

**EVALUATING THE OPERATIONAL & SAFETY ASPECTS OF ADAPTIVE  
TRAFFIC CONTROL SYSTEMS IN PENNSYLVANIA**

by

**Zulqarnain H. Khattak**

BSC Civil Engineering, NWFP University of Engineering & Technology Peshawar, Pakistan

2014

Submitted to the Graduate Faculty of

Swanson School of Engineering in partial fulfillment

of the requirements for the degree of

Master of Science in Civil Engineering

University of Pittsburgh

2016

UNIVERSITY OF PITTSBURGH  
SWANSON SCHOOL OF ENGINEERING

This thesis was presented

by

Zulqarnain H. Khattak

It was defended on

March 25<sup>th</sup>, 2016

and approved by

Eric T. Donnell, Ph.D., P.E, Professor, Departmental of Civil & Environmental Engineering,

The Pennsylvania State University

Mark C. Szewcow, Adjunct Professor, Departmental of Civil & Environmental Engineering,

University of Pittsburgh

Thesis Advisor: Mark J. Magalotti, Ph.D., P.E, Senior Lecturer, Departmental of Civil &

Environmental Engineering, University of Pittsburgh

Copyright © by Zulqarnain H. Khattak

2016

**EVALUATING THE OPERATIONAL & SAFETY ASPECTS OF ADAPTIVE  
TRAFFIC CONTROL SYSTEMS IN PENNSYLVANIA**

Zulqarnain H. Khattak, M.S

University of Pittsburgh, 2016

Adaptive Signal Control Technology (ASCT) is a novel Intelligent Traffic System (ITS) technology developed to optimize cycle lengths, green times or phasing sequences for traffic signals based on the changing traffic volumes collected from advanced detectors. While ASCT are considered to improve mobility and reduce congestion, they also have the potential to reduce crashes and improve traffic safety.

This research explored these potential safety benefits of adaptive signal control systems through a two-step process. During the first stage, a 22 intersection corridor on Center Ave and Baum Boulevard, recently deployed with SURTRAC adaptive signals was selected and travel time runs were conducted with and without SURTRAC in operation using a GPS mobile app known as GPS tracks. The results did provide indications for safety benefits through reduced stops made along the intersections and improvement in travel time.

During the second stage of the research project, 41 urban/suburban intersections from the state of Pennsylvania with SURTRAC and In-Sync ASCT deployments were selected and evaluated for their safety benefits using the Empirical Bayes (EB) before and after predictive method. National Safety Performance Functions (SPF) were selected for total and fatal & injury crash categories to calculate expected average crash frequencies for the selected intersections. The calculated expected average crash frequencies were used along with the observed crash

frequencies from Pennsylvania Department of Transportation (PennDOT) crash reports in the rigorous EB method to calculate crash modification factors for adaptive signal control system. The findings, which evaluated a correlation based upon the development of Crash Modification Factor (CMF) proved the potential of ASCT to reduce crashes and improve traffic safety since the CMF values for total and fatal & injury crashes for both of the systems (SURTRAC & In-Sync) showed a significant correlation. Deploying ASCT was found to reduce total crashes by 34% with a CMF value of 0.66 and fatal & injury crashes by 45% with a CMF value of 0.55. CMF=1 means no change in safety conditions and CMF<1 indicates a reduction in crashes. The CMF correlations were found to be statistically significant at a 95% confidence level. The research findings will enable engineers and professionals to predict the potential reduction in crashes that would be expected after deploying ASCT at any new intersection.

## TABLE OF CONTENTS

<b>PREFACE.....</b>	<b>XIV</b>
<b>1.0 INTRODUCTION.....</b>	<b>1</b>
<b>1.1 BACKGROUND.....</b>	<b>1</b>
<b>1.2 HYPOTHESIS.....</b>	<b>3</b>
<b>1.3 OBJECTIVES.....</b>	<b>4</b>
<b>1.4 METHODOLOGY.....</b>	<b>4</b>
<b>1.5 SUMMARY:.....</b>	<b>6</b>
<b>2.0 LITERATURE REVIEW.....</b>	<b>7</b>
<b>2.1 INTRODUCTION.....</b>	<b>7</b>
<b>2.2 SAFETY AND ADAPTIVE TRAFFIC SIGNALS.....</b>	<b>8</b>
<b>2.3 HIGHWAY SAFETY MANUAL.....</b>	<b>8</b>
<b>2.3.1 Crash Modification Factor.....</b>	<b>9</b>
<b>2.4 ACADEMIC RESEARCH.....</b>	<b>11</b>
<b>2.4.1 Illinois Department of Transportation.....</b>	<b>12</b>
<b>2.4.2 Virginia Department of Transportation.....</b>	<b>12</b>
<b>2.4.3 University of Nevada.....</b>	<b>13</b>

2.4.4	Park City, Utah .....	13
2.4.5	Salt Lake City, Utah .....	14
2.5	NCHRP REPORT .....	14
2.5.1	AVAILABLE ASCT SYSTEMS .....	15
2.5.2	WIDELY DEPLOYED SYSTEMS AND THEIR COSTS & BENEFITS	16
2.6	CASE STUDIES.....	17
2.6.1	In Sync Report .....	17
2.6.2	Greesham, Oregon.....	19
2.6.3	Portland, Oregon .....	19
2.6.4	Route 291, Missouri.....	20
2.7	SUMMARY .....	20
3.0	METHOD FOR TESTING THE HYPOTHESIS.....	22
3.1	PROPOSED METHOD TO EVALUATE SAFETY ASPECTS OF ASCT	22
3.2	CURRENT PRACTICE REGARDING ASCT .....	23
3.2.1	Safety Benefit .....	24
3.3	TRAFFIC CONTROL SYSTEMS.....	25
3.4	FIELD STUDY.....	27
3.5	SELECTION OF TEST LOCATIONS.....	30
3.5.1	Crash Data Collection .....	35
3.6	METHOD/ STEPS FOR DEVELOPING CRASH MODIFICATION FACTOR .....	36
3.6.1	Before Deployment Period Calculations.....	43
3.6.1.1	CMF's for Intersections.....	44

3.6.1.2	Calibration Factor.....	46
3.6.1.3	Weighted Adjustment, w .....	47
3.6.1.4	Expected Average Crash Frequency .....	48
3.6.2	After Deployment Period Calculations for Expected Average Crash Frequency .....	49
3.6.2.1	Predicted Average Crash Frequency .....	49
3.6.2.2	Adjustment Factor, r .....	50
3.6.2.3	Expected Average Crash Frequency .....	50
3.6.3	Index of Effectiveness.....	51
3.6.4	Crash Modification Factor .....	52
3.6.5	Safety Effectiveness (%).....	52
3.6.6	Standard Error, $\sigma$ .....	53
3.6.7	Statistical Significance.....	53
3.7	SUMMARY .....	54
4.0	ANALYSIS OF RESULTS.....	55
4.1	VEHICULAR SPEEDS, STOPS AND TRAVEL TIME (FIELD DATA)...	55
4.1.1	Travel Speed.....	56
4.1.2	Travel Time .....	58
4.1.3	Vehicular Stops .....	59
4.2	CRASH RATES AND CRASH MODIFICATION FACTORS .....	62
4.2.1	Crash Rates .....	62
4.2.2	Crash Modification Factor .....	66
4.2.3	Analysis of Results & Confidence Levels .....	71

4.2.3.1	Confidence Interval.....	72
4.2.4	Practical Application.....	74
4.3	GUIDELINES .....	75
5.0	SUMMARY AND CONCLUSIONS .....	77
5.1	SUMMARY OF RESULTS .....	77
5.1.1	Review of Tests Conducted.....	77
5.1.2	Vehicular Stops and Crash Modification Factor.....	78
5.2	CONCLUSIONS.....	79
5.3	RECOMMENDATIONS FOR FUTURE RESEARCH .....	79
APPENDIX A	.....	81
BIBLIOGRAPHY	.....	84

## LIST OF TABLES

Table 2-1 Summary of Existing Adaptive Signal Control Systems with different detections .....	15
Table 3-1 Available Adaptive System in Pennsylvania.....	26
Table 3-2 East Liberty Intersections with Surtrac Adaptive Signals Pittsburgh, (Allegheny) .....	33
Table 3-3 Montgomery County Intersections with In-Sync Adaptive Signals, Montgomery .....	33
Table 3-4 Upper Merion Intersections with In-Sync Adaptive Signals, Montgomery .....	34
Table 3-5 Safety Performance Functions for Urban/Suburban Intersections (12-10 HSM) .....	42
Table 4-1 Crash Rates for Intersections.....	62
Table 4-2 Crash Rate Comparison for Before & After Period .....	64
Table 4-3 Overall Crash Modification Factor Results for all Intersections.....	68
Table 4-4 Crash Modification Factor Results for Surtrac and In-Sync .....	69
Table 4-5 Crash Modification Factor Results for four & three legged Intersections .....	70
Table 4-6 Z-Values based on Confidence Interval .....	73
Table 5-1 Before Deployment Period Calculations Example.....	81
Table 5-2 Before Deployment Period Calculations Example (Continued) .....	81
Table 5-3 Before Deployment Period Calculations Example (Continued) .....	82
Table 5-4 After Deployment Period Example Calculations .....	82

Table 5-5 After Deployment Period Example Calculations (Continued)..... 83

## LIST OF FIGURES

Figure 3-1 Baum/Centre Surtrac Intersections .....	28
Figure 3-2 Corridor GPS Tracks.....	29
Figure 3-3 Crossings GPS Tracks.....	30
Figure 3-4 Allegheny County East Liberty Intersections, City of Pittsburgh Pennsylvania .....	31
Figure 3-5 Montgomery County Intersections, Montgomery Township Pennsylvania .....	32
Figure 3-6 Montgomery County Upper Merion Intersections, Upper Marion Township Pennsylvania .....	32
Figure 3-7 Flow chart for CMF calculation.....	39
Figure 4-1 Baum Travel Speed comparison with and without ASCT in operation.....	56
Figure 4-2 Center Average Travel Speed with and without ASCT .....	57
Figure 4-3 Baum Travel Time with and without ASCT in Operation .....	58
Figure 4-4 Center Ave Travel Time with and without ASCT in Operation .....	59
Figure 4-5 Baum Number of Stops with and Without Surtrac in Operation .....	60
Figure 4-6 Center Ave Number of Stops with and Without Surtrac in Operation .....	61
Figure 4-7 CMF Calculation.....	67
Figure 4-8 Plot Showing Confidence Level of CMF.....	72
Figure 4-9 CMF with 95% Confidence Interval (Total Crashes) .....	73

Figure 4-10 CMF with 95% Confidence Interval (FI Crashes) ..... 74

## **PREFACE**

This thesis is submitted as a part of Master's degree requirement in Transportation Engineering at University of Pittsburgh. It contains work done from June 2015 till March 2016, which is solely conducted by the author. This thesis is a result of a long process and tireless effort. The long days and nights spent in conducting this research and writing up the thesis cannot be simply expressed by this document.

Several people have contributed in different ways to this thesis. I would first like to thank my advisor Mark J. Magalotti, who trusted me and supported me to pursue my master's degree at University of Pittsburgh during a situation when others used to say that master's students are not productive enough in terms of research. Without his support and guidance, I would never have conducted such an amazing research or even finished my master's education. Furthermore, I would like to thank researchers from Carnegie Mellon University for their help with travel time data collection. I would also like to thank my committee members for their guidance.

At the end, I would like to thank my parents; who beyond all odds trusted me and sent me to the United States for pursuit of my dream.

"Thank you, reader. If you are on this line then you at-least read the first page of my thesis".

## **1.0 INTRODUCTION**

This chapter gives an overview of the research and introduces the basic concepts of the process. It introduces the background, hypothesis, objectives and methodology of this research. The research focused on adaptive traffic signals, which is a novel ITS technology used for traffic signal control. The main focus was to identify the influence of adaptive signals on road safety (i.e. increase or decrease in the number and type of road crashes) through observing the crash data, crash rates and potentially developing guidelines for a Crash Modification Factor (CMF) in order to find the true level of safety associated with adaptive traffic signals.

## **1.1 BACKGROUND**

ITS may be defined as the combination of high technology equipment and improvements in information systems, communication, sensors and advanced mathematical methods with the conventional world of surface transportation. William Phelps Eno can be regarded as the great-grandfather of ITS. His work in traffic control during the early days of highway transportation set the stage for the use of today's modern technologies, which addresses the same issues with which he was concerned; congestion and safety. [1]

Adaptive Signal Control Technology (ASCT) is a novel Intelligent Traffic System (ITS) technology developed to optimize cycle lengths, green times or phasing sequences for traffic signals based on the changing traffic volumes collected from advanced detectors, in order to reduce traffic congestion and improve traffic safety. Before the emergence of ASCT, traffic engineers were limited to only using the Time-of-Day (TOD) timing plans, which is a set of signal-timing plans that runs on a specified schedule for multiple hour time periods during specific days of the week. Because these predetermined TOD timing plans cannot accommodate variable and unpredictable traffic demands within those particular time periods, the control delay of traffic signals may generally increase with the passage of time until those outdated signal timing plans are retimed; while ASCT help traffic signals frequently adjust timing and phasing scenarios in live conditions to accommodate changing traffic patterns and thus improve the traffic signal operations by providing efficient flow of traffic with less stops and delays which in turn improves traffic safety.

The algorithm of the adaptive traffic control systems not only considers the needs of vehicles, but they also consider the needs of humans; who are driving the vehicles through detection of vehicles at intersections in order to prevent drivers from un-necessary stops and delays. Although adaptive signal control technologies (ASCTs) have been implemented in dozens of states, the effect of these novel signals operations on road safety are still unknown. In optimization of signal timing patterns, split or green time is subject to limitations such as minimum green times, pedestrian interval requirements and maximum green times. Additionally, the adaptive traffic control systems can gather the data (pedestrian calls and current queues on the side street) to determine whether to normally initiate or skip a phase for the side street thus potentially reducing the turning crashes and crashes with pedestrians.

## 1.2 HYPOTHESIS

The author hypothesized that along with the operational benefits, adaptive traffic signals may have safety benefits in terms of reducing the travel time and total number of stops, which may lead to fewer road crashes. Adaptive traffic signals may save precious human lives by reducing the impact of delays such as aggressive driving thus leading to decrease in the number of road crashes and making roadways and intersections much safer.

The adaptive traffic control systems theoretically can reduce vehicular travel time, number of stops, delay, vehicular emissions and fuel consumption and thus will not exhaust the drivers, putting less burden and psychological stress and enabling them to drive more efficiently thus reducing the chances of road crashes. The author did not choose any simulation method to determine the safety benefits because it seems very difficult for any computer algorithm to simulate so many parameters on which safety depends, in a single network model.

The impact of adaptive traffic control systems on traffic safety was evaluated in the research through collection of crash data for the before and after deployment conditions of adaptive traffic signals. The data was then analyzed for increases or decreases in crash number, rates and potentially leading to developing a methodology for a Crash Modification Factor (CMF) using the Empirical Bayes Predictive method prescribed in Highway Safety Manual. Crash Modification Factor is a multiplicative factor used to compute expected number of crashes after implementing a given countermeasure (adaptive traffic signals in our case)

### **1.3 OBJECTIVES**

The objectives of this thesis were to identify how the use of adaptive traffic control systems have influenced the road safety (reduction in number of road crashes) and how these systems affect driving behaviors; to determine what level of safety is actually associated with the adaptive traffic control systems through the analysis of crash number, rates and potentially developing guidelines for Crash Modification Factor using the methods prescribed in Highway Safety manual (HSM) [2].The crash modification factor would help to understand the actual level of safety associated with adaptive traffic signals in a better way.

### **1.4 METHODOLOGY**

As the main the theme of this research was to measure the impact of ASCT on traffic safety thus it involved various steps explained as follows:

The research study consisted of two parts. During the first part of the research, a field study was performed by driving vehicles through one of the corridors in Pittsburgh, Pennsylvania with and without the deployment of ASCT to collect the data for vehicular speeds, stops and other vehicular performance changes; which were later analyzed for any performance and safety benefits regarding ASCT.

During the second part of the research, data for road crashes was collected for both before and after deployment conditions of adaptive traffic signals systems for specific corridors in

Pennsylvania. Since it was hypothesized that adaptive traffic signals can help as a countermeasure in reducing the road crashes (mainly rear end crashes), the intersections locations were analyzed for reduced crash types, numbers and crash rates that may have resulted by the deployment of adaptive traffic signals. A methodology was developed using one set of data and then tested on the other set of data to determine what number, type and rates of crash reductions resulted.

All of this data analysis was then used for developing a study methodology to evaluate the proposed hypothesis and using the methodology to develop a crash modification factor for the adaptive signal control technologies using the method prescribed in Highway Safety Manual. Crash modification factors represent the relative change in crash frequency due to a change in one specific roadway condition (traffic signals in our case) while all other conditions and site characteristics remain constant [2]. The Empirical Bayes before/after safety evaluation method was used for developing the crash modification factor methodology because it clearly addresses the regression to the mean problem by incorporating crash information from other similar sites into the evaluation through the use of SPF (Safety Performance Functions).

Once the crash modification factors were developed, they were then analyzed for statistical significance and compared to the base conditions given in the Highway Safety Manual (i.e. CMF=1 meaning no change in safety conditions; which is crash reduction in our case provided by the countermeasure of adaptive traffic signals at the intersections). The difference between the crash rates for the before and after deployment conditions of adaptive signal control technologies and the crash modification factors developed provided a true measure for the safety aspect of adaptive traffic signals i.e. “How much safety improvement does adaptive traffic signals provide?”

## **1.5 SUMMARY:**

The author introduced the readers to the whole project by first giving a brief description of ASCT technology and then throws light on the hypothesis i.e. to find the safety benefits of ASCT systems. The author hypothesized that adaptive traffic signals may have safety benefits in terms of reducing the number of crashes (mainly rear end crashes) by reducing the total number of stops at each intersection and thus providing efficient flow of vehicles. In order to scrutinize the hypothesis, the author proposed to evaluate the before and after deployment crash data for adaptive traffic signals to evaluate the crash types, number and rates and ultimately developing a potential methodology for Crash Modification Factors(CMF) of adaptive traffic signals; in order to find out how much safety improvement is associated with adaptive traffic signals. The Crash Modification factor would reveal the improvement provided by the adaptive signals in terms of reducing crashes while all other conditions remain constant.

## **2.0 LITERATURE REVIEW**

This chapter focused on describing the previous research work that has been performed on ASCT and road safety which is relevant to the research and thesis and also provides a discussion on various methods used by researchers for measuring the performance of traffic operations and safety under ASCT deployments based upon the research achievements.

### **2.1 INTRODUCTION**

The adaptive traffic control system is a rising novel ITS technology throughout the world and it has been implemented in the US and overseas for the past few decades. The Federal Highway Administration (FHWA) is giving its full support to the research related to various aspects of adaptive signal control technologies (ASCTs) and there are a lot of funding opportunities available for research and implementation of ASCT systems. There are many invaluable research studies performed by research centers, state departments of transportations (DOTs), and municipal traffic agencies; describing the potential benefits of adaptive traffic signal control technologies ranging from operational benefits to the safety benefits. This section explores the various studies on particular adaptive traffic signal systems performed by above mentioned

departments and agencies in order to develop a method to evaluate the potential benefits brought by the adaptive traffic signal systems.

## **2.2 SAFETY AND ADAPTIVE TRAFFIC SIGNALS**

Traffic safety is one of the major concerns for transportation engineers throughout the world as it involves the effort for saving precious human lives which would otherwise be lost and it also involves the effort for minimizing the economic loss in terms of damages caused by traffic accidents. According to AASHTO; on average, there are five crashes at intersections every minute and one person dies at every hour of every day at an intersection somewhere in the United States [3]; making safety and more importantly safety at intersections, one of the major concerns. It is hypothesized that Adaptive traffic signals can help as a countermeasure for this concern in reducing these road crashes (mainly rear end crashes) by decreasing the time spent waiting in long queues, thus providing efficient flow of vehicles and improving the road conditions (increasing headway between vehicles and improving level of service (LOS)).

## **2.3 HIGHWAY SAFETY MANUAL**

The Highway Safety manual (HSM) is a resource published by American Association for State Highway and Transportation Officials (AASHTO) in order to incorporate safety in road and highway design. Before the HSM, there was no standard guide among transportation officials or

planners to follow and a common practice was to look at the crash frequencies and rates at a site and deem it as a high crash site requiring improvement based on high numbers or rates of crashes. Thus, in 1999 during the annual meeting of Transportation Research Board (TRB) a need was felt for a standard guide to be used for highway safety leading to the publication of Highway Safety Manual in 2006 and its acceptance later on in 2009.

The HSM provides knowledge and tools to facilitate the decision making process regarding safety. The main feature of HSM is to consider the characteristics of each segment of a roadway regarding safety and then provide detailed countermeasures available for that particular segment to achieve improved safety levels. HSM is now used by a broad array of transportation officials across the globe and is considered a standard document concerning highway safety. Although, each state in the US is allowed to have its own safety standards but in the absence of safety standards for a particular state, (HSM) should be considered the standard document.

### **2.3.1 Crash Modification Factor**

As defined by the Highway Safety Manual, a CMF is “an index of how much crash experience is expected to change following a modification in design or traffic control” at a particular location [2]. Each CMF is a numerical value that provides the ratio of the expected number of crashes over some unit of time after a change is made to the expected number of crashes for the same time period had the change not been made. Equation 1 shows how the ratio is applied to develop a CMF for a particular countermeasure [4].

CMF= Expected number of crashes if a change is made/ Expected number of crashes if a change is not made

$$(1 - \text{CMF}) * 100\%. \quad (1)$$

The true value of the CMF for any countermeasure will always be unknown until after the countermeasure is implemented. The reported value is only an estimate of the potential true value obtained from a statistical analysis of reported crash data for countermeasures that have been implemented. This reported value (referred to as a point estimate) provides an estimate of the effectiveness of the potential change of countermeasure on crash frequency. CMF values less than 1.0 indicates that the change should reduce crash frequency, while CMF values greater than 1.0 indicates that the change should increase crash frequency. CMF values equal to 1.0 indicates that the change is expected to have no impact on crash frequency.

Since the true CMF value is unknown, there is always some error associated with the point estimate of the CMF. The size of this error provides an indication of the precision of the point estimate. Small errors indicate that the point estimate is precise and the CMF is known with a high degree of certainty, while larger errors suggest that the true CMF may differ significantly from the point estimate. The magnitude of this error depends on several factors, such as the:

- Type of study performed.
- Analysis method used to obtain the estimate.
- Amount of data used to estimate the CMF.
- Variation in the actual crash data used to estimate the CMF.

Various methods exist to estimate CMFs. Rigorous statistical methods to account for variation in the crash data produce less error in the CMF estimates. Studies with more crash data (either from more sites or over a longer period of time) and more geographic variation in the data also provide estimates with smaller errors than those that use little data or data constrained to a

smaller geographic area. Most research studies that estimate a CMF also include an estimate of the amount of error associated with the point estimate. The magnitude of this error is reported as the standard deviation of the error in the point estimate, and this value is referred to as the standard error of the CMF. Careful consideration of the standard error is critical to understanding the range of possible impacts that a highway modification or countermeasure may have on expected crash frequency. One way to quantify this range is by calculating the confidence interval for the true value of the CMF.

Since each state has different conditions such as weather, driver population, local roadway, roadside conditions, traffic composition, typical geometrics and traffic control measures; the CMF developed and provided in the HSM, based on conditions of a particular state, may not be used directly for crash prediction of other states. Hence, the highway safety manual highly encourages each state to develop their own crash modification factor based on their conditions and crash data. The highway safety manual also provides information about the state from which the data was used to develop CMF, so in the absence of CMF for a particular state, the national CMF listed in highway safety manual can be used for any state according to calibration techniques listed in HSM; to make conditions between the two states comparable.

## **2.4 ACADEMIC RESEARCH**

In recent years adaptive signal control technology has seen a lot of development and a significant amount of academic research have been conducted on ASCT's. The most recent research, which is relevant to this thesis has been reviewed and summarized below.

#### **2.4.1 Illinois Department of Transportation**

In 2013, Illinois Center for Transportation conducted a study to determine the safety benefit and costs associated with adaptive traffic signals. They distributed an online survey to 62 agencies that had implemented ASCT in the United States and received response from 22 agencies about the system type, detection type and cost of ASCT implementation. The average cost per intersection to the agencies that responded was \$38,223, when cost data from all agencies were included, but it was \$28,725 when cost data from agencies with the lowest and highest figures were excluded. Detailed volume, geometry was provided for six specific intersections and crash data was provided for three of the six intersections. Each of these three intersection exhibited crash reduction but the sample size was too small for statistical testing. The scope of the study was very limited; thus only limited conclusions could be drawn. Although the data was limited but it was concluded that there are safety benefits associated with implementing ASCT.[5]

#### **2.4.2 Virginia Department of Transportation**

In 2015, the safety effectiveness of Adaptive traffic signals was evaluated by Virginia department of transportation. A total of 47 urban and sub-urban intersections where ASCT was deployed in Virginia were analyzed. ASTC was found to produce crash modification factor of 0.83 with a standard error of 0.05. All crash types were found to be reduced, but safety benefits varied from corridor to corridor and at different volume levels. It was concluded that ASCT can potentially reduce both total and fatal injury crashes and public agencies should consider both safety and mobility aspects when justifying ATSC projects. The research only utilized crashes at

the intersections and neglecting crashes occurring at side streets or mid-blocks which can also affect the safety associated with adaptive signals. The research used only one year of after deployment crash data while the safety analysis requirement is to have at least three years of crash data from HSM. [6]

### **2.4.3 University of Nevada**

In 2011, University of Nevada conducted a study on Sydney Coordinated Adaptive Traffic System (SCATS). The two major parameters that were focused included travel time and number of stops. Travel time and number of stops were the two major performance measures evaluated in the study. The evaluation was performed on before and after deployment data of SCATS and by comparing the data with TOD coordinated plan operations, no significant improvements were found. The study did not focus on safety benefits. [7]

### **2.4.4 Park City, Utah**

In 2010, Park city, Utah installed adaptive traffic signal (SCATS) to improve efficiency of the network. Before installation of SCATS, field evaluation was conducted for the previous time of day signal timings. The before-on and off-on studies were performed which showed that 62.5% of the performance indicators were the same. The improvements were more distinct for off-on study. On the basis of the results, it was concluded that off-on is an alternative method to evaluate benefits of those adaptive traffic signals with many network changes. The study only focused on finding the operational benefits rather than safety benefits.[8]

### **2.4.5 Salt Lake City, Utah**

In 2004, a study was conducted to evaluate performance of SCOOT during incidents. The incidents were defined by variables: midblock locations, one-lane closure, and incident durations of 15, 30 and 45 minutes, and v/c (Volume/Capacity) ratios of six different networks: 0.80, 0.85, 0.90, 0.95, 1.00 and 1.05. The FHWA micro simulator CORSIM was used to test a theoretical network and two real-world networks: Salt Lake City Downtown Network and Fort Union Area Network. The results of the simulation indicated that SCOOT could provide additional benefits during incidents and the marginal benefits were quantified. [9]

## **2.5 NCHRP REPORT**

The Federal Highway Administration has always been active in transportation field for any newly arriving technology and studied the adaptive signal control technologies through a program known as The National Cooperative Highway Research Program (NCHRP). In 2010, the research program published a cooperative research report: NCHRP SYNTHESIS 403, which covers the most recent information and details on ASCT usage [10]. The main focus of the study was to interview agencies that supervised the installation and operation of adaptive traffic control systems, conduct a literature review from previous studies, do surveys of ASCT vendors and users in order to provide details on practices for ASCT operations. The following sections provide a summary of information presented in the report.

### 2.5.1 AVAILABLE ASCT SYSTEMS

There was a list of different types of ASCT system available and along with their vendors at the time of the report in 2010. Each type of ASCT system has some variation compared to the other according to the report. The widely available ones reported included SCATS, SCOOT, OPAC, RHODES, BALANCE, INSYNC, ACS LITE, ATCS, TUC and UTOPIA. Each of these signal systems has its own working mechanism and detection technology for the incoming vehicles. For example near stop line detectors are efficient in calculating queue lengths and are used by BALANCE. Upstream (mid-block) and upstream (far side) detectors are used by SCATS, UTOPIA, ACS LITE and RHODES. Due to these variations, each of the system has a varying performance and the NCHRP report gives a detailed description of all of these systems along with the detection technology. Table 2-1 gives a list of these ASCT systems along with their detection mechanism from the report.

**Table 2-1 Summary of Existing Adaptive Signal Control Systems with different detections**

<i>System</i>	<i>Detection Mechanism</i>
SCOOT	Exit loops
SCATS	Stop bar loops
OPAC	Exit loops
RHODES	Fully actuated design
BALANCE	Loops near Stop bar
INSYNCE	Loops near Stop bar
ACS Lite	Stop bar loops upstream

**Table 2-2 (Continued)**

ATCS	Fully actuated design
TUC	System loops
UTOPIA	Fully actuated design

## **2.5.2 WIDELY DEPLOYED SYSTEMS AND THEIR COSTS & BENEFITS**

According to the results of the survey conducted by the NHRCP research team, most of the adaptive signals are operated by local agencies and California and Florida are the states with most of the ASCT deployments. Most of the systems had been installed on roadways with speed limits of 35-40 mph. SCOOTs and SCATS were the most widely deployed technologies because of the available support for these technologies. The installation of ASCT is influenced by many factors such as impact of ongoing projects in a high growth area, existing infrastructure (detection, hardware and communication) and availability of funding. The usual length of ASCT project implementation is about 18 months.

The implementation and operating cost of ASCT is also given in the NCHRP report. According to the report, on average the cost of installation for an ASCT system is \$65,000 per intersection and after installation there are various type of costs associated with the maintenance of hardware and software and efficient operation of ASCT. But in comparison with the re-timing costs of the conventional traffic signal systems, these are much less.

The report also provides discussion regarding the benefits associated with adaptive traffic signals. According to the report, ASTCs are known to have several advantages over traditional traffic signal timing operations with TOD plans. The primary area of benefits that can be achieved by an ASCTC deployment is operational efficiency, measured through the reduction of delays, stops, and other negative measures of traffic performance. ATCS deployment also improves the safety of traffic operations through reduction of some efficiency related performance measures, which highly correlate with some safety metrics (e.g., a reduction in the number of stops reduces the chance of rear-end collisions).

## **2.6 CASE STUDIES**

Different cities and Department of Transportation (DOT's) have deployed and analyzed ASCT's in order to address the variable and every day increasing traffic demand. Some of the studies are summarized below. These studies were selected because they provide discussion on the most recent research done regarding benefits of ASCT.

### **2.6.1 In Sync Report**

Rhythm Engineering published a report regarding the safety and operational benefits of adaptive traffic signals. The report evaluated the In-Sync signal deployments in Columbia County;

Georgia, Topeka; Kansas, Lee's Summit; Missouri and Springdale; Arkansas. The report was compiled by an independent consultant for their system.

The crash data for before and after deployment of In Sync systems for each of these four locations Columbia County; Georgia, Topeka; Kansas, Lee's Summit; Missouri and Springdale; Arkansas was collected and analyzed. During a period of one year from 2009 to 2010 for Washington road in Georgia, significant reductions in stops, travel time and delay was observed. A reduction of 26% for total crashes and 31% reduction at intersections were observed. Similarly during a time period of four years from 2009 to 2012 (two years before and two years after) for the 21<sup>st</sup> Street in Topeka Kansas, the before and after data showed reduction in total number of crashes and especially reduced rear-end collisions compared to the previously operating coordinated time of day plans. A reduction of about 30 collisions per year was observed, leading to 24% fewer crashes. Similarly, during a period of three years from 2009 to 2011(two years before and one year after) for the 12 signals along 2.5 miles of Chipman road in Lee's Summit in Missouri, the before and after data evaluation lead to the conclusion that InSync resulted in 95% reduction in stops and 87% reduction in delay leading to a total crash reduction of 17% over the previous time of day coordinated signals. The Highway 71, Arkansas results for one year before and after data evaluation from 2009 to 2010 also showed a crash reduction of about 30% (with 61 accidents in the before period and 44 accidents in the after period).

Although the Rhythm Engineering report predicted some safety benefits to be associated with In-sync adaptive traffic signals, the report was based on only comparisons of the total number of accidents for the before and after deployment of the In-sync signals at intersections without including crash data for mid blocks, which could also influence the operational and safety aspects of adaptive traffic signals.[11]

### **2.6.2 Greesham, Oregon**

A study regarding the benefits of Adaptive traffic signals was conducted by DKS Associates after city of Greesham, Oregon implemented SCATS system to reduce the congestion and improve traffic conditions. The study was based on survey regarding traffic signals along Burnside Road corridor while they were operating in two different control modes.

According to the report, SCATS improved the operational efficiency of arterials by reducing the travel time and number of stops compared to the traditional time of day coordination plans. As the city of Greesham preferred the progression of major roads compared to the side streets thus the report suggested focusing on the balance between travel times for major roads and minor streets. The report also provided the cost-benefit analysis of the system and reported a cost-benefit ratio of 1.4 by averaging benefits between peak and off peak hours but the benefit was only associated with delay and fuel consumption. There was no reporting on crash benefits. [12]

### **2.6.3 Portland, Oregon**

Kittelson and Associates was responsible for planning and evaluation of SCATS adaptive signals along 3.7 miles of Powell Boulevard in Portland, Oregon. The traditional time of day plans were compared to the SCATS operations and the major performance measures included level of service (LOS) and delay under both operations.

The study only compared the before and after implementation travel times of the two systems and the results indicated that the overall positive effect of SCATS adaptive signals was minor and it did not improve the vehicle travel time by significant amount. The early morning traffic volumes were assumed to be too low to trigger cycle length changes and the evening peaks pushed the cycle times to their preset maximum values and ASCT was unable to respond to those traffic demands. No safety benefits were reported. [13]

#### **2.6.4 Route 291, Missouri**

Midwest Research Institute (MRI) was asked to evaluate the performance of In-Sync systems using before and after study when Missouri Department of Transportation installed them along the Route 291 corridor. GPS and PC software was installed in vehicles and four vehicle runs were conducted along the route. Data collected included time of travel, number of stops, vehicle emissions and fuel consumption, which was estimated from average speed and travel time but no detailed benefit-cost analysis, was provided. The report also provided some future recommendations but no safety benefits were reported. [14]

## **2.7 SUMMARY**

Thorough literature review revealed that Adaptive traffic control systems is a novel and promising ITS technology that can improve the current road infrastructure and it has a lot of operational and safety benefits associated with it. Although, recent studies have been conducted

for evaluating the benefits of ASCT but there is still no single method for predicting the safety benefits of ASCT. An appropriate method for evaluating the benefits of ASCT will further promote the research and use of ASCT. By quantifying safety benefits the many benefit/cost studies conducted could quantify the monetary value of the safety benefits. It is recommended to develop a methodology for finding the Crash Modification Factor (CMF) for Adaptive signal control system technology based on the method proposed in highway safety manual. As each adaptive signal control system uses a different algorithm and may provide varying level of safety benefits, a standard method needs to be proposed that could be used to find the safety benefits associated with any type of Adaptive signal system. Each state has its own Safety performance Functions thus, a methodology needs to be developed using the national safety performance functions that can be used in any state later-on.

### **3.0 METHOD FOR TESTING THE HYPOTHESIS**

This chapter provides an overview of the method proposed by the researcher to evaluate the safety aspects of ASCT along with the description of the field evaluation for the twenty three intersections based recently deployed SURTRAC adaptive signal system in Baum and Center corridors in Pittsburgh, Pennsylvania. The chapter then concludes with detailed explanation of the methodology used for developing the crash modification factor.

#### **3.1 PROPOSED METHOD TO EVALUATE SAFETY ASPECTS OF ASCT**

The author proposed two steps for the method to evaluate the hypothesis that adaptive traffic signals systems have safety benefits associated with them. In the first step, the author proposed to conduct a field study through driving vehicles with and without the deployment of adaptive traffic signals. For the second step, the author proposed to collect crash data for before and after deployment conditions for adaptive traffic signals in Pennsylvania and then first evaluate the collected data through traditional methods for safety through crash number, rate and frequency reduction and ultimately develop a potential methodology for crash modification factor for ASCT through method prescribed in highway safety manual. The author choose to develop a methodology for finding a crash modification factor for ASCT instead of actuated signals. Currently the HSM has no CMF for the coordination or actuation of traffic signals.

While this approach, which theoretically seems like going one step ahead of the current HSM signal CMFs (i.e. skipping actuated signals and coordinated systems and evaluating the installation of adaptive signals), but in reality the fact is that many of the new deployments are ASCT's and are replacing traditional coordinated signals systems that use time of day plans. Transportation planners and traffic engineers need a CMF to quantify the benefit of this new technology. Currently these benefits are only being evaluated relative to reductions in delays but not safety. This research would provide a tool for quantifying the benefits of systems in terms of safety.

### **3.2 CURRENT PRACTICE REGARDING ASCT**

There is no widely accepted practice regarding ASCT for finding its operational and safety benefits. Each state has their own perspective about evaluating the benefits of ASCT. The Pennsylvania Department of Transportation (PennDOT) uses form TE153; known as the Adaptive Signal Control System Evaluation form that provides a method for evaluation of the systems engineering process for adaptive signal systems when selecting locations for installation and developing an operations plan. It follows the guidelines provided by federal Highway Administration Model Systems Engineering Documents for adaptive signal control technology and PennDOT's directions for adaptive signal systems in publication 46 [15]. The form consists of various sections about information regarding the current site, previous deployment, concerns on current site operations, acceptable vendors etc. After evaluating all this information, a recommendation is made regarding the deployment of ASCT at the site. Although this document

evaluates various information before making a recommendation, it still fails to quantify any safety benefits of ASCT. The crash modification factor developed in this project can later on be used to check the safety benefits of deploying ASCT at a new site by comparing the information about crashes occurring at the site (collected through TE 153) with a CMF value, for justifying whether the deployment would be beneficial in terms of safety.

Most of the current research is based on only simple before and after deployment studies of Adaptive signal systems, to evaluate their operational and safety benefits through comparisons. The author after thorough literature review proposed using the Highway Safety manual method for developing a potential Crash Modification Factor for ASCT, which would provide a rigorous tool for finding the potential safety benefits brought by the ASCT system. Safety benefits would also be determined through more traditional methods of comparing crash rates for intersections and mid-block locations.

### **3.2.1 Safety Benefit**

A study regarding safety in transportation engineering almost always focuses on the frequency and type of crashes along the road. The statement that adaptive traffic signals has safety benefits may be supported by this research. Many studies have proven that adaptive signals reduce the total number of stops at an intersection. The reduced number of stops will lead to fewer number of road crashes, mainly rear end crashes, which makes up a high percentage of the total crashes [10]. The drivers would not be required to push the brake pedal at each intersection as frequently and make unnecessary stops for few minutes, reducing their frustration, ultimately reducing crashes. The red light running accidents will also decrease [10].

Theoretically the ASCT systems have safety benefits associated with them in reducing the number of stops and offering progressive traffic flow, which can reduce the number of accidents. Practically the safety benefits of ASCT depends on a number of factors such as intersection design, crash data, crash severity, sight distance and a number of other parameters thus it is very difficult to evaluate crash reduction by any currently available simulation software as it seems quite complex for any computer algorithm to simulate so many parameters in a single network model.

The Highway Safety manual; which is a standard for safety concerns in transportation engineering currently doesn't have any discussion about adaptive signal systems and the reason may be that it's a novel ITS technology still under research. The HSM has a detailed explanation for many countermeasures to reduce crashes and one of those countermeasures is adding a simple signal control system to an intersection which is expected to reduce all crashes except rear end crashes, which is a reasonable conclusion but at this point there is nothing about coordinated signals or ASCT in HSM [2].

### **3.3 TRAFFIC CONTROL SYSTEMS**

There is a wide variety of adaptive traffic control systems available, manufactured by various vendors. For the purpose of this research, all presently deployed ASCT systems in Pennsylvania were analyzed in terms of crash data availability and the ones with most available crash data were selected for further evaluation with a minimum criteria of two years of after deployment crash data being available. Table 3-1 provides a list of available ASCT systems, operating in

Pennsylvania, and after analyzing them, In-Sync and Surtrac were selected for the study, which had up to three to five years of after deployment data available.

**Table 3-1 Available Adaptive System in Pennsylvania**

<b>System</b>	<b>No of Intersections (Working)</b>	<b>Years of Crash Data Available (After Deployment)</b>
<b>In-Sync</b>	<b>135</b>	<b>3 years</b>
<b>Centrac Adaptive (Econolite)</b>	<b>10</b>	<b>2 years</b>
<b>Surtrac</b>	<b>31</b>	<b>5 years</b>
<b>ACS Lite</b>	<b>28</b>	<b>2 years</b>

In-Sync is an adaptive signal control technology manufactured by Rhythm Engineering. In-Sync adaptive traffic control constantly gathers traffic condition data, then analyzes, optimizes and adapts the signal timings in real-time, every second to serve the changing traffic demand.

Scalable Urban Traffic Control (SURTRAC) is an innovative adaptive signal control technology manufactured by the Robotics Institute of Carnegie Mellon University. The system uses a decentralized approach; where each intersection behaves independently and allocate its green time based on real time traffic at the intersection. The projected outflow is then communicated to the neighboring intersections to anticipate the incoming vehicles and this intelligent coordination helps to maximize the green corridor. SURTRAC is expected to work best for urban settings but is scalable to road networks of any size, since there is no centralized computational bottleneck.

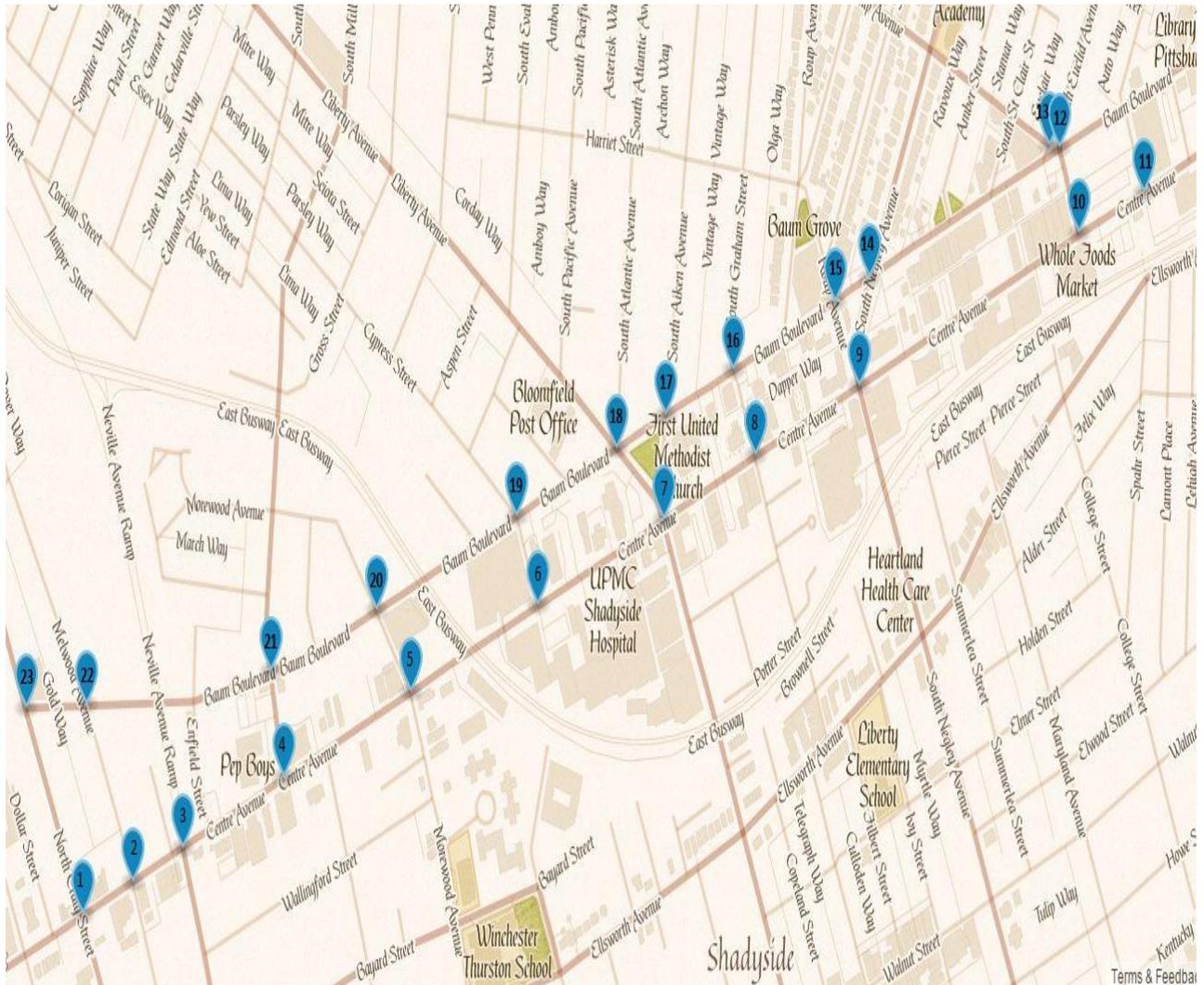
### 3.4 FIELD STUDY

A field study was conducted for the 23 intersections at Baum/Centre corridor in Pittsburgh, Pennsylvania to first evaluate the main theme of author's hypothesis that adaptive traffic signals reduce the number of stops and travel time which may lead to fewer road crashes. The traffic signals at these 23 intersections have recently been converted to expand the current SURTRAC (Scalable Urban Traffic Control) adaptive traffic signals due to the recent surge in traffic experienced by these routes, leading to excessive delays and queues at these 23 intersections.

Hence, a field study was conducted with and without the intelligent SURTRAC adaptive traffic signals in operation to test the performance efficiency of the newly deployed adaptive traffic signals and determine if any significant improvements were provided by the deployment of the SURTRAC adaptive traffic signals. This is another method of evaluating both the operational and safety performance of adaptive traffic control systems in the field by measuring the improvements provided by adaptive traffic control and comparing the performance measures such as travel time, speed and stops for before (with a regular time of day coordination plan) and after (with adaptive traffic control in operation) deployment conditions.

The 23 intersections in the corridor at Baum/Centre are shown in figure 1. A series of travel time runs were performed with and without the operation of SURTRAC for comparing the performance of SURTRAC and the previous time of day coordinated signals. Travel time runs without the operation of SURTRAC were conducted during the start of September 2015 and those with the operation of SURTRAC were conducted during the end of September and start of

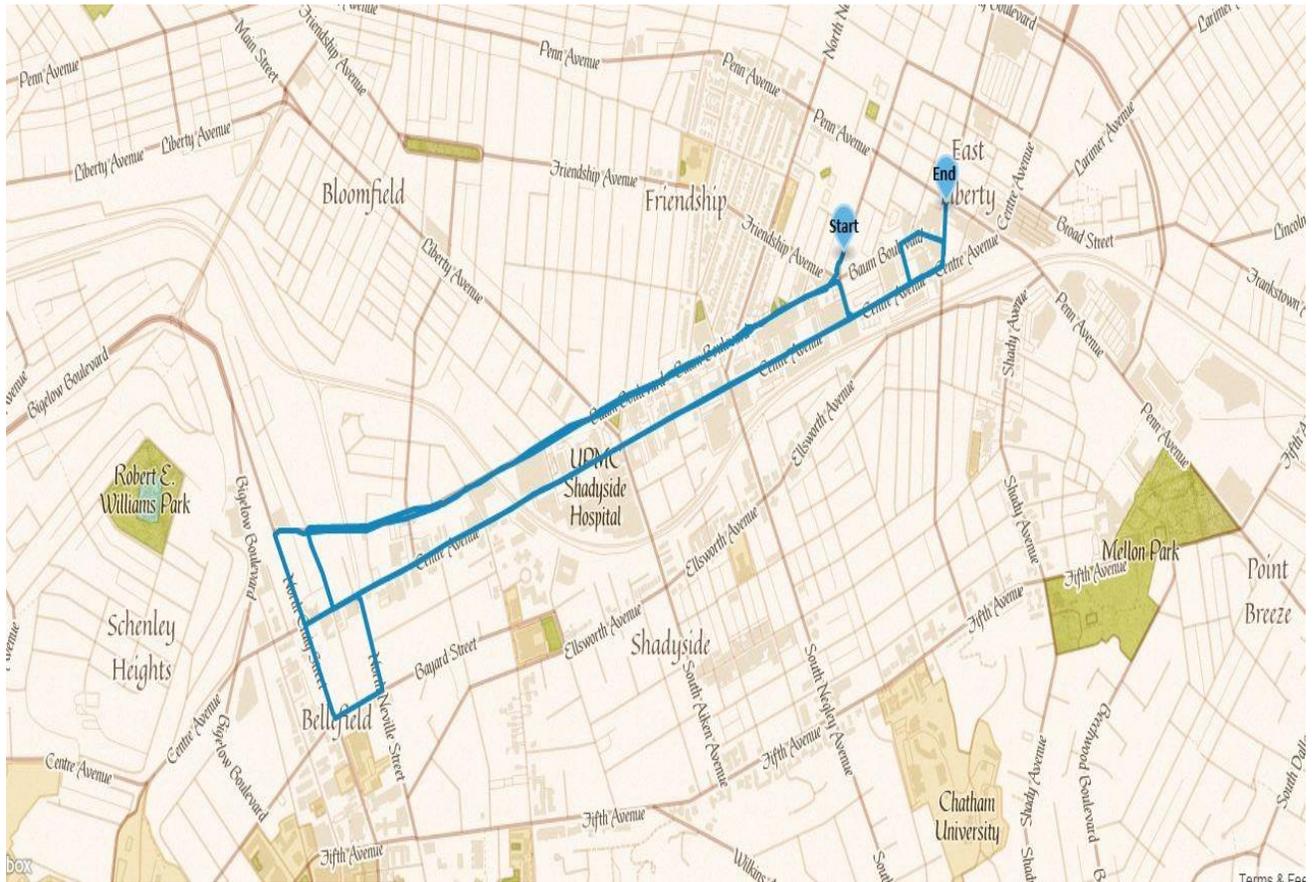
October 2015. The Apple mobile app known as GPS tracks was used for collection of travel data for each run.



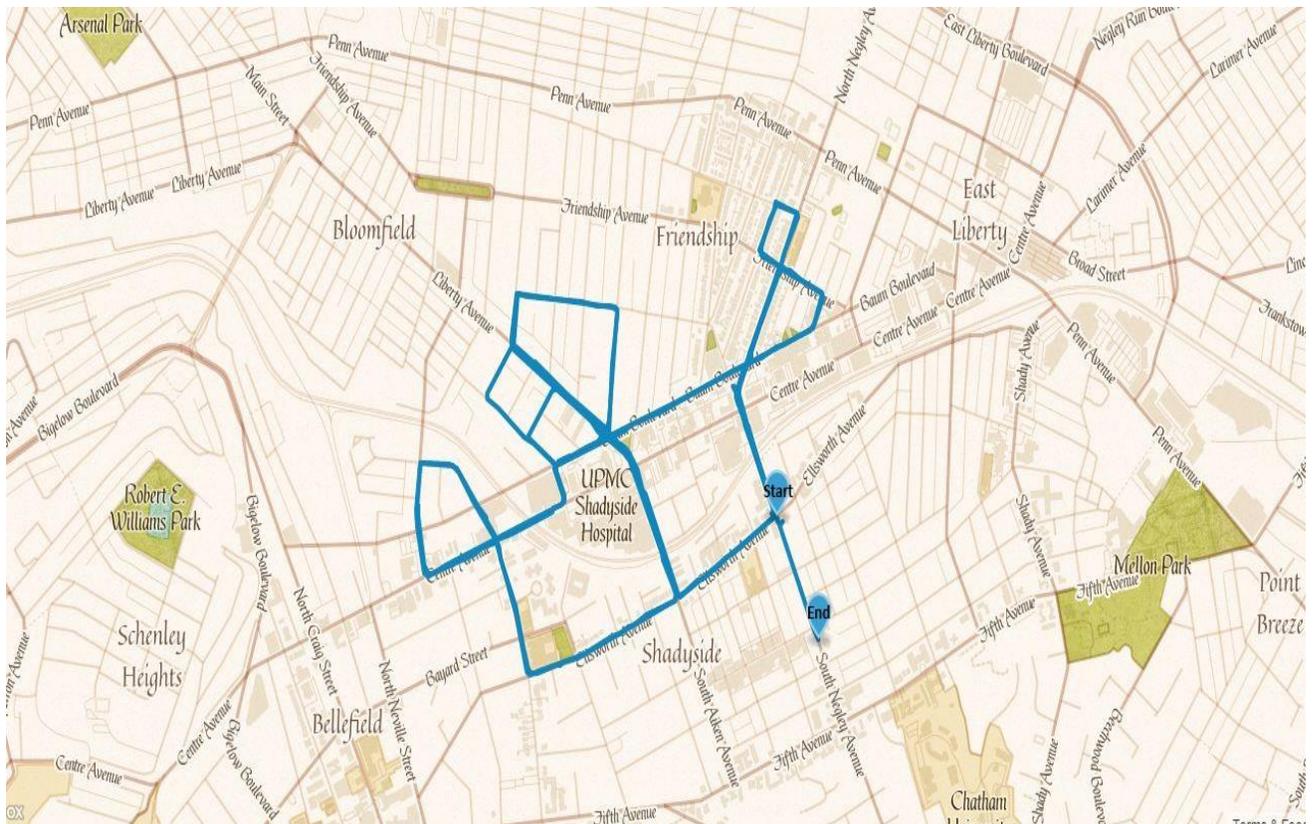
**Figure 3-1 Baum/Centre Surtrac Intersections**

Two different control criteria were measured which included traveling the corridors in a linear route and crossing the corridors covering all of the intersections and driving movements influencing the SURTRAC performance. Travel runs were conducted on a weekday during AM

peak (8-9 PM), Mid-day (12-1 PM) and PM peak (4-5 PM) conditions. The mobile app recorded GPS traces of the travel runs shown in figure 3-2 and 3-3. The data collected for all the travel runs was then processed using GPS babel and Viking software to report the desired performance measures such as travel times, speed, number of stops etc. The results of this field study are discussed later in this research for comparison to predicted safety benefits of ACST systems.



**Figure 3-2 Corridor GPS Tracks**



**Figure 3-3 Crossings GPS Tracks**

### **3.5 SELECTION OF TEST LOCATIONS**

After reviewing the list of all of the intersections currently installed with ASCT deployments throughout the state of Pennsylvania, which was provided by PennDOT. Those systems and intersections that had available crash data for a significant period of time after installation of the ASCT were selected for study. These intersections, in three different regions of Pennsylvania, were selected as test locations. The selected locations included the East Liberty section of Pittsburgh with a 9 intersection system, the Montgomery Township system with 20 intersections and the Upper Merion Township system with 12 intersections. The locations of all the selected

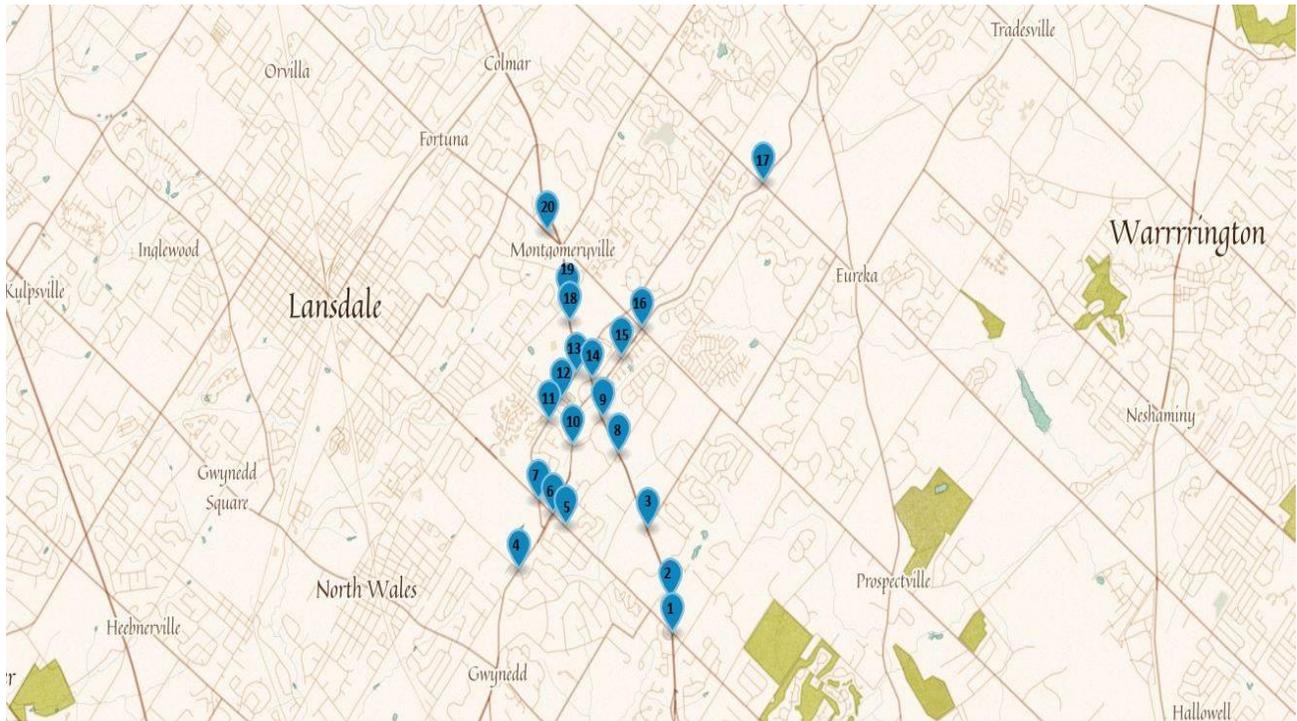
intersections are shown in figures 3-4 to 3-7 while table 3-2 to 3-4 provides details of the selected intersections along with installation dates and type of the adaptive signals systems installed.

**\*Markers are intersections with Adaptive traffic signals in operation**



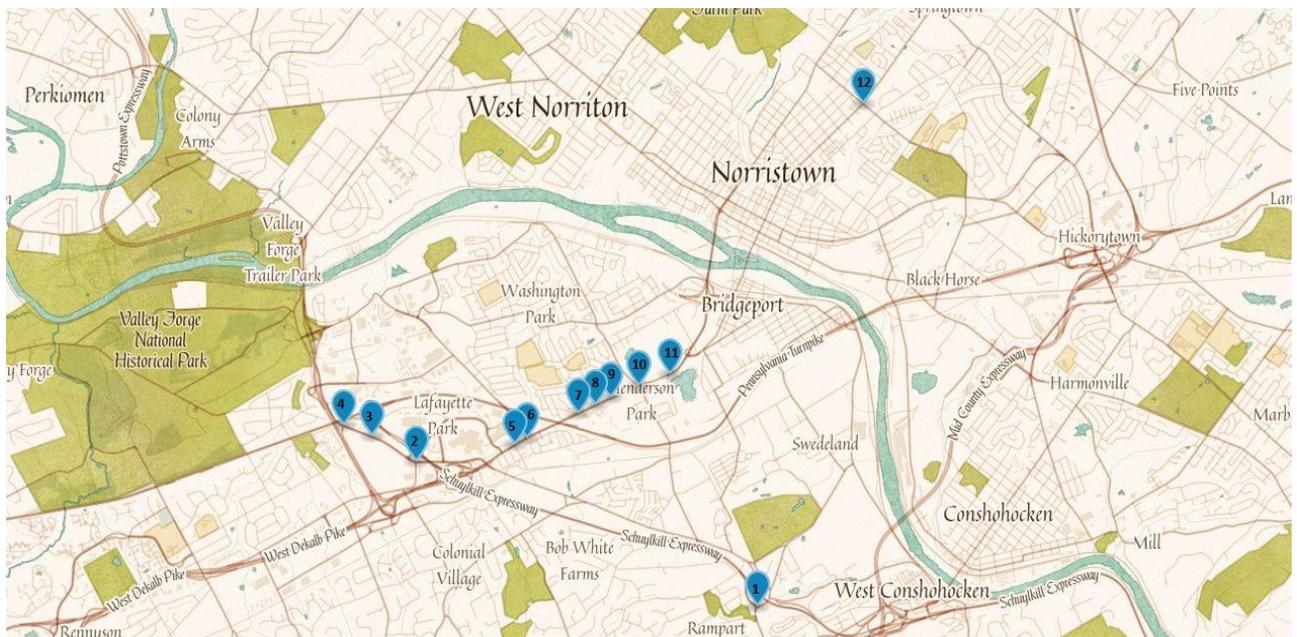
**Figure 3-4 Allegheny County East Liberty Intersections, City of Pittsburgh Pennsylvania**

**\*Markers are intersections with Adaptive traffic signals in operation**



**Figure 3-5 Montgomery County Intersections, Montgomery Township Pennsylvania**

**\*Markers are intersections with Adaptive traffic signals in operation**



**Figure 3-6 Montgomery County Upper Merion Intersections, Upper Marion Township Pennsylvania**

**Table 3-2 East Liberty Intersections with Surtrac Adaptive Signals Pittsburgh, (Allegheny)**

<b>Intersection</b>	<b>County</b>	<b>Date Installed</b>	<b>Municipality</b>
<b>Penn Circle and Highland Ave.</b>	Allegheny	4/21/2010	City of Pittsburgh
<b>Penn Circle and Citizens Bank Drive</b>	Allegheny	4/21/2010	City of Pittsburgh
<b>Penn Circle and Penn Ave.</b>	Allegheny	4/21/2010	City of Pittsburgh
<b>Penn Circle and Kirkwood St.</b>	Allegheny	4/21/2010	City of Pittsburgh
<b>Penn Circle and Broad St.</b>	Allegheny	4/21/2010	City of Pittsburgh
<b>Penn Circle and Station St.</b>	Allegheny	4/21/2010	City of Pittsburgh
<b>Penn Ave. and Highland Ave.</b>	Allegheny	4/21/2010	City of Pittsburgh
<b>Broad St. and Larimer Ave.</b>	Allegheny	4/21/2010	City of Pittsburgh
<b>Penn Ave. and East Busway</b>	Allegheny	4/21/2010	City of Pittsburgh

**Table 3-3 Montgomery County Intersections with In-Sync Adaptive Signals, Montgomery**

<b>Intersection</b>	<b>County</b>	<b>Date Installed</b>	<b>Municipality</b>
<b>Welsh rd (63) and Stump rd</b>	Montgomery	10/9/2012	Montgomery
<b>SR 202 and Welsh rd (63)</b>	Montgomery	10/9/2012	Montgomery
<b>SR 202 Parkway and Welsh Rd (63)</b>	Montgomery	12/3/2013	Montgomery
<b>SR 202 Parkway and Kanpp Rd</b>	Montgomery	12/3/2013	Montgomery
<b>Bethlehem Pike &amp; Knapp Road</b>	Montgomery	8/14/2012	Montgomery
<b>SR 202 and Cheswick dr/Mall Dr</b>	Montgomery	10/9/2012	Montgomery
<b>Sr 202 and Montgomery mall Dr</b>	Montgomery	10/9/2012	Montgomery
<b>SR 309 (Bethlehem Pike) &amp; Welsh Road</b>	Montgomery	8/14/2012	Montgomery

<b>Table 3-3 (Continued)</b>			
<b>Bethlehem Pike &amp; Hartman Road</b>	Montgomery	8/14/2012	Montgomery
<b>Bethlehem Pike &amp; English Village</b>	Montgomery	8/14/2012	Montgomery
<b>Bethlehem Pike &amp; Stump Road</b>	Montgomery	8/14/2012	Montgomery
<b>Bethlehem Pike &amp; North Wales Road</b>	Montgomery	8/14/2012	Montgomery
<b>SR 202 Parkway and Connector A (309)</b>	Montgomery	8/14/2012	Montgomery
<b>Bethlehem Pike &amp; Mall Drive North</b>	Montgomery	8/14/2012	Montgomery
<b>SR 202 and Sr 309 (five points)</b>	Montgomery	8/14/2012	Montgomery
<b>SR 202 Parkway and Horsham Rd</b>	Montgomery	12/3/2013	Montgomery
<b>SR 202 Parkway and Costco Dr</b>	Montgomery	12/3/2013	Montgomery
<b>SR 202 Parkway and County Line Rd</b>	Montgomery	12/3/2013	Montgomery
<b>SR 202 and Gwynmont Dr</b>	Montgomery	10/09/2012	Montgomery
<b>SR 202 and Hancock rd</b>	Montgomery	10/09/2012	Montgomery

**Table 3-4 Upper Merion Intersections with In-Sync Adaptive Signals, Montgomery**

<b>Intersection</b>	<b>County</b>	<b>Date Installed</b>	<b>Municipality</b>
<b>N Gulph rd and Guthrie Rd</b>	Montgomery	10/15/2012	Upper Merion
<b>N Gulph rd and Goddard Blvd</b>	Montgomery	10/15/2012	Upper Merion
<b>N Gulph rd and N. Warner Rd</b>	Montgomery	10/15/2012	Upper Merion
<b>SR 202 and Long Rd</b>	Montgomery	12/21/2011	Upper Merion
<b>SR 202 and Allendale Rd</b>	Montgomery	12/21/2011	Upper Merion

<b>Table 3-4 (Continued)</b>			
<b>SR 202 and Brandywine Ln</b>	Montgomery	12/21/2011	Upper Merion
<b>SR 202 and King Circle</b>	Montgomery	12/21/2011	Upper Merion
<b>SR 202 and Town Center</b>	Montgomery	12/21/2011	Upper Merion
<b>SR 202 and Henderson Rd</b>	Montgomery	12/21/2011	Upper Merion
<b>SR 202 and Saulin Blvd</b>	Montgomery	12/21/2011	Upper Merion
<b>SR 202 and dekalb Pike</b>	Montgomery	12/21/2011	Upper Merion
<b>N Gulph rd and I 76 Ramp/Village Dr</b>	Montgomery	12/21/2011	Upper Merion

### **3.5.1 Crash Data Collection**

In total, there are 427 intersections planned with adaptive traffic signal deployment in Pennsylvania, out of which 124 intersections are in operational condition that were selected for the research. All the intersections, were analyzed in terms of availability of the crash data and the ones that had large amount of data available in terms of number of years after installation, were selected. The crash data was then collected from the Pennsylvania Department of Transportation for the forty two intersections in total, which included nine intersections in East Liberty Section of Pittsburgh City with two years of before and five years of after crash data, twenty intersections in Montgomery County of Pennsylvania consisting of four years of before and three years of after crash data, twelve intersections in Upper Merion region with four years of before and three years of after deployment crash data. All of these intersections were considered to have sufficient before and after deployment data to evaluate the crash benefits. The crash data was then thoroughly analyzed for different type of crashes for each of the selected intersections and was separated for each intersection for calculation purposes in order to test the hypothesis.

### **3.6 METHOD/ STEPS FOR DEVELOPING CRASH MODIFICATION FACTOR**

This section provides a detailed methodology for developing crash modification factor for ASCT using the Empirical Bayes method and comparison with the traditional crash rate ranking methodology. Safety performance functions (SPF's) forms the basis of the Empirical Bayes method, which are regression equations calculated formed from sites with similar characteristics and used to determine long term expected crash frequency based on vehicular volumes at specific intersections. Although crash modification factors are supposed to be developed using local safety performance functions, as encouraged by HSM, but in the absence of local safety performance functions, HSM does recommend the use of national SPF's hence this section provides a methodology for the calculation of a CMF for ASCT technology using Pennsylvania crash data and national SPF's which should be localized when regional SPF's are available. This methodology provides an initial step towards the development of a CMF for ASCT installations.

Before the HSM methodology, there was no crash evaluation standard that considered characteristics of intersections and traffic control types among transportation officials or planners to follow. The common practice was to determine the crash frequencies and rates at a particular site and deem it as a high or low crash site, when compared to similar locations based on roadway classifications, requiring safety improvements based on the number or rates of crashes. The HSM provides three different methods for safety evaluation including crash estimation through observed data, indirect safety measures for identifying high crash locations and

statistical analysis techniques (involving the use of regression equations for crash estimation to improve reliability of estimation models).

The Empirical Bayes predictive method prescribed in highway safety manual as a part of statistical analysis techniques was used for developing a methodology to estimate the crash modification factor for ASCT in Pennsylvania. The Empirical Bayes method was selected because it is considered be much more reliable and rigorous; which takes observed crash frequency into account and combines it with long term expected crash frequencies calculated through the use of statistical models (safety performance functions) thus eliminating the regression to the mean bias and misleading estimate problems associated with the traditional crash rates and frequency safety evaluation methods. The traditional crash rate method is also presented for comparison with the more rigorous Empirical Bayes method.

The crash rate performance normalizes the number of crashes relative to traffic volumes by dividing total number of observed crashes by the Average Annual Daily Traffic (AADT) traffic entering the intersection, measured as million vehicles entering (MEV).

$$\text{Crash rate} = \frac{\text{Observed crash frequency } (N_{\text{observed}})}{\text{Million entering vehicles (MEV)}}$$

The million entering vehicles are calculated using the total traffic volume for both major and minor streets and normalized based on years of crash data and number of days in the whole year.

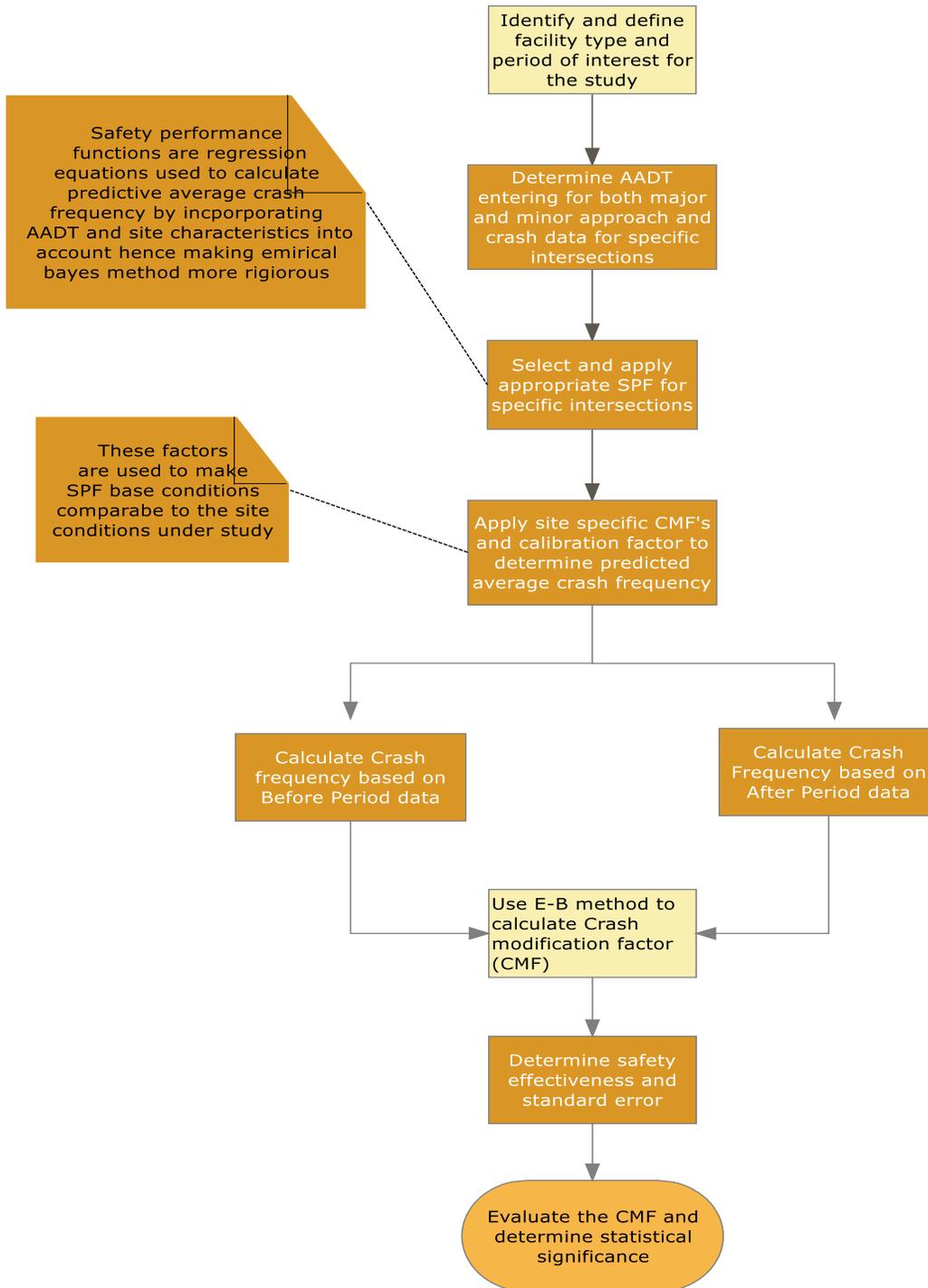
This is the method used to determine MEV, given by:

*Million entering vehicles (MEV)*

$$= \frac{\text{Total entering vehicles (TEV)}}{1,000,000} * (\text{number of years}) * 365$$

Based on the above crash rate calculation, the intersections are typically ranked in descending order, with the site having the highest crash rate ranked first for consideration of safety improvements. The ranking is then utilized for future improvement work to be assigned to particular sites based on consideration that the site is experiencing a high crash rate and requires improvement. A more detailed crash evaluation is then performed to develop mitigation measures.

Alternatively, the Empirical Bayes methodology was used in the research, which is illustrated in the Figure 3-8 flow chart, followed by a detailed explanation of how it has been utilized.



**Figure 3-7 Flow chart for CMF calculation**

The first step involved the selection of study locations and identification of facility types because study locations were needed that had an operating and crash history of ASCT for

determining a CMF. Then the next important step was to define the period of interest considering the availability of data for before and after deployment of the ASCT system. Once the systems with sufficient operating history in the after conditions were identified; for those that had a minimum of 2 years of crash data, it was determined that they would provide an appropriate data set for development of the CMF for Pennsylvania.

The next step was to obtain average annual daily traffic (AADT) data for the selected locations (intersections). The AADT values are required for both before and after deployment years for both major and minor streets. Because the researcher could only obtain traffic data for a specific year growth factors based on roadway classifications from PennDOT were used to convert traffic data from one specific year to the next desired year in order to have AADT volumes for both before and after deployment periods. This information was needed to calculate crash frequencies through the safety performance functions.

The next step was selection of appropriate Safety performance function (SPF) for each of the available types of intersections. SPF's are used to add statistical reliability to the crash data because simple crash data collected is not reliable in itself due to different factors. These SPF's calculate the long term expected cash frequency from regression models created using similar sites with predefined base conditions. Conditions that may vary at an intersection that could impact crash data are characteristics such as type of traffic control, left turn lanes and traffic signal phasing. These SPFs are then used to adjust the data for those sites with similar characteristics to our sites. The expected crash frequencies are then combined with the observed crash frequencies from crash data and finally used in calculating the CMF through the EB method.

The Highway safety manual encourages the use of local safety performance functions developed by each state but in the absence of SPF's for a particular state, a list of safety performance functions is provided in the Highway safety manual based on national data. As the SPF's for Pennsylvania are still in development the national SPF's from the highway safety manual were selected and adjustment factors and calibration factors were applied for the selected sites in Pennsylvania in order to adjust the base conditions used for developing the national SPF's of HSM comparable to our selected intersections in Pennsylvania.

The intersections were classified as Urban/Suburban intersections according to the HSM method (a community with population greater than 5,000 according to FHWA) [2] and appropriate safety performance functions were selected for them, as provided in table 3-6. The Highway safety manual provides the values of coefficients for  $AADT_{maj}$  and  $AADT_{min}$  along with the over-dispersion parameter (k) to apply SPF for different types of crashes at these urban/suburban locations. The over-dispersion parameter indicates the statistical reliability of a particular SPF (the closer the value to zero, the more reliable is the estimate. The general equation for an SPF in urban/suburban region provided in highway safety manual volume 2 chapter 12 is given in equation 1. The purpose of calculating N is to correct the crash frequency calculated in the base conditions for the type of intersection control and crash types using the regression equations.

$$N_{spf} = \exp(a + b * \ln(AADT_{maj}) + c * \ln(AADT_{min})) \quad (1), 12-21 HSM$$

Where,

$N_{spf}$  = Predicted Average crash frequency determined with applicable SPF

$a, b, c$  = Coefficients of SPF regression equations

$AADT_{maj}$  = Average Annual Daily traffic on major street approach

$AADT_{min}$  = Average Annual Daily traffic on minor street approach

Table 3-6 was used to select the SPF functions needed to apply to an intersection where ASCT has been installed. All of the study intersections were 3 or 4 legged signalized intersections.

**Table 3-5 Safety Performance Functions for Urban/Suburban Intersections (12-10 HSM)**

Type	Crash	Safety Performance Functions	Over-dispersion parameter (k)
4-Legged Signalized	Total	$\exp(-10.99 + 1.07 * \ln(AADT_{maj}) + 0.23 * \ln(AADT_{min}))$	0.39
4-Legged Signalized	FI	$\exp(-13.14 + 1.18 * \ln(AADT_{maj}) + 0.22 * \ln(AADT_{min}))$	0.33
3-Legged Signalized	Total	$\exp(-12.13 + 1.11 * \ln(AADT_{maj}) + 0.26 * \ln(AADT_{min}))$	0.33
3-Legged Signalized	FI	$\exp(-11.58 + 1.02 * \ln(AADT_{maj}) + 0.17 * \ln(AADT_{min}))$	0.30

FI= Fatal +Injury Crashes

K= Over-dispersion parameter indicating variability from the mean

### ***Example***

Let's assume we have a 4 legged signalized intersection with  $AADT_{maj} = 10000$  and  $AADT_{min} = 5000$  and observed annual total crashes as 12, then the average crash frequency is calculated by taking first equation from table 3-6,

$$N_{spf} = \exp(-10.99 + 1.07 * \ln(10000) + 0.23 * \ln(5000))$$

$$= N_{spf} = 2.28$$

### 3.6.1 Before Deployment Period Calculations

After calculating the appropriate SPF for each intersection, the second step was to calculate the predicted average crash frequency for each intersection. The HSM provide two options for calculating crash frequency, either to calculate for each year and then sum them or to assume that there is not much difference in the traffic volumes in the before condition for each year and calculate the expected average crash frequency and then multiply it by the total number of years for crash data in the before period to get total expected crash frequency in the before period.

The total predicted crash frequency was determined using the SPF through the second approach as a predictor for the after period as shown in equation (2). The CMFs that were applied are discussed in the following section.

$$N_{predicted(b)} = N_{spf} * (CMF_{1x} * CMF_{2x} * CMF_{3x} * \dots * CMF_{yx}) * C_x \quad (2), 10-1 HSM$$

$$N_{predicted(b)} =$$

*Predicted Average crash frequency for specific year for site x in the before condition*

$$CMF_{yx}$$

*= Crash modification factors specific to site type x, geometric design and traffic control feature y*

$$C_x$$

*= Adjustment*

*/calibration factor to make the conditions used for calculating SPF and site conditions comparable*

### 3.6.1.1 CMF's for Intersections

The SPF's developed by HSM have specific base conditions representing the general geometric design and traffic control features for the intersections used in those calculations. Those base conditions may or may not be comparable to the intersections that we are studying hence, CMF's exist for specific geometric design and traffic control features to make site conditions at our specific intersections comparable to those used as base conditions for SPF's. Following are the features that were used and the corresponding CMFs selected for application in formula (2).

#### *Intersections with Left Turn Lanes*

The base condition used for SPF's was absence of left turn lanes on intersection approaches with CMF value of 1. Most of intersections in our study had left turn lanes hence, specific a CMF value was used to make the conditions comparable. Table 3.6.1 provide details on using CMF values for presence of left turn lanes, based on work of Harwood et al [2].

**Table 3.6.1 CMF for Installation of Left Turn Lanes of Intersections (12-24)**

Intersection type	Traffic Control	Number of Approaches with Left turn lanes			
		One	Two	Three	Four
3 leg	Minor road stop control	0.67	0.45	—	—
	Traffic signal	0.93	0.86	0.80	—
4 leg	Minor road stop control	0.73	0.53	—	—
	Traffic signal	0.90	0.81	0.73	0.63

Looking at table 3.6.1, first the intersection type was selected based whether it was 3 legged or 4 legged and after that the number of approaches having left turn lanes were selected giving us a particular CMF value to apply.

### ***Right turn on Red***

The base condition for CMF is permitting right turn on red at all approaches to a signalized intersection. The CMF for prohibiting right turn on red has been derived from the work of Clark and given by equation 12-35 of HSM.

$$CMF_{4i} = 0.98^{(n_{prohib})} \quad (12-35)$$

*CMF<sub>4i</sub>* = crash modification factor for the effect of prohibiting right turns on red on total crashes

*n<sub>prohib</sub>* = number of signalized intersection approaches for which right turn on red is prohibited

Using equation 12-35, the number of lanes on which right turn on red was prohibited were selected for *n<sub>prohib</sub>* by visually looking at the intersections on google maps and judging the patterns for right turns.

### ***Example***

Let's assume for the same 4 legged intersection, we have left turn lanes existing on two approaches giving us a CMF value of 0.81 to apply and a right turn on red prohibited on all 4 approaches, giving us a right turn adjustment value of  $0.98^{(4)} = 0.92$  and let's assume adjustment factor calculated using equation A-1 comes out to be 0.7 so the predicted average crash frequency can be calculated using equation (2) as follows:

$$N_{predicted(b)} = 2.28 * (0.81 * 0.92) * 0.7$$

$$N_{predicted(b)} = 1.19$$

### 3.6.1.2 Calibration Factor

Although, the SPF's as a part of the HSM research were developed from the most consistent and complete datasets the crash frequencies may still vary to large extent due to a variety of reasons including different crash reporting mechanisms and procedures and variation in conditions between the areas under study for those used for developing SPF's. Hence, in order to obtain the most reliable results, the SPF's in HSM part C needed to be calibrated for each specific location. The calibration procedure is provided in HSM part C appendix A, which was used in the research.

$$Cx = \frac{\sum \text{Observed Crash Frequency}}{\sum \text{Predicted Average Crash Frequency}} \quad (\text{A-1 HSM})$$

For calculating  $Cx$ , first the predicted average crash frequency for each of the intersection was calculated without this factor, summed up over the entire intersections and then the summation of observed crashes was divided by the calculated summation of predicted crashes. After calculating  $Cx$ , it was used in equation (2) to calibrate all values for  $N_{predicted}$ .

### 3.6.1.3 Weighted Adjustment, w

Next step involved the calculation of the weighted adjustment (w) for each intersection in the before period using equation (3).

$$W_{i,B} = \frac{1}{1+k\sum N_{predicted}} \quad (3), 9A.1-2 HSM$$

Where,

*k = Overdispersion parameter provided with SPF functions*

*N<sub>predicted</sub> = predicted average crash frequency in the before period*

The weighted adjustment is utilized later on in calculating expected average crash frequency in the before period. The predicted average crash frequency in the previous step was calculated using the safety performance function (SPF's) and since these SPF's are statistical equations which always have some margin of error associated with them. The over-dispersion parameter (k) v are utilized in the weighted adjustments to make the estimates more reliable.

#### ***Example***

Using the same 4 legged intersection, k value is 0.39 from table 3-6, the weighted adjustment from equation 3 is calculated as follows using the previously calculated N<sub>predicted</sub>:

$$W_{i,B} = \frac{1}{1 + 0.39 * 0.16}$$

$$W_{i,B} = 0.94$$

### 3.6.1.4 Expected Average Crash Frequency

The next step involved the calculation of expected average crash frequency for each intersection in the before period using equation (4) for each year which were summed over entire intersections to find the total expected average crash frequency for all years in the before period.

$$N_{expected,B} = w_{i,B} * N_{predicted} + (1 - w_{i,B}) * N_{observed,B} \quad (4), 9A.1-1 HSM$$

Where,

$N_{expected}$  = *Expected average crash frequency at site i over entire before period*

$w_{i,B}$  = *weighted adjustment*

$N_{observed,B}$

= *Observed crash frequency for a particular site in the entire before period*

#### ***Example***

Using the same 4 legged intersection, with 12 observed crashes, the expected average crash frequency can be calculated using equation (4) as follow:

$$N_{expected,B} = 0.94 * 1.19 + (1 - 0.94) * 12$$

$$N_{expected,B} = 1.84$$

Similar calculations were done for each of the study intersection for both before and after deployment period data using each of the step specified and at the end CMF was calculated using equation 10.

### 3.6.2 After Deployment Period Calculations for Expected Average Crash Frequency

This section provides details of the calculations required for the after deployment period of the adaptive signal control system.

#### 3.6.2.1 Predicted Average Crash Frequency

During this step, the predicted average crash frequency was calculated for each year in the after deployment period using equation (5). The calculated average crash frequency for each year in the after period was summed up to achieve the total expected average crash frequency in the after period, which is the same methodology as the before period

$$N_{predicted,A} = N_{spf} * (CMF_{1x} * CMF_{2x} * CMF_{3x} * ... .. CMF_{yx}) * C_x \quad (5)$$

$N_{predicted(A)}$

= Predicted Average crash frequency for specific year for site x in the after period

$CMF_{yx}$  = Crash modification factors specific to site type x, geometric design and traffic control y

$C_x$

= Adjustment factor to make the conditions used for calculating SPF and site conditions comparable

### 3.6.2.2 Adjustment Factor, r

The next step involved the calculation of adjustment factor in the after period to account for the differences between the before and after periods of crash data in the duration, number of years, and traffic volumes at each site using equation (6).

$$r_i = \frac{\sum N_{predicted,A}}{\sum N_{predicted,B}} \quad (6), 9A.1-3HSM$$

### 3.6.2.3 Expected Average Crash Frequency

This step involved the calculation of expected average crash frequency in the after period in the absence of treatment. The expected crash frequency was calculated through the product of the adjustment factor and expected average crash frequency in the before period using equation (7).

$$N_{expected,A} = N_{expected,B} * r_i \quad (7), 9A.1-4HSM$$

Where,

$N_{expected,A}$  = *Expected average crash frequency in the after period*

$r_i$  = *Adjustment factor*

### 3.6.3 Index of Effectiveness

The overall effectiveness of the treatment was then calculated in the form of index of effectiveness using equation (8), which is the ratio of observed crash frequencies in the after period to the expected crash frequencies in the after period for all the sites.

$$OR' = \frac{\sum_{All\ sites} N_{observed,A}}{\sum_{All\ sites} N_{expected,A}} \quad (8), 9A1-7HSM$$

While the index of effectiveness calculated in equation (8) is considered to be biased hence an adjustment is needed to obtain an unbiased estimate of treatment effectiveness in terms of an adjusted index of effectiveness, OR, provided in equation (9)

$$OR = \frac{OR'}{1 + \frac{Var(\sum_{All\ sites} N_{expected,A})}{(\sum_{All\ sites} N_{expected,A})^2}} \quad (9), 9A.1-8 HSM$$

Where,

$$Var\left[\sum_{All\ sites} N_{expected,A}\right] = \sum_{All\ sites} [(r_i)^2 * N_{expected,B} * (1 - w_{i,B})]$$

### 3.6.4 Crash Modification Factor

The odds ratio calculated above is the crash modification factor for ASCT traffic control systems which was the main goal of the research. The formula for Crash modification factor can be used in the form provided in equation (10) below.

$$CMF = \frac{\sum_{All\ sites} N_{observed,A} / \sum_{All\ sites} N_{expected,A}}{1 + \sum_{All\ sites} [(r_i^2) * N_{expected,B} * (1 - w_{i,B})]} / (\sum_{All\ sites} N_{expected,A})^2 \quad (10), 9A.1-8 HSM$$

Where,

$N_{observed,A}$  = Observed crash frequency in the after period from crash data

$N_{expected,A}$  = Expected average crash frequency in the after period

$N_{expected,B}$  = Expected average crash frequency in the before deployment period

$r_i$  = Adjustment factor

### 3.6.5 Safety Effectiveness (%)

The safety effectiveness of the treatment as a percentage was calculated using equation (11), which is a function of the CMF developed in the previous step.

$$Safety\ Effectiveness = (1 - CMF) * 100 \quad (11), 9 A.1-10 HSM$$

Where,

CMF= Crash Modification Factor

### 3.6.6 Standard Error, $\sigma$

During this step, the standard error or effectiveness of the odds ratio was calculated using equation (12), which was later-on utilized for judging the statistical significance of the estimated safety effectiveness.

$$\sigma = \frac{(OR)^2 \left[ \frac{1}{N_{observed,A}} + \frac{Var(\sum All sites N_{expected,A})}{(\sum All sites N_{expected,A})^2} \right]}{1 + \frac{Var(\sum All sites N_{expected,A})}{(\sum All sites N_{expected,A})^2}} \quad (12), 9A.1-11HSM$$

### 3.6.7 Statistical Significance

The last step involved judging statistical significance of the calculated safety parameters. It involved making comparison between the ratio of safety effectiveness and standard error based on the established criteria for different confidence levels in the Highway Safety Manual:

- If  $Abs[\text{Safety Effectiveness}/\sigma] < 1.7$  then conclude that the treatment is not significant at the 90 percent confidence level.

- If  $\text{Abs}[\text{Safety Effectiveness}/\sigma] \geq 1.7$  then conclude that the treatment is significant at the 90 percent confidence level.
- If  $\text{Abs}[\text{Safety Effectiveness}/\sigma] \geq 2.0$  then conclude that the treatment is significant at the 95 percent confidence level.

### 3.7 SUMMARY

The author initially provides an overview of the methodology to be used for the Pennsylvania data to find the safety effectiveness or a CMF for adaptive traffic signals using the HSM method. The readers are introduced to the test locations selected for the project. Since the research had two parts; for the first part, the Baum/Centre section in Pittsburgh, Pennsylvania was selected, where a field evaluation was conducted on Surtrac adaptive traffic signals. For the second part of the research regarding the development of Crash modification factor, three different locations with two types of signal deployments (Surtrac and InSync) were selected. The locations selected included Montgomery County in Pennsylvania, Upper Merion region in Pennsylvania and East liberty section in Pittsburgh, Pennsylvania.

The author further provides detailed discussion of the methodology used for evaluating the safety aspects of adaptive traffic signals using the development of crash modification factor. The next step in the research applies the methodology presented to determine a CMF for the adaptive systems in Pennsylvania.

## **4.0 ANALYSIS OF RESULTS**

This chapter provides a discussion of the final results obtained from the research project. The chapter begins with providing results for an alternative method used to test the hypothesis; that includes the performance measure (vehicular speeds, stops and travel time) with and without adaptive traffic signals in operation. The chapter then provides the primary results of the research i.e. comparison of Crash modification factor (CMF) calculated for the two different types of adaptive traffic signals analyzed (SURTRAC & In-Sync) in order to determine the expected safety benefits provided by adaptive traffic signals. The chapter also provides a methodology for general application of the CMF to locations considered for adaptive traffic signal deployment and provides a description of the current crash rate method used for selecting sites for improvement.

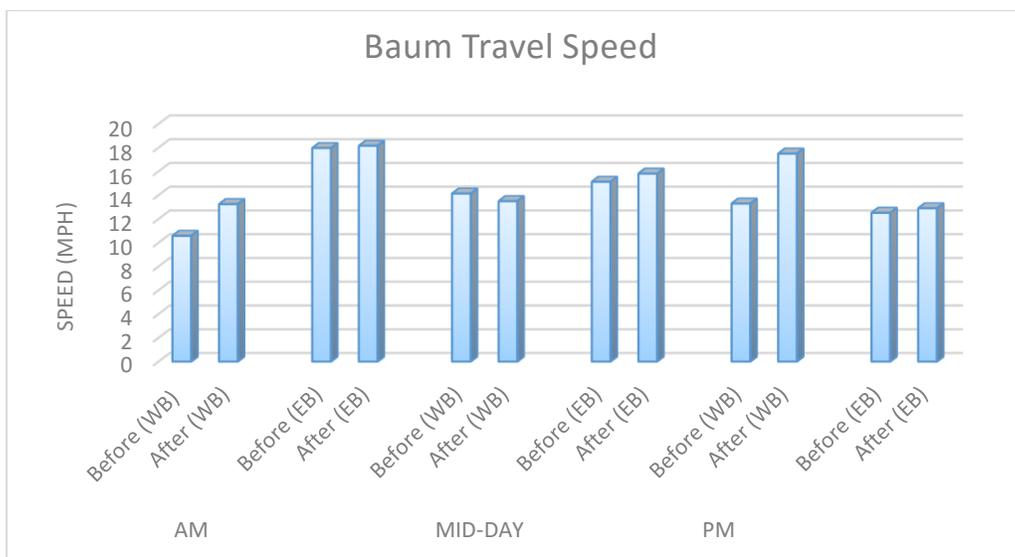
### **4.1 VEHICULAR SPEEDS, STOPS AND TRAVEL TIME (FIELD DATA)**

The travel run data collected through GPS tracks was analyzed and separated for various performance measure (such as speed, stops and travel time) in order to analyze the performance of the SURTRAC adaptive traffic signals and to scrutinize the improvements brought by deployment of the system in the 23 intersections corridor of Baum/ Center in Pittsburgh, Pennsylvania. GPS data analysis packages (GPS Babel and Viking) were used for the analysis.

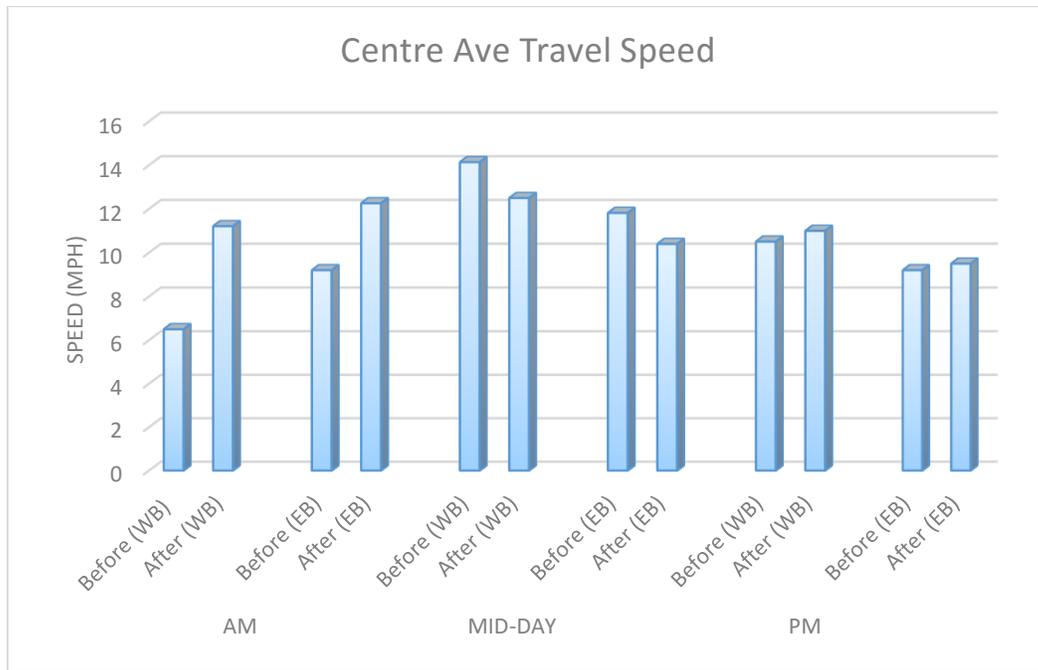
These performance measures can be used as an insight into the operational and safety benefits of adaptive traffic signals since safety is closely related with the number of stops made during the travel; which is the hypothesis of the research that adaptive traffic signals can improve safety by decreasing the number of stops made during travel. The results of performance measures are provided in the sections below with detailed comparison.

### 4.1.1 Travel Speed

The travel time data analyzed through the GPS Viking is provided in Figures 9 and 10 for comparative analysis of adaptive traffic signal systems. The travel speed for AM peak is improved by the deployment of adaptive traffic signals in both the eastbound and westbound directions for both Baum Boulevard while during mid-day, the speed remains somewhat constant.



**Figure 4-1 Baum Travel Speed comparison with and without ASCT in operation**

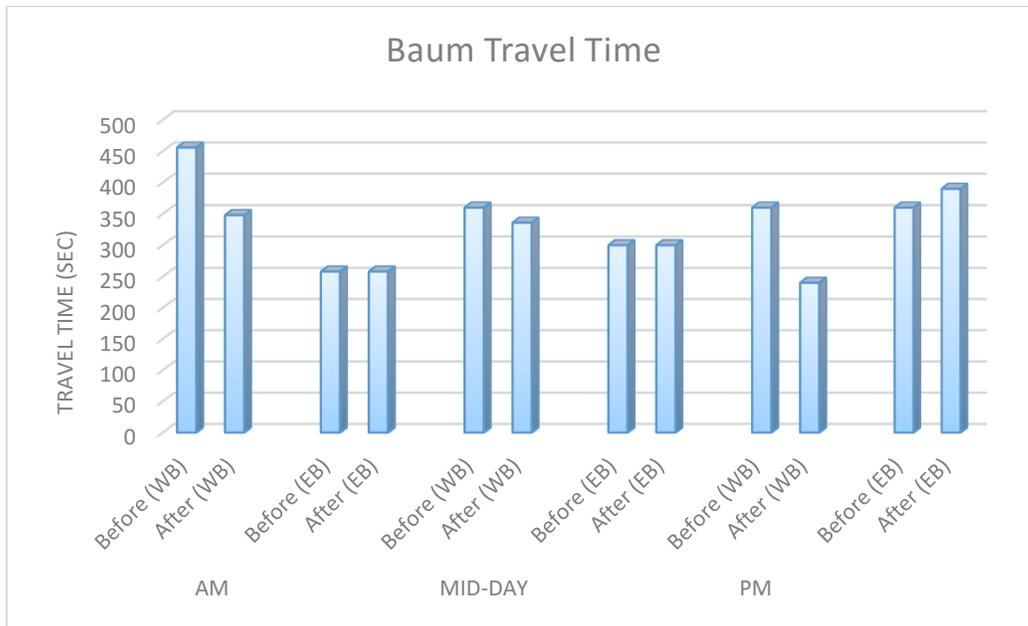


**Figure 4-2 Center Average Travel Speed with and without ASCT**

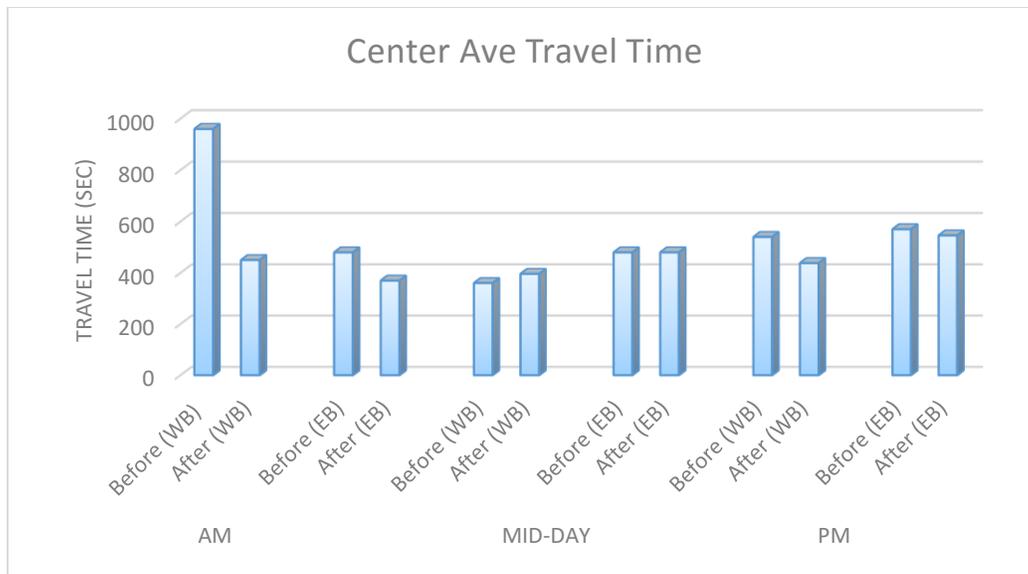
Similarly, for the Center Avenue improvement is observed in travel speed both in the AM and PM peaks in both the eastbound and westbound directions while a very small or negligible reduction is observed during the mid-day. The highest improvement is observed in the westbound direction during the AM peak which is about 83%. This is expected because this is the predominant direction of flow in the AM peak. There were no abrupt changes in speed observed which confirms that adaptive traffic signals provide fluent flow of traffic which is considered to be a factor contributing towards safety improvement and operation.

### 4.1.2 Travel Time

Travel time data was also evaluated as a part of performance measures. Time plays an important role both from the standpoint of monetary value and safety. Travel time data extracted through Viking is provided Figure 4-3 and 4-4 for comparative analysis. From Figure 4-3, it is observed that SURTRAC does improve travel on Baum Boulevard in terms of reducing time of travel. The highest improvement observed is in westbound direction both in the AM and PM peaks, which resulted in 25% and 33% reductions respectively. Travel time in the eastbound direction remained somewhat constant.



**Figure 4-3 Baum Travel Time with and without ASCT in Operation**



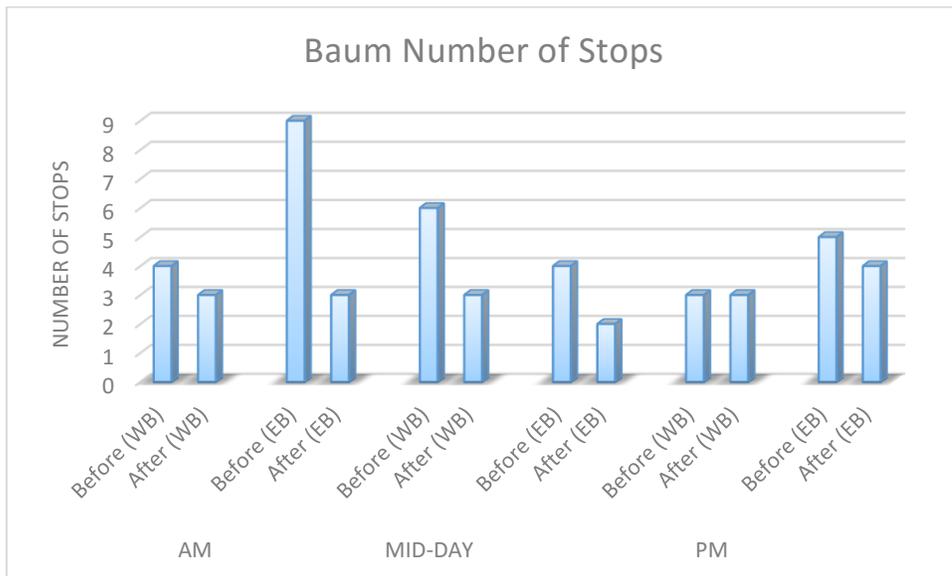
**Figure 4-4 Center Ave Travel Time with and without ASCT in Operation**

Similarly, looking at the travel time data for Center Avenue, it is observed that travel time is reduced on Center Avenue with the highest improvement observed during AM peak in westbound direction, which is a 55% reduction in travel time. Travel time is also observed to be reduced during the PM peak but remains somewhat constant during the mid-day period.

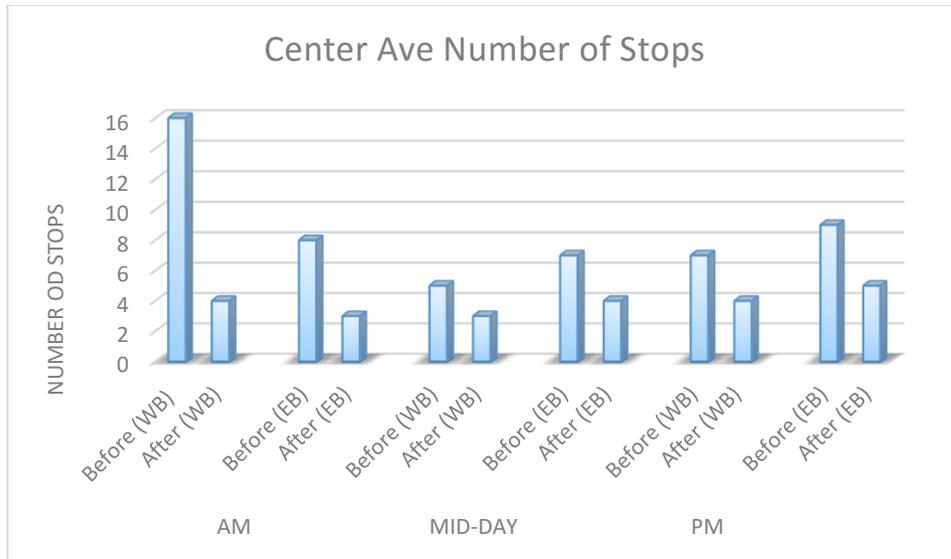
### 4.1.3 Vehicular Stops

Vehicular stops play the most vital role in safety, as was the hypothesis of the research that the fewer the stops made by the vehicles, the fewer the number of stops may reduce the chances of some types of road crashes, particularly rear end crashes as drivers would not be required to start and stop intermittently, instead would have an efficient travel with fewer stops. Stops were defined as a special case when vehicle speeds dropped below 3 miles per hour. The number of stops made by the vehicles during the travel study on Baum/Center Avenue corridors after installation is provided in Figures 4-5 and 4-6. From Figure 4-5, it can be observed that the

SURTRAC adaptive signals provides a significant amount of improvement in terms of number of stops made by the vehicles. Number of stops were observed to be reduced in each of the three peak time periods of the day and in each travel direction (i.e. westbound and eastbound). The highest reduction in number of stops observed is around 69% for eastbound direction during the AM peak.



**Figure 4-5 Baum Number of Stops with and Without Surtrac in Operation**



**Figure 4-6 Center Ave Number of Stops with and Without Surtrac in Operation**

Similarly, looking at the bar graph for Center avenue (figure 4-6), it can be observed again that SURTRAC reduces the number of stops made during the travel periods. The highest reduction is from 16 stops made during the AM peak in the westbound direction to just 3 stops made during the same period with SURTRAC in operation, which is 87% reduction in stops. The stops made are reduced in each direction of travel and during each of the peak periods observed. Hence, it is concluded that SURTAC has both safety and operational benefits; with reduction in stops, therefore lesser crashes are to be expected.

## 4.2 CRASH RATES AND CRASH MODIFICATION FACTORS

This section presents the safety evaluation results for the selected intersections in Pennsylvania. Crash rates are calculated and discussed as a traditional safety evaluation approach and crash modification factor evaluation results are also provided in detail.

### 4.2.1 Crash Rates

The crash rates were calculated for the study intersections in order to provide an overview of the traditional safety evaluation methodology used by transportation engineers. Crash rates utilizes the combination of crash frequency and vehicle exposure (traffic volume entering measured as million entering) for safety evaluations. Table 4-1 provides the crash rates for all of the selected study intersections in the after period along with their ranking based on crash rates.

**Table 4-1 Crash Rates for Intersections**

Intersection	County	Crash Rate (crashes/MEV)	Rank
<b>Penn Ave. and East Busway</b>	Allegheny	0.937	1
<b>SR 202 Parkway and Welsh Rd (63)</b>	Montgomery	0.833	2
<b>Penn Circle and Penn Ave.</b>	Allegheny	0.753	3
<b>SR 202 and Welsh rd (63)</b>	Montgomery	0.624	4
<b>SR 202 and Sr 309 (five points)</b>	Montgomery	0.590	5
<b>SR 202 Parkway and Kanpp Rd</b>	Montgomery	0.520	6
<b>Sr 202 and Montgomery mall Dr</b>	Montgomery	0.468	7
<b>SR 309 (Bethlehem Pike) &amp; Welsh Road</b>	Montgomery	0.387	8
<b>Penn Ave. and Highland Ave.</b>	Allegheny	0.375	9
<b>Bethlehem Pike &amp; Stump Road</b>	Montgomery	0.373	10
<b>Penn Circle and Broad St.</b>	Allegheny	0.336	11
<b>Penn Circle and Kirkwood St.</b>	Allegheny	0.302	12
<b>SR 202 Parkway and Connector A (309)</b>	Montgomery	0.300	13
<b>Broad St. and Larimer Ave.</b>	Allegheny	0.291	14
<b>SR 202 and Cheswick dr/Mall Dr</b>	Montgomery	0.263	15

**Table 4-1 (Continued)**

<b>N Gulph rd and Guthrie Rd</b>	Montgomery	0.259	16
<b>N Gulph rd and N. Warner Rd</b>	Montgomery	0.218	17
<b>SR 202 Parkway and Horsham Rd</b>	Montgomery	0.213	18
<b>SR 202 and Brandywine Ln</b>	Montgomery	0.164	19
<b>Bethlehem Pike &amp; North Wales Road</b>	Montgomery	0.149	20
<b>SR 202 and King Circle</b>	Montgomery	0.148	21
<b>Bethlehem Pike &amp; Knapp Road</b>	Montgomery	0.146	22
<b>N Gulph rd and I 76 Ramp/Village Dr</b>	Montgomery	0.143	23
<b>SR 202 and Gwynmont Dr</b>	Montgomery	0.133	24
<b>Penn Circle and Citizens Bank Drive</b>	Allegheny	0.128	25
<b>Bethlehem Pike &amp; English Village</b>	Montgomery	0.116	26
<b>Bethlehem Pike &amp; Hartman Road</b>	Montgomery	0.111	27
<b>SR 202 and Henderson Rd</b>	Allegheny	0.107	28
<b>Bethlehem Pike &amp; English Village</b>	Montgomery	0.101	29
<b>Welsh rd (63) and Stump rd</b>	Montgomery	0.078	30
<b>SR 202 and Long Rd</b>	Montgomery	0.075	31
<b>SR 202 and Long Rd</b>	Montgomery	0.059	32
<b>SR 202 and Allendale Rd</b>	Montgomery	0.051	33
<b>SR 202 and Saulin Blvd</b>	Montgomery	0.027	34
<b>Bethlehem Pike &amp; Mall Drive North</b>	Montgomery	0.022	35
<b>SR 202 and Town Center</b>	Montgomery	0.020	36
<b>SR 202 and dekalb Pike</b>	Montgomery	0	37
<b>SR 202 and Hancock rd</b>	Montgomery	0	38
<b>Penn Circle and Highland Ave.</b>	Allegheny	0	39
<b>SR 202 Parkway and Costco Dr</b>	Montgomery	0	40
<b>Penn Circle and Station St.</b>	Allegheny	0	41

Based on the calculated crash rates, the intersections are ranked accordingly in descending order with the intersection having highest crash rate being ranked first. This ranking could be used by officials to deem if an intersection or specific location is a high crash site needing further evaluation and countermeasure for improving safety. An example calculation for intersection 1 is shown provided below.

The intersection had total entering vehicles, sum of  $AADT_{maj}$  and  $AADT_{min}$  as 13154 vehicles per day and a crash frequency of 8 observed crashes during a 2 years period. The million vehicles entering were calculated as:

$$MEV = \frac{13154}{1,000,000} * (2) * 365 = 9.60$$

Then, crash rate was calculated by dividing the observed crash frequency by million vehicles entering as follow:

$$Crash\ rate = \frac{9}{9.60} = 0.94$$

Similarly, to provide a better illustration of the crash rate method, crash rates were calculated for both before and after deployment period and comparison is provided in table 4-2.

**Table 4-2 Crash Rate Comparison for Before & After Period**

<b>Intersection</b>	<b>County</b>	<b>Before CrashRate (crashes/MEV)</b>	<b>After Crash Rate (crashes/MEV)</b>
<b>Penn Circle and Highland Ave.</b>	Allegheny	0	0.385
<b>Penn Circle and Citizens Bank Drive</b>	Allegheny	<b>0.128</b>	<b>0.777</b>
<b>Penn Circle and Penn Ave.</b>	Allegheny	0.753	0.684
<b>Penn Circle and Kirkwood St.</b>	Allegheny	0.302	0.122
<b>Penn Circle and Broad St.</b>	Allegheny	0.336	0.135
<b>Penn Circle and Station St.</b>	Allegheny	0	1.183
<b>Penn Ave. and Highland Ave.</b>	Allegheny	<b>0.375</b>	<b>0.403</b>
<b>Broad St. and Larimer Ave.</b>	Allegheny	<b>0.291</b>	<b>0.352</b>
<b>Penn Ave. and East Busway</b>	Allegheny	0.937	0.840
<b>SR 202 and Hancock rd</b>	Montgomery	0	0.053
<b>Welsh rd (63) and Stump rd</b>	Montgomery	<b>0.078</b>	<b>0.247</b>
<b>SR 202 and Welsh rd (63)</b>	Montgomery	0.624	0.519
<b>SR 202 Parkway and Welsh Rd (63)</b>	Montgomery	0.833	0.635
<b>SR 202 Parkway and Kanpp Rd</b>	Montgomery	0.520	0.191
<b>Bethlehem Pike &amp; Knapp Road</b>	Montgomery	0.146	0.166
<b>SR 202 and Cheswick dr/Mall Dr</b>	Montgomery	0.263	0.177
<b>Sr 202 and Montgomery mall Dr</b>	Montgomery	0.468	0.179
<b>SR 309 (Bethlehem Pike) &amp; Welsh Road</b>	Montgomery	<b>0.387</b>	<b>0.506</b>
<b>Bethlehem Pike &amp; Hartman Road</b>	Montgomery	<b>0.111</b>	<b>0.133</b>
<b>Bethlehem Pike &amp; English Village</b>	Montgomery	<b>0.116</b>	<b>0.156</b>
<b>Bethlehem Pike &amp; Stump Road</b>	Montgomery	0.373	0.219
<b>Bethlehem Pike &amp; North Wales Road</b>	Montgomery	<b>0.149</b>	<b>0.250</b>
<b>SR 202 Parkway and Connector A (309)</b>	Montgomery	0.300	0.259
<b>Bethlehem Pike &amp; Mall Drive North</b>	Montgomery	<b>0.022</b>	<b>0.154</b>
<b>SR 202 and Sr 309 (five points)</b>	Montgomery	0.590	0.567

**Table 4-2 (Continued)**

SR 202 Parkway and Horsham Rd	Montgomery	0.213	0.441
SR 202 Parkway and Costco Dr	Montgomery	0	0.047
SR 202 Parkway and County Line Rd	Allegheny	0.075	0.306
N Gulph rd and I 76 Ramp/Village Dr	Montgomery	0.143	0.831
N Gulph rd and Guthrie Rd	Montgomery	0.259	0.024
N Gulph rd and Goddard Blvd	Montgomery	0.104	0.102
N Gulph rd and N. Warner Rd	Montgomery	0.218	0.023
SR 202 and Long Rd	Montgomery	0.059	0.104
SR 202 and Allendale Rd	Montgomery	0.051	0.091
SR 202 and Brandywine Ln	Montgomery	0.164	0.218
SR 202 and King Circle	Montgomery	0.148	0.128
SR 202 and Town Center	Montgomery	0.020	0.047
SR 202 and Henderson Rd	Montgomery	0.107	0.130
SR 202 and Saulin Blvd	Allegheny	0.027	0.190
SR 202 and dekalb Pike	Montgomery	0	0.086

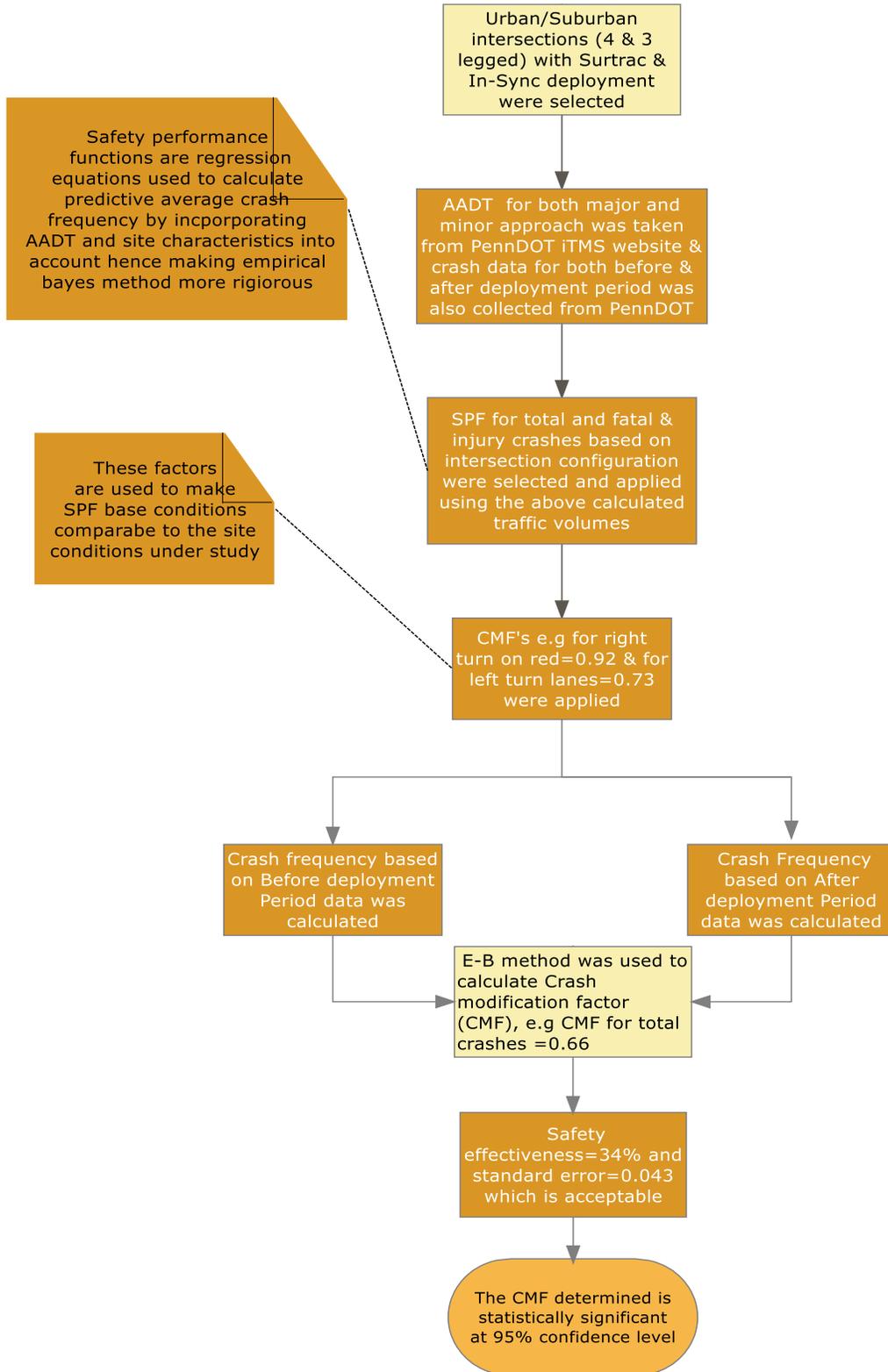
We can observe from the crash rate method that most (19/41) of the intersections show a reduction in crash rates in the after deployment period while a few highlighted in red are showing a little increase in the after period data. This increase could be due to the inaccuracy in crash data and its recording procedures (regression to the mean) and the difference in years of crash data for both before and after data. This crash rate method totally relies on the observed crash data. Similarly, the zero crash rate which appears to be meaningless is due to the fact that there were no crashes reported in those years.

The limitations of the crash rate method are evident from this comparison of the before and after deployment period data. This method can be regarded as useful only for identifying the vulnerability of particular intersections relative to each other and for comparing and prioritizing those intersections for effective treatments based on crash rates. Beyond this prioritization, the crash rate method is not effective in providing details about the amount of reduction in crashes that may occur after an improvement (deploying adaptive traffic signals in our case) is made at the intersection.

#### **4.2.2 Crash Modification Factor**

Crash modification factor calculations for ASCT system installations was the main theme of this research project to provide an estimate of the amount of change expected in crash experience after implementing a countermeasure, which in our case is the installation of an adaptive traffic control system. The true value of the CMF for any countermeasure will always be unknown until after the countermeasure is implemented. However evaluating early installations of a countermeasure, such as ASCT in Pennsylvania, provides the opportunity to predict benefits for future installations. The reported value is only an estimate of the potential value obtained from a statistical analysis of reported crash data for countermeasures that have been implemented. This reported value (referred to as a point estimate) provides an estimate of the effectiveness of the potential change of countermeasure on crash frequency.

The Empirical Bayes predictive before and after method explained in chapter 3 was used for calculating crash modification factor (CMF). How the method was applied to the Pennsylvania data is provided in flowchart Figure 4-7.



**Figure 4-7 CMF Calculation**

Using the method explained above in flowchart, CMF was first calculated for both the systems (Surtrac and In-Sync) together for all of the study intersections. An example of how the calculations were performed is provided in Appendix A. The results obtained are provided below:

**Table 4-3 Overall Crash Modification Factor Results for all Intersections**

Crash Severity	Safety Measure (CMF)	Std. Error	Safety Effectiveness
Total	0.66	0.043	34%
FI	0.55	0.037	45%

\*FI= Fatal & Injury crashes

From table 4-3, it can be observed that adaptive traffic control system at urban/suburban intersections improve safety by reducing crash frequency for both total and fatal/injury crash categories. For total crashes, a CMF value of 0.66 is observed, which predicts a reduction in crashes and a safety effectiveness of 34%. The results estimates a 34% reduction in total crashes would be observed with deployment of adaptive traffic signals at intersections. The standard error for the CMF is 0.043. Similarly, a CMF value of 0.55 is observed for fatal and injury crashes, which predicts a safety improvement and the safety effectiveness of 45% resulting in a reduction in fatal and injury crashes by 45% to be observed after deployment of adaptive traffic control systems. The standard error for the CMF is 0.037.

Using the same Empirical Bayes approach, as explained in chapter 3, a CMF value was also separately calculated for the two different systems evaluated; which included Surtrac and In-Sync and the results are provided in Table 4-4.

**Table 4-4 Crash Modification Factor Results for Surtrac and In-Sync**

Type	Crash Severity	Safety Measure (CMF)	Std. Error	Safety Effectiveness
Surtrac	Total	0.43	0.06	57%
Surtrac	FI	0.53	0.11	47%
Insync	Total	0.58	0.04	42%
Insync	FI	0.43	0.03	57%

\*FI= Fatal & Injury crashes

From table 4-4, it can be observed that both Surtrac and In-sync when installed at urban/suburban intersections improve safety by reducing the crash frequency for both total and fatal injury crashes. With Surtrac, for total crashes, a CMF value of 0.43 is observed, which means a reduction in crashes and a safety effectiveness of 57% resulting in a 57% reduction in total crashes would be observed with deployment of Surtrac signals at intersections. The standard error for the CMF is 0.06. Similarly, a CMF value of 0.53 is observed for fatal and injury crashes, which results in a safety improvement and the safety effectiveness of 47% means that a reduction in fatal and injury crashes by 47% would be observed after the deployment of Surtrac adaptive traffic control systems. The standard error for the CMF is 0.11.

Similarly, for In-sync a CMF value of less than 1 is observed for both total and fatal injury crashes which mean reduction in crashes and improvement in safety effectiveness. For

total crashes, a CMF value of 0.58 with safety effectiveness of 42% resulting reduction in total crashes by 42% would be observed after deployment of In-Sync adaptive signals at intersections. For fatal and injury crashes, a CMF value of 0.43 is observed along with 57% safety effectiveness which results in a reduction in fatal injury crashes by 57%. The standard error for the CMF is 0.03.

After analyzing the two systems together and then separately for their safety improvement, the systems were again analyzed for the amount of reduction in crashes and safety improvement at the two different type of intersections present, specifically four legged and three legged intersections. Table 4-5 provides detailed results for CMF at three and four legged intersections.

**Table 4-5 Crash Modification Factor Results for four & three legged Intersections**

Type	Crash Severity	Safety Measure (CMF)	Std. Error	Safety Effectiveness
4 legged	Total	0.61	0.045	39%
4 legged	FI	0.45	0.038	55%
3 legged	Total	0.42	0.107	58%
3legged	FI	0.29	0.035	71%

\*FI= Fatal & Injury crashes

From Table 4-5, it can be observe that deploying adaptive traffic control systems improves safety at both 3 legged and 4 legged intersections. At four legged intersection, the CMF value for total crashes is 0.61 with a safety effectiveness of 39% which means that deploying adaptive traffic control signals at 4 legged intersections would reduce total crashes by 39%. Similarly, for fatal injury crashes, CMF is 0.45 with safety effectiveness of 55% results

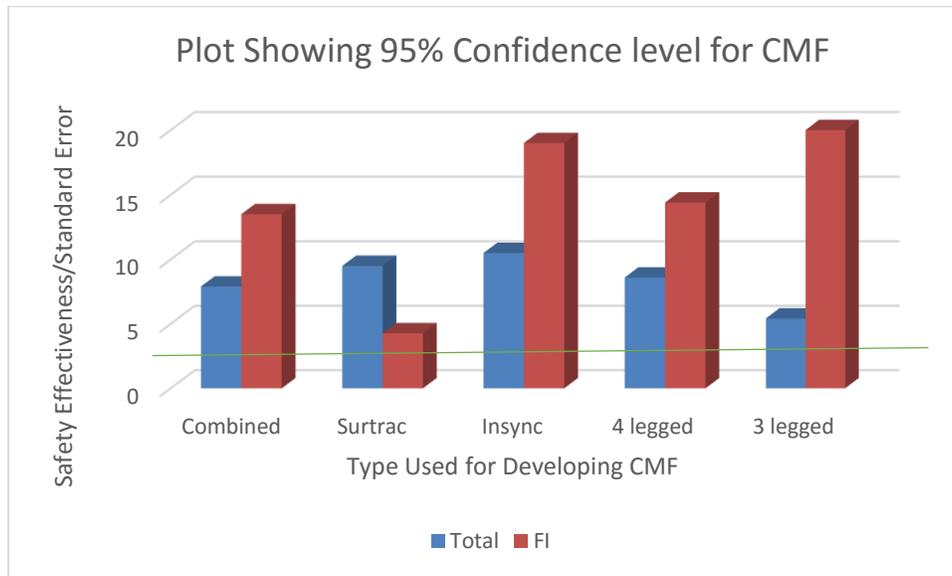
which means that deploying adaptive traffic control systems at 4 legged intersections would reduce fatal injury crashes by 55%. The standard error for the two CMFs is 0.045 and 0.038. Again from Table 4-4, at 3 legged intersections the CMF value for total crashes is 0.42 with a safety effectiveness of 58% meaning that adaptive traffic signals deployment would reduce the total crashes at 3 legged intersections by 58% while deploying adaptive traffic control systems at 3 legged intersections will reduce fatal and injury crashes by 73% corresponding to the CMF value of 0.29 and safety effectiveness of 71% respectively. The standard error for total and fatal injury crashes is 0.107 and 0.035.

#### **4.2.3 Analysis of Results & Confidence Levels**

The Empirical Bayes method used to calculate Crash Modification Factor supports the author's hypothesis that adaptive traffic control systems helps in improving traffic safety in terms of reducing the number of crashes taking place at intersections. The results were further analyzed for their statistical significance and confidence intervals using the method provided in the Highway Safety Manual. The method is based on a comparison of safety effectiveness and standard error for establishing the confidence level.

- If  $\text{Abs} [\text{Safety Effectiveness}/\sigma] < 1.7$  then conclude that the treatment is not significant at the 90 percent confidence level.
- If  $\text{Abs} [\text{Safety Effectiveness}/\sigma] \geq 1.7$  then conclude that the treatment is significant at the 90 percent confidence level.
- If  $\text{Abs} [\text{Safety Effectiveness}/\sigma] \geq 2.0$  then conclude that the treatment is significant at the 95 percent confidence level.

Based on the above described rule, the results were evaluated as follows:



**Figure 4-8 Plot Showing Confidence Level of CMF**

According to the guidelines provided to check the statistical significance of results obtained through the Empirical Bayes predictive method in HSM, it is observed that all of the results achieved (from Figure 4-8) have values of Abs [Safety Effectiveness/Standard error] >2.0 shown by the fact that all the values crosses the 95% confidence line, which justifies that all of the results are highly statistically significant at a 95% confidence level adding further reliability to the test results.

#### **4.2.3.1 Confidence Interval**

Since the most common method of evaluating significance is confidence interval, this section provides and a method and the results for a confidence interval of calculated CMF values. The confidence interval provides an upper and lower bound under which the true value

lies. It is a combination of the point estimate value of CMF and standard error with certainty of confidence level, given by [4]:

$$\text{Confidence interval of CMF} = \text{CMF} + Z * \text{STD.ERROR}$$

*CMF* = Calculated point estimate value of Crash Modification Factor

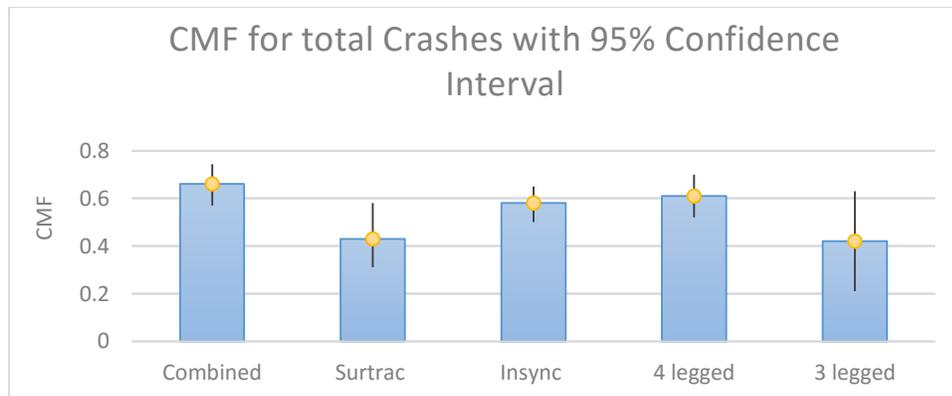
*Z* = Level of certainty or confidence using

*STD.ERROR* = standard error of CMF

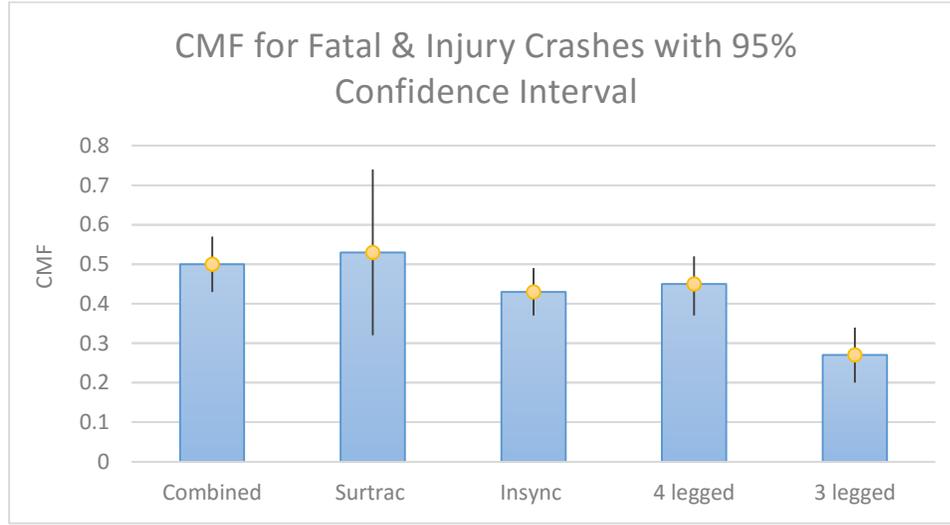
**Table 4-6 Z-Values based on Confidence Interval**

<b>Confidence Interval desired</b>	<b>Z-Value</b>
<b>90%</b>	<b>1.64</b>
<b>95%</b>	<b>1.96</b>
<b>99%</b>	<b>2.58</b>

Using the above method for calculation of confidence interval, the following results were obtained for confidence interval of total and fatal injury crashes.



**Figure 4-9 CMF with 95% Confidence Interval (Total Crashes)**



**Figure 4-10 CMF with 95% Confidence Interval (FI Crashes)**

The above results for 95% confidence intervals clearly justifies the safety benefits of adaptive signal control system as both the upper and lower bound values are below 1; which means that even if we are above or below the point estimate value for calculated CMF, deployment of adaptive traffic signals would still result in reduction of crash frequency.

#### **4.2.4 Practical Application**

The above derived CMF proves the safety benefits of adaptive signal control systems and their application to real world problems. The CMF values can be applied practically in the field to each of the relevant types of intersection. Let's take as an example, the case of a 4 legged intersection in urban community of Pennsylvania that experiences 15 crashes per year out of which 50% are angle crashes, 30% are fatal and injury crashes, 20% are rear end crashes. So, in

order to find the change in crash frequency after the countermeasure of deploying adaptive signal control systems, the procedure would be as follows:

*Total Expected crash frequency without countermeasure,  $N = 15$  crashes per year*

*Fatal and injury crashes expected,  $N_{fi} = 4.5$*

*Total crashes after countermeasure =  $CMF * N$*

*=  $.66 * 15 = 9.9$  crashes per year*

*Similarly, for Fatal & injury crashes after countermeasure =  $CMF_{fi} * N_{fi}$*

*=  $0.5 * 4.5$*

*=  $2.25$  crashes per year*

Hence, the deployment of adaptive signal control system would bring down total crashes to 9.9 and fatal and injury crashes to 2.25 per year which is a huge improvement.

### **4.3 GUIDELINES**

After analyzing the results presented, several conclusions were made that can be utilized for suggesting guidelines regarding the impact of adaptive traffic control systems on traffic safety. During the planning for future projects for installation of adaptive traffic control systems, crash modification factors should be given prime importance during the planning and design phase in analyzing the safety benefits that can be derived at particular locations by deploying the ASCT system.

Crash Modification factors will provide transportation engineers with a tool for analyzing the different intersections with and without ASCT deployment in order to compare present

conditions without ASCT to future conditions with ASCT. The CMFs can be used for predicting the improvement in safety that would be provided in terms of reduction in crashes occurring at those intersections. The crash modification factor should also be incorporated into the TE 153-Pennsylvania Adaptive Signal Control System evaluation document for evaluating adaptive traffic control systems for their safety benefits before approving them for deployment. Overall adaptive traffic control system proved to improve traffic safety by reducing total crashes by 50%, which is a huge improvement.

## **5.0 SUMMARY AND CONCLUSIONS**

This chapter provides a summary of results to conclude whether the results support the hypothesis (i.e. adaptive signal control technology have safety benefits) or not. The chapter then concludes with providing guidelines for future research.

### **5.1 SUMMARY OF RESULTS**

This section provides a review of methods used for evaluating the hypothesis and then provides a summary of the results.

#### **5.1.1 Review of Tests Conducted**

In order to test the hypothesis, a two method approach was applied. During the first stage, a field study was conducted in a twenty three intersection grid network of Pittsburgh, Pennsylvania with the newly deployed Surtrac adaptive traffic signals. Field data was collected using mobile app GPS tracks with and without the adaptive traffic signals in operation.

During the second stage, forty one intersections were selected with nine intersections operating on Surtrac in East Liberty section of Pittsburgh, twenty intersections operating on In-Sync in Montgomery Township, Pennsylvania and twelve intersections operating on In-Sync in

Upper Merion Township, Pennsylvania. Crash data and traffic volume data was collected for the study intersections for both before and after deployment period and Empirical Bayes predictive method was applied to calculate the expected average crash frequencies in both before and after deployment periods ultimately leading to development of Crash Modification Factor for ASCT.

### **5.1.2 Vehicular Stops and Crash Modification Factor**

The evaluation of field test data revealed that adaptive traffic signals do have benefits both in terms of safety and operation. Surtrac were found to reduce the number of stops made along the corridor at all the three peak periods observed (AM, Mid-day and PM peak) along both Baum Boulevard and Center Aveue. The highest reduction in number of stops observed was 69% for eastbound direction during the AM peak on Baum Boulevard and 87% reduction in stops for Am peak in westbound direction on Center Aveue. The results prove the significance of the hypothesis that adaptive signals have safety benefits in terms of reducing number of stops.

Similarly, the results for Crash modification factor also proves the hypothesis that adaptive traffic signals have documented safety benefits as the derived CMF's for both Surtrac and Insync for total and FI crashes were lower than 1, meaning that deployment of these adaptive traffic signals would reduce both total and& fatal and injury crashes and improve safety. The statistical significance of the results were also checked using the method prescribed in Highway Safety manual and the CMF values were found to be statistically significant at 95% confidence interval.

## **5.2 CONCLUSIONS**

The hypothesis that adaptive traffic signals may have safety benefits in terms of reducing the number of stops ultimately leading to reduction in road crashes is confirmed by the two approaches adopted for testing the hypothesis. Adaptive traffic signals, when deployed at intersections are expected to reduce the number of stops made along the corridor and are also expected to reduce the number of road crashes compared to typical time of day coordination. The expected reduction in crashes provided by ASCT is in the range of (30-70) %.

## **5.3 RECOMMENDATIONS FOR FUTURE RESEARCH**

This section provides recommendations for future research related to safety benefits of adaptive traffic control systems. Although, this research used a rigorous statistical method, the Empirical Bayes approach for finding the safety benefits of adaptive traffic signals, there are still many other avenues to explore to study the safety benefits of ASCT systems.

This research used the national Safety performance Functions (SPF's) for calculating the expected average crash frequencies due to non-availability of regional SPF's for Pennsylvania. It is expected that the results won't differ with regional SPF's but future research should still consider the use of regional SPF's and make comparisons for results derived using both regional and national SPF's. Although, this research considered two different types of adaptive traffic signal systems (SURTRAC and In-Sync) and made comparisons for safety benefits achieved with each type but future research should incorporate other type of available adaptive traffic

signals and look for correlations between different available systems. Along with the above proposed lines of research, the author also proposes to study the impacts of adaptive traffic signals on human factors (fatigue and stress level) in a before and after study for evaluating the safety benefits, using a controlled environment such as a traffic simulator for future studies.

## APPENDIX A

### EMPERICAL BAYES METHOD EXAMPLE CALCULATIONS

**Table 5-1 Before Deployment Period Calculations Example**

Intersection	AADTmaj,A	AADTmin,A	AADTmaj,B	AADTmin,B	Before Deployment	
					Nspf total	Nspf FI
SR 202 and Hancock rd	23579	10785	23793	10883	6.892178	2.216487
Welsh rd (63) and Stump rd	17471	8314	17630	8390	2.920963	0.940654
SR 202 and Welsh rd (63)	19470	17472	19647	17630	6.274349	1.966236
SR 202 Parkway and Welsh Rd (63)	14980	9465	15116	9550	4.116251	1.260976
SR 202 Parkway and Kanpp Rd	8165	6179	8239	6235	1.949404	0.561005
Bethlehem Pike & Knapp Road	28922	3902	29185	8251	5.088935	1.56849
SR 202 and Cheswick dr/Mall Dr	8165	2120	8239	2140	1.524349	0.443398
Sr 202 and Montgomery mall Dr	8165	1987	8239	2005	1.501674	0.437087

\*AADT means average annual daily traffic, A means after period and B means before period

**Table 5-2 Before Deployment Period Calculations Example (Continued)**

Intersection	Predicted average crash frequency	Predicted average crash frequency	Overdispersion k	Weighted adjustment
	before total with factors	before fi		
SR 202 and Hancock rd	12.86402473	0.886594962	0.39	0.166196617
Welsh rd (63) and Stump rd	5.974665926	0.376261452	0.33	0.336514545
SR 202 and Welsh rd (63)	11.71086695	0.786494296	0.39	0.17962228
SR 202 Parkway and Welsh Rd (63)	7.68284857	0.504390343	0.39	0.250230779
SR 202 Parkway and Kanpp Rd	3.638497963	0.22440185	0.39	0.413391537
Bethlehem Pike & Knapp Road	10.40912987	0.627396147	0.33	0.225478489
SR 202 and Cheswick dr/Mall Dr	2.845148367	0.177359086	0.39	0.474021745
Sr 202 and Montgomery mall Dr	2.802825483	0.174834677	0.39	0.477759817

\*fi means fatal and injury crashes

**Table 5-3 Before Deployment Period Calculations Example (Continued)**

Intersection	Expected Average Crash Frequency		Weighted adjustment for FI	Expected average crash frequency N(ex), fi, before
	N (ex), total, before			
SR 202 and Hancock rd	2.137957392		0.7430679	0.658800256
Welsh rd (63) and Stump rd	6.02010562		0.88954812	6.003347027
SR 202 and Welsh rd (63)	42.21069012		0.765267405	34.14195914
SR 202 Parkway and Welsh Rd (63)	39.42940855		0.835622777	22.44895338
SR 202 Parkway and Kanpp Rd	17.05143117		0.919526091	15.56255209
Bethlehem Pike & Knapp Road	12.1508628		0.828472459	7.833670263
SR 202 and Cheswick dr/Mall Dr	7.244749172		0.935304918	2.101189744
Sr 202 and Montgomery mall Dr	11.68339611		0.936166965	7.908342309

\*ex stands for expected, fi means fatal and injury crashes

**Table 5-4 After Deployment Period Example Calculations**

Intersection	After deployment calculations		Predicted average crash frequency	
	Nspf total	Nspf fi	Npre, After total	Npre, After fi
SR 202 and Hancock rd	6.811683138	2.188622663	10.89752908	0.984880198
Welsh rd (63) and Stump rd	2.88490328	0.921301381	5.161143185	0.414585621
SR 202 and Welsh rd (63)	6.201032605	1.941501396	9.920592573	0.873675628
SR 202 Parkway and Welsh Rd (63)	4.068263052	1.245148024	6.508525723	0.560316611
SR 202 Parkway and Kanpp Rd	1.926672733	0.553963071	3.082347155	0.249283382
Bethlehem Pike & Knapp Road	4.146732883	1.36831021	7.418578747	0.615739595
SR 202 and Cheswick dr/Mall Dr	1.506447546	0.437796918	2.410058661	0.197008613
Sr 202 and Montgomery mall Dr	1.484165307	0.4316009	2.374410887	0.194220405

\*fi means fatal and injury crashes

**Table 5-5 After Deployment Period Example Calculations (Continued)**

Intersection	Expected average crash freq	Expected average crash freq
	Nex, after, total	Nex, after,FI
SR 202 and Hancock rd	1.800149846	0.728289351
Welsh rd (63) and Stump rd	5.06889999	6.636569532
SR 202 and Welsh rd (63)	35.54119815	37.74319306
SR 202 Parkway and Welsh Rd (63)	33.19937244	24.81682957
SR 202 Parkway and Kanpp Rd	14.35722307	17.20406276
Bethlehem Pike & Knapp Road	10.23096806	8.65995205
SR 202 and Cheswick dr/Mall Dr	6.100043973	2.322819549
Sr 202 and Montgomery mall Dr	9.837363358	8.742500372

\*fi means fatal and injury crashes

## BIBLIOGRAPHY

- [1] J. S. Sussman, *Perspectives on Intelligent Transportation Systems (ITS)*. Springer Science & Business Media, 2008.
- [2] A. 9781560514770:, “Highway Safety Manual,” 2010.
- [3] AASHTO, “American Association for State Highway and Transportation Officials,” 2005.
- [4] V. Gayah and E. Donnell, “Establishing Crash Modification Factors and Their Use,” pp. 814–865, 2014.
- [5] P. By, M. Lodes, and R. F. Benekohal, “Safety Benefits of Implementing Adaptive Signal Control Technology :,” no. 12, 2013.
- [6] J. Ma, M. D. Fontaine, F. Zhou, D. K. Hale, and M. O. Clements, “Estimation of the Safety Effects of an Adaptive Traffic Signal Control System,” in *Transportation Research Board 94th Annual Meeting*, 2015.
- [7] Z. Tian, F. Ohene, and P. Hu, “Arterial Performance Evaluation on an Adaptive Traffic Signal Control System,” in *6th International Symposium on Highway Capacity and Quality of Service*, 2011, vol. 16.
- [8] C. Kergaye, A. Stevanovic, and P. Martin, “Comparison of Before-After Versus Off-On Adaptive Traffic Control Evaluations,” *Transp. Res. Rec. J. Transp. Res. Board*, vol. 2128, pp. 192–201, Dec. 2009.
- [9] J. and P. T. M. B.R.Chilukuri, Joseph Perrin, “SCOOT and Incidents: Performance Evaluation in Simulated Environment.”

- [10] “Transportation Research Board, NCHRP SYNTHESIS 403, ‘Adaptive Traffic Control Systems: Domestic and Foreign State of Practice,’” 2010.
- [11] “InSync Adaptive Traffic Control Shows Initial Safety Benefits by Rhythm Engineering.,” 2010.
- [12] D. Associates, ““Gresham Phase Three Traffic Signal System Optimization Adaptive Traffic Signal Control System Benefits Report,”” 2008.
- [13] Oregon Department of Transportation, “Powell SCATS Evaluation.”
- [14] Missouri Department of Transportation, “Evaluation of an Adaptive Traffic Signal System:Route 291 in Lee’s Summit, Missouri.”
- [15] Federal Highway Administration, “Model Systems Engineering Documents for Adaptive Signal Control Technology ( ASCT ) Systems,” no. August, 2012.