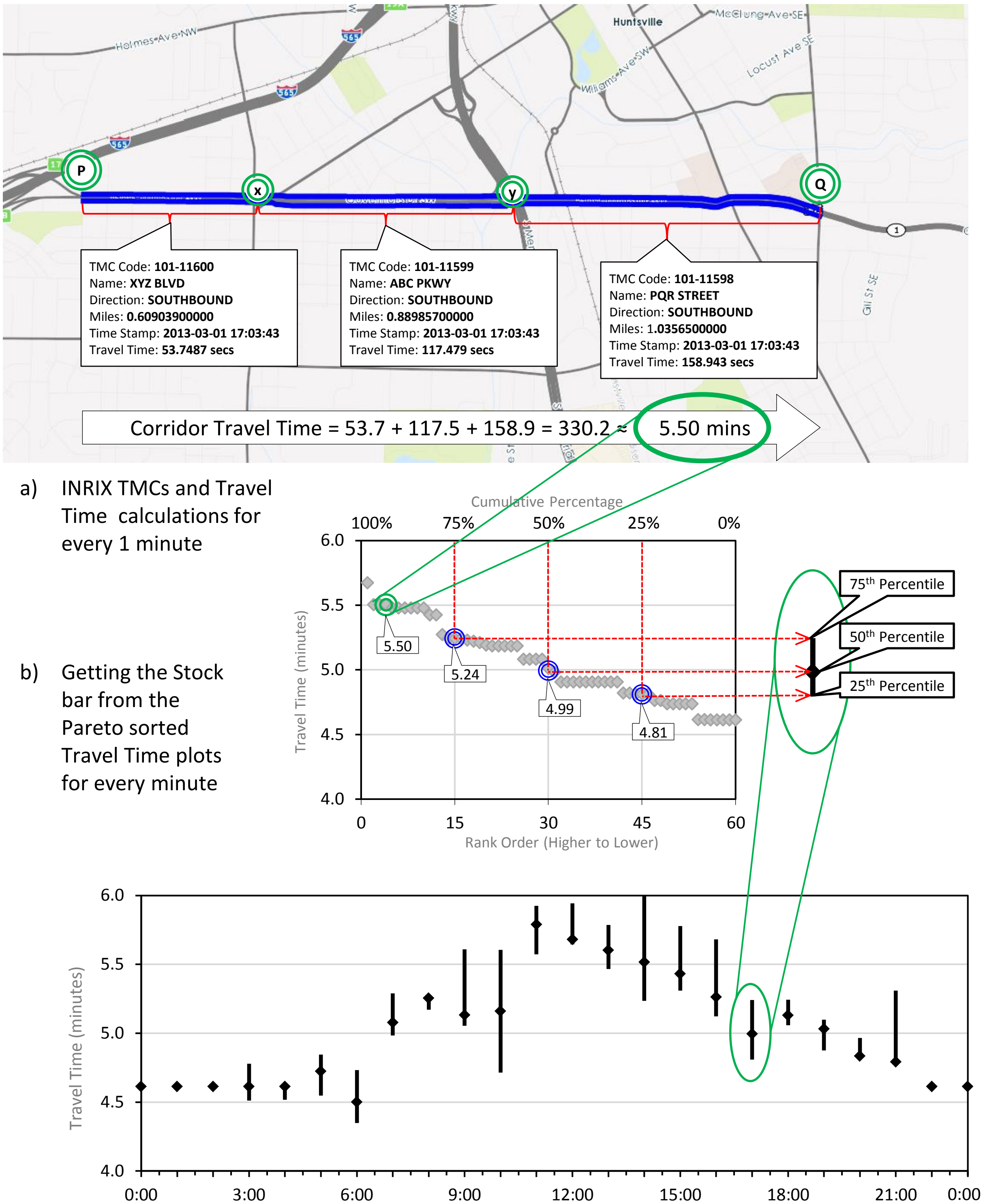
Collecting travel time data is one of the most critical pieces of data used for assessing the mainline corridor performance. The accuracy of travel time data also has high implications since even the smallest inaccuracies can sway the research findings or the decision made by the planners. The proliferation of wireless technologies and mobile devices has opened up the entire space for using and collecting travel time data. Two major prevalent state-of-art data collection techniques are (1) Bluetooth MAC-address matching and (2) commercially available crowdsourced data.

4.4.1 Bluetooth Data Collection – Before (ATCS Off) / After (ATCS On)

For the Montgomery corridor, Bluetooth monitoring stations (BMS) were installed on the corridor to capture conditions before and after ATCS was installed. Bluetooth-enabled devices in the vehicles traveling along the corridor serve as in-vehicle units that can be anonymously recorded and location/time-stamped by the roadside BMS for the purpose of vehicle identification. The BMS system calculates travel time through the analysis of subsequent detections. For the study corridor, Bluetooth stations were installed in October 2012 and full data was made available since November 2012 until current. To observe the before traffic conditions, the ATCS was turned off for one week from November 5th - November 9th, 2012. If the post-ATCS signal timing parameters and the field conditions remain significantly unchanged from the pre-ATCS condition, the before and off evaluations provides statistically equivalent performance measures (Kergaye, Stevanovic, & Martin, 2010b). Since to the best of our knowledge, no such significant changes were noticed on the study corridor during the ‘ATCS Off’ period, this period can be considered to serve as ‘before-ATCS’ condition. The following week onwards, ATCS was turned back on for the rest of the ‘after-ATCS’ condition.

4.4.2 Crowd Sourced Data – Long-Term Monitoring

Deploying Bluetooth stations along the roadside incur significant costs and time. Crowdsourced data (which is a newer and emerging method of measuring and assessing travel times on corridors) provides an alternative. “Crowdsourcing involves leveraging the combined intelligence, knowledge, or experience of a group of people to answer a question, solve a problem, or manage a process” (Michigan Department of Transportation (MDOT) & Center for Automotive Research, 2015). This technique leverages the network of connected devices (probe devices) such as computers, smartphones and other mobile devices to provide crowdsourced traffic data. For the study purpose, probe data was obtained from commercially available sources for the four-year period January 2011 to December 2014. This data availability is one way to review speeds and travel time data even years before a project begins. The travel time along the corridor can be easily derived by considering the travel time of individual road segments that make up the corridor. The data for each segment consists of the unique segment code (known as a traffic message channel or TMC in the figure), name, direction of travel, length of the segment, time stamp and the travel time. Figure 4.3.(a) shows how the corridor PQ is made up of three segments Px, xy, and yQ.



c) 24 hour Travel Times Stock Plot

Figure 4.3 Stock Plot Generation Process using Crowdsourced Data

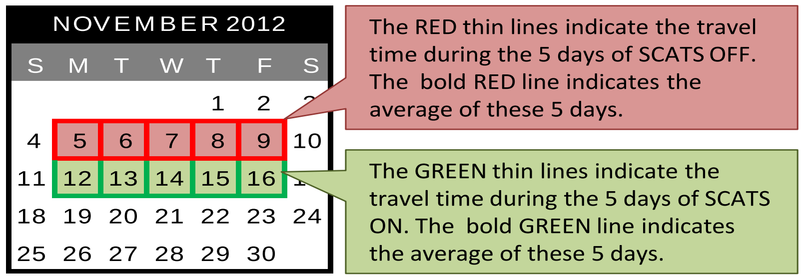
The total travel time for the corridor spanning from P to Q which is 5.50 mins is the combined sum of travel times of individual segments Px, xy, and yQ. The average travel time is stamped every minute. Figure 4.3.(b) shows the cumulative distribution of travel time for 60 min period. It also shows how a stock plot for one hour period is generated using the cumulative distribution of the sixty travel times, time stamped every minute in that hour. Distribution of travel time over longer periods can be obtained by repeating this process. Figure 4.3.(c) shows the stock plot of travel time for a 24 hour period. Such plots are extremely useful for travel time studies since it shows the trend, pattern, and variability in travel time.

4.5 Results and Discussion

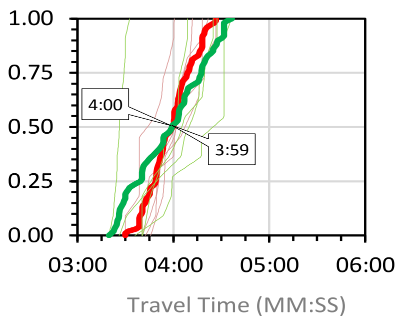
As discussed in the introduction, different analyses will need to be conducted at different times before, during, and after ATCS implementation (Figure 4.1). For the before period, different simulation techniques can be used but are also challenging to configure depending on the availability of ATCS configuration files (often times these configuration files will only be available from the vendor after the system has been turned on in the field). The results and discussion in this paper will start with reviewing various analyses during the implementation phase (reference Figure 4.1, callouts “4.1.iv” and “4.1.v”, where callout “x.i” refers to callout “i” in Figure. x) for vendor and policy-maker feedback. Also, the after analysis is examined where data and reports are more widely available for review (reference Figure 4.1, callouts “4.1.vi” and “4.1.vii”). These select analyses for the different phases are discussed in the following sections of the paper.

4.5.1 Corridor Travel Time Analysis of the Initial Before/After ATCS Implementation

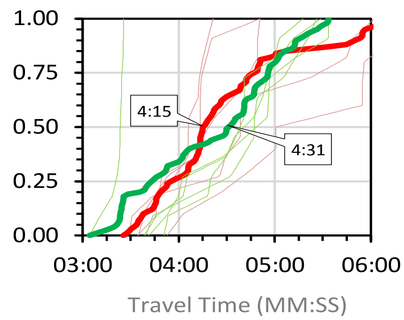
Immediately after the ATCS is activated, corridor travel times can be examined to identify any issues by direction and by during different time periods. For this study, Bluetooth data was analyzed during the first two week period – one week when ATCS was turned off and the immediately following week when the ATCS system was turned back on (ideally, this analysis could be conducted the week before the ATCS is turned on without further interruption to the system). Since two weeks that are considered for analysis are consecutive, it would be fair to assume that there are no significant changes in traffic conditions during these two weeks and can be considered as equivalent to before-ATCS and after-ATCS conditions. Figure 4.4 shows the cumulative distribution of the travel time for these two weeks (note that the SCATS system referred to in the figures is the ATCS system evaluated in this paper). The thinner red and green lines indicate the cumulative distribution of each of the weekday, while the bold lines indicate the average of the five weekdays. Figure 4.4.(a) shows the calendar indicating the time periods for which the analysis is being carried out. Figure 4.4.(b), (d), (f) shows the plots for northbound AM peak, off-peak and PM peak periods, whereas Figure 4.4.(c), (e), (g) shows the plots for southbound direction for the similar periods. As can be seen from the graphs, the travel times during the week when the ATCS is turned on as indicated by the green lines, are better than the travel times during the week when the ATCS is turned off as indicated by the red lines. For example, referring to Figure 4.4.(d), the median travel time during the ATCS-off period is 4:17 min as compared to the median travel time during the ATCS-on period, which is 4:06. Similar phenomena can be seen during PM peak period, where the median travel time for after-ATCS is better (smaller) than the median travel time during before-ATCS.



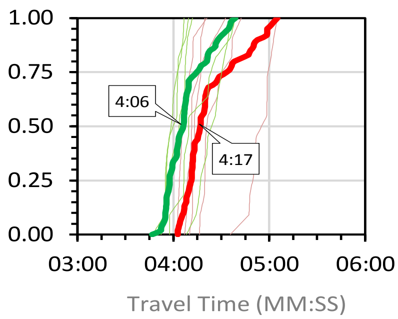
a) Calendar showing the SCATS evaluation time period using Bluetooth data



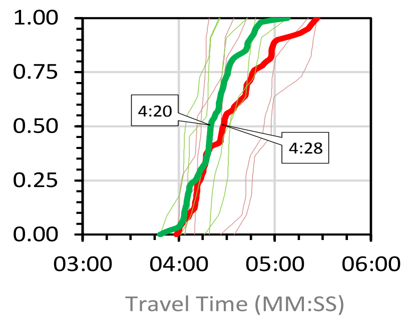
b) NB 07:30-08:30 AM Peak (Bluetooth Data)



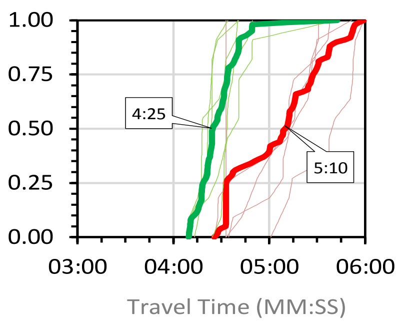
c) SB 07:30-08:30 AM Peak (Bluetooth Data)



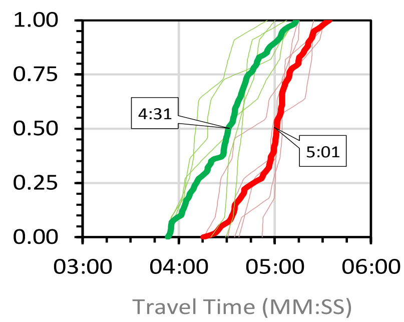
d) NB 13:30-14:30 PM Off Peak (Bluetooth Data)



e) SB 13:30-14:30 PM Off Peak (Bluetooth Data)



f) NB 16:30-17:30 PM Peak (Bluetooth Data)



g) SB 16:30-17:30 PM Peak (Bluetooth Data)

Figure 4.4 ATCS Off (one week) vs ATCS On (one week) (Bluetooth Data)

Interestingly, while the AM peak travel times hardly show any improvement; the improvement in the travel time as considered by the difference between the travel times during the before-ATCS and the after-ATCS period is higher during the PM peak period in both northbound and southbound directions. This analysis clearly indicates that ATCS performs better than the TOD signal plan. However, this analysis is performed based on travel time data for only one week period. In order to verify the consistency and repeatability of performance, a further similar analysis is performed for a longer period.

4.5.2 Corridor Travel Time Analysis of the Early Post ATCS-Implementation Period

After the ATCS has been on and the vendor has made several early changes, the first-month performance can be analyzed in a similar fashion using the Bluetooth travel time data. Figure 4.5 shows the similar travel time cumulative distribution plots over a period of four weeks in the month of November 2012. As shown in Figure 4.5.(a), the first week is the before-ATCS period considered while the rest of three weeks is the after-ATCS period. Once again, the ATCS performs better during the PM peak period in both directions than the other time periods studied. Examining the corridor travel times with a statistically robust approach is more useful than floating car studies which may not accurately characterize performance over several hour periods of week-to-week. Corridor travel time analysis during this period establishes the consistency of the ATCS performance. If not, it would be advisable to extend this analysis period till it gets established.

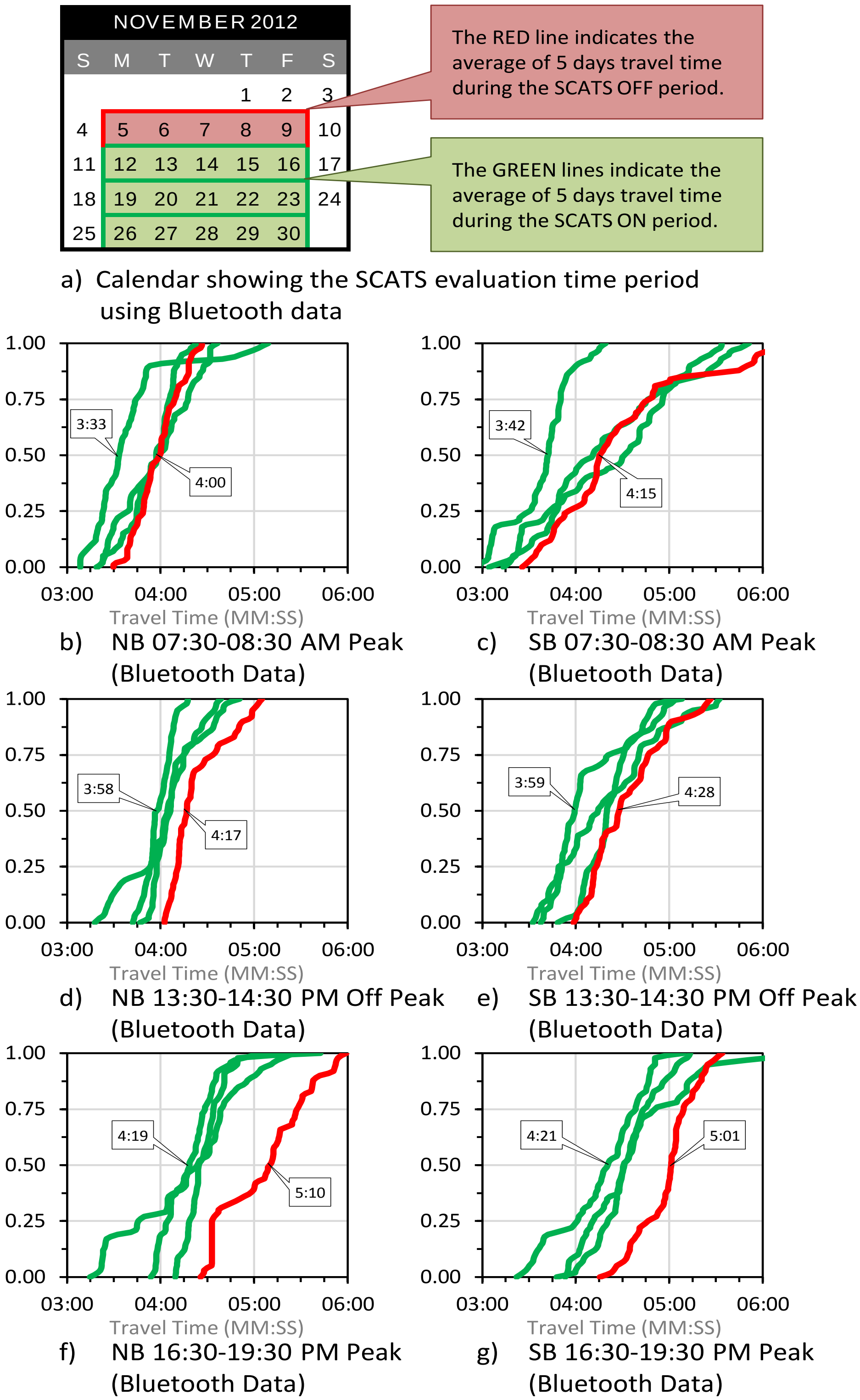


Figure 4.5 ATCS Off (one week) vs ATCS On (three weeks) (Bluetooth Data)

4.5.3 Long-Term Before and After Analysis with Crowd Sourced Data

After the initial examination of corridor travel time performance, a long-term monitoring approach should be adopted to check for seasonal variability and other trends. Several studies have been performed recently that compare various different methods and techniques that have been used to collect travel time data (Remias et al., 2013). These studies are essentially focused on finding the technology that most reliably and accurately collects the data. Although the procedural findings of these studies vary, they all underscore the importance of higher sample size for higher accuracy and reliability (Elefteriadou, Kondyli, & George, 2014; Tahmasseby, 2015). To verify and validate the results from the Bluetooth data analysis, a similar analysis was further performed on crowdsourced probe data.

Figure 4.6 shows the stock plot of the corridor travel time generated using the crowdsourced data as explained in earlier sections. The travel time is plotted over a four-year period for northbound and southbound directions for different time periods. These plots show how the travel time distribution changes with changes in ATCS settings. During the initial period from October 2012 to October 2013, the ATCS seems to perform better than the original TOD signal plan. The same effect can also be observed in Figure 4.7, which shows the cumulative distributions of the travel times between the periods of these changes.

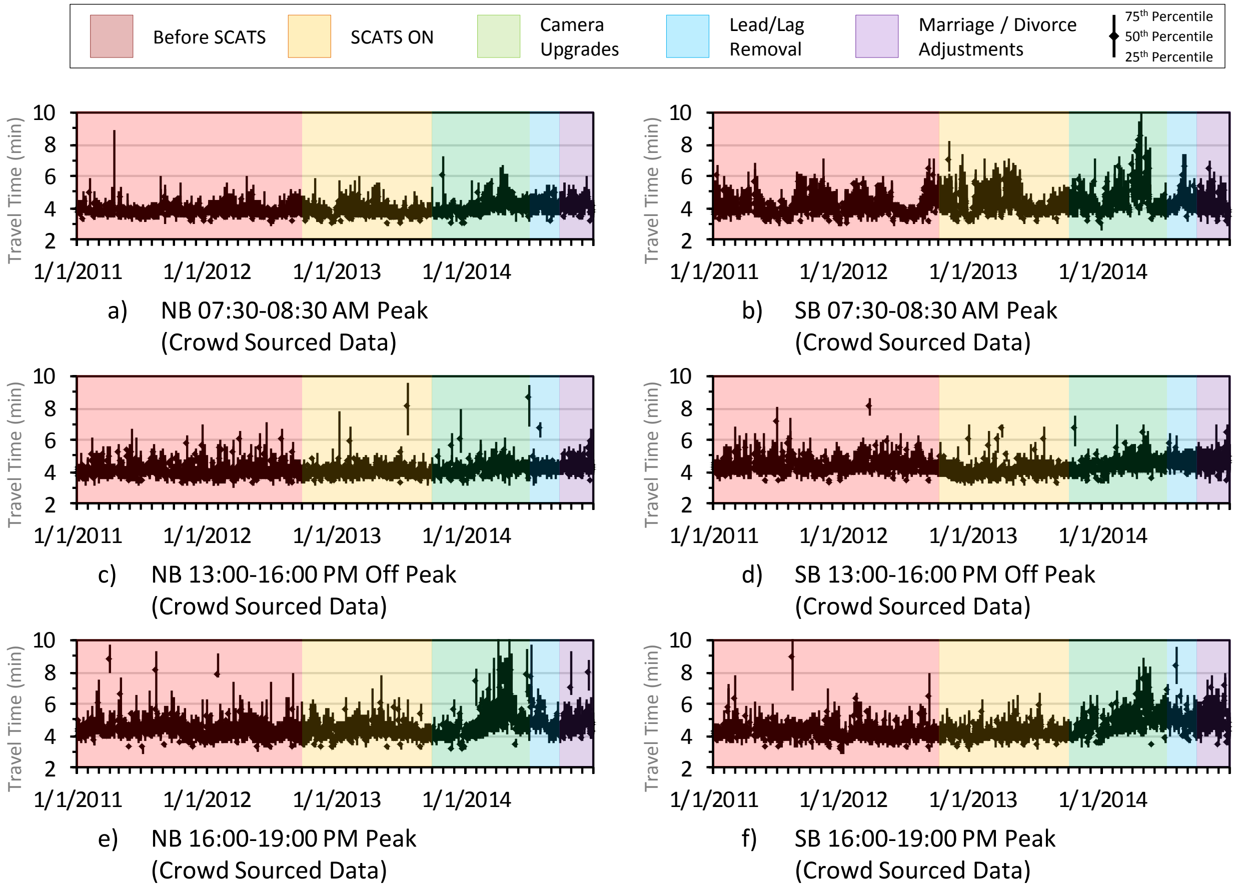


Figure 4.6 Travel Time Distribution for long-term Before and After Analysis (Crowd Sourced Data)

These graphs corroborate the results from the Bluetooth data. The morning peak period hardly shows any improvement as depicted by the orange curves, which illustrate the ATCS performance after installation. The evening off-peak and peak period shows improvements in travel time as was seen with Bluetooth data. The trends shown by the crowdsourced data matches exactly to those shown by the Bluetooth data. The minor difference in the magnitudes of travel time can be contributed to the difference in data sampling rates as well as the sampling period. While Bluetooth data was collected for a month, the crowdsourced data ranges for about 12 months for after-ATCS but earlier to any changes made to the system.

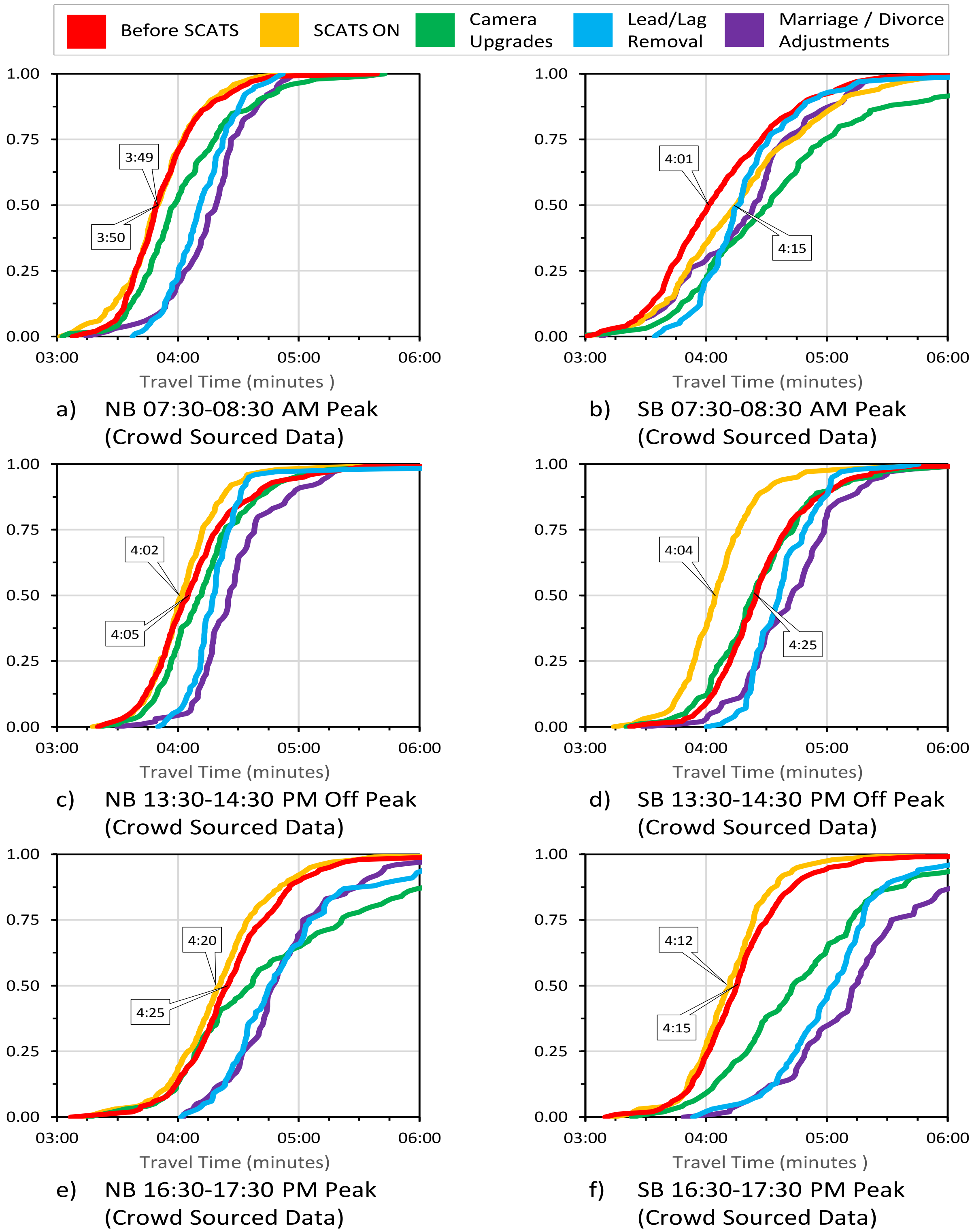


Figure 4.7 Travel Times (Crowd Sourced Data)

It can also be seen that the ATCS performance deteriorates when the local agency takes over and makes camera upgrades in October 2013. The removal of Lead / Lag sequencing further deteriorates the ATCS performance as indicated by the lighter blue lines. Finally, the adjustments in the marriage/divorce settings further downgrade the ATCS performance. Note that, each of these changes resulted in higher mainline travel times but are justified in side-street improvements as discussed in the next section.

4.5.4 After-Implementation Analysis Using Simulation

While travel time data is useful for characterizing mainline performance, side-street performance will need to be evaluated differently to examine the tradeoffs in operational policy goals. One useful tool can be microsimulation which gives the unique capability of conducting a very detailed analysis of the ATCS on the field. Once the ATCS has been turned on and the system is in place, microsimulation models can be calibrated and validated to match different performance measures in the field (Kergaye, Stevanovic, & Martin, 2010a).

Weekday volumes, turning movement counts at each intersection, vehicle compositions were collected between 14:00 – 18:00 for the study corridor. The travel time data was collected using multiple floating cars that made multiple runs over multiple days. The saturation flow data for intersections which was initially collected for a separate study was also used (Majeed, Zephaniah, Mehta, & Jones, 2014). The before-ATCS optimized field TOD signal timing parameters and the after-ATCS fine-tuned field ATCS signal configurations were retained from the Traffic Engineering Department. Relevant geometric data was collected from field observations and aerial imagery. The existing operational data was used to develop VISSIM (version 5.4) microsimulation model. Detector locations (for both before-ATCS and after-

ATCS), signal phases, and other geometric conditions in the simulation models were adjusted to match those in the field.

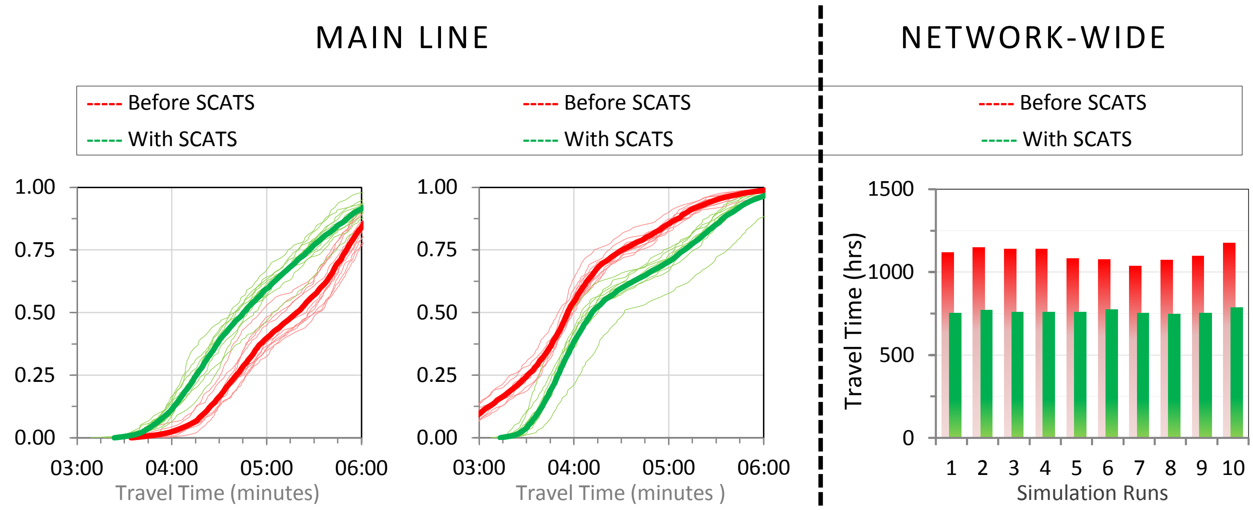
The before-SCATS model was calibrated manually using a trial-and-error approach. Volume balancing was performed using Synchro to avoid any directional data inconsistencies. Various VISSIM parameters such as driving behavior, lane change parameters, speed distributions and the routing decisions combined were used to match the link volumes, turning movement counts and queues at each intersection. Speed distributions and speed decisions were based on posted speed limits and travel times.

Both networks before- and after-ATCS were simulated for 10 replications. Different random seeds were used across the 10 replications to capture the stochastic variation in traffic characteristics. Warm-up periods of 30 minutes were used to fill the network corridor to the given traffic conditions prior to recording performance measures. Simulation durations of 60 minutes were used to evaluate the network performance (Dowling, Skabardonis, & Alexiadis, 2004). The model was validated by comparing the modeled and field volumes, turn movement counts at each signalized intersection, travel times between the signalized intersections and end-to-end corridor travel times.

SCATSIM was used to run the after-ATCS simulation model. SCATSIM allows for the replication of the SCATS adaptive control in the VISSIM environment. The fine-tuned field ATCS signal configurations were used in the SCATSIM. No additional calibration or validation efforts were made for the after-ATCS simulation model. As a result, the after-ATCS simulation model was similar to the before-ATCS model in all respects except for the signal control. This allowed for the comparison of same baseline conditions under different signal control systems and hence objective evaluation of ATCS performance.

The simulation results for the corridor travel time are shown in Figure 4.8 and are consistent with the field travel time observations. Mainline as well as network-wide performances were analyzed separately as shown in the two sections of Figure 4.8. The mainline performance includes the end-to-end corridor performance and excludes the side-streets performance. The network-wide travel time includes side-streets performance in addition to the mainline performance. Travel times in the mainline northbound direction show little improvement under ATCS control. However, in the southbound mainline direction travel time increases under ATCS control. It is important here to note the very important aspect of the microsimulation technique. It can provide a truly objective comparison of the ATCS performance by simulating the before-ATCS traffic conditions with the after-ATCS signal controller which is not possible with other data sources. However, the network-wide performance shows that the total network travel time as measured by the sum of travel times of all individual vehicles that traveled the network has significantly improved after-ATCS. This can be seen in Figure 4.8.(c).

While the mainline performance shows mixed results, the network-wide performance clearly indicates consistent and significant improved performance. At this stage, this contrast can be attributed to the only uncommon factor between the two performance measures, the side-streets. To validate this notion, the queue lengths and node-wise delays per vehicle were examined for the main line and side-streets separately.



a) NB Travel Time (Simulation)

b) SB Travel Time (Simulation)

c) Total Travel Time (Simulation)

Figure 4.8 Travel Time (Simulation)

Figure 4.9.(a) & (b) shows the average of the left turn and through movement queue lengths formed at every intersection in the northbound and southbound direction respectively. Although the average queue lengths at every intersection in the northbound direction (Figure 4.9.(a)) are shorter under the ATCS regime, the average queue lengths in the southbound direction are little longer (Figure 4.9.(b)) with ATCS. However, the queue lengths on the side-streets show about 58% improvement in queue lengths. The same tradeoff is seen from the node-wise average delay per vehicle calculated as the average of the left turns and through movement for every intersection. Although the delays on the mainline in either direction are smaller, the side-street delays show greater improvements with ATCS.

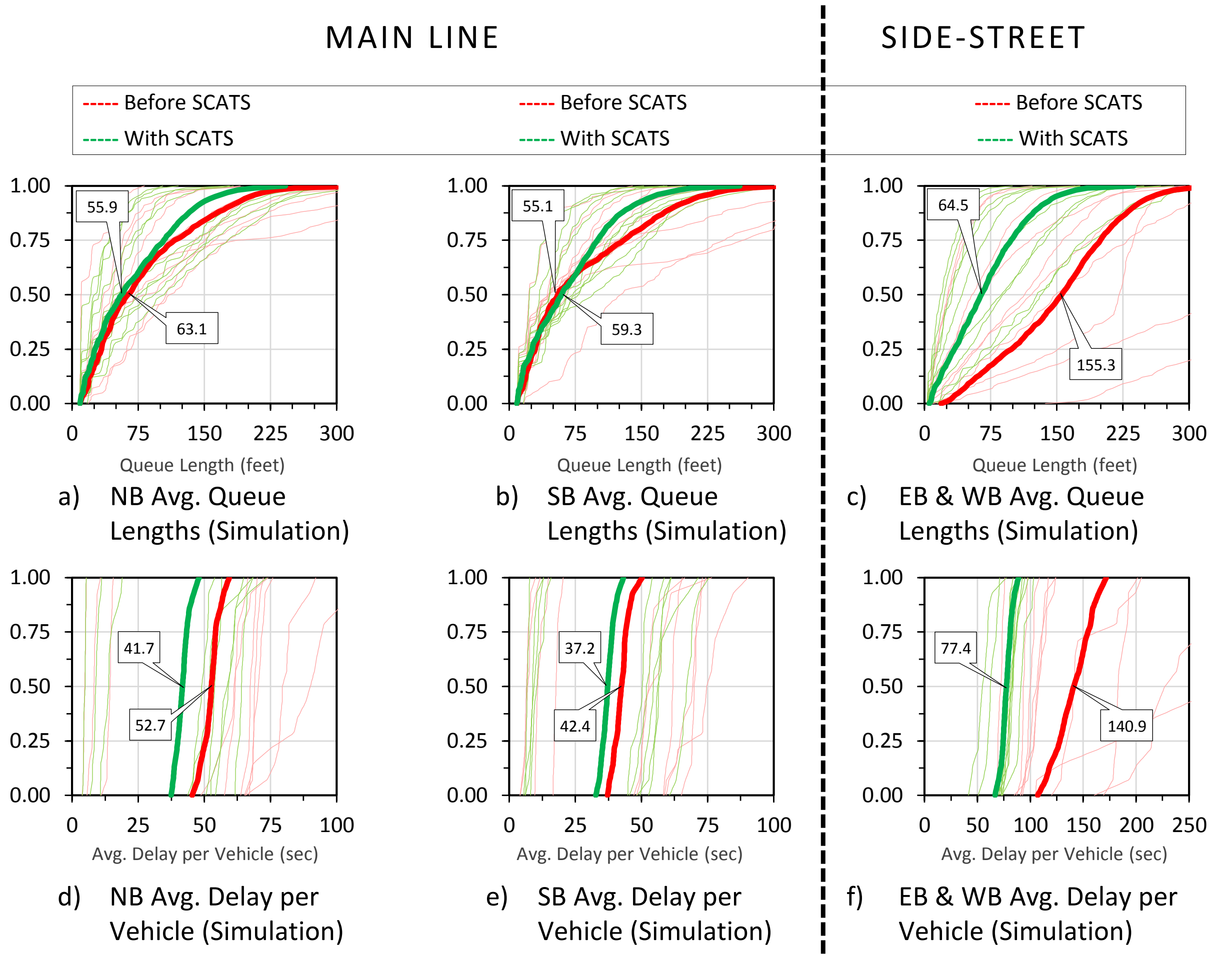


Figure 4.9 Comparison of Main Line and Side-street Performances (Simulation)

Figure 4.9.(d), (e), (f) show the average delay per vehicle for every intersection. The average side-street delay per vehicle improves by about 45%. This validates the notion that the improvement in the network-wide performance is mainly contributed by the improved side-streets performance. This is important feedback for system operators as they continuously try to balance operational performance goals between mainline travel time and delay on the side-streets. This analysis can be further extended to find other interesting results. While various data sources of travel time data can be used to characterize the corridor performance before-ATCS or

after-ATCS, a well calibrated and validated simulation model can still be used to analyze additional measures that characterize ATCS performance.

4.6 Conclusions

ATCS systems are an advanced tool that can improve traffic operations. The ATCS implementation case study in this paper was performed to compare the arterial performance before, during, and after ATCS deployment by examining the travel time data and demonstrate different analyses that can be conducted at different phases of the ATCS implementation. The methodologies discussed will help transportation engineers, planners, and policy makers to monitor the system performance and improvements at any point of the ATCS implementation process. As policies and timings are adjusted, this type of feedback is an effective way to continuously monitor the ATCS and quantify benefits. The study yielded the following general conclusions/recommendations:

(1) Different sources of travel time data can be used to characterize the corridor performance before-ATCS or after-ATCS. This study shows that the corridor travel times measured by Bluetooth data as well as crowdsourced data are very close and showed similar trends. The minor differences in the travel time arise out of different sampling rates and periods.

(2) Early data collection before the ATCS installation begins is recommended. Newer crowdsourced data can provide a long-term look at mainline corridor travel times over the life (including before and during installation) of an ATCS.

(3) A well-calibrated and validated simulation model can deliver results close enough to the field conditions. The advantage of simulation technique is to compare the same baseline

traffic conditions under different signal control systems, which may not be possible to evaluate with other data sources.

(4) Depending on operational policies and goals, performance measures other than mainline travel time may need to be considered. Although corridor travel time is a typical traditional way to assess arterial improvements, other measures need to be studied for comprehensive evaluation of new, complex systems such as ATCS. This paper leveraged calibrated simulation models to gain detailed insight of side-street and network-wide performance measures in order to supplement the information gleaned from the travel time data.

(5) As every technique has its own limitations, multiple evaluation techniques should be used to improve evaluations and resulting decision making. Engineers and other persons involved with the implementation will need to think out their own detailed analysis plan to reflect project-specific timelines, performance goals, and other considerations.

Considering these conclusions, it is worthwhile to note that while data is becoming more available, using the data for effective evaluation and analysis still remains an evolving standard that may tend to be project specific. Future work in this area should consider using ATCS-specific reporting data and also traffic controller data collected over time to assess performance changes.

4.7 References

Day, C., Ernst, J., Brennan, T., Chou, C.-S., Hainen, A., Remias, S., … Bullock, D. (2012). Performance Measures for Adaptive Signal Control. Transportation Research Record: Journal of the Transportation Research Board, 2311, 1–15.

Day, C. M., Brennan, T. M., Hainen, A. M., Remias, S. M., Premachandra, H., Sturdevant, J. R., … Bullock, D. M. (2012). Reliability, Flexibility, and Environmental Impact of Alternative Objective Functions for Arterial Offset Optimization. Transportation Research Record: Journal of the Transportation Research Board, 2259, 8–22.

Day, C. M., Ernst, J. M., Brennan, T. M., Chou, C.-S., Hainen, A. M., Remias, S. M., … Bullock, D. M. (2012). Adaptive Signal Control Performance Measures : A System-in-the-Loop Simulation Case Study. Transportation Research Record, 2311, 1–15.

Dutta, U., McAvoy, D., Lynch, J., & Vandeputte, L. (2008). Evaluation of the Scats Control System. Report No: MIOH UTC TS4. Detroit, Michigan.

Eghtedari, A. G. (2006). Measuring Benefits of Adaptive Traffic Signal Control: Case Study of Mill Plain Boulevard, Vancouver, Washington. In Transportation Research Board 85th Annual Meeting.

Federal Highway Administration (FHWA) - USDOT. (n.d.). Every Day Counts - Adaptive Signal Control Technology. Retrieved September 5, 2016, from https://www.fhwa.dot.gov/innovation/everydaycounts/pdfs/asct_brochure.pdf

FHWA IF-02-047, U. (2002). Life-cycle cost analysis primer. Retrieved from www.fhwa.dot.gov/asset/lcca/010621.pdf

Hansen, B. G., Martin, P. T., & Perrin ., H. J. (2007). SCOOT Real-Time Adaptive Control in a CORSIM Simulation Environment. Transportation Research Record: Journal of the Transportation Research Board, 1727, 27–30.

Hatcher, G., Burnier, C., Greer, E., Hardesty, D., Hicks, D., Jacobi, A., … Mercer, M. (2014). Intelligent Transportation Systems Benefits, Costs, and Lessons Learned: 2014 Update Report. Washington, DC. Retrieved from http://www.itsknowledgeresources.its.dot.gov/its/bcllupdate/

Howard/Stein-Hudson Associates, I. (2010). The Benefits of Retiming / Rephasing Traffic Signals in the Back Bay. Retrieved from www.cityofboston.gov/.../the benefits of traffic signal retiming report_tcm3-18554.pdf

Hunter, M., Wu, S. K., Kim, H. K., & Suh, W. (2012). A Probe-vehicle-based Evaluation Of Adaptive Traffic Signal Control. IEEE Transactions on Intelligent Transportation Systems, 13(2), 704–713.

Hutton, J., Bokenkroger, C., & Meyer, M. (2010). Evaluation of an Adaptive Traffic Signal System: Route 291 in Lee's Summit, Missouri. Jefferson City, Missouri. Retrieved from http://trid.trb.org/view.aspx?id=916407

Jayakrishnan, R., Mattingly, S. P., & McNally, M. G. (2000). Performance Study of SCOOT Traffic Control System with Non-Ideal Detectorization : Field Operational Test in the City of Anaheim. Report UCI-ITS-WP-00-27. Irvine, California.

Kergaye, C., Stevanovic, A., & Martin, P. (2010). Comparative Evaluation of Adaptive Traffic Control System Assessments Through Field and Microsimulation. Journal of Intelligent Transportation Systems, 14(2), 109–124.

Kergaye, C., Stevanovic, A., & Martin, P. T. (2008). An evaluation of SCOOT and SCATS through microsimulation. In International Conference on Application of Advanced Technologies in Transportation. Athens, Greece.

Liu, D., & Cheu, R. L. (2004). Comparative Evaluation of Dynamic TRANSYT and SCATS-Based Signal Control Logic using Microscopic Traffic Simulations. In Transportation Research Board. Washington, D.C.

Lodes, M., & Benekohal, R. F. (2013). Safety Benefits of Implementing Adaptive Signal Control Technology : Retrieved from https://www.ideals.illinois.edu/handle/2142/45786

Martin, P. T., & Stevanovic, A. (2008). Adaptive Signal Control V - SCATS Evaluation in Park City, Utah. Retrieved from http://www.mountain-plains.org/pubs/pdf/MPC08-200.pdf.

Office of the Assistant Secretary for Research and Technology (OST-R) - US DOT. (n.d.). Arterial Management - Traffic Signal Control Operation Strategies. Retrieved May 9, 2016, from http://www.itsdeployment.its.dot.gov/Results.aspx

Park, B. (Brian), & Chang, M. (2002). Realizing Benefits of Adaptive Signal Control at an Isolated Intersection. Transportation Research Record, 1811, 115–121.

Park, B. (Brian), & Chen, Y. (2010). Quantifying the benefits of coordinated actuated traffic signal systems : A case study. VTRC 11-CR2. Richmond, Virginia.

Park, B. (Brian), Chen, Y., Cho, H., & Yun, I. (2014). Quantifying the benefits of adaptive split feature on the operation of coordinated actuated traffic signal system. KSCE Journal of Civil Engineering, 19(1), 311–317.

Peters, J. M., McCoy, J., & Bertini, R. (2007). Evaluating an Adaptive Signal Control System in Gresham. In ITE Western District Annual Meeting.

Roads and Maritime Services. (n.d.). An Introduction to Scats 6. South Wales, Australia: Roads and Maritime Services. Retrieved from http://www.scats.com.au/files/an_introduction_to_scats_6.pdf

Salem, O. (Sam), Chen, J. (Xifan), & Salman, B. (2015). Enhancing TSM&O Strategies through Life Cycle Benefit/Cost Analysis: Life Cycle Benefit/Cost Analysis & Life Cycle Assessment of Adaptive Traffic Control Systems and Ramp Metering Systems. Syracuse, NY. Retrieved from http://ntl.bts.gov/lib/55000/55200/55222/SU_TranLIVE__FinalReport_Enhancing_TSMO_Strategies.pdf

SRF Consulting Group Inc. (2000). Adaptive Urban Signal Control and Integration. October.

Stevanovic, A. (2010). NCHRP Synthesis 403 Adaptive Traffic Control Systems : Domestic and Foreign State of Practice. Washington, D.C.

Tian, Z., Ohene, F., & Hu, P. (2011). Arterial performance evaluation on an adaptive Traffic Signal control system. Procedia - Social and Behavioral Sciences, 16, 230–239.

US DOT FHWA. (2008). Traffic Signal Timing Manual.

Wang, J., Robinson, B., Shelby, S. G., Cox, K. B., & Townsend, W. (2010). Evaluation of ACS Lite Adaptive Control using Sensys Arterial Travel Time Data. ITS America 20th Annual Meeting & Exposition, 1–19.

CHAPTER 5

LIFE-CYCLE BENEFIT-COST ANALYSIS OF ADAPTIVE SIGNAL CONTROL USING SYSTEM-WIDE PERFORMANCE MEASURES

5.1 Introduction

Adaptive Traffic Control Systems (ATCS) are becoming increasingly utilized in the U.S. and other countries. ATCS are traffic signal systems that continuously detect the vehicular traffic and uses the information to compute the optimal signal timing parameters in real-time to respond to the actual traffic conditions (US DOT FHWA, 2008). In addition to traffic conditions, ATCS also consider demand and system capacity to develop the signal timing plans (Stevanovic, 2010). ATCS is effective for the arterial system with higher variability and unpredictability which results in excessive delays and stoppages (Federal Highway Administration (FHWA) - USDOT, n.d.)

In the U.S., there are more than 4,200 signalized intersections under ATCS control (Office of the Assistant Secretary for Research and Technology (OST-R) - US DOT, n.d.). Various ATCSs are available, each based on different working principle and appropriate for different networks (Stevanovic, 2010). ATCSs are usually evaluated for reductions in travel time, delay, number of stops, queue lengths, etc. These studies are discussed in the following section. Although the current ATCS implementation can be easily evaluated either by using before-and-after field data or by simulating the before-and-after conditions, it is difficult to determine two things about ATCS: i) the exact period for which the ATCS benefits can be gained in future and ii) the ATCS benefits in future periods as these might change with change in traffic demand. These make the quantification of future ATCS benefits nearly impossible. However, with the use of microsimulation such evaluation of performance improvements over the entire lifecycle of the ATCS (including adjusting for changing traffic conditions) is possible. Furthermore, this approach can be used to perform benefit-cost analysis (BCA) which is useful for justifying engineering decisions. Such analysis can provide transportation planners and engineers with a broader and clearer picture of their investment decision.

The objective of this paper is to demonstrate how to perform a more accurate BCA than the previous research for any ATCS implementation over its lifecycle using microsimulation techniques. In case the implementation of ATCS is still under contemplation, the ATCS signal timing configurations (personalities, for a SCATS system) can be requested from the vendor and the BCA can be conducted. This analysis is possible due to the ability of microsimulation technique to simulate experimental traffic scenarios that accommodate predicted changes in traffic networks over their lifetime.

5.2 Literature Review

Many studies related to the quantification of benefits of different aspects of traffic signal exist in literature and practice. These studies can be classified based on their scope of the study, the traffic signal aspect being studied and the approach used for analyzing benefits.

First, the scope of evaluation studies can vary from a single intersection to a corridor to an urban grid or other configuration networks. Historically, evaluation studies have been mainly performed for arterial systems. For examples, an evaluation study in Indiana was conducted for a 5.2 mile corridor consisting of eight coordinated intersections (C. M. Day, Brennan, et al. 2012). Another study was focused on two shorter arterials; first consisted of five actuated isolated signalized intersections and the other was six coordinated actuated signalized intersections (Park & Chen 2010). Other studies that involved evaluation of arterials are (Park et al. 2014; Wang et al. 2010; Hutton et al. 2010; Eghtedari 2006; Peters et al. 2007; Kergaye et al. 2008; C. Day et al. 2012; C. M. Day, Ernst, et al. 2012). However, a study for Boston Transportation Department is focused on larger network of approximately 280 intersections over 20 different travel corridors (Howard/Stein-Hudson Associates 2010). Another study was focused on a six-node traffic network in downtown Salt Lake City (Hansen et al. 2007). Some evaluation studies are even based on hypothetical case studies (Salem et al. 2015; Park & Chang 2002).

Past studies have shown that microsimulation models, if well calibrated and validated, can replicate the field conditions accurately (Kergaye et al. 2010). Thus, the literature shows evaluation studies being performed using both, field before-and-after data, as well as microsimulation techniques. A study on InSync ATCS for MO 291 in Lee's Summit and another study on ACS Lite ATCS in Atlanta, GA both used field before-and-after data for their evaluations (Wang et al. 2010; Hutton et al. 2010). Other evaluation studies which were performed primarily to evaluate the benefits used field measured before-and-after data for their evaluations (Eghtedari 2006; Peters et al. 2007; Tian et al. 2011; SRF Consulting Group Inc. 2000; Jayakrishnan et al. 2000; Hunter et al. 2012; Salem et al. 2015). Another study which evaluated performances of four different objectives of traffic signals on an arterial system made use of anonymous probe vehicle travel time data for their study (C. M. Day, Brennan, et al.

2012). Instead of before-and-after data, some studies were performed by turning off the ATCS for a brief period to collect the non-ATCS data and then use it for evaluating the ATCS performance (Martin & Stevanovic 2008; Dutta et al. 2008). Other studies used different microsimulation techniques to quantify the ATCS benefits. These studies are based on the use of Synchro (Howard/Stein-Hudson Associates 2010; Park & Chen 2010), CORSIM (Hansen et al. 2007), or VISSIM ((Kergaye et al. 2008; Martin & Stevanovic 2008; C. M. Day, Ernst, et al. 2012) simulation softwares. One study on quantifying the benefits of an adaptive split feature of coordinated actuated traffic signal system used simulation and then validated the impacts using field before-and-after data (Park et al. 2014). Another study on quantifying the safety benefits of ATCS system used surveying approach to collect all relevant ATCS related information from the agencies that had implemented ATCS (Lodes & Benekohal 2013).

Literature also shows that traffic signal evaluation studies are often performed for different purposes. ATCS related studies were mainly performed to evaluate the potential benefits of ATCS over existing traffic signal control (Park & Chang 2002; Wang et al. 2010; Hutton et al. 2010; Eghtedari 2006; Peters et al. 2007; Hansen et al. 2007). However, one study compared the performance of two ATCSs (SCATS and SCOOT) over coordinated actuated traffic control (Kergaye et al. 2008). Another study evaluated both, an ATCS and ramp metering system as part of its transportation system improvement program (Salem et al. 2015). In another effort to improve traffic operations and safety in the city of Boston, MA; benefits of signal retiming efforts were estimated (Howard/Stein-Hudson Associates 2010). A study was conducted for Virginia DOT to quantify the benefits of coordinated actuated traffic signal system (Park & Chen 2010). A follow-up of this study was to quantify the impacts of implementing an adaptive split feature on coordinated actuated traffic signal system (Park et al. 2014). A small study conducted by the University of Illinois at Urbana-Champaign was focused on the estimation of safety-related benefits of ATCS (Lodes & Benekohal 2013). Another study demonstrates the use of travel time data to assess the reliability of travel time, user cost savings, and environmental benefits by optimizing the offset for four different objectives (C. M. Day, Brennan, et al. 2012). In similar other study, fully actuated control was compared with traditional time-of-day and traffic-responsive control both with and without the use of the adaptive control system ACS-Lite (C. M. Day, Ernst, et al. 2012).

Finally, studies also differ in the criteria used to evaluate the benefits. For example, C. M. Day, Brennan, et al. (2012), used reliability, flexibility, and environmental impact as their basis for benefit evaluation. Some studies considered the reduction in delays as benefits (Park et al. 2014; Park & Chang 2002; C. M. Day, Ernst, et al. 2012). Some other studies have considered multiple traffic MOEs (travel time, delay, queue length, number of stops) in their evaluations (Wang et al. 2010; Hutton et al. 2010; Eghtedari 2006; Peters et al. 2007; Hansen et al. 2007; Kergaye et al. 2008). Other studies focused on the analysis of BCR for their evaluations. The magnitude of benefits of signal retiming was estimated as BCR of 83:1 (Howard/Stein-Hudson Associates 2010). Another analysis indicated the coordinated actuated traffic signal system has a BCR of 461.3 against the non-coordinated system (Park & Chen 2010). A study on estimation of safety related BCR for implementing ATCS concluded that ATCS implementation improves safety (Lodes & Benekohal 2013). LCCA to assess the benefits of ATCS showed the conservative BCR for a typical ATCS deployment to range between 6.5 and 13.

5.3 Motivation

This study is motivated to answer the two questions regarding ATCS implementations that still remains unanswered - i) how long can one expect to continue to gain benefits from an ATCS implementation and ii) how much benefit can be expected over its lifecycle.

According to NCHRP 403, pre-installation evaluation of ATCS can prove to be very useful for deciding to implement ATCS. Since the capital costs and other infrastructural changes required to successfully implement an ATCS are extensive, it should be ensured that ATCS provides superior performance over a longer period (Stevanovic, 2010). However, it is difficult to determine how long that period may be, at least based on functional performance. This study develops a methodology to address this question in identifying the period and then conducting further analyses.

Further, although a wide range of benefits from ATCS implementations are reported (Hatcher et al., 2014; Stevanovic, 2010), some other studies indicate no benefits or even degraded performance. For example, ATCS deployment in the City of Anaheim, CA failed to show any significant benefits (Jayakrishnan et al., 2000). Another study in Minneapolis shows that although ATCS was helpful during special events, there were no significant benefits during peak hour travel time (SRF Consulting Group Inc., 2000). Evaluation of ATCS performance of an arterial in Las Vegas showed that no significant improvement on arterial progression was achieved in the field (Tian et al., 2011). This implies that while benefits from ATCS implementation may be expected, they are not guaranteed. Hence, it is critical to have a good estimate of the benefits of an ATCS deployment.

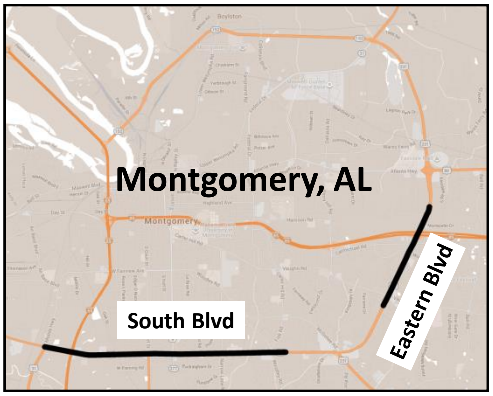
However, although the performance gains by deploying ATCS can be measured in various ways, it is important for transportation agencies to recognize the worth of these benefits. Thus, it is imperative for the transportation agency to quantify the monetary benefits of ATCS implementation to understand the righteousness about their investment decision and also serve as a guideline for their future ITS investments. BCA is an economic analysis tool that compares benefits and costs in selecting optimal projects or implementation alternatives (FHWA IF-02-047, 2002), can be very useful in such cases. Two pieces of information that are important for effective BCA are i) the future benefits of ATCS and ii) the lifespan of ATCS. However, as the traffic demand changes in future (most likely increasing), the benefits from ATCS are expected to change as shown in some studies (Park & Chang, 2002; Salem et al., 2015). Also, since every ATCS implementation is unique (Salem et al., 2015; Stevanovic, 2010), the performances of such ATCS implementations are not directly transferable to any other implementations. This greatly limits the possibility of extrapolating the current benefits to the future and hence evaluating the benefits over the lifecycle of the ATCS implementation. This study also develops a methodology to assess the future benefits of ATCS.

5.4 Research Objective

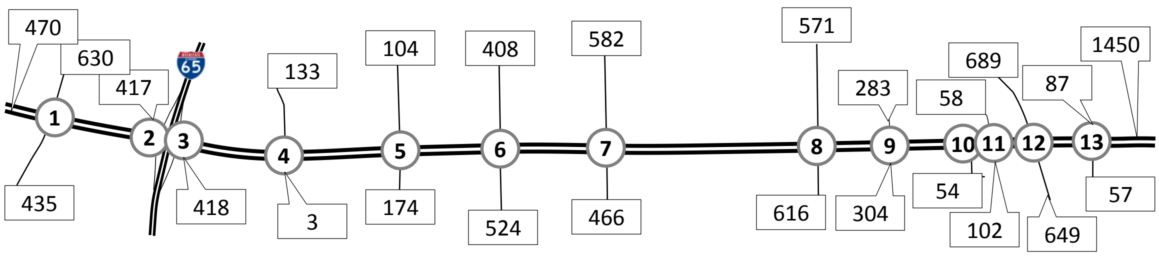
The purpose of this paper is to develop a new and more accurate procedure for determining the BCA for ATCSs over the *actual* lifespan of systems. This technique is demonstrated and applied to an ATCS system on two principal arterial corridor systems by evaluating the SCATS performance for both current and future traffic conditions. By assessing the SCATS performance under different traffic conditions (which includes accommodations for future projected traffic growth), not only the ATCS benefits can be more accurately determined, but also the effective life of the ATCS can be more accurately known.

5.5 Research Evaluation Methodology

In 2012, SCATS was deployed on 35 intersections of US-80 in Montgomery, AL. The study arterials used in this study are the two subsystems of the SCATS implementation on this corridor and were analyzed separately due to vendor recommendations and adaptive system characteristics. The first system is US-80/South Blvd which runs east-west direction between Mobile Hwy and Brantford Blvd and consists of 13 intersections. The second system is US-80/US-231/Eastern Blvd which runs SW-NE direction between Hitching Post Ln and Shirley Ln and consists of 10 intersections. The map of the two arterials along with other details is provided in Figure 5.1 and Figure 5.2. The figures also show the current and forecasted demand for next 10 years on the two corridors, which is important for accurate BCA. The primary question that is being addressed in this paper is how SCATS will perform under future demand conditions.



Total peak hour demand: **9684**



Demand Growth over next 10 years period

Period	*Volume*
0	9684
1	9878
2	10075
3	10277
4	10482
5	10692
6	10906
7	11124
8	11346
9	11573
10	11805

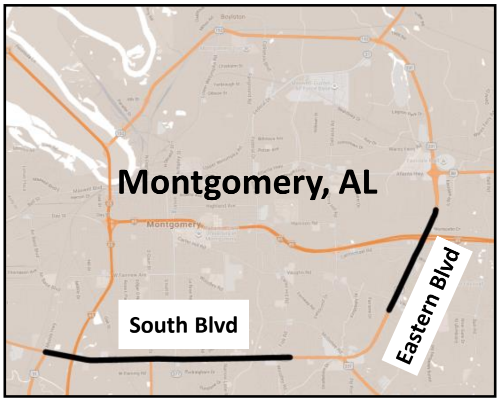
** Assuming 2% annual growth rate in traffic volumes*

E.South Blvd / US-82:

- Major arterial Four lanes, 5.0 miles long
- Low to moderate traffic volume
- Average traffic volume per intersection - 3200 vph
- Several irregular-spaced intersections
- 13 intersections (left to right)

1. Mobile Hwy
2. I-65 SB Ramp
3. I-65 NB Ramp
4. Davenport Dr
5. Rosa L Parks Ave
6. S Court St
7. Norman Bridge Rd
8. Narrow Lane
9. Morrow Dr
10. Woodley Square
11. Bonaparte Blvd
12. Woodley Rd
13. Brantford Blvd

Figure 5.1 Map of South Blvd/US-80 with Current and Forecasted Demand

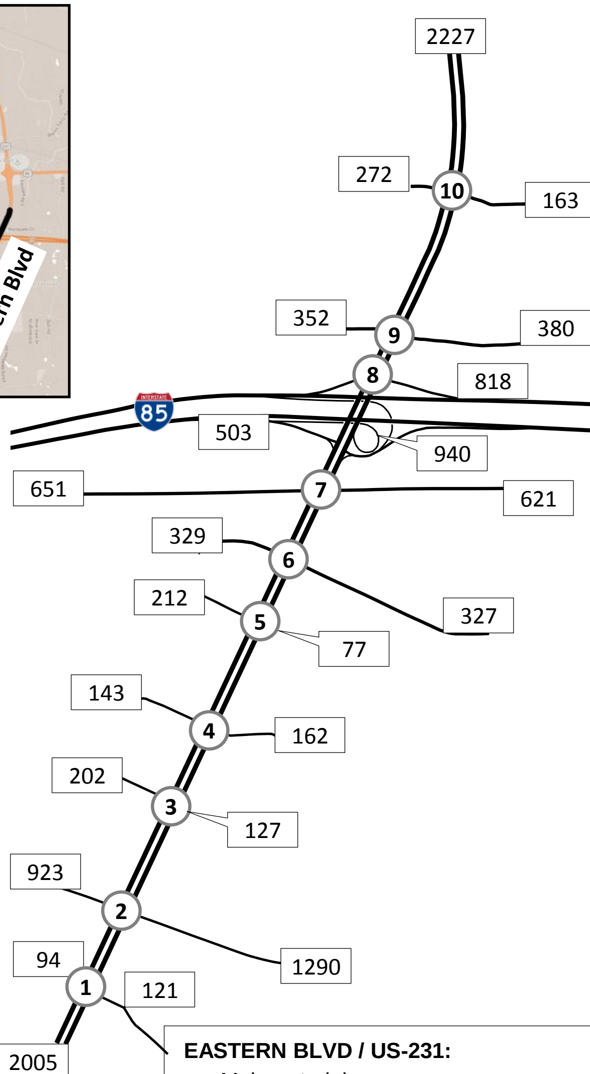


Total peak hour demand: **12939**

Demand Growth over next 10 years period

Period	***Volume***
0	12939
1	13198
2	13462
3	13731
4	14006
5	14286
6	14571
7	14863
8	15160
9	15463
10	15773

** Assuming 2% annual growth rate in traffic volumes*



EASTERN BLVD / US-231:

- Major arterial
- Six lanes, 2.3 miles long
- Moderate to heavy traffic volume
- Average traffic volume per intersection - 4900 vph
- Several closely-spaced intersections
- 10 intersections (bottom to top)

1. Hitching Post Ln
2. Vaughn Rd
3. Young Barn Rd
4. Arbor Station Rd
5. Haskell Dr
6. Woodmere Blvd
7. Carmichael Rd
8. I85 SB Off-ramp
9. Monticello Dr
10. Shirley Ln

Figure 5.2 Map of Eastern Blvd/US-231 with Current and Forecasted Demand

Weekday vehicle composition and traffic counts for every intersection between 14:00 and 18:00 were collected for the two corridors before SCATS was implemented. The travel time data was also collected using multiple floating cars that made multiple runs over multiple days. Volume balancing was performed using Synchro to avoid directional inconsistencies. Microsimulation models of the corridors were developed in VISSIM using the collected data. The necessary TOD signal timing parameters (before-SCATS) and the SCATS fine-tuned field signal configurations (after-SCATS) were used in the respective models. SCATSIM was used for simulating the SCATS control logic. Detector locations (for both TOD and with-SCATS), signal phases, and other geometric conditions in the simulation models were adjusted to match those in the field. Different driving behavior, lane change parameters, speed distributions and routing decisions were tested to calibrate the simulation model. Validation was performed by comparing the field and the simulated volumes at each intersection, travel times between the signalized intersections and end-to-end corridor travel times. The TOD model was calibrated and validated for existing conditions. Once this was complete, the traffic control logic in the simulation software (VISSIM) was replaced with the SCATSim software which used the actual SCAT personalities from the field provided by the vendor and DOT. The SCATS controlled simulation models were the same as the TOD models except for the signal control. This allowed for objective comparison of same baseline conditions, but under different signal control systems.

For both networks, each simulation consisted of 10 replications of 5 hours each which includes the 4-hour (14:00 – 18:00) count data period, half hour of a warm-up period and another half hour of a cool-down period at the end of the simulation. Most simulation results were collected for every 5 minute interval. However, results for only 16:30-17:30 period, which is the

PM peak hour period for both corridors, were used for analysis purpose. Since some of the peak hour traffic elements are consequences of the pre-peak hour traffic, simulating for a reasonable period of the pre-peak period prior to the peak hour period, allowed the simulation network to build up the peak hour traffic conditions as close to the reality as possible.

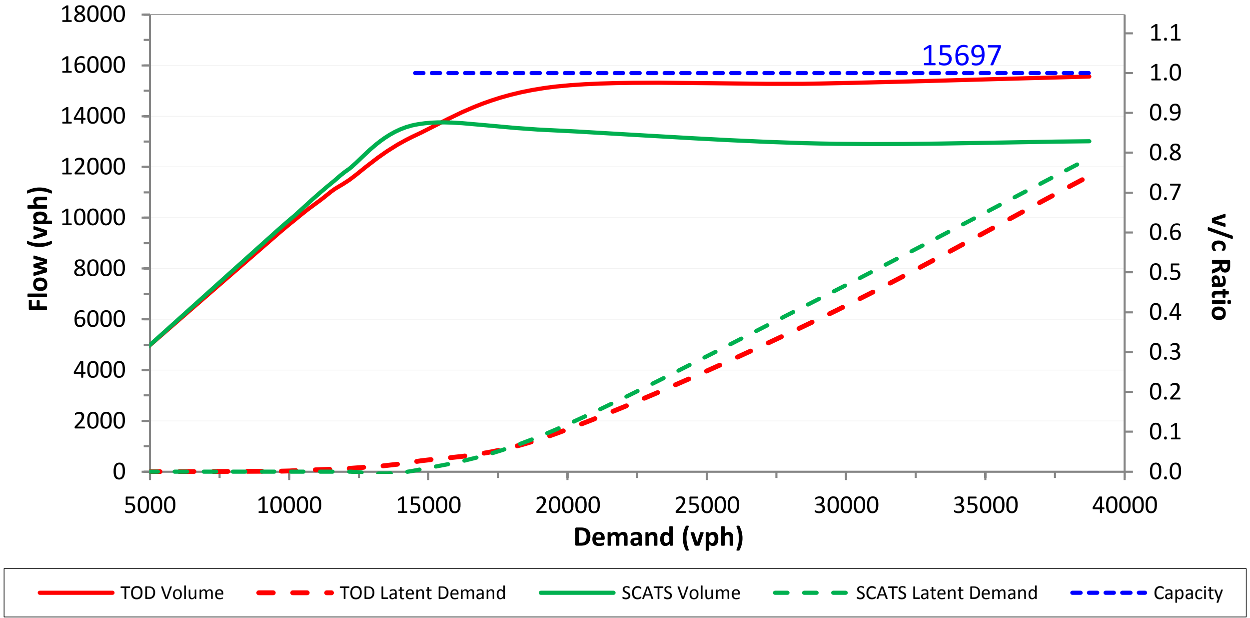
To evaluate future performance, each simulation model was run several times by varying all vehicle inputs (demand) using a common growth factor for each run. The growth factors were randomly selected but were multiples of 5s and 10s (i.e. 1.05 for a growth of 5% and 1.1 for a growth of 10%). It should be noted that while this simple growth approach was used, actual projections from transportation planners could be used which would further enhance the analysis than past studies. The models were also run for negative growth factors. This was insightful for showing that SCATS performance at lower demands will have a different performance improvement. For every demand scenario, the corresponding traffic volume, car and truck delays, latent demand and delays were measured. These outputs were measured on a system-wide basis to capture the network-wide SCATS performance instead of per intersection or per link basis. Thus, all the performance measures presented in this paper represent the system-wide performances. The traffic volumes were measured by placing data collection points at every exit point of the corridor. The sum of all vehicles exiting at all exit points at any given time is the throughput of the system. Although delays are internally measured for every individual vehicle, it was aggregated for a system-wide measure. Latent demand and latent delay are generated on a system-wide basis by.

5.6 Results / Analysis

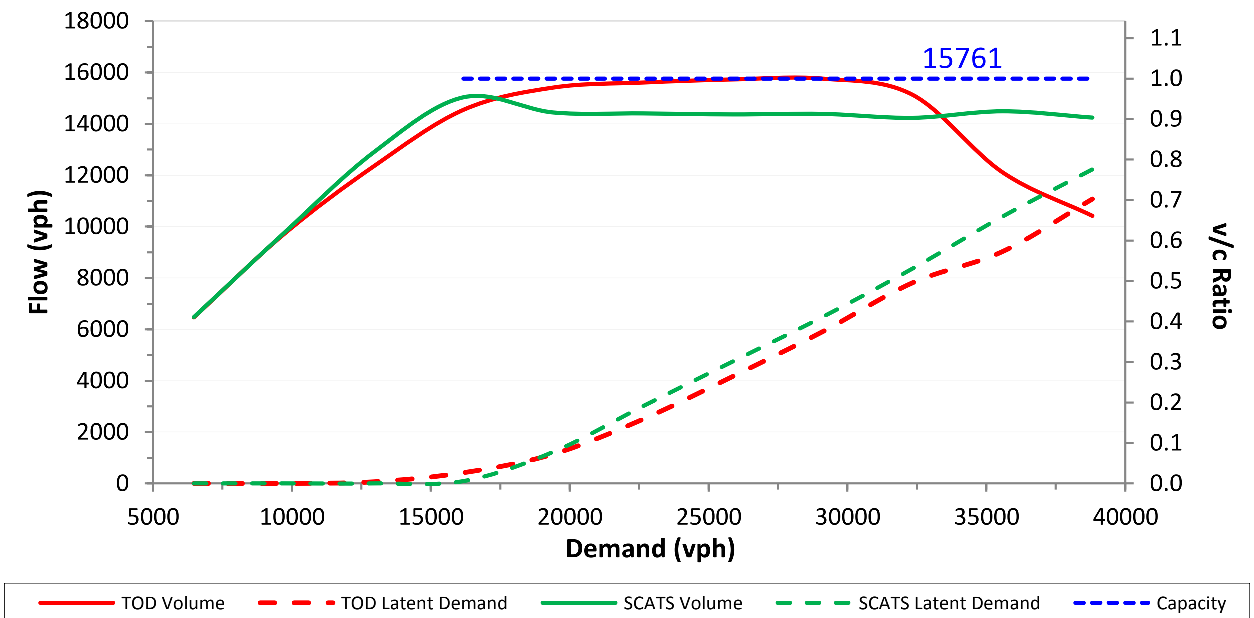
The BCA was performed in three different steps. First, the corridor demands were continuously increased in steps to determine the corridor capacity. With these capacities, volume-to-capacity (v/c) ratios for each level of demand were calculated and the corresponding delays were obtained from the simulation results. The delays were further used to compute the benefits for each demand level and the BCR was determined. The details of the analyses and the results are discussed in the following sections.

5.6.1 Network Capacity Analysis

As the demand was increased, the first thing that was looked at was how the system flows change with the change in demand. This was essential because knowing the changes in system flows with increasing demand and understanding the corresponding changes in traffic and ATCS performances forms a critical part of this study. With increasing demand, the corridor should be expected to gradually reach higher saturation level, until it is completely saturated and then oversaturated. This is shown in Figure 5.3. For both corridors, as the demand increases, the flow increases initially but then flattens at a certain point. The flow is restricted even if the demand is increased further. This, in general, follows the similar pattern as the fundamental traffic speed-flow-density diagram. Drawing parallels between the two, the maximum permitted flow is considered as system capacity which is analogous to the link capacity in the fundamental diagram.



(a) South Blvd



(b) Eastern Blvd

Figure 5.3 Distribution of Flow with Increasing Demand

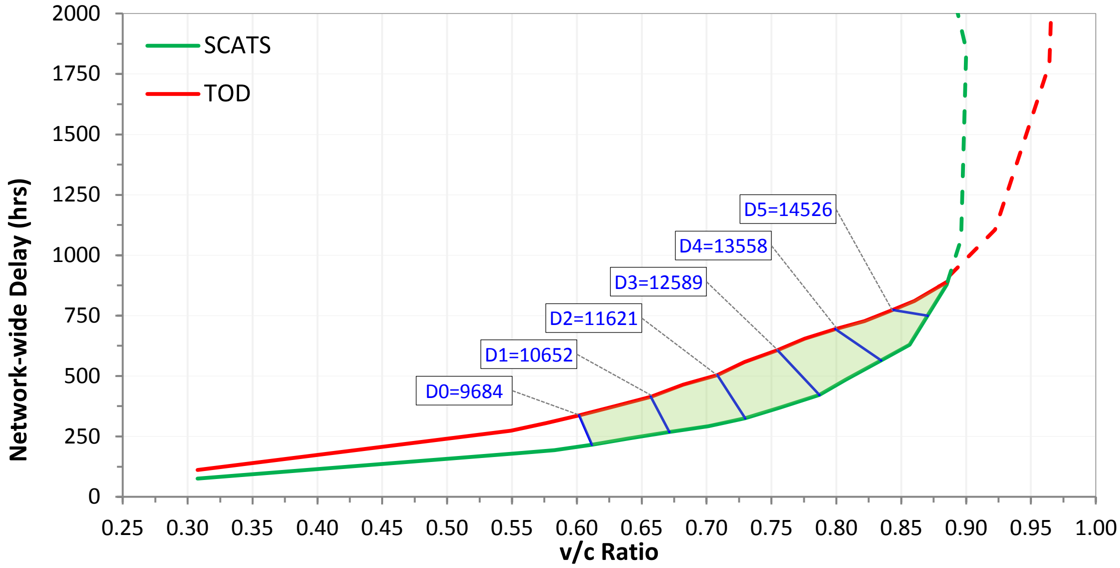
Considering the system capacity as the maximum permitted flow, a v/c ratio is determined corresponding to each demand. The TOD flow reaches capacity (i.e. v/c ratio of 1.0) at some level of growth. However, the maximum v/c ratio for SCATS flow is in the vicinity of 0.9. This is due the SCATS control logic of targeting a degree of saturation (DS) of 0.9. DS represents how effectively the road is being used (Roads and Maritime Services, n.d.) and is defined as the ratio of effectively used green time to the total available green time at every intersection (Liu & Cheu, 2004). SCATS continuously makes changes to the cycle length and phase splits to maintain the DS at the level of around 0.9 on competing approaches (Roads and Maritime Services, n.d.). This explains why the SCATS flow tends to have a v/c ratio around 0.9 with increasing demand.

As the demand increases, the latent demand starts building up and then increases exponentially indicating the increase in unserved demand as the total demand on the network increases. The latent demand curves for TOD and SCATS are shown in dotted red and green lines respectively. This unserved demand is impossible to measure in reality since travelers stuck in traffic that may see no possibility of even entering the corridor might leave and resort to alternate less congested route. Nowadays with increasing GPS users, most drivers would have received advance warning about the congestion ahead and they would have already detoured even before hitting the corridor. However, microsimulation allows the latent demand to be captured and measured which is an important advantage to using microsimulation for this analysis.

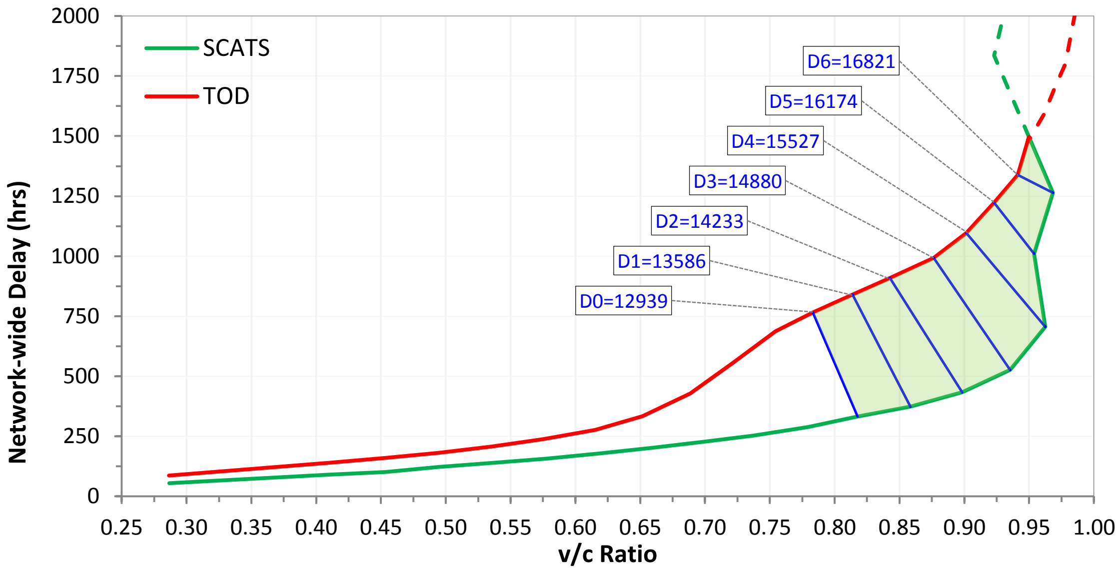
5.6.2 Network-wide Delays

The second thing which was studied was the change in network-wide delay with changing demand. As seen from the capacity graphs in Figure 5.4, for the same demand, the flows under TOD and SCATS control are different. SCATS flow is higher than TOD until v/c ratio of about 0.9, and vice versa beyond it. To normalize the effect of volume differences, delays were plotted against v/c ratio. As shown in Figure 5.4, the blue slanting lines indicate various demand levels. D0 is the present case whereas D1, D2… are the future anticipated demand levels. Different v/c ratio for TOD and SCATS for the same demand indicates SCATS serves higher volume than TOD until the point where the two curves intersect. Let this point of intersection be called as "Threshold point".

The delays vs v/c ratio graph displays a very important phenomenon. The graphs show increasing difference between the TOD delays and the SCATS delays as the demand (and also v/c ratio) increases, indicating an increase in benefits with SCATS as the demand increases. However, as the v/c ratio approaches 0.9 region, the benefits starts diminishing as have been shown in the past (Park & Chang, 2002). The two curves subsequently cross each other at threshold point, with TOD taking over SCATS beyond this point. This is a very critical finding as this can severely affect the BCA evaluations. Hence, threshold point can be defined as the point where SCATS fails to yield greater than TOD benefits. As such, the threshold point is the effective lifespan of SCATS which should be considered for more precise BCA. It should also be noted that this threshold point is determined based on only the peak-hour performances. The shaded area between the two curves indicates the total delay benefits that can be accrued from the present traffic state until the threshold point.



(a) South Blvd



(b) Eastern Blvd

Figure 5.4 Distribution of Network-wide Delays

5.6.3 Benefit-Cost Analysis

BCA is an economic analysis tool that compares benefits and costs in selecting optimal projects or implementation alternatives (FHWA IF-02-047, 2002). BCA for this study was performed using the same numerical data, the vehicle demand can be plotted with the delay and the BCA can be determined. These are shown in Figure 5.5. The topmost graphs (Figure 5.5.i) show the difference in network-wide delays between TOD and SCATS for the two corridors. Each vertical line indicates a one-year period. Thus, these graphs show an increase in delays with an increase in traffic demand over a period of several years in future. The black dotted vertical line indicates the threshold point where SCATS ceases to yield benefits over TOD.

The second graphs (Figure 5.5.ii) show the percentage change in delays. The third graphs (Figure 5.5.iii) show the changes in latent delays for TOD and SCATS over the same period. It is interesting to note that although TOD performs better than SCATS beyond the threshold point as can be seen from the first graph (Figure 5.5.i), SCATS still has lower latent demand in the same region. If the combined effect of both delay and latent delay is considered, SCATS still can be considered to perform better than TOD beyond the threshold point. It seems that the impact of SCATS ability to permit higher flow through the system thereby reducing the latent delays is higher than the impact of the increase in SCATS delay beyond the threshold point.

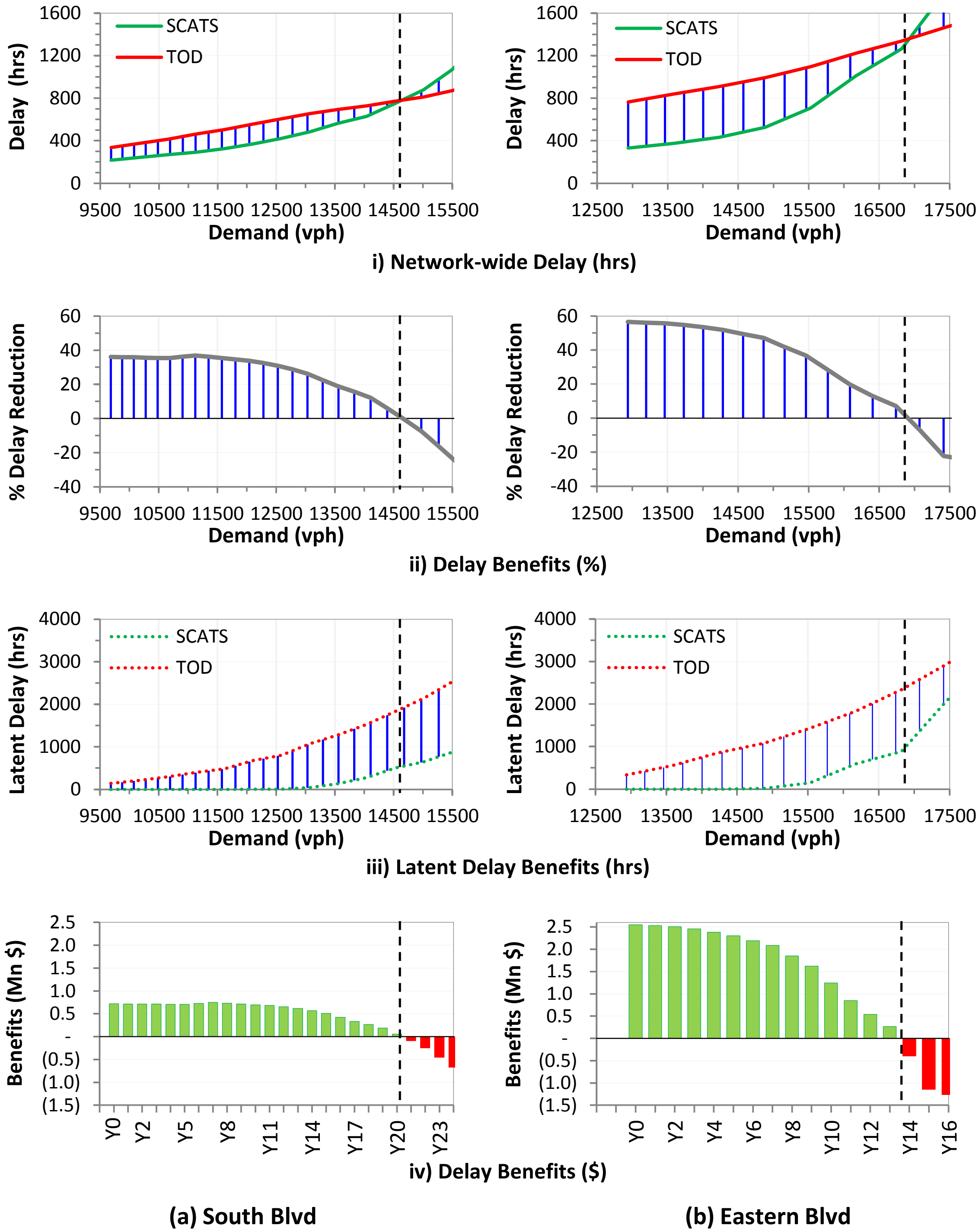


Figure 5.5 Peak Hour Benefits with SCATS

The fourth graphs (Figure 5.5.iv) show the monetary equivalent of delay benefits. The horizontal axis shows the period with Y0 as the base year in which this analysis is performed followed by subsequent years ahead. This graph also shows that the threshold point for the South Blvd is 20 years while it is 13 years for Eastern Blvd. The annual delay benefits are determined by assuming 2% average annual growth in traffic demand. This is a very conservative figure to be considered, since based on the analysis of the past 10 years AADTs, this number should have been about 1%.

The following equations were applied to establish the monetary benefits:

$$\Delta Delay = Delay_{TOD} - Delay_{SCATS}$$ **Equation (5.1)**

Where, $Delay_{TOD}$ is the network delay under TOD, $Delay_{SCATS}$ is the network delay under SCATS and $\Delta Delay$ is the change in delays. The change in delays was associated with the user cost savings. Two types of users are considered for evaluation purpose – commercial vehicles and passenger cars. Thus, the user costs can be derived as follows:

$$User_{CV} = \Delta Delay_{CV} * \%CV * Occu_{CV} * DC_{CV}$$ **Equation (5.2)**

where, $User_{CV}$ is the user cost for a commercial vehicle in \$, $\Delta Delay_{CV}$ is the delay benefit for commercial vehicles in hours which is an output from the simulation model, $\%CV$ is the percentage of commercial vehicle traffic which is known based on count data, $Occu_{CV}$ is the average occupancy in persons/vehicle which taken from the Texas Transportation Institutes (TTI) 2015 Urban Mobility Report (UMR) and DC_{CV} is the delay cost in \$/hr used from TTI's 2015 UMR. Similarly, costs for passenger cars is calculated by

$$User_{Car} = \Delta Delay_{Car} * \%Car * Occu_{Car} * DC_{Car}$$ **Equation (5.3)**

where, $User_{Car}$ is the user cost for a passenger vehicle, $\Delta Delay_{Car}$ is the delay benefit for passenger car, *%Car* is the percentage of car traffic, $Occu_{Car}$ is the average passenger car occupancy and DC_{Car} is the delay cost in $/hr and the data retrieved from the similar sources as commercial vehicles.

In addition to the user costs, potential savings from fuel consumption are derived as following:

$$Fuel_{CV} = \Delta Delay_{CV} * IU_{CV} * Price_{Diesel}$$ **Equation (5.4)**

$$Fuel_{Car} = \Delta Delay_{Car} * IU_{Car} * Price_{Gasoline}$$ **Equation (5.5)**

where, *Fuel* is the fuel cost, Δ*Delay* is the delay benefit in hours, *IU* is idling fuel usage in gal/hr, *Price* is the fuel cost in $/gal.

The CO2 emission costs are calculated as follows:

$$CO_2\ Cost = IU * CO_2 * \$_{Equivalent}$$ **Equation (5.6)**

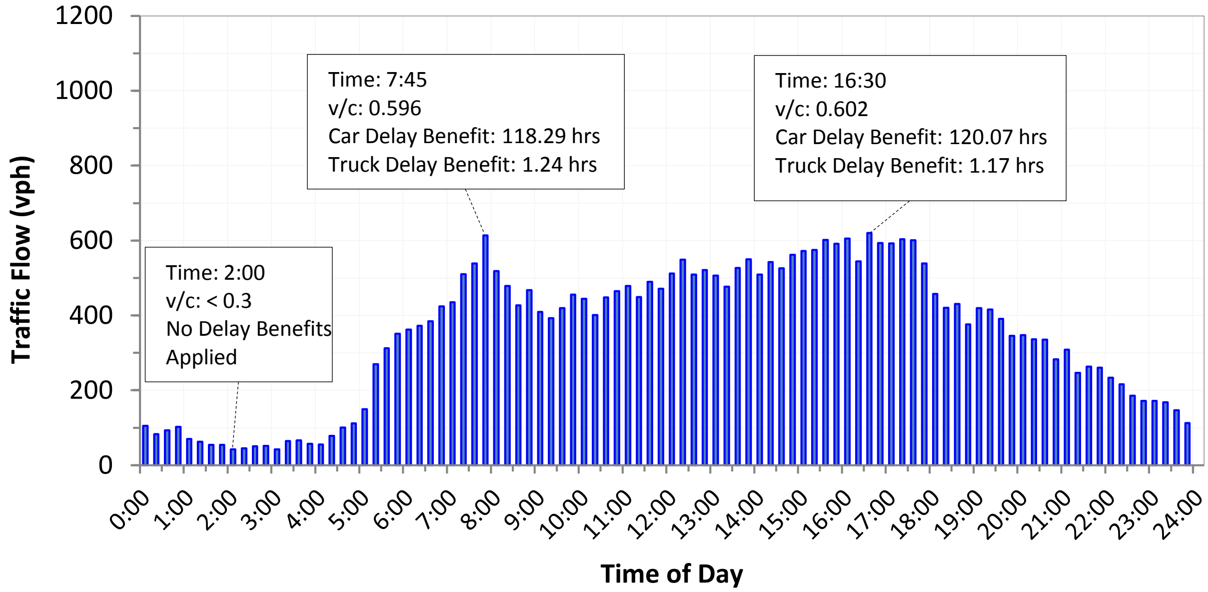
where, *IU* is the idling fuel usage in gal/hr, CO_2 is the carbon dioxide emissions in tons/gallon, and $equivalent is the monetary equivalent of CO_2 in $/ton.

Table 5.1 shows the details and sources of various cost figures that have been used for evaluating the costs and benefits. The delay benefits shown in Figure 5.5 are analyzed based on the peak hour traffic volumes. These benefits were further extrapolated to the other times of the day using the 24-hour count data shown in Figure 5.6. The v/c ratios were applied to each 15-minute volume interval and the corresponding delay benefits were used from Figure 5.4 to derive the 24-hour delay benefits as shown in Figure 5.6. For example, the 24-hour count data in the case of South Blvd in Figure 5.6a, shows that the highest flow of 621 vph occurs during 16:30 - 16:45 period. Thus, for the base scenario, peak hour v/c ratio of 0.602 corresponding to the base scenario demand (D0 = 9684 in Figure 5.4a) and its corresponding delay benefits were applied to this 15-minute period. However, the flow for 7:45 – 8:00 period is 614 vph, which is 0.99 times of the peak volume (621 vph). Thus, the v/c ratio of 0.596 (0.602 x 0.99) and its corresponding delay benefits are applied to this 15-minute period. This procedure was repeated for all other 15-minute flows to derive the 24-hour delay benefits. Further, the same procedure was repeated for different demand scenarios.

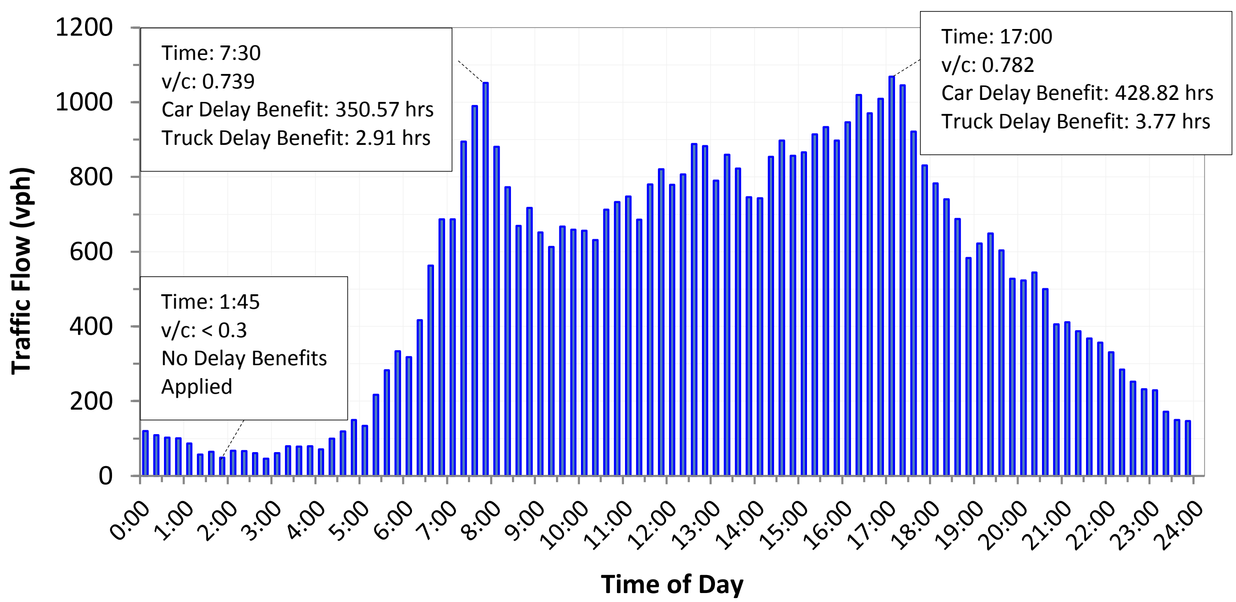
To be on a conservative side, no benefits were considered for the time periods with v/c ratio of less than 0.3, since at such low volumes, delay benefits may be very insignificant as can be seen from the tail ends of curves in Figure 5.4. This process was repeated for different future demand for several years ahead. Table 5.2 summarizes the benefits and costs for the two corridors over next 30 year period for South Blvd and 25 year period for Eastern Blvd.

Table 5.1 Table showing different Costs and its Sources

CATEGORY	ITEM	VALUE	SOURCE
SCATS	Hardware / Software Cost	$60,000	Adaptive Traffic Control Systems in the United States http://www.hdrinc.com/about-hdr/knowledge-center/white-papers/2010-adaptive-traffic-control-systems-in-the-united-states-u
	Annual Maintenance Cost	$9,000	US DOT ITS Knowledge Resource http://www.itscosts.its.dot.gov/ITS/benecost.nsf/
	Consumer Price Index (2010 to 2015)	1.09	http://www.bls.gov/data/inflation_calculator.htm
Passenger Car	Average Occupancy	1.25 (person per car)	TTI's Urban Mobility Report 2015
	Delay Hour Cost	$17.67	
	Idling Gasoline Usage	0.275 (gallons / hr)	US Department of Energy http://energy.gov/eere/vehicles/
	Gas Price	$2.43	http://www.statista.com/statistics/
	CO2 Emissions (gasoline)	8887 (grams / gallon)	US Environmental Protection Agency https://www.epa.gov/greenvehicles/
	Monetary Equivalent of CO2 Emissions	$22 ($/ton)	EPA Analysis of the American Clean Energy and Security Act of 2009 HR2454 https://www3.epa.gov/climatechange/Downloads/EPAactivities/HR2454_Analysis.pdf.
Truck (Commercial Vehicle)	Average Occupancy	1 (person per truck)	TTI's Urban Mobility Report 2015
	Delay Hour Cost	$94.04	
	Idling Diesel Usage	0.623 (gallons / hr)	US Department of Energy http://energy.gov/eere/vehicles
	Diesel Price	$2.50	http://www.statista.com/statistics
	CO2 Emissions (diesel)	10180 (grams / gallon)	US Environmental Protection Agency https://www.epa.gov/greenvehicles
Other	Discount Rate	4.00%	Assumption
	Annual Working Days	260	Assumption 52 weeks x 5 working days per week



(a) South Blvd



(b) Eastern Blvd

Figure 5.6 24 Hour Traffic Profile

Table 5.2 Summary of Benefits and Costs for Current and Future Demand

S O U T H   B L V D

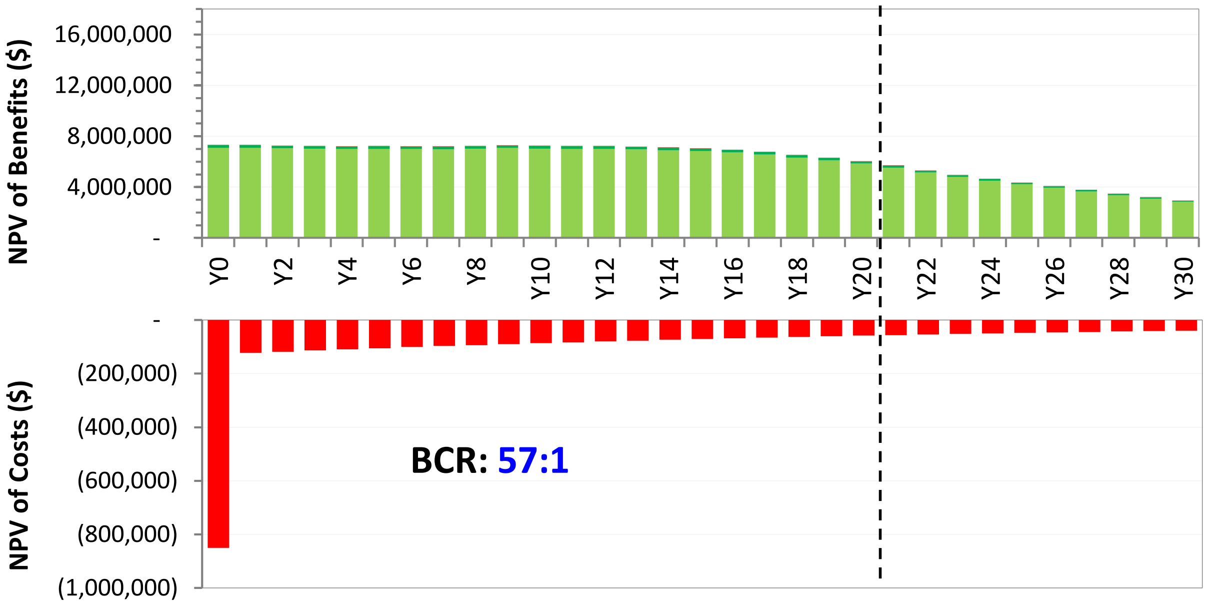
Period	Demand	Car				Truck				Cost	NPV Cost
		24 Hour Delay Benefits	NPV Delay Benefits	NPV Energy Benefits	NPV Emission Benefits	24 Hour Delay Benefits	NPV Delay Benefits	NPV Energy Benefits	NPV Emission Benefits		
		A	$B = A * (1.25) * (\$17.67) * (260\ days) * (1.04)^{-n}$	$C = A * (0.275) * (\$2.43) * (1.04)^{-n}$	$D = A * (0.275) * (8887) * (\$22) * 10^{-6}$	E	$F = E * (1.00) * (\$94.04) * (260\ days) * (1.04)^{-n}$	$G = E * (0.623) * (\$2.50) * (1.04)^{-n}$	$H = E * (0.275) * (10180) * (\$22) * 10^{-6}$	$I1 = \$60{,}000 * 13\ intx * (1.09)$ $I2 = \$9{,}000 * 13\ intx * (1.09)$	$J = I * (1.04)^{-n}$
Y0	9444	1153	$6,621,800	$200,340	$16,119	19	$466,255	$7,726	$1,110	$850,200	$850,200
Y5	10692	1405	$6,631,775	$200,642	$16,143	19	$374,956	$6,213	$893	$127,530	$104,820
Y10	11805	1742	$6,758,500	$204,476	$16,452	17	$273,997	$4,540	$653	$127,530	$86,155
Y15	13033	2083	$6,643,121	$200,985	$16,171	14	$188,395	$3,122	$449	$127,530	$70,813
Y20	14390	2188	$5,733,543	$173,466	$13,957	11	$119,898	$1,987	$286	$127,530	$58,203
Y25	15888	1926	$4,149,469	$125,541	$10,101	8	$69,453	$1,151	$165	$127,530	$47,839
Y30	17541	1582	$2,800,618	$84,732	$6,817	6	$45,209	$749	$108	$127,530	$39,320

E A S T E R N   B L V D

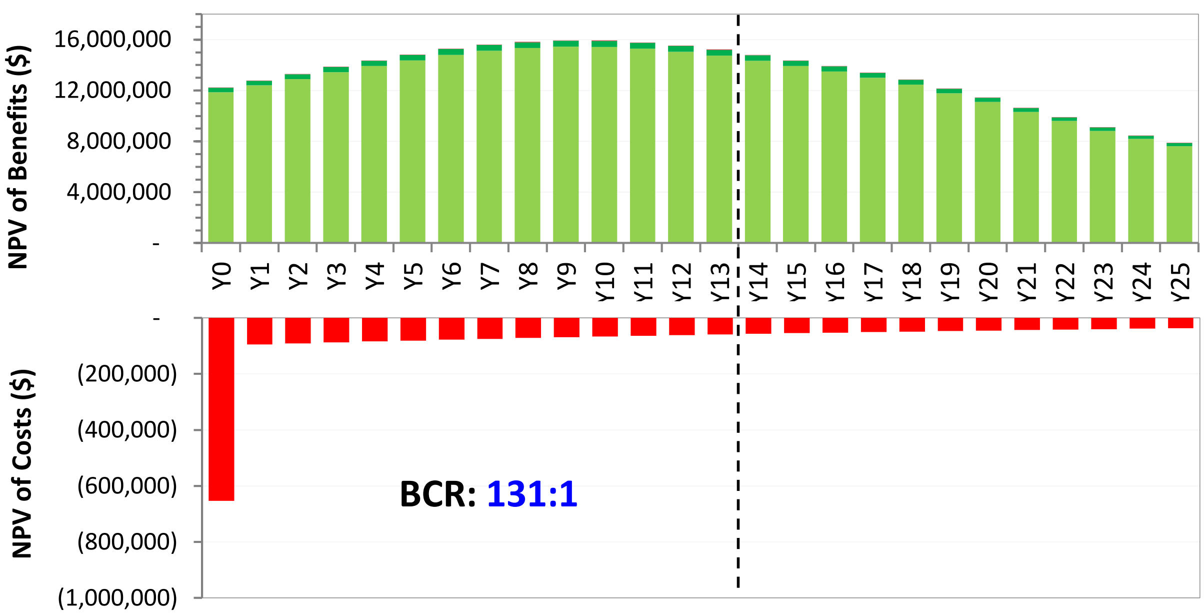
Period	Demand	Car				Truck				Cost	NPV Cost
		24 Hour Delay Benefits	NPV Delay Benefits	NPV Energy Benefits	NPV Emission Benefits	24 Hour Delay Benefits	NPV Delay Benefits	NPV Energy Benefits	NPV Emission Benefits		
		A	$B = A * (1.25) * (\$17.67) * (260\ days) * (1.04)^{-n}$	$C = A * (0.275) * (\$2.43) * (1.04)^{-n}$	$D = A * (0.275) * (8887) * (\$22) * 10^{-6}$	E	$F = E * (1.00) * (\$94.04) * (260\ days) * (1.04)^{-n}$	$G = E * (0.623) * (\$2.50) * (1.04)^{-n}$	$H = E * (0.275) * (10180) * (\$22) * 10^{-6}$	$I1 = \$60{,}000 * 10\ intx * (1.09)$ $I2 = \$9{,}000 * 10\ intx * (1.09)$	$J = I * (1.04)^{-n}$
Y0	12939	2010	$11,544,662	$349,280	$28,103	13	$319,885	$5,301	$475	$654,000	$654,000
Y5	14286	2952	$13,932,764	$421,531	$33,916	22	$439,389	$7,281	$652	$98,100	$80,631
Y10	15773	3861	$14,978,360	$453,165	$36,461	28	$459,843	$7,620	$683	$98,100	$66,273
Y15	17414	4235	$13,503,724	$408,551	$32,871	31	$415,395	$6,883	$617	$98,100	$54,471
Y20	19227	4117	$10,789,613	$326,436	$26,265	27	$299,943	$4,970	$445	$98,100	$44,772
Y25	21228	3443	$7,416,043	$224,370	$18,052	23	$211,239	$3,500	$314	$98,100	$36,799

The BCA for the two corridors is shown in Figure 5.7. It is notable to see that the annual benefits based on 24-hour volumes extend even beyond the effective lifecycle. This is because while the life of ATCS shown in Figure 5.7 considers 24-hour delay benefits, the effective life determined earlier (in Figure 5.5.iv) is based on only the peak hour delay benefits. However, assuming that ATCSs are expected to display its best capabilities under peak hour conditions, which often is the primary objective of installing ATCSs, the effective life based on peak hour performance was considered for evaluating the BCRs. Thus, the BCR of 57:1 for South Blvd is based on 20 years effective life of SCATS. Similarly, for Eastern Blvd, BCR was evaluated to 131:1 based on effective life 13 years for SCATS.

SCATS can still remain functional beyond its effective life (determined based on peak-hour performance), although may not be able to deliver its best during the peak hour period. Based on this analysis, it can be concluded that implementing SCATS on arterial corridors may prove beneficial.



(a) South Blvd



(b) Eastern Blvd

Figure 5.7 Benefit-Cost Analysis

5.7 Conclusions And Recommendations

ATCSs are often used to increase performance. These performance gains are important for justifying decisions to go with one control technology over another. To economically validate the use of an ATCS, different economic performance calculations can be used. This paper developed and independently validated the benefits of SCATS for two arterial corridors in Montgomery, Alabama. The results for both corridors were similar in terms of BCR higher than 1 indicating that benefits higher than the costs can be gained by implementing SCATS. The study yielded the following general conclusions/recommendations:

(1) Microsimulation can be a useful tool for more accurate LCCA and BCA if used correctly. The capability of simulating experimental traffic scenarios using microsimulation techniques makes this possible. Determining the system-wide capacity by varying the demand levels using microsimulation forms an important takeaway of this study.

(2) For the same demand, SCATS is able to improve the system throughput by allowing a higher flow of vehicles. SCATS also shows better latent delay performance which otherwise is difficult to measure in field studies.

(3) The effective life of SCATS is decided by the point where its benefits yield to TOD. This point was found to be in the vicinity of 90% v/c ratio. The SCATS controller logic of maintaining 90% DS on every approach of the intersection likely limits the SCATS performance beyond this point.

(4) Even beyond the threshold point, the cumulative effect of delay and latent delay with SCATS is superior (smaller) to TOD. This is because, beyond the threshold point, SCATS still allows higher flows through the system thereby reducing the latent delays

and the impact of which on the net delay is higher than the impact of higher delays by SCATS.

(5) BCR for the two corridors is found to be 57:1 and 131:1. While this is a specific conclusion to the case studies presented herein, it does establish a reference for other corridors and ATCS.

The above conclusions and practices in this section can help traffic planners, practitioners and engineers in their future ITS investment related decision making.

5.8 References

Day, C., Ernst, J., Brennan, T., Chou, C.-S., Hainen, A., Remias, S., … Bullock, D. (2012). *Performance Measures for Adaptive Signal Control*. Transportation Research Record: Journal of the Transportation Research Board, 2311, 1–15.

Day, C. M., Brennan, T. M., Hainen, A. M., Remias, S. M., Premachandra, H., Sturdevant, J. R., … Bullock, D. M. (2012). *Reliability, Flexibility, and Environmental Impact of Alternative Objective Functions for Arterial Offset Optimization*. Transportation Research Record: Journal of the Transportation Research Board, 2259, 8–22.

Dutta, U., McAvoy, D., Lynch, J., & Vandeputte, L. (2008). *Evaluation of the Scats Control System.* Report No: MIOH UTC TS4. Detroit, Michigan.

Eghtedari, A. G. (2006). *Measuring Benefits of Adaptive Traffic Signal Control: Case Study of Mill Plain Boulevard, Vancouver, Washington*. In Transportation Research Board 85th Annual Meeting.

Federal Highway Administration (FHWA) - USDOT. (n.d.). *Every Day Counts - Adaptive Signal Control Technology*. Retrieved September 5, 2016, from https://www.fhwa.dot.gov/innovation/everydaycounts/pdfs/asct_brochure.pdf

FHWA IF-02-047, U. (2002). *Life-cycle cost analysis primer*. Retrieved from www.fhwa.dot.gov/asset/lcca/010621.pdf

Hansen, B. G., Martin, P. T., & Perrin ., H. J. (2007). *SCOOT Real-Time Adaptive Control in a CORSIM Simulation Environment*. Transportation Research Record: Journal of the Transportation Research Board, 1727, 27–30.

Hatcher, G., Burnier, C., Greer, E., Hardesty, D., Hicks, D., Jacobi, A., … Mercer, M. (2014). *Intelligent Transportation Systems Benefits, Costs, and Lessons Learned: 2014 Update* Report. Washington, DC. Retrieved from http://www.itsknowledgeresources.its.dot.gov/its/bcllupdate/

Howard/Stein-Hudson Associates, I. (2010). *The Benefits of Retiming / Rephasing Traffic Signals in the Back Bay*. Retrieved from https://www.cityofboston.gov/images_documents/The%20Benefits%20of%20Traffic%20Signal%20Retiming%20Report_tcm3-18554.pdf.

Hunter, M., Wu, S. K., Kim, H. K., & Suh, W. (2012). *A Probe-vehicle-based Evaluation Of Adaptive Traffic Signal Control.* IEEE Transactions on Intelligent Transportation Systems, 13(2), 704–713.

Hutton, J., Bokenkroger, C., & Meyer, M. (2010). *Evaluation of an Adaptive Traffic Signal System: Route 291 in Lee's Summit, Missouri*. Jefferson City, Missouri. Retrieved from http://trid.trb.org/view.aspx?id=916407

Jayakrishnan, R., Mattingly, S. P., & McNally, M. G. (2000). *Performance Study of SCOOT Traffic Control System with Non-Ideal Detectorization : Field Operational Test in the City of Anaheim.* Report UCI-ITS-WP-00-27. Irvine, California.

Liu, D., & Cheu, R. L. (2004). *Comparative Evaluation of Dynamic TRANSYT and SCATS-Based Signal Control Logic using Microscopic Traffic Simulations*. In Transportation Research Board. Washington, D.C.

Lodes, M., & Benekohal, R. F. (2013). *Safety Benefits of Implementing Adaptive Signal Control Technology* : Retrieved from https://www.ideals.illinois.edu/handle/2142/45786

Martin, P. T., & Stevanovic, A. (2008). Adaptive Signal Control V - SCATS Evaluation in Park City, Utah. Retrieved from http://www.mountain-plains.org/pubs/pdf/MPC08-200.pdf.

Office of the Assistant Secretary for Research and Technology (OST-R) - US DOT. (n.d.). *Arterial Management - Traffic Signal Control Operation Strategies*. Retrieved May 9, 2016, from http://www.itsdeployment.its.dot.gov/Results.aspx

Park, B. (Brian), & Chang, M. (2002). *Realizing Benefits of Adaptive Signal Control at an Isolated Intersection*. Transportation Research Record, 1811, 115–121.

Park, B. (Brian), & Chen, Y. (2010). *Quantifying the benefits of coordinated actuated traffic signal systems : A case study*. VTRC 11-CR2. Richmond, Virginia.

Park, B. (Brian), Chen, Y., Cho, H., & Yun, I. (2014). *Quantifying the benefits of adaptive split feature on the operation of coordinated actuated traffic signal system*. KSCE Journal of Civil Engineering, 19(1), 311–317.

Peters, J. M., McCoy, J., & Bertini, R. (2007). *Evaluating an Adaptive Signal Control System in Gresham*. In ITE Western District Annual Meeting.

Roads and Maritime Services. (n.d.). *An Introduction to SCATS 6*. South Wales, Australia: Roads and Maritime Services. Retrieved from http://www.scats.com.au/files/an_introduction_to_scats_6.pdf

Salem, O. (Sam), Chen, J. (Xifan), & Salman, B. (2015). *Enhancing TSM&O Strategies through Life Cycle Benefit/Cost Analysis: Life Cycle Benefit/Cost Analysis & Life Cycle Assessment of Adaptive Traffic Control Systems and Ramp Metering Systems*. Syracuse, NY. Retrieved from http://ntl.bts.gov/lib/55000/55200/55222/SU_TranLIVE__FinalReport_Enhancing_TSMO_Strategies.pdf

SRF Consulting Group Inc. (2000). *Adaptive Urban Signal Control and Integration*. October.

Stevanovic, A. (2010). *NCHRP Synthesis 403 Adaptive Traffic Control Systems : Domestic and Foreign State of Practice*. Washington, D.C.

Tian, Z., Ohene, F., & Hu, P. (2011). *Arterial performance evaluation on an adaptive Traffic Signal control system*. Procedia - Social and Behavioral Sciences, 16, 230–239.

US DOT FHWA. (2008). *Traffic Signal Timing Manual*.

Wang, J., Robinson, B., Shelby, S. G., Cox, K. B., & Townsend, W. (2010). *Evaluation of ACS Lite Adaptive Control using Sensys Arterial Travel Time Data*. ITS America 20th Annual Meeting & Exposition, 1–19.

CHAPTER 6

CONCLUSIONS

There are more than 4,200 adaptive traffic signals in the U.S. Performance of some of these signals were evaluated in past studies using different techniques and approaches. This dissertation makes the following contributions by conducting multi-perspective evaluations of ATCS implementations in the state of Alabama. The first contribution compared the performances of three meta-heuristics algorithm for calibrating the microsimulation models. The algorithmic calibration was found to be superior to the manual calibration approach. This finding verifies the notion that heuristics algorithms are useful for calibrating complex microsimulation models.

Calibrated and validated microsimulation models were used to perform a series of different evaluations of the ATCS performance in comparison to non-adaptive or TOD performance. Although microsimulation techniques can be effectively used to gain insights into present and future ATCS operations, use of field data from various data sources such as crowdsourced data and Bluetooth MAC address matching can still be helpful to supplement the insights from the microsimulation evaluations. Microsimulation was also used for simulating the ATCSs' future operations to perform BCA. Specific conclusions from each chapter are catalogued in the following sections:

6.1 Calibration of Microsimulation

The first work studied the relevance and impact of the use of meta-heuristics for calibrating the microsimualtion models. It also compared the performances of three meta-heuristics – GA, SA and TS. The conclusions from this work follow:

(1) Amongst the three heuristics, the number of best solutions, the best solutions and the convergence to the best solutions for TS were better than with GA and SA. Thus, TS performs better than GA and SA for calibrating the microsimulation models.

(2) However, all three meta-heuristics have the ability to perform better calibration than the manual calibration process since all three meta-heuristics were able to find calibration parameters better than the manual process.

(3) In general, the automated approach using meta-heuristics can be relied upon to calibrate the simulation models very effectively.

(4) Use of meta-heuristics for calibrating microsimulation models can save a considerable amount of time. The meta-heuristics took approximately 90 hours for finding the best calibration parameters which was significantly lesser than the time required to calibrate the model manually.

6.2 Comparative assessment of SCATS and TOD operations

While most research studies in the past indicate that ATCS offers positive benefits for traffic operations, there are few ATCS implementation studies that show the opposite. Thus, the performance of three different SCATS implemented arterial systems was analyzed and produced the following conclusions:

(1) The three arterial systems were first assessed in the traditional way by evaluating the corridor travel time and delay performances. These initial evaluations indicated very insignificant or no improvements in the performance when SCATS was introduced. Hence, other performance measures were evaluated.

(2) The network-wide performance of SCATS showed overall improvements in terms of travel time, delays, and speeds on unsaturated networks. Unsaturated conditions are where ATCS tends to work especially well. On the contrary, saturated (and especially over-saturated) conditions constrain vehicle movements due to higher traffic volumes limiting the SCATS performance.

(3) SCATS also showed improvements over TOD in terms of side-street queue lengths as well as shorter cycle-to-cycle queue lengths. This added capacity created by the shorter queue lengths over the network can be leveraged for additional network enhancements.

(4) The major benefits of SCATS can be attributed to the improvements in the side-street performance and the left-turn movements on the corridor mainline. While this is specific to these particular corridors in this study, SCATS balances the performances between the mainline and side street to gain network-wide improvements.

6.3 Analyses Techniques for ATCS evaluations

An ATCS system is expected to deliver traffic operations improvements after its installation. To measure and quantify the improvements, continuous feedback of the system performance is important to engineers and agencies. With constant changes taking place in the traffic and signal systems, continuous monitoring of such systems becomes imperative. The forms and extent of data availability at various stages of ATCS implementation may vary and it is important to understand which of the different analyses and techniques at different stages is recommended.

(1) Comparison of the corridor travel times measured by Bluetooth data and crowdsourced data show that they are very close and displays similar trends.

(2) Use of newer crowdsourced data can be helpful in providing a long-term feedback of the mainline corridor travel times over different stages of ATCS implementation – before, during and after.

(3) A well-calibrated and validated microsimulation model delivers results that are very close to the field data. It also offers an advantage of comparing the same baseline traffic conditions under different signal control systems.

(4) Microsimulation technique can be leveraged to gain detailed insights of other performance measures to supplement the information gained from field data.

(5) Decision makers, engineers, and policy makers involved in ATCS implementations should chart out their own plan of detailed analysis and techniques to use during the various stages of the project lifecycle.

6.4 Life-cycle BCA of SCATS

Although performance evaluations of ATCS systems were widely conducted in the past, it lacks an evaluation methodology to detemine the value of the ATCS implementation from tranportation agency's perspective. BCA offers this information by considering the potential stream of benefits and costs over the lifecycle of ATCS. However, predicting the future ATCS benefits and its effective lifecycle is often a challenge.

(1) Microsimulation techniques can be utilized very effectively to simulate future traffic conditions and to determine the ATCS's effective lifecycle and future benefits more accurately.

(2) SCATS performs better than TOD until the threshold point which is in the vicinity of 0.9 v/c ratio. This is due to the SCATS ability to allow higher flow through the system thus increasing the system throughput and reducing the delays. However, SCATS performance declines beyond the threshold point. The SCATS control logic of targeting 0.9 DS level limits its performance beyond the threshold point, resulting in longer delays

(3) SCATS continues to yield benefits even beyond its effective life. This is because the SCATS effective life is determined on the basis of only peak-hour benefits which ignores the gains from rest of the travel periods. When the 24-hour period benefits are considered, SCATS still displays superior performance beyond its effective life.

(4) The BCR of SCATS for the two corridors is more than one, indicating comparatively more benefits than the costs involved.

Currently, there may be some disconnect between the transportation planning agencies, traffic signal system designers (ATCS implementers), the ATCS vendors, and the ATCS users. It is suggested that agencies should secure early support from the ATCS vendor (Stevanovic, 2010), perhaps even during the planning phase. Like SCATSIM, which is the SCATS logic simulator, simulation interfaces for many other ATCSs are available from the major ATCS vendors. Transportation agencies can use such interfaces along with the evaluation methodologies developed in this dissertation during the ATCS design (pre-installation) phase to estimate the operational benefits of ATCS at different scales. Further, the BCA methodology can be effectively used of discover the potential worth of an ATCS deployment. Additionally these methods can also be used to compare the performances of different ATCSs, which shall help the agencies to make decisions about the suitability of ATCS to their areas of traffic concerns. Overall, the contributions of this dissertation are very significant for the transportation agencies for making effective decisions regarding choice of and investments in ATCS.

CHAPTER 7

FUTURE WORK

This dissertation closely examined the performance evaluations of SCATS operations in various different perspectives – different corridor characteristics, future benefits, and different data sources. While this work covers many areas, the following points should be considered to extend this work in the future:

(1) Similar performance evaluations to be performed on other ATCSs that are implemented in the U.S. and other nations. This would include analysis at least of SCOOT, ACS Lite, RHODES, and other ATCS that can be configured in a microsimulation environment.

(2) The lifecycle BCA to be performed considering the signal retiming effect as shown in Figure 7.1. Preventative signal retiming may prolong the lifetime of traditional non-adaptive traffic signal control. Although, the cost of such retiming and actual benefit may vary.

(3) The methodologies discussed in this dissertation can be extended for comparative assessment of different ATCSs as well. Such analyses if performed during the pre-installation phase can provide valuable information on the relevance and choice of more suitable ATCS for the given corridor which can offer the transportation agencies huge savings.

(4) As can be seen from Figure 5.5.i, for the same demand, the delay benefits with SCATS differ widely on the two different corridors. Future work may also involve further investigation into this phenomena. Identifying the underlying factors which cause SCATS performance to vary from corridor to corridor, can further help the transportation agencies and practitioners to predict the possible benefits that can be gained by implementing an ATCS.

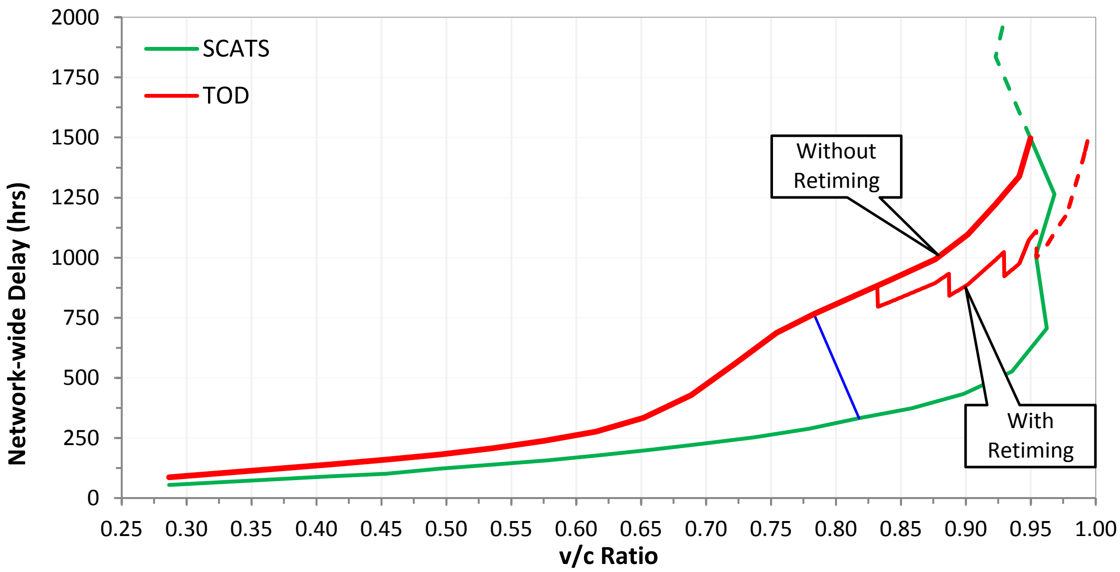


Figure 7.1 Example of SCATS Performance with Signal Retiming Effect

REFERENCES

Chong-White, C., Millar, G., & Aydos, J. C. (2014). Scenarios Demonstrating Congestion Management Policies using SCATS : Stage 2. In *26th ARRB Conference – Research driving efficiency* (pp. 1–17). Sydney, Australia.

Day, C. M., Ernst, J. M., Brennan, T. M., Chou, C.-S., Hainen, A. M., Remias, S. M., … Bullock, D. M. (2012). Adaptive Signal Control Performance Measures : A System-in-the-Loop Simulation Case Study. *Transportation Research Record*, *2311*, 1–15.

Dutta, U., McAvoy, D., Lynch, J., & Vandeputte, L. (2008). *Evaluation of the Scats Control System*. *Report No: MIOH UTC TS4*. Detroit, Michigan.

Eghtedari, A. G. (2006). Measuring Benefits of Adaptive Traffic Signal Control: Case Study of Mill Plain Boulevard, Vancouver, Washington. In *Transportation Research Board 85th Annual Meeting*.

Gord & Associates, I. (2007). *Adaptive versus Traditional Traffic Control Systems - A field-based comparative assessment*. Retrieved from https://www.pinellascounty.org/mpo/ITS/Final-Evaluation-Paper-Field-Studies-040907.pdf.

Hansen, B. G., Martin, P. T., & Perrin ., H. J. (2007). SCOOT Real-Time Adaptive Control in a CORSIM Simulation Environment. *Transportation Research Record: Journal of the Transportation Research Board*, *1727*, 27–30. http://doi.org/10.3141/1727-04

Hatcher, G., Burnier, C., Greer, E., Hardesty, D., Hicks, D., Jacobi, A., … Mercer, M. (2014). *Intelligent Transportation Systems Benefits, Costs, and Lessons Learned: 2014 Update Report*. Washington, DC. Retrieved from http://www.itsknowledgeresources.its.dot.gov/its/bcllupdate/

Hunter, M. P., Wu, S. K., Kim, H. K., & Suh, W. (2012). A probe-vehicle-based evaluation of adaptive traffic signal control. *IEEE Transactions on Intelligent Transportation Systems*, *13*(2), 704–713. http://doi.org/10.1109/TITS.2011.2178404

Hutton, J., Bokenkroger, C., & Meyer, M. (2010). *Evaluation of an Adaptive Traffic Signal System: Route 291 in Lee's Summit, Missouri*. Jefferson City, Missouri. Retrieved from http://trid.trb.org/view.aspx?id=916407

Jayakrishnan, R., Mattingly, S. P., & McNally, M. G. (2000). *Performance Study of SCOOT Traffic Control System with Non-Ideal Detectorization : Field Operational Test in the City of Anaheim*. *Report UCI-ITS-WP-00-27*. Irvine, California.

Kergaye, C., Stevanovic, A., & Martin, P. (2010a). Comparative Evaluation of Adaptive Traffic Control System Assessments Through Field and Microsimulation. *Journal of Intelligent Transportation Systems*, *14*(2), 109–124. http://doi.org/10.1080/15472451003719764

Kergaye, C., Stevanovic, A., & Martin, P. T. (2008). An evaluation of SCOOT and SCATS through microsimulation. In *International Conference on Application of Advanced Technologies in Transportation*. Athens, Greece.

Kergaye, C., Stevanovic, A., & Martin, P. T. (2010b). Comparison of Before-After Versus Off-On Adaptive Traffic Control Evaluations. *Transportation Research Record: Journal of the Transportation Research Board*, *2128*, 192–201. http://doi.org/10.3141/2128-20

Lowrie, P. R. (1982). Sydney Co-ordinated Adaptive Traffic System - Principles, Methodology, Algorithms. *IEEE Conference Publication*, (207), 67–70.

Martin, P. T., & Stevanovic, A. (2008). *Adaptive Signal Control V - SCATS Evaluation in Park City, Utah*. Retrieved from http://www.mountain-plains.org/pubs/pdf/MPC08-200.pdf.

Martin, P. T., Stevanovic, A., & Stevanovic, I. (2005). *Adaptive Signal Control IV - Evaluation of Adaptive Traffic Control System in Park City* (Vol. UT – 05.16).

Nguyen, V. N. (1996). Evaluation of SCATSIM – RTA Adaptive Traffic Network Simulation Model. *Transportation Research Record*, *1566*, 8–19.

Peters, J. M., McCoy, J., & Bertini, R. (2007). Evaluating an Adaptive Signal Control System in Gresham. *ITE Western District Annual Meeting*.

Roads and Maritime Services. (n.d.). An Introduction to Scats 6. South Wales, Australia: Roads and Maritime Services. Retrieved from http://www.scats.com.au/files/an_introduction_to_scats_6.pdf

RTA (Roads and Traffic Authority), & TYCO. (n.d.). SCATS Booklet. Retrieved from www.traffic-tech.com/pdf/scatsbooklet.pdf

Schrank, D., Eisele, B., Lomax, T., & Bak, J. (2015). *2015 Urban Mobility Scorecard*.

Shelby, S., & Bullock, D. (2008). An Overview and Performance Evaluation of ACS Lite–A Low Cost Adaptive Signal Control System. *Transportation …*, 1–17. Retrieved from https://w3.usa.siemens.com/mobility/us/en/urban-mobility/road-solutions/adaptive-software/Documents/ACS_Lite_Overview_TRB_2008_CD.pdf

SRF Consulting Group Inc. (2000). *Adaptive Urban Signal Control and Integration*. *October*.

Stevanovic, A. (2010). *NCHRP Synthesis 403 Adaptive Traffic Control Systems : Domestic and Foreign State of Practice*. Washington, D.C.

Stevanovic, A., Kergaye, C., & Stevanoic, J. (2012). Long-Term Benefits of Adaptive Traffic Control Under Varying Traffic Flows During Weekday Peak Hours. *Transportation Research Board: Journal of the Transportation Research Board*, *2311*, 99–107. http://doi.org/10.3141/2311-09

Taale, H., Fransen, W. C. M., & Dibbits, J. (1998). The second assessment of the SCOOT sytem in Nijmegen. In *IEEE Road Transport Information and Control* (pp. 109–113). London, United Kingdom.

Tian, Z., Ohene, F., & Hu, P. (2011). Arterial performance evaluation on an adaptive Traffic Signal control system. *Procedia - Social and Behavioral Sciences*, *16*, 230–239. http://doi.org/10.1016/j.sbspro.2011.04.445

Wang, J., Robinson, B., Shelby, S. G., Cox, K. B., & Townsend, W. (2010). Evaluation of ACS Lite Adaptive Control using Sensys Arterial Travel Time Data. *ITS America 20th Annual Meeting & Exposition*, 1–19.