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Evaluating the Safety Effects of Signal Improvements

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ABSTRACT

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As a result of high crash frequencies on roadways, transportation safety has become a high priority for the United States Department of Transportation and the Utah Department of Transportation. A large percentage of fatal and injury crashes on roadways occur at intersections and traffic signals have been implemented to reduce these severe crashes. There is a need to evaluate the effectiveness of the traffic signal improvements through the development of Crash Modification Factors (CMFs). Recent research has shown that traditional safety evaluation methods have been inadequate in developing CMFs. In recent years, Bayesian statistical methods have been utilized in traffic safety studies to more accurately analyze the effectiveness of safety improvements. The hierarchical Bayesian method is an advanced statistical technique that has the capability to account for the shortcomings of traditional methods and to more fully reflect the effectiveness of safety improvements.

This report uses a hierarchical Bayesian model to analyze the effectiveness of new traffic signal installations and modified traffic signals. CMFs were developed for multiple scenarios for both new and modified traffic signals. A benefit-to-cost (B/C) analysis was also performed for each improvement to determine how long it would take to recover the cost of installation. The results showed that there was an increase in overall crashes for both new signal installations and modifications to existing signals. The severe crash analysis revealed that there was an increase in non-severe crashes and a reduction in severe crashes; the improvements are effectively reducing severe crashes and improving safety at intersections. The B/C analyses indicate that there is a safety benefit to both improvements and that new signal installation costs can be recovered in approximately 5 years while the installation of a left-turn signal modification can be recovered in approximately 9 weeks.

Keywords: Bayesian, safety, traffic signal, transportation, Crash Modification Factor, benefit-to-cost analysis, crash severity, signal modification

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1 INTRODUCTION

National statistics show that in 2009 there were approximately 5,505,000 crashes in the United States with about 2,210,000 (40 percent) of these crashes occurring at intersections. An estimated 30,797 fatal crashes and 1,517,000 injury crashes occurred in 2009 with 6,770 (22 percent) and 699,000 (46 percent) fatal and injury crashes occurring at intersections, respectively (NHTSA 2011). As a result of the high number of crashes, transportation safety has become very important to the United States Department of Transportation (USDOT) and the Federal Highway Administration (FHWA). To improve safety, transportation agencies can focus on building new infrastructure or improving the existing infrastructure.

In the recent past there has been a shift from building new infrastructure to managing and maintaining the current infrastructure. Transportation engineers now focus their attention on making changes to the current system to improve efficiency and safety (Davis and Aul 2007). Because transportation agencies have limited funding, it is important to identify the effects of improvements to know which is best for the available funding.

Similar to the goals of the USDOT and the FHWA, the Utah Department of Transportation (UDOT) is focused on reducing crashes on the transportation system. Through the “Zero Fatalities” campaign, there is an emphasis on reducing crashes that cause fatalities and incapacitating injuries (Utah Safety Leadership Team 2007). This research project provides

UDOT with more information to use in determining what signal improvements should be implemented in the future to reduce severe crashes in a cost effective manner.

1.1 Problem Statement

The purpose of this research was to determine the safety effects of signal improvements at intersections as a function of crash reduction. Crash Modification Factors (CMFs) and benefit-to-cost (B/C) ratios were developed for different signal improvements including the installation of new traffic signals and modifications to existing traffic signals.

1.2 Objectives

The first objective of the research was to utilize UDOT databases to collect data on signalized intersection locations throughout the state that have had intersection improvements made to determine the safety benefits of such improvements. The second objective was to develop CMFs for each improvement with a focus on specific crash types and severities. The final objective was to determine B/C ratios for use in evaluating the effectiveness of the various signal improvements.

1.3 Organization

This report is organized into the following chapters: 1) Introduction, 2) Literature Review, 3) Data Collection, 4) Analysis Procedures, 5) New Signal Results, 6) Modified Signal Results, and 7) Conclusions. A References section and an Appendix follow the indicated chapters.

2 LITERATURE REVIEW

A comprehensive literature review was performed on factors relating to safety improvements at intersections from both a national and international perspective. The research was performed by locating recent safety analyses and comparing the conclusions for different safety improvements at intersections. Safety analysis is important to perform at each individual intersection because it is a way for local authorities to quantify the impact of an improvement to an intersection with respect to safety, where safety is generally measured by the frequency and severity of crashes that occur at the intersection. By quantifying the change in the number of crashes before and after a signal improvement, the effectiveness of the improvement can be assessed. There are multiple ways to estimate the change in crashes, but this report focuses on the use of CMFs.

The literature review covers several topics related to the research. First, safety is defined and traffic signal warrants are discussed. Next, methods to predict crashes are discussed. Then, a discussion of different methods of analysis to evaluate safety will be presented, after which the safety analysis of signalized intersections is discussed including results from previous studies. Finally, B/C analyses are discussed.

2.1 Safety Definition

To analyze safety on a roadway, it is important to first understand what safety means in relation to traffic and how it is measured. The Highway Safety Manual (HSM) defines safety as the number of crashes that are expected to occur at a given intersection or road segment per unit time (AASHTO 2010). This study focused on crashes that occur at or near an intersection. The HSM defines an intersection as an area where two or more roadways or highways meet. An intersection related crash is one that occurs in the intersection itself or on an approach within the functional area of the intersection which is approximately 250 feet upstream and downstream of the intersection (AASHTO 2010).

Safety is measured by the frequency and severity of crashes, so it is important understand some of the characteristics of crash statistics that can have an effect on safety. This section discusses the characteristics of crash statistics that can be used to determine the proper statistical tools to be used, including the primary factors contributing to crashes, the random nature of crashes, and the regression-to-the-mean (RTM) bias.

2.1.1 Crash Contributing Factors

There are three primary groups of factors that can contribute to crashes: human, vehicle, and roadway/environmental factors. Human factors include age, judgment, driver skill, attention, experience, fatigue, etc., while vehicle factors are the safety features and design flaws of the vehicle. Roadway and environmental factors include the geometric alignment, cross-section, traffic control devices, grade, weather, visibility, etc. The combination of multiple factors can cause crashes to be more severe (AASHTO 2010). In order to improve safety, engineers try to reduce the effects of these factors; the only factors that can be controlled by better engineering are the roadway geometry, grade, and the use of traffic control devices. When these elements are designed and utilized properly, safety is expected to improve as the frequency of severe crashes decreases. This report focuses on the use of traffic signals to improve safety at intersections.

2.1.2 Crashes as Random Events

While there are trends and factors that increase the likelihood of crashes, it is important to note that crashes are random events and therefore cannot be perfectly predicted. The nature of crashes is a very complex and random process when only considering the known factors that were discussed in Section 2.1.1. It is important to note that there are unknown factors that also contribute to crashes. The "Handbook of Road Safety Measures" states that "as far as crashes are concerned, there is not necessarily a very close connection between the causes of the problem and its solution" (Elvik and Vaa 2004).

Statistical tools can be used to correctly model crash behavior. One problem that occurs because of the random nature or crashes is that when using a short-term analysis period it is nearly impossible to determine if the short-term trends reflect the long-term behavior of the site (AASHTO 2010). The fluctuation of the frequency of crashes makes it difficult to determine whether a change in the number of crashes is a result of a specific treatment or natural fluctuations in crashes. This phenomenon is referred to as RTM bias.

2.1.3 Regression-to-the-Mean Bias

The RTM bias occurs when researchers apply a treatment to a site that is experiencing unusually high or low crashes and analyze the improvements based on crash counts alone. These sites are chosen based on short-term trends rather than long-term crash frequency patterns. When this happens it is likely that the effects of a treatment at a location would be inaccurately overestimated. Figure 2-1 portrays the difference between the portrayed reduction in crashes and the actual reduction in crashes when the RTM is accounted for (AASHTO 2010, Gross et al. 2010, Hauer 1997, Hauer et al. 2002). The RTM reduction in crash frequency is the difference between the crash frequency at the time of the treatment and the expected average crash frequency. The actual reduction is the difference in crash frequency between the expected average crash frequency and the observed crash frequency. The perceived reduction in crash frequency is the RTM reduction plus the actual reduction in crash frequency. When RTM bias is not taken into account the perceived reduction could be much larger or smaller than the actual reduction depending on the frequency of crashes the year that the treatment was implemented at the site.

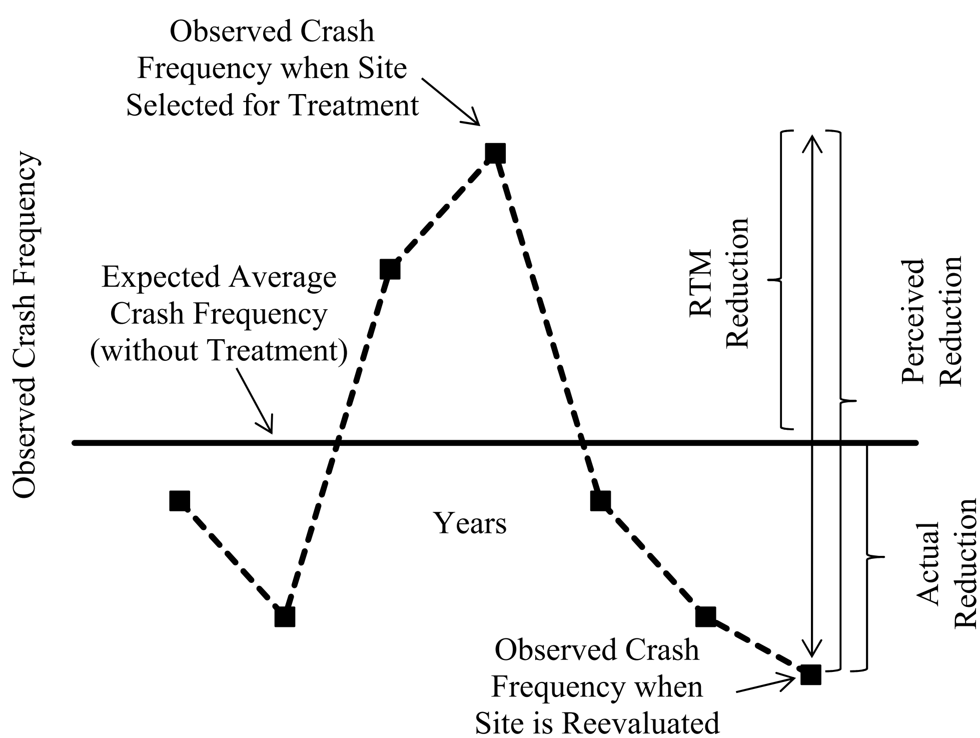


Figure 2-1: Perceived vs. actual reduction in crashes (adapted from AASHTO 2010).

2.2 Signal Warrants

Traffic signals are used by engineers in an attempt to reduce the frequency and severity of crashes at intersections as described in Section 2.1.1. It is important for traffic engineers and transportation agencies to know when to use traffic signals at an intersection. The Manual on Uniform Traffic Control Devices (MUTCD) provides guidelines for engineers and transportation agencies to use when determining when to install a new traffic signal at an intersection. The guidelines for installing signal upgrades, however, are less formal. This section will discuss new signal warrants and left-turn phasing warrants.

2.2.1 New Signal Warrant

The 2009 edition of the MUTCD provides nine warrants that engineers must analyze when deciding whether or not there is a need for a traffic signal at an intersection (FHWA 2009). The nine warrants are:

1. Eight-Hour Vehicular Volume
2. Four-Hour Vehicular Volume
3. Peak Hour
4. Pedestrian Volume
5. School Crossing
6. Coordinated Signal System
7. Crash Experience
8. Roadway Network
9. Intersection Near a Grade Crossing.

A traffic signal should only be installed if one or more of the warrants are met and an engineering study indicates that installing a traffic signal will improve the overall safety or operation of the intersection (FHWA 2009).

2.2.2 Left-Turn Phasing Warrants

Unlike the warrants provided for new traffic signal implementation, the MUTCD does not provide warrants for signal upgrades such as left-turn phasing. Instead this is left up to state and local governments while research agencies have provided warrants that states can consider adopting into their own regulations. Based on the literature and state and local guidelines, there are several different aspects to consider when implementing left-turn phases: delay, traffic volume, crash/conflict history, intersection geometry, and speed (Zhang et al. 2005).

Studies performed by Arizona State University and the University of Hawaii provided similar warrants that were based on several parameters: traffic volume, intersection geometry, speed, and crash history. Flow charts were developed in both cases to display the methodology that needs to be followed to select a left-turn phase appropriate for the intersection. It is unclear whether the states of Arizona or Hawaii adopted these suggestions and put them into practice; however, the guidelines provided can be very useful to state agencies as they determine left-turn phasing warrants (Matthias and Upchurch 1985, Zhang et al. 2005).

UDOT has developed warrants internally for left-turn phasing at existing signalized intersections. These warrants were originally developed in 1995, revised in 2006, and again revised in 2011. The 2011 revisions discuss the signal head display for protected/permissive phases. This revision was added because of the recent implementation of Flashing Yellow Arrow (FYA) signal faces in some areas of Utah. The warrants for a protected/permissive left-turn phase are:

1. A left-turn phase may be installed when the left-turn volume exceeds 100 vehicles per hour and a traffic engineering study reveals that the left-turn demand to capacity ratio is greater than or equal to 90 percent for any one hour of the day.
2. A left-turn phase may be installed when a three-year average left-turn crash rate exceeds 0.80 crashes per million vehicles.
3. A left-turn phase may be installed when both 80 percent of the volume (80 left-turn vehicles) and capacity ratio ($v/c \geq 0.72$) for Warrant 1 and 80 percent of the left-turn crash rate (0.64) for Warrant 2 is satisfied.
4. A left-turn phase may be installed when left-turn volume frequently exceeds storage capacity, resulting in interruption of through traffic flow as determined by an engineering study (UDOT 2011a).

Warrants for the installation of a signal head display for protected/permissive phases, specifically FYA signal faces are warranted at:

1. New traffic signals;
2. Existing traffic signals that meet minimum infrastructure and equipment requirements (UDOT 2011a).

2.3 Crash Prediction Methods

When analyzing the safety effects of a specific treatment at a site, an analyst can determine the actual percent change in crashes between the before and after periods by collecting actual crash data. To draw significant conclusions from the analysis, however, it is also necessary to estimate the number of crashes in the after period had there been no change to the system. This is more difficult to accomplish because predictions have to be made with statistical models rather than by observational studies. This section discusses three of the methods used to make these estimations: CMFs, Safety Performance Functions (SPFs), and local calibration factors.

2.3.1 Crash Modification Factors

A CMF is a factor that represents the percentage of crashes that changed at an intersection due to a specific treatment while all other conditions remain constant. Equation 2-1 shows how to calculate a CMF for the change in expected crash frequency from site condition ‘a’ to site condition ‘b.’ The site conditions ‘a’ and ‘b’ represent specified base conditions and the applied specific treatment at an intersection, respectively (AASHTO 2010).

$$CMF = \frac{Expected\ Average\ Crash\ Frequency\ with\ Site\ Condition\ b}{Expected\ Average\ Crash\ Frequency\ with\ Site\ Condition\ a} \qquad (2\text{-}1)$$

“A Guide to Developing Quality Crash Modification Factors,” produced by the FHWA, reports that there are multiple methods that can be used to calculate CMFs. These include traditional before-after studies, empirical Bayesian (EB) studies, hierarchical Bayesian studies, and some other less prevalent methods (Gross et al. 2010). These methods demonstrate how to predict the crash frequency after a change has been made at the site and are discussed in Section 2.4. Once the crash frequency has been found it can be applied to Equation 2-1 to calculate the CMF.

The HSM provides guidelines to develop CMFs as well. Following the calculation of a crash reduction factor (CRF), the CMF can be estimated using Equation 2-2 (AASHTO 2010).

$$CMF = 1.0 - \frac{CRF\ (\%)}{100} \qquad (2\text{-}2)$$

A CMF greater than 1.00 indicates a negative reduction in crashes meaning there was an increase in crashes after the treatment implementation. For example if the CMF for installing a new traffic signal at an intersection was 1.05, this would indicate that the crash frequency would increase by 5 percent after the installation of a traffic signal. Similarly, a CMF less than 1.00 represents a decrease in crashes. A CMF equal to 1.00 indicates that there was no change in the number of crashes after the improvement (Gross et al. 2010).

2.3.2 Safety Performance Functions

SPFs are used to estimate the average crash frequency for a facility type with specified base conditions. These functions predict the crash experience at a given site based on its traffic and physical conditions. SPFs are generally a function of annual average daily traffic (AADT), segment length, and a variety of additional attributes. SPFs are used to account for the RTM phenomenon that was discussed in Section 2.1.3 and for time trends and traffic volume changes. These functions can also be calibrated for each year to reflect time trends.

The regression parameters of SPFs are found by assuming crash frequencies follow a negative binomial distribution. This is similar to a Poisson distribution but better models crash frequencies. The Poisson distribution is used when the variance equals the mean of the data. In crash data, however, the variance is usually greater than the mean and is said to be over-dispersed (AASHTO 2010). SPFs are weighted with the observed crash counts so that they accurately reflect a specific site. The SPF weight is derived with an over-dispersion parameter and depends on the number of years of data that are available before treatment. Sites with a lower over-dispersion parameter have more weight placed on the crashes predicted from the SPF and less weight on the observed crash frequency. If many years of crash data are available, however, the weight placed on predicted crashes is reduced (Gross et al. 2010).

The HSM has developed SPFs for specific facility types: rural two-lane two-way roads, rural multilane highways, and urban and suburban arterials. These facility types each contain specific site types such as signalized and unsignalized intersections, and divided and undivided roadway segments (AASHTO 2010).

2.3.3 Local Calibration Factor

One difficulty that many transportation engineers face when applying results of national transportation safety studies to their local conditions is that the results often cannot be directly translated to the local area. Geographic regions are different in many ways as climates, animal populations, driver populations, and crash reporting methods vary. An example of this is that in Utah snow can be a factor in crashes while in Southern California, snow will not be a factor. To adjust for the differences in jurisdictions, the HSM method includes local calibration factors that can be developed to adjust the base model for local crash tendencies (AASHTO 2010). Similar to CMFs, calibration factors are multiplied by the crash frequencies developed by the SPF. Calibration factors are calculated using the relationship in Equation 2-3.

$$C_i = \frac{\sum observed\ crashes}{\sum predicted\ crashes} \qquad (2\text{-}3)$$

where, C_i = local calibration factor for site type *i*.

On a roadway that experiences less crashes than those used in the development of the SPF the calibration factor is less than 1.0. Similarly a calibration factor greater than 1.0 is used on roadways that experience more crashes than the roadways used in the SPF development (AASHTO 2010). CMFs can also be used with SPFs and local calibration factors to estimate the crash frequency at a site more accurately. Multiplying all of these together reduces the amount of error by correcting the uncertainty of both known and unknown factors that affect crashes on a roadway.

2.4 Methods of Analysis

This research uses CMFs to analyze the change in crashes after an improvement. There are multiple methods to develop CMFs as was mentioned in Section 2.3.1. This section looks at three different methodologies that are used for calculating CMFs: the traditional before-after method, EB method, and hierarchical Bayesian method. For all methodologies it is important to separate the different sample sites based on crash type, severity, geometry, treatment type, or other significant differences in the sites.

2.4.1 Traditional Before-After Method

The traditional before-after analysis of crashes is one of the most commonly used methods in determining CMFs. In the traditional before-after study, the CMF is found by estimating the actual change in the frequency of crashes that occurred within a specific time frame before and after the implementation of a treatment. The time frame is typically three or more years before and after the improvement. The traditional before-after method is useful when one is only trying to get a general idea of how safety has been affected. It is not an ideal method, however, if a researcher wants to accurately estimate future crashes at the site (Gross et al. 2010, Hauer 1997).

One problem that arises when performing traditional before-after studies occurs when there are relatively few crashes over a long period of time. This causes a larger standard error, which may lead to results that are too imprecise to be useful. Instead, a researcher would need numerous crashes in a short time period to produce accurate results with a small standard deviation (Hauer et al. 2002).

Other problems that occur during traditional before-after studies have to do with biases in the data. When using this method to develop CMFs it is important to look at other factors in the area that may be affecting the crashes at the study site. One possible bias occurs when the traffic volume has changed before and after the installment of the treatment at a given site. Traffic volume has an effect on the number of crashes and this change needs to be accounted for in the analysis.

There are multiple reasons for the crash frequency to fluctuate on a roadway including specific treatments, changes in site conditions over time, or simply natural fluctuations. This fluctuation in data can lead to the RTM phenomenon. Since researchers need a site with a high number of crashes in a small time period, RTM bias is likely to occur in the traditional before-after analysis.

2.4.2 Empirical Bayes Method

The EB method is quickly becoming one of the most common statistical methods used in safety studies and is described in detail by Hauer (1997). The HSM provides guidelines to produce CMFs using the EB method (AASHTO 2010). Bayesian methods provide more accurate results by combining information in accident counts with information about safety from similar sites. The information from similar entities is contained in the SPFs previously discussed in Section 2.3.2. Equation 2-4 demonstrates how these factors combine to estimate the expected number of crashes for a specific site.

$$N_{expected} = w \times N_{predicted} + (1 - w) \times N_{observed} \quad (2\text{-}4)$$

where, w = weighting factor,

$N_{expected}$ = estimate of expected average crash frequency,

$N_{predicted}$ = predicted value, and

$N_{observed}$ = observed crash frequency at the site.

The weighting factor (w) determines how much "weight" is given to the two estimate methods: the estimate derived using SPFs based on roadways with similar characteristics and the estimate of the expected number of crashes on the study site. The over-dispersion parameter (k) that corresponds with each SPF is used to determine the weighting factor. This means that the reliability of the safety estimation depends both on the strength of the crash record and the reliability of the SPF used. The reliability of the model is also represented in the weighting factor. The calculation of the weighting factor is shown in Equation 2-5.

$$w = \frac{1}{1 + k \times (\sum_{all\ years} N_{predicted})} \quad (2\text{-}5)$$

where, k = over-dispersion parameter of the associated SPF used to determine $N_{predicted}$, and

$N_{predicted}$ = predicted value.

Many recent studies performed to develop CMFs have used the EB methods to produce more statistically correct results. One advantage of using the EB method over the traditional before-after method is that the EB method adjusts for the RTM bias by determining the expected crash frequency of an entity (Hauer 1997). This is important for analyses that estimate safety partially or completely by crash history. Another advantage to using the EB method is that before data can be collected for as many years as reliable data are available prior to the treatment being installed. This improves the results of the model and can be more accurate than the three year period that is generally used in traditional before-after analyses, as long as the conditions remain the same.

Along with these advantages come some possible disadvantages with the EB method. One of the biggest disadvantages is the amount of time and effort that has to be put into the development of the factors used to implement the EB method (Gross et al. 2010). Another problem is that the EB method does not account for all uncertainty factors. It is important to make sure that data used in calculating the SPFs are the same as those used in the analysis (Powers and Carson 2004). It is often difficult for local jurisdictions to develop their own CMFs using local data because a large sample is needed to obtain confidence intervals (Davis and Aul 2007). Finally this method will not work unless both observed and predicted crash frequencies can be obtained for the roadway under analysis (Gross et al. 2010). These issues have led researchers to develop the hierarchical Bayesian approach that improves upon the EB method (Christianson and Morris 1997).

2.4.3 Hierarchical Bayesian Method

The hierarchical Bayesian method has emerged in recent years as a useful alternative to the EB approach. Christianson and Morris (1997) were some of the first researchers to use the hierarchical Bayesian method. The method was further changed to implement Markov Chain Monte Carlo (MCMC) computations (Davis 2000). The hierarchical Bayesian approach is similar to the EB method but allows researchers to specify complex model forms. This method uses as much historic data as can be found in order to more accurately predict the future crashes at a site.

There are several advantages that the hierarchical Bayesian method has over the EB method. One advantage is that it allows the use of smaller sample sizes to produce a valid model. This is useful for situations where the treatment is not used often or when evaluating the effects on rare crash types. Another important advantage is that spatial correlation is considered in the hierarchical Bayes method. This makes it possible to reduce effects caused by neighboring intersections and areas where a treatment was made that could affect the volume or crash data at the location being observed. It is also possible to utilize prior knowledge of data to the modeling along with newly collected data (Gross et al. 2010). The main problem with the hierarchical Bayesian method is that it is very complex and requires training in statistical methods.

The hierarchical Bayesian method was used for the analyses in this study. Brigham Young University (BYU) has developed a computer program that uses hierarchical Bayesian statistical methods to analyze crash data. The methodology used in the model will be discussed in Chapter 4. This method uses crash data before the improvement to create a distribution of crashes that is used to estimate the future crashes at a site. This analysis produces a more accurate prediction of future crashes even when little data are available (Olsen 2011, Olsen et al. 2011, Schultz et al. 2010, Schultz et al. 2011).

2.5 Safety Analysis of Signalized Intersections

Safety analyses have been performed for many years and it was important to identify these previous studies in the literature to compare results with the current study. This section discusses the methods and results found in the literature evaluating the safety impacts of installing a new traffic signal and modifying an existing traffic signal to include a left-turn signal phase. It is expected that the results from this research project will be similar to those found in the literature, although they will not be exactly the same. This section presents results from previous studies on the installation of a new signal and left-turn signal modifications.

2.5.1 New Signal

As cities become more populated, the streets become congested and traffic signals become warranted to improve safety, traffic progression, and to facilitate mobility. In order to justify the installation of a new traffic signal, warrants must be met. These warrants were discussed in Section 2.2.1 of the report. The installation of a traffic signal can have both positive and negative effects at the intersection, depending on the conditions surrounding the installation.

Several studies have been conducted to evaluate the effects of installing a new signal. Most of the studies use the traditional before-after method to determine the safety impacts. Both the total number of crashes and the effect on crash types were evaluated in the studies. A study published by the Transportation Research Board (TRB) in 2003 identified the general trends that were found in multiple traffic studies where a new traffic signal had been installed (McGee et al. 2003). This report identified the impacts of a new signal installation on overall crashes, right angle crashes, and rear-end crashes. A majority of the research showed that signal installation reduces the overall crash frequency at an intersection, although there were some exceptions. In regards to right angle crashes, there was a decrease in crashes at intersections for a majority of the studies. The TRB report indicates that, in general, there is a rise in rear-end crash frequency with the installation of a traffic signal (Agent 1988, Datta and Dutta 1990, Datta 1991, King and Goldblatt 1975).

Studies performed in Iowa and Indiana, produced similar safety impacts of installing a signal. Both studies showed an approximate 15 percent reduction in overall crashes after the installation of a signal (Ermer and Sinha 1991, Thomas and Smith 2001). For similar studies performed in Kentucky and Florida, researchers found closer to a 20 percent reduction in crashes. The studies in Kentucky and Florida also found that there was approximately a 60 percent reduction in right-angle crashes at intersections after the installation of a signal (Agent et al. 1996, Gan et al. 2005). A study performed at rural intersections in Minnesota and California found that installing a traffic signal at a rural intersection reduced total crashes by 44 percent, right-angle crashes by 77 percent, left-turn crashes by 60 percent, while rear-end crashes increased by 58 percent (Harkey et al. 2008).

The results from these studies indicate that, in general, the installation of a traffic signal decreases the frequency of overall crashes at an intersection. When focusing on crash types, however, there was a decrease in head-on and angle crashes while there was an increase in rear-end crashes after the installation of a traffic signal.

2.5.2 Modify Existing Signal

At high-volume intersections it is often necessary to install a left-turn signal with a corresponding left-turn phase included in the signal cycle. There are four main options for signal phasing that can be implemented in such circumstances including: permissive only, protected only, protected/permissive (i.e., leading), and permissive/protected (i.e., lagging).

Permissive only signalizations are signals that do not have a protected phase for left-turning traffic. The traffic must use gaps in oncoming traffic to make the turn. This left-turn phase is effective at intersections where the volume of left turns is relatively low, and the opposing traffic volume is small enough to allow vehicles to proceed safely through the gaps (Hauer 2004).

The protected only phase is an exclusive phase for left-turning traffic that allows vehicles to turn left without yielding to oncoming traffic. This type of phasing is implemented at high volume intersections, on roadways with very high speeds, and in situations with multiple turn lanes or limited sight distance (Hauer 2004). Protected left-turn phasing is also implemented at intersections with inadequate sight distance. Protected left-turn phasing is effective because the risk of having a crash between left turning vehicles and through vehicles is greatly reduced.

The protected/permissive (i.e., leading) left-turn phasing is a protected phase followed by a permissive phase. This allows left-turning vehicles to continue turning left if there was not enough time to do so during the protected phase. Permissive/protected (i.e., lagging) left-turn phases provide vehicles with a permissive left-turn and then a protected phase after through traffic has been stopped (Hauer 2004).

This project focused on the modifications that have to do with left-turn phases, primarily the use of protected only and protected/permissive left-turn phasing. Multiple studies were found in the literature for left-turn signal modifications using traditional before-after and Bayesian methods. In a study performed by Harkey et al. (2008), left-turn phase modifications were analyzed. Two of the modifications were conversions to protected only signals with the results combined to increase the sample size. The researchers found that when upgrading a permissive or permissive/protected signal to a protected only phase, left-turn crashes decreased by 99 percent, while overall crashes remained unchanged (Harkey et al. 2008).

In a similar study conducted in Kentucky, the results showed that upgrading to a protected only left-turn phase produced a 25 percent reduction in total crashes and a 70 percent reduction in left-turn crashes. For permissive only signals there was a 10 percent reduction in crashes. When upgrading to a protected/permissive phase at a signal there was approximately a 12 percent reduction in crash frequency (Agent et al. 1996). Other studies performed across the United States showed similar results with a decrease in crashes after the installation of a left-turn signal (Gan et al. 2005, Knapp et al. 2005, Maze et al. 1994). The results from these studies indicate a decrease in overall and left-turn crash frequencies for left-turn signal modifications.

2.6 Benefit-to-Cost Analysis

A final portion of this project consisted of computing B/C ratios for each type of intersection studied. The cost of installation was used for the costs, while benefits were determined by the reduction in crash frequency and the corresponding dollar values depending on the severity of the crash. This section will discuss crash severity, crash costs, and the process of calculating a B/C ratio.

2.6.1 Crash Severity

The HSM defines crash severity as “the level of injury or property damage due to a crash” (AASHTO 2010). The KABCO scale is used in the HSM to divide crashes into categories based on injury severity. The crash severity levels of KABCO are:

K – Fatal injuries;

A – Any injury other than a fatal injury that prevents the injured person from walking, driving, or continuing normal activities the person was previously capable of;

B – Non-incapacitating evident injury including those injuries that can be seen at the scene of the crash, but is not fatal or incapacitating;

C – Any injury reported or claimed that are not evident or in the previous categories;

O – No injury, property damage only (AASHTO 2010).

The severity of crashes identified in the crash database provided by UDOT use similar crash severity levels, but use numerical categories (1–5) rather than the KABCO scale. The correlation of the UDOT and HSM severity categories is shown in Table 2-1.

Table 2-1: HSM and UDOT Severity Levels

HSM Severity Level	UDOT Severity Level	Crash Type
K	5	Fatal
A	4	Incapacitating Injury
B	3	Non-incapacitating injury
C	2	Possible Injury
O	1	Property Damage Only

2.6.2 Crash Costs

The estimated change in crash frequency can be converted to a monetary value through the use of societal crash costs established by the FHWA (AASHTO 2010). These societal costs have been developed for crashes of each level of the KABCO scale. The estimated costs include the monetary losses associated with medical care, emergency services, property damage, and lost productivity. These values were recently updated to more accurately reflect the true cost of crashes (Duvall and Gribbin 2009).

UDOT has developed its own crash cost estimates based on the 2009 FHWA standards. The UDOT crash costs use FHWA costs as a base but assign the same monetary value to both fatal and incapacitating injury crashes. This variation from FHWA reflects the lifelong burden and costs that an incapacitation injury incurs on society (UDOT 2009). A comparison of the UDOT and FHWA societal crash costs are shown in Table 2-2.

Table 2-2: FHWA and UDOT Crash Costs by Severity (Duvall and Gribbin 2009, UDOT 2009)

Severity	Collision Type	FHWA Crash Costs	UDOT Crash Costs
5 (O)	Fatal	$5,800,000	$785,000
4 (C)	Incapacitating Injury	$401,538	$785,000
3 (B)	Non-incapacitating injury	$80,308	$80,000
2 (A)	Possible Injury	$42,385	$42,000
1 (K)	Non-injury	$4,462	$4,400

2.7 Chapter Summary

There are multiple methodologies used to determine the effectiveness of safety improvements and if the improvement is cost effective. Evaluating the change in crashes from the implemented treatments using a CMF is an effective way to assess the effectiveness of specific treatments. Traditional before-after and Bayesian statistical methods are typically used to develop CMFs. The traditional before-after analysis of crash data is often insufficient in determining the actual effects of a treatment because of incorrect assumptions that all other factors remain unchanged. The RTM phenomenon is also not taken into consideration in this analysis and can skew the results of the analysis. The EB and hierarchical Bayesian methods are more accurate methodologies to follow when analyzing crash data. The hierarchical Bayesian method was used in this study to analyze the safety effects of installing a new traffic signal or modifying left-turn phasing at an existing traffic signal.

A model developed by BYU was used to perform the analyses and develop CMFs reflecting the change in crash frequency after the improvement. A B/C analysis was performed for both new and modified traffic signals to identify if the reduction in crashes produces enough savings to be beneficial in respect to the installation cost. The results from these analyses are discussed in Chapter 5 and Chapter 6.

3 DATA COLLECTION

To determine the safety effects of new traffic signal installations and modifications to existing signals, intersection and crash data were gathered for intersections throughout the state of Utah. This chapter discusses the process used to select the study sites, details about the intersection data, and details about the crash data and AADT data used for analysis.

3.1 Site Selection

Study sites were selected from databases containing lists of UDOT projects completed at signalized intersections throughout the state of Utah over the past nine years. To select applicable sites from these lists it was necessary to focus on the date that the signal installation or modification occurred and the type of modification performed. The databases provided a funding year for the project that was not always consistent with the date that the construction took place; thus it was necessary to determine when the actual project was completed. The use of these lists and GoogleEarth made it possible to create a list of potential study sites. Researchers then conducted site visits to each intersection on the potential list in order to compile the actual date of the project and what was done at the intersection during the project. The log book located in each signal control cabinet was used to identify this information.

Based on sensitivity analyses and discussions with the Technical Advisory Committee (TAC), it was determined that at least two years of before and after data would be required for each intersection analyzed in the study. Typically, three years of before and after crash data would be recommended for each signal; however, researchers and the TAC determined that since 2002-2011 crash data would be used the sample size of signals would be too small for that many years of data. With three years of data before and after the improvement, only signals installed or modified from 2005-2008 could be used in the study. Using at least two years of before data and two years of after data in the analysis allowed signals installed or modified from 2004-2009 to be analyzed.

3.2 Intersection Data

There were a total of 108 intersections selected for the study: 77 new signals and 31 modified signals. The 77 new signals that were selected for analysis are shown in Table 3-1. The list of 31 modified signals and corresponding data are shown in Table 3-2. Information about each intersection was included in the lists of signals including: route, milepost, cross street, city, speed, and functional class. This section discusses the importance of mileposts, functional area, and speed in relation to this study.

Table 3-1: List of New Signals

Route	MP	Cross Street	City	Speed	Functional Class
SR-6	176.143	2550 East	Spanish Fork	60	Other Principal Arterial
SR-6	177.200	SR-198	Spanish Fork	60	Other Principal Arterial
SR-9	4.950	3700 West	Hurricane	55	Other Principal Arterial
SR-9	5.352	3400 West	Hurricane	55	Other Principal Arterial
SR-18	0.808	900 South	St. George	45	Other Principal Arterial
SR-32	12.655	SR-150	Kamas	35	Minor Arterial
SR-36	56.781	2000 North	Tooele	40	Other Principal Arterial
SR-36	59.298	Erda Way	Tooele	60	Other Principal Arterial
SR-36	60.821	Bates Canyon Road	Tooele	60	Other Principal Arterial
SR-39	4.341	1200 West	Ogden	50	Other Principal Arterial

Table 3-1: Continued

Route	MP	Cross Street	City	Speed	Functional Class
SR-40	113.839	State Street	Roosevelt	55	Other Principal Arterial
SR-40	121.403	7500 East	Fort Duchesne	50	Other Principal Arterial
SR-40	142.052	1000 South	Vernal	50	Other Principal Arterial
SR-40	142.818	500 South	Vernal	50	Other Principal Arterial
SR-40	145.866	500 South	Naples	45	Other Principal Arterial
SR-40	148.242	SR-45	Naples	45	Other Principal Arterial
SR-52	0.535	1200 West	Orem	45	Other Principal Arterial
SR-52	1.543	400 West	Orem	40	Other Principal Arterial
SR-68	33.570	Harvest Hills Blvd	Saratoga Springs	50	Minor Arterial
SR-68	44.305	11010 South	South Jordan	45	Other Principal Arterial
SR-71	2.247	1830 West	South Jordan	45	Other Principal Arterial
SR-74	1.550	1120 North	American Fork	35	Minor Arterial
SR-74	3.131	10400 North	Highland	45	Minor Arterial
SR-82	0.993	1400 South	Garland	40	Major Collector
SR-89	277.868	SR-116	Mt. Pleasant	55	Other Principal Arterial
SR-89	343.758	600 North	Lindon	55	Other Principal Arterial
SR-89	343.976	800 North	Lindon	55	Other Principal Arterial
SR-89	348.539	300 West	American Fork	35	Other Principal Arterial
SR-89	349.759	900 West	American Fork	45	Other Principal Arterial
SR-89	350.670	850 East	Lehi	35	Minor Arterial
SR-89	351.796	300 West	Lehi	50	Minor Arterial
SR-89	352.239	1500 North	Lehi	50	Minor Arterial
SR-91	28.204	1250 North	Logan	35	Other Principal Arterial
SR-91	40.004	Main St.	Richmond	45	Minor Arterial
SR-97	4.675	2200 West	Roy	35	Minor Arterial
SR-102	15.497	1000 West	Tremonton	40	Minor Arterial
SR-106	8.294	SR-225	Farmington	35	Minor Arterial
SR-107	1.503	3000 West	West Point	40	Major Collector
SR-108	5.003	700 South	Syracuse	45	Minor Arterial
SR-108	6.505	800 North	West Point	45	Minor Arterial
SR-108	8.011	2300 North	Clinton	45	Minor Arterial
SR-111	2.318	7800 South	West Point	50	Minor Arterial
SR-114	2.906	1390 North	Provo	45	Minor Arterial
SR-114	5.194	1000 South	Orem	45	Minor Arterial
SR-114	6.473	Center St.	Orem	45	Minor Arterial
SR-114	7.510	SR-52	Orem	45	Minor Arterial
SR-114	10.223	700 North	Lindon	50	Minor Arterial
SR-120	1.547	800 South	Richfield	45	Other Principal Arterial
SR-121	37.804	2500 West	Maeser	45	Minor Arterial

Table 3-1: Continued

Route	MP	Cross Street	City	Speed	Functional Class
SR-121	38.818	1500 West	Maeser	45	Minor Arterial
SR-126	1.242	500 North	Layton	40	Minor Arterial
SR-126	2.845	1600 North	Layton	45	Minor Arterial
SR-130	3.503	1045 North	Cedar City	45	Other Principal Arterial
SR-130	3.914	1325 North	Cedar City	45	Other Principal Arterial
SR-130	6.435	3000 North	Cedar City	55	Minor Arterial
SR-146	0.217	200 South	Pleasant Grove	30	Minor Arterial
SR-151	0.504	3200 West	South Jordan	40	Minor Arterial
SR-151	2.978	1055 West	South Jordan	45	Minor Arterial
SR-151	3.536	Riverfront Pkwy	South Jordan	45	Minor Arterial
SR-165	7.759	3200 South	Nibley	45	Minor Arterial
SR-172	8.521	300 South	Salt Lake City	50	Other Principal Arterial
SR-178	0.247	1270 West	Payson	35	Minor Arterial
SR-189	3.275	1450 North	Provo	35	Other Principal Arterial
SR-191	124.484	400 East	Moab	45	Other Principal Arterial
SR-198	5.859	600 East	Payson	30	Minor Arterial
SR-198	6.261	1000 East	Payson	40	Minor Arterial
SR-198	9.105	400 North	Salem	40	Minor Arterial
SR-198	10.494	Woodland Hills Dr.	Salem	55	Minor Arterial
SR-201	7.683	8000 West	Magna	55	Other Freeway-Expressway
SR-203	0.979	Shadow Valley Dr.	Ogden	50	Other Principal Arterial
SR-224	7.259	Meadow	Park City	45	Other Principal Arterial
SR-224	9.224	Old Ranch Rd.	Salt Lake City	45	Other Principal Arterial
SR-224	10.302	Bobsled Blvd.	Park City	55	Other Principal Arterial
SR-235	2.045	1700 North	North Ogden	50	Minor Arterial
SR-235	2.429	2000 North	North Ogden	50	Minor Arterial
SR-273	0.504	Haight Creek Dr.	Kaysville	45	Minor Arterial
SR-273	1.460	550 South	Kaysville	40	Minor Arterial

Table 3-2: List of Modified Signals

Route	MP	Cross Street	City	Speed	Functional Class
SR-6	173.984	800 North	Spanish Fork	65	Other Principal Arterial
SR-40	17.006	SR-113	Heber	35	Other Principal Arterial
SR-48	6.499	4800 West	West Jordan	50	Minor Arterial
SR-52	1.037	800 West	Orem	45	Other Principal Arterial
SR-71	14.184	Vine Street	Murray	45	Other Principal Arterial
SR-77	7.397	1750 West	Springville	40	Minor Arterial

Table 3-2: Continued

Route	MP	Cross Street	City	Speed	Functional Class
SR-89	335.590	800 North	Provo	40	Other Principal Arterial
SR-89	336.531	1720 North	Provo	60	Other Principal Arterial
SR-89	347.971	SR-74	American Fork	35	Other Principal Arterial
SR-89	350.056	SR-73	Lehi	45	Other Principal Arterial
SR-89	413.052	SR-79	Ogden	40	Other Principal Arterial
SR-89	458.970	400 North	Logan	40	Other Principal Arterial
SR-91	1.965	SR-89	Brigham City	55	Other Principal Arterial
SR-91	26.886	200 North	Logan	35	Other Principal Arterial
SR-108	1.568	Freeport Center	Clearfield	45	Minor Arterial
SR-114	0.363	900 West	Provo	35	Other Principal Arterial
SR-118	14.680	SR-120	Richfield	45	Minor Arterial
SR-126	10.737	4000 South	Roy	50	Minor Arterial
SR-126	12.726	2550 South	West Haven	55	Minor Arterial
SR-130	0.211	Cross Hollow Rd.	Cedar City	55	Other Principal Arterial
SR-130	4.720	1925 North	Cedar City	45	Other Principal Arterial
SR-151	2.145	Beckstead Ln.	South Jordan	40	Minor Arterial
SR-151	3.536	Riverfront Pkwy.	South Jordan	45	Minor Arterial
SR-154	22.267	California Ave.	Salt Lake City	55	Other Principal Arterial
SR-171	4.511	4800 West	West Valley City	40	Other Principal Arterial
SR-171	10.433	West Temple	South Salt Lake	35	Other Principal Arterial
SR-172	1.994	4700 South	Salt Lake City	45	Other Principal Arterial
SR-172	4.995	2700 South	West Valley City	45	Other Principal Arterial
SR-173	5.262	3600 West	Taylorsville	45	Minor Arterial
SR-173	9.635	100 West	Murray	40	Minor Arterial
SR-270	0.006	900 South	Salt Lake City	30	Minor Arterial

3.2.1 Functional Area

Functional area was an important aspect of this research project. The functional area of an intersection is the area that extends upstream and downstream from the physical intersection area including any auxiliary lanes and their associated channelization as illustrated in Figure 3-1 (AASHTO 2001). For this study, the functional area was estimated for each intersection by plotting the number of crashes on a route with the mileposts of corresponding intersections. The results of these graphs showed that the crashes fluctuated around the intersections and that a somewhat large functional area would be needed to capture all of the crashes at the intersection. There were concerns that a large functional area would capture crashes from neighboring intersections, thus GoogleEarth was used to find the distances to adjacent intersections.

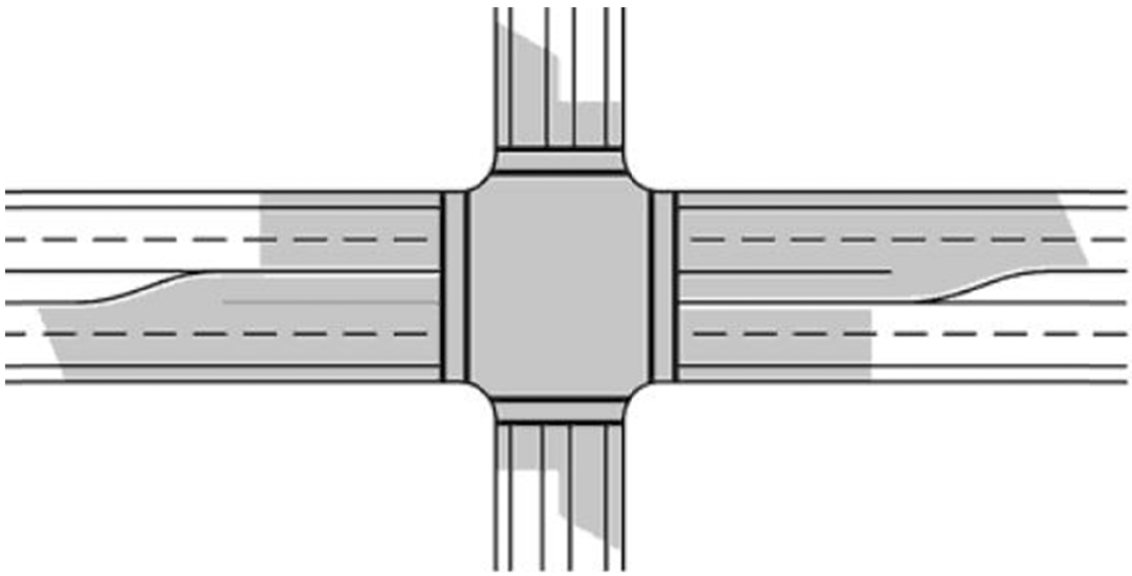


Figure 3-1: Functional area of an intersection (AASHTO 2001).

Rather than calculating an individual functional area for each intersection, the general conditions of the low-speed and high-speed roadways were evaluated. It was determined that intersections on low-speed roadways (< 45 mph) would have a functional area of 0.05 miles (265 feet) upstream and downstream of the intersection because in general the adjacent intersections were within 0.10 miles (528 feet) of the analyzed intersection. Intersections at high-speed intersections (≥ 45 mph) would use a functional area of 0.10 miles (528 feet) upstream and downstream of the intersection, as many left-turn bays extended more than 0.05 miles on high-speed roadways and researchers determined that the smaller functional area would not capture all of the crashes that were influenced by the intersection.

The functional areas selected for the intersections in this study are consistent with recommendations from the HSM which states that an intersection related crash "occurs at the intersection itself or on an intersection approach within 250 feet of the intersection and is related to the presence of the intersection" (AASHTO 2010).

3.2.2 Mileposts

Mileposts were used to identify which section of the route was being analyzed. Over the past 10 to 15 years, UDOT has made changes to the mileposts along state routes to make them more accurate. Although these changes have improved accuracy in general, these changes have made it difficult to compare historical data collected along state routes. In order to account for the changes, UDOT has worked to adjust the mileposts in older datasets to reflect the current system making it possible to use the older datasets; however there are still concerns with accuracy from years prior to 2002.

The mileposts for each intersection in this project were identified using the highway reference information provided on the UDOT website (UDOT 2012). The milepost that is recorded is the location of the center of the intersection. For the analysis, beginning and ending mileposts were identified to include the functional areas of each intersection that were previously discussed. These mileposts reference the state route that is identified as the major street for each intersection.

3.2.3 Speed

The speed at an intersection is important for a safety analysis because the speed of vehicles can affect the severity of crashes that occur at an intersection. In addition to severity impacts, it is anticipated that the presence of a traffic signal at a high speed intersection will cause a higher frequency of crashes due to the greater speed differential. The speeds for the 108 intersections in this study were obtained from the UDOT speed database (unpublished data from UDOT Traffic and Safety). The speeds ranged from 30 to 65 mph. High speed intersections were determined to be intersections with speeds of 45 mph or greater; while low speed intersections had speeds less than 45 mph.

3.3 Crash Data

After the list of intersections was established, crash data were needed for each intersection. Crash data were compiled for at least two years before and after the project date as discussed in Section 3.1. The year that the project actually occurred was not included in the analysis to account for any crashes due to construction or driver unfamiliarity with the signal.

Raw crash data were provided by the UDOT Traffic and Safety Division from the UDOT crash database. The UDOT crash database contains records and statistics obtained from police reports for crashes that occurred on all Utah state highways. The crash database was organized according to route and mileposts so that each crash could be correlated with a signal in the study. Subsets of the crash database were also collected for different crash types: rear-end, head-on, left-turn angle (LT angle), and sideswipe crashes.

As mentioned in Section 3.2.2, mileposts have shifted along state routes over the years for a variety of reasons. UDOT has worked to account for these adjustments in the datasets that were provided for this project, but to utilize the most accurate data as possible, it was determined that the analysis should only be conducted for the years 2002-2011, as the data since 2002 have been adjusted the most consistently and completely. The study sites were therefore limited to those intersections that had signals installed or modified in the years 2004-2009 to allow for at least two years of before and after data in the analysis.

3.4 AADT Data

AADT data are used to measure total volume of vehicle traffic on a highway or other roadway. Although previous research has determined that a generally non-linear relationship exists between crashes and AADT (Hauer 1997), AADT is still an important parameter to use in predicting crash frequency and was used as a covariant in the development of the model.

AADT data were collected for individual segments on Utah roadways using the annual "Traffic on Utah Highways" reports available on the UDOT website (UDOT 2011b). Each annual report provides AADT on Utah highways for the corresponding year as well as the previous two years. Each route is broken down to sections usually defined by physical barriers (county or state boundaries) or where changes in roadway attributes occur (such as intersections or interchanges). A spreadsheet was developed using AADT reports from the past 10 years. An example taken from the 2011 report (UDOT 2011b) is shown in Figure 3-2.

ROUTE NAME	BEG. ACCUM. MILEAGE	END ACCUM. MILEAGE	LOCATION DESCRIPTION	2011 AADT	2010 AADT	2009 AADT
0015	244.820	248.850	SR 198 Santaquin	30,480	31,320	31,675
0015	248.850	250.940	SR 178 Payson Salem	35,250	33,940	34,775
0015	250.940	253.570	SR 115 Payson/Benjamin	43,275	44,480	46,290
0015	253.570	257.280	SR 164 South Spanish Fork	43,400	43,930	45,010
0015	257.280	257.640	SR 156 Spanish Fork Main Street	57,225	59,860	58,340
0015	257.640	259.980	SR 6 Spanish Fork	76,680	80,195	78,175
0015	259.980	261.820	SR 77 Springville	89,410	93,525	91,155
0015	261.820	263.370	SR 75 North Springville/Provo	97,780	102,280	99,685
0015	263.370	265.620	SR 189 University Avenue Provo	86,335	90,310	88,020
0015	265.620	269.070	SR 114 Provo Center Street	104,600	110,110	102,660
0015	269.070	270.680	SR 265 BYU Diagonal/University Pkwy	126,000	132,630	123,610
0015	270.680	271.690	Orem Center Street	132,800	139,820	130,305
0015	271.690	272.880	SR 52 800 North Orem	140,225	147,610	137,570
0015	272.880	275.330	SR 241 Lindon Pleasant Grove	139,325	146,660	136,680
0015	275.330	276.500	Local Road (Route 2907) American Fork/Lindon	130,550	137,435	128,085
0015	276.500	278.590	SR 180 500 East American Fork	126,975	133,650	124,560
0015	278.590	279.730	SR 145 Main St American Fork	122,050	128,475	119,735
0015	279.730	282.330	SR 73 Lehi	119,570	118,035	110,005
0015	282.330	284.020	1200 West Lehi	123,110	121,530	113,260
0015	284.020	288.290	SR 92 Highland (Alpine)	136,575	134,820	125,650
0015	288.290	289.830	SR 140 14600 South Bluffdale (State Prison)	140,995	132,595	130,250
0015	289.830	291.370	SR 154 Bangerter Highway	163,780	133,210	130,855
0015	291.370	292.596	SR 71 12300 South Draper Riverton	150,000	142,670	140,145

Figure 3-2: Example of UDOT 2011 "Traffic on Utah Highways" annual report (UDOT 2011b).

3.5 Chapter Summary

Data collection was a very important task in this study. Databases provided by UDOT were combined with site visits to identify 108 intersections that had a traffic signal installed or modified between the years 2004-2009. The functional area, milepost, speed, and functional class were identified for each of the intersections in the study. Crash data were also collected from 2002-2011 to allow at least two years of before and after data to be used for each of the signals. AADT data were obtained for each intersection to be used as a parameter in the statistical model. The analyses that follow utilized the AADT and crash data to calculate the crash frequencies within the functional area of each intersection before and after the signal improvement.

4 ANALYSIS PROCEDURES

A hierarchical Bayesian model was used to determine the safety impacts of both new and modified signal installations as a function of crash reduction. A statistical model created by the BYU Statistics and Civil & Environmental Engineering Departments, was used to analyze several different scenarios. The new and modified signals were analyzed for multiple scenarios: all signals, LT angle crashes, head-on crashes, rear-end crashes, sideswipe crashes, speed, and functional class. This section discusses each of the scenarios that were analyzed. Following the discussion on the various analysis scenarios, details in the development of the model are provided. Finally, the B/C analysis used in the study is discussed. The results for each of the outlined scenarios are provided in Chapter 5 and Chapter 6 for new signals and modified signals, respectively.

4.1 Analysis Scenarios

This section describes the analysis scenarios performed for both new and modified signals. Several scenarios were analyzed including an overall analysis on all crashes and a severe crash analysis. Scenarios were also analyzed for crash types (LT angle, head-on, rear-end, and sideswipe), high speed (≥ 45 mph) and low speed (< 45 mph) intersections, and functional class.

4.1.1 Overall Crash Analysis

An overall crash analysis was performed on all crashes, including all crash severities, that occurred at sites before and after the installation of a traffic signal or the modification of an existing signal. At least two years of before and after data were necessary for each site in the analysis and the year that the installation occurred was excluded from the analyses for each site.

Overall crash analyses were performed on the total lists of new signal installations and signal modifications as well as for subsets of the data based on crash type, speed, and functional class. These other analyses are discussed later in Section 4.1, beginning in Section 4.1.3.

4.1.2 Severe Crash Analysis

Because a primary objective of this project was to evaluate the safety effects of signal improvements, specifically regarding high severity crashes, an analysis was performed on the data wherein severe and non-severe crashes were analyzed separately. Common practice by UDOT is to classify severe crashes as Severity 4(A) and Severity 5(K) while non-severe crashes include Severity 1(O), Severity 2(C), and Severity 3(B) crashes.

Severe crash analyses were performed on the total lists of new signal installations and signal modifications as well as for subsets of the data based on crash type, speed, and functional class. These other analyses are discussed in the remainder of Section 4.1.

4.1.3 Crash Type Analysis

A crash type analysis was performed for signal improvements to identify which specific crash types were increased or decreased. Four crash types were analyzed: LT angle, head-on, rear-end, and sideswipe crashes. A subset of the UDOT crash database was created for each of the crash types and used in the analysis. Based on the literature, the crash types of major concern were rear-end and LT angle crashes. It was anticipated from the literature results that there would be a decrease in LT angle crashes, while there would likely be an increase in rear-end crashes as discussed in Section 2.5.

4.1.4 Speed Analysis

Subsets of the lists of signals were made for high and low speed intersections. The purpose of the speed analysis was to identify whether traffic signals have a greater impact on crashes at high or low speed intersections. High speed intersections are those with a speed limit of 45 mph and greater; while low speed intersections have a speed limit of less than 45 mph as described in Section 3.2.1. Of the 108 total intersections in the study, 74 were high speed intersections and 34 were low speed intersections.

4.1.5 Functional Class Analysis

An analysis was performed to evaluate how crashes at intersections were affected by traffic signal improvements for different functional classifications. Two groups of functional classes were analyzed to ensure an adequate sample size. The first group is labeled as "other" and includes intersections classified as other principal arterials and other freeway/expressways; 56 intersections were identified as "other." The second group is labeled as "minor arterial" and includes both those classified as minor arterials and major collectors; 52 intersections were identified as "minor arterial." The functional classification of each intersection was reported previously in Table 3-1 and Table 3-2.

4.2 Development of Hierarchical Bayesian Model

A set procedure was followed in the analysis of crash data for the selected sites. A hierarchical Bayesian model based on previous research conducted at BYU was constructed to perform the analysis (Schultz et al. 2010). The development of the model was necessary to more accurately determine the safety impact of signal installations and modifications. This section outlines the development of the model by first outlining the background of the hierarchical Bayesian model, then identifying model specification and estimation, and finally model calibration (Olsen 2011, Olsen et al. 2011, Schultz et al. 2010, Schultz et al. 2011).

4.2.1 Background of Hierarchical Bayesian Modeling

In order to understand how the model utilized in this study operates, a few foundational statistical principles must be discussed. With respect to notation, denote $p(\cdot)$ as a marginal distribution and $p(\cdot\,|\,\cdot)$ as a conditional distribution. The foundation of Bayesian statistics is Bayes' rule outlined in Equation 4-1 (Gelman 2004):

$$p(\theta, y) = p(y)p(\theta|y) \tag{4-1}$$

where, y = crashes per mile, and

θ = mean number of crashes per mile.

This equation can be rearranged and written as outlined in Equation 4-2:

$$p(\theta|y) = \frac{p(\theta,y)}{p(y)} = \frac{p(y|\theta)p(\theta)}{p(y)} \tag{4-2}$$

The distribution $p(\theta)$ denotes the prior distribution for θ. The prior, also referred to as a prior probability distribution, of an uncertain quantity p is the probability distribution that would express the uncertainty about p before the data are taken into account. It is meant to attribute uncertainty associated with that data rather than randomness to the uncertain quantity. The prior is useful in that it allows the incorporation of information available into the model before the collection of data and reflects the belief of what will happen. The distribution $p(y|\theta)$ is the likelihood of the data given the parameter θ. The conditional distribution $p(\theta|y)$ is the posterior distribution of θ given the data. The posterior distribution is used to draw conclusions in this study.

4.2.2 Model Specification and Estimation

A hierarchical Bayesian model was constructed for the analysis. The model uses crash data and AADT data of selected analysis sites as inputs. Other covariates may also be included. It was assumed that y_i is Poisson distributed as outlined in Equation 4-3:

$$y_i \sim Poisson(\theta_i). \tag{4-3}$$

The Poisson distribution is utilized due to crash data being classified as count data. This distribution is easily able to include the exposure parameter (AADT) associated with the number of miles in a given segment. The estimation of the mean number of crashes within the functional area of a given intersection is then calculated using Equation 4-4.

$$\log(\theta_i) = \beta_{O(T_j)} + \beta_1 AADT_i, \tag{4-4}$$

where, θ_i = the mean number of crashes within the functional area,

$AADT_i$, = AADT for the i^{th} observation, and

(T_j), = an indicator variable stating which category the i^{th} observation is in

where, $T_j = \begin{cases} 1 \text{ if in the category before, non-severe,} \\ 2 \text{ if in the category before, severe,} \\ 3 \text{ if in the category after, non-severe,} \\ 4 \text{ if in the category after, severe.} \end{cases}$

This result is the consideration of four intercepts: one for the before non-severe data, one for the before severe data, one for the after non-severe data, and one for the after severe data. AADT is constrained to be the same for each category. Note that the analysis could be restricted to categories 1 and 3 or 2 and 4, respectively in order to do a specific before-after analysis on non-severe data or severe data. Also, by the same means, the analysis can be performed for a specific severity level. The log transformation was chosen as part of the standard Poisson regression procedures.

The prior for each β_k where $k \in \{O1, O2, O3, O4, 1\}$ is normally distributed as defined in Equation 4-5 where each *Oj* represents one of the four categories.

$$\beta_k \sim Normal\ (0,1) \tag{4-5}$$

These priors are quite uninformative, which reflects the lack of convincing evidence to suggest more specific priors.

The posterior distribution for the β parameters is expressed in Equation 4-6.

$$\pi(\beta|y) \propto P(y|\beta)\pi(\beta_{O_1})\pi(\beta_{O_2})\pi(\beta_{O_3})\pi(\beta_{O_4})\pi(\beta_1) = \frac{\exp(\sum_{i=1}^{m} \exp(X_i\beta))}{\prod_{i=1}^{m} y_i!} \times$$
$$\frac{1}{(\sqrt{2\pi})^3} exp\left[-\frac{1}{2}({\beta_{O_1}}^2 + {\beta_{O_2}}^2 + {\beta_{O_3}}^2 + {\beta_{O_4}}^2 + {\beta_1}^2)\right] \tag{4-6}$$

where, X_i = matrix containing appropriate covariates to satisfy the model, and

m = total number of observations.

Due to the complexity of the posterior distribution, rather than deriving the distribution theoretically, it was determined to sample from the posterior using MCMC methodology. This involves beginning with initial values and sampling each of the β_k parameters one at a time from the complete conditional distributions, using the newly sampled value in ensuing complete conditional calculation. The results of the algorithm are a number of random draws from the posterior distribution for each of the β_k parameters. In this study, each site was modeled with its own set of β parameters for both overall and severe crashes. The modeling code developed for the analysis is included in Appendix A.

4.2.3 Model Calibration

The traditional before-after method was used to verify that the hierarchical Bayesian statistical model was calculating reasonable results for the CMFs and to obtain actual numbers of before crashes per year for each severity to be used in the B/C analysis. The number of before and after crashes per year were found for each severity at each signal in the study. The crashes that occurred during the year that the signal was installed or modified were not included in the analysis. The average number of before and after crashes per year for each severity of the KABCO cycle, as discussed in Section 2.6, were calculated and used to find a CRF for each severity. The CRF was calculated using Equation 4-7. A CMF was calculated from the CRF using Equation 2-2. The resulting CMFs are shown in comparison to the hierarchical Bayesian model outputs in Chapter 5 and Chapter 6 for new and modified signals, respectively.

$$CRF = \frac{(Average\ Before\ Crashes - Average\ After\ Crashes)}{Average\ Before\ Crashes} * 100 \quad (4\text{-}7)$$

4.3 Benefit-to-Cost Analysis

A B/C analysis was performed for the new and modified signals using a standard methodology provided by UDOT. The data needed for the B/C analyses were CMFs for each severity, the average number of before crashes per intersection per year (cr/int/yr) for each severity, the project service life, and the project cost. A traffic growth factor of 1.5 percent and a discount rate of 9.0 percent were used for each analysis based on UDOT standards (unpublished spreadsheet from UDOT Traffic and Safety). The maintenance costs were not included in the cost analyses, thus a 10 year project service life was used for both new signal installations and signal modifications in accordance with standard UDOT practice.

The estimated reduction of crashes for each crash severity was calculated by multiplying the CRFs by the average frequency of before crashes per intersection. The benefit was then calculated by multiplying the estimated reduction of crashes for each severity by the corresponding cost per crash as shown previously in Table 2-2. The benefits for each severity were summed to estimate the total annual crash benefits. With the total annual crash benefit for the current year, the future crash benefits were estimated for each of the years in the project service life using a 1.5 percent traffic growth rate in Equation 4-8 and converted into a present worth benefit using a 9.0 percent discount rate in Equation 4-9 (Fricker and Whitford 2004). The B/C ratios for new and modified signals were found by summing the present worth benefits for each year and comparing that to the project cost. It should be noted that the B/C ratio focuses specifically on safety benefits and costs, and does not take into consideration any operational benefits or costs due to the installation of new signals or modification to existing signals.

$$(Crash\ Benefits)_n = A_1 * (1 + g)^{n-1} \qquad (4\text{-}8)$$

where, A_1 = annual crash benefit for $n = 1$,

g = traffic growth rate, and

n = number of years.

$$(Present\ Worth\ of\ Crash\ Benefits)_n = (Crash\ Benefits)_n * \frac{1}{(1+i)^n} \qquad (4\text{-}9)$$

where, i = discount rate.

The cost used in the B/C ratio only included the cost of installation or modification to the signal. Annual maintenance costs were not included in the analysis which is why a 10 year project service life was used when calculating the benefit. The operational costs were also excluded in the analysis. The installation or modification of a traffic signal can lead to an increase in vehicle delay and red light running rates, which were not taken into account in the B/C analyses.

Standard project costs for installing a new signal and installing a type 5 left-turn signal head were estimated by UDOT. The new signal installation cost estimates ranged from $200,000 to $250,000 including construction costs, design effort, inspection, and state furnished materials. It was assumed that the cost was for a standard three-or four-legged intersection and did not include right-of-way costs or utility impact costs. It was determined by researchers and the TAC to use $250,000 for this analysis.

For modified signals the cost for installing a type 5 left-turn signal head was estimated to be between $11,600 and $22,500 including wiring, some conduit and potholing, adding a junction box on each corner, and traffic control. The modified signal costs did not include any roadway or concrete items, only the signal head replacement. Researchers and the TAC determined that a $22,500 modified signal cost be used for this B/C analysis.

The B/C ratio was calculated using Equation 4-10. Since the annual benefits change each year, the return-on-investment was then calculated using Equation 4-11.

$$B/C = \frac{Total\ Present\ Worth\ Benefits}{Project\ Cost} \quad (4\text{-}10)$$

$$P_g = \frac{A_1\left[1-\left(\frac{1+g}{1+i}\right)^n\right]}{i-g}\ if\ g \neq i \quad (4\text{-}11)$$

where, P_g = installation cost.

4.4 Chapter Summary

Several analyses were performed for both new signal installations and signal modifications using the hierarchical Bayesian model developed by BYU. An overall crash analysis was performed to identify the impact a traffic signal improvement has on the total frequency of crashes not based on severity. The severe crash analysis was used to evaluate the effects of the signal improvements on severe and non-severe crashes for all signals, high speed and low speed intersections, and intersections of different functional classes. Analyses were also performed for LT angle, head-on, rear-end, and sideswipe crashes separately. Following the CMF calculations a B/C analysis was performed for the new and modified signals using UDOT methodologies.

5 NEW SIGNAL RESULTS

Following the data collection and development of a hierarchical Bayesian model, the methodologies were applied to the study sites that had a new traffic signal installed to estimate the safety impacts of new traffic signal installations. This chapter presents the analysis methodology, the results for each of the analysis scenarios, and the resulting B/C analysis for the installation of a new signal.

5.1 Analysis Methodology

A hierarchical Bayesian analysis was performed on the data collected at the sites where a new traffic signal had been installed using the methodology outlined in Chapter 4. Five analyses were performed on the new traffic signals as outlined in Section 4.1. A B/C analysis was also performed on the new signals using the UDOT methodology outlined in Section 4.3.

A plot of the actual before and after crash data points and the mean of the posterior predictive distribution was produced for each analysis. This plot represents the mean regression line through the data points from a Bayesian perspective. The reduction in crashes was calculated by taking the mean of the posterior distribution of differences between the two intercepts. The plot is not included in the report for each of the analyses because the results are reflected in the corresponding output tables.

The hierarchical Bayesian model also provides output for each of the scenarios. The output includes the before and after posterior mean values with units of cr/int/yr and the projected reduction in crashes. These values are displayed in output tables where the reduction in crashes is displayed as a CRF where a positive number represents a decrease in crashes and a negative number represents an increase in crashes. The corresponding CMF was also calculated for each scenario using Equation 2-2 where values less than 1.00 reflect a reduction in crashes and those greater than 1.00 reflect an increase in crashes. The total and average frequencies of crashes were found for each analysis scenario to represent the sample size.

5.2 Overall Crash Analysis

The first analysis performed on the new traffic signals was an overall crash analysis to identify the overall safety impacts of traffic signals as described in Section 4.1.1. The analysis was conducted for all 77 intersections with a new signal installation using the hierarchical Bayesian statistical model and included all severities. The distributions of crashes per year by AADT for the overall before and after crashes are shown in Figure 5-1. This figure indicates that overall there was an increase in crashes after the installation of a traffic signal.

Table 5-1 displays the resulting CRF and CMF for the overall crash analysis of new signal installations. Overall there was an increase in crashes with the installation of a traffic signal. These are not surprising results because as signals are installed more rear-end and other non-severe crashes may occur; the goal is to decrease severe crashes and fatalities.

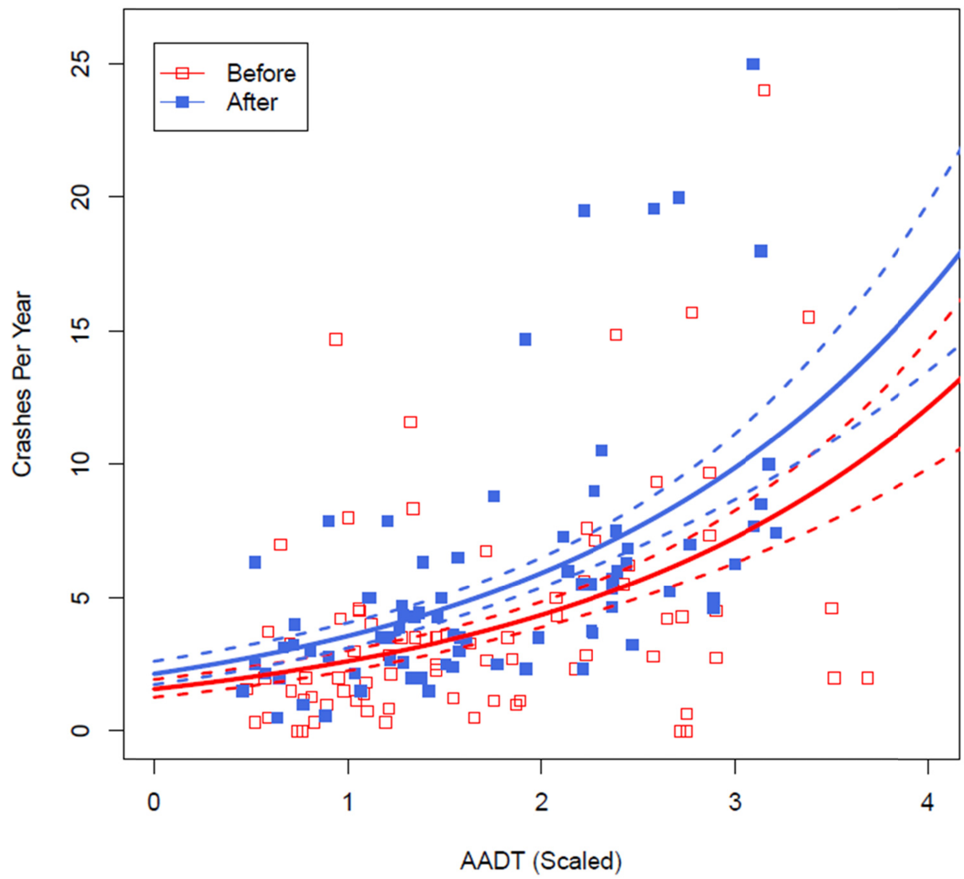


Figure 5-1: Overall crashes for new traffic signals.

Table 5-1: Overall Crash Analysis Results for New Signal Installations

	Before/After Total Crash Frequency	Before/After Crash Frequency (cr/int/yr)	Before/After Posterior Mean (cr/int/yr)	CRF	CMF
Overall	1443/2323	4.61/6.00	10.51/14.29	-35.9%	1.36

5.3 Severe Crash Analysis

To identify if the traffic signals are reducing severe crashes, an analysis that separated severe and non-severe crashes was performed. Severe crashes included Severity 4(A) and Severity 5(K) crashes as was discussed in Section 2.6; non-severe crashes include severities 1(O), 2(C), and 3(B). The results for the severe crash analysis for new signals are shown in Table

5-2. This analysis included all 77 of the intersections in the study that had a new traffic signal installed.

Table 5-2: Crash Analysis Results by Severity for New Signal Installations

	Before/After Total Crash Frequency	Before/After Crash Frequency (cr/int/yr)	Before/ After Posterior Mean (cr/int/yr)	CRF	CMF
Non-Severe (1-3)	1356/2273	4.31/5.85	9.65/13.69	-41.9%	1.42
Severe (4-5)	87/50	0.29/0.15	0.71/0.40	44.5%	0.55

The results indicate that there is an estimated 45 percent reduction in severe crashes and an estimated 42 percent increase in non-severe crashes with the installation of a new traffic signal. These results are not surprising because a traffic signal should decrease the fatalities and incapacitating injuries that occur with head-on collisions and crashes involving left-turning vehicles, but more non-severe rear-end crashes may occur. These assumptions are further analyzed in Section 5.4.

5.4 Crash Type Analysis

Since the severe crash analysis indicated an expected increase in non-severe crashes and an expected decrease in severe crashes, a crash type analysis was performed on the data to estimate a change in crashes based on a specific crash type: LT angle, head-on, rear-end, and sideswipe crashes.

5.4.1 Left-Turn Angle Crashes

A LT angle crash is a crash that involves a vehicle making a left turn or a U-turn at an intersection. It is anticipated, based on the information presented in the Literature Review

(Section 2.5.1), that the installation of a traffic signal should result in a decrease of LT angle crashes, particularly severe LT angle crashes. The resulting CRFs and CMFs for overall, severe, and non-severe LT angle crashes are shown in Table 5-3.

Table 5-3: LT Angle Crash Analysis Results for New Signal Installations

LT Angle	Before/After Total Crash Frequency	Before/After Crash Frequency (cr/int/yr)	Before/After Posterior Mean (cr/int/yr)	CRF	CMF
Overall (1-5)	266/426	0.85/1.10	1.52/2.02	-33.3%	1.33
Non-Severe (1-3)	240/418	0.76/1.07	1.06/1.72	-62.6%	1.63
Severe (4-5)	26/8	0.09/0.03	0.18/0.10	47.8%	0.52

The results indicate similar results as the overall and severe crash analyses; there is an estimated increase in non-severe crashes and decrease in severe crashes. There is an estimated 33 percent increase in overall crashes. It should be noted, however, that there was less than one LT angle cr/int/yr before the installation of a traffic signal for the list of signals included in this study. The crash frequency indicates that the increase in crashes for overall and non-severe crashes was less than one cr/int/yr, thus the resulting CMFs should be used with caution.

5.4.2 Head-On Crashes

A head-on crash analysis was performed for the new signal installations. The results of the head-on crash analysis are shown in Table 5-4. The results show a decrease in both non-severe and severe crashes for the installation of new signals. These results are not surprising based on the Literature Review in Section 2.5.1. The crash frequency before and after the installation of a traffic signal was less than one cr/int/yr on average. Because of the low frequency of crashes, particularly for severe crashes, the resulting CMFs should be used with caution.

Table 5-4: Head-on Crash Analysis Results for New Signal Installations

Head-on	Before/After Total Crash Frequency	Before/After Crash Frequency (cr/int/yr)	Before/After Posterior Mean (cr/int/yr)	CRF	CMF
Overall (1-5)	197/108	0.63/0.24	1.89/0.82	57.0%	0.43
Non-Severe (1-3)	175/95	0.56/0.22	1.50/0.64	58.0%	0.42
Severe (4-5)	22/13	0.07/0.02	0.18/0.12	35.8%	0.64

5.4.3 Rear-End Crashes

An analysis of rear-end crashes at newly installed traffic signals was performed using the hierarchical Bayesian model. It is anticipated that rear-end crashes are primarily non-severe and will therefore reflect the results from the severe crash analysis and result in an increase in crashes. The results for the analysis are shown in Table 5-5.

Table 5-5: Rear-end Crash Analysis Results for New Signal Installations

Rear-End	Before/After Total Crash Frequency	Before/After Crash Frequency (cr/int/yr)	Before/After Posterior Mean (cr/int/yr)	CRF	CMF
Overall (1-5)	435/1104	1.40/2.83	5.07/10.97	-116.3%	2.16
Non-Severe (1-3)	425/1090	1.37/2.78	4.66/10.15	-118.0%	2.18
Severe (4-5)	10/14	0.03/0.05	0.21/0.27	-34.7%	1.35

As expected there is an increase in overall, severe, and non-severe rear-end crashes. These crashes are somewhat expected because a new signal may cause more stops in traffic and a higher likelihood that a rear-end crash may occur. The sample size of severe rear-end crashes was very small with less than 0.1 cr/int/yr before and after the installation of a traffic signal, thus the CMF for severe rear-end crashes should be used with caution.

5.4.4 Sideswipe Crashes

The final crash type analysis was for sideswipe crashes. The resulting CRFs and CMFs from the hierarchical Bayesian model are shown in Table 5-6. The crash frequencies indicate that the sample size was very small for this analysis, especially for the severe crashes with only 0.02 cr/int/yr before the installation of a traffic signal. The results follow in the same trends as the severe and LT angle crash analyses with a decrease in severe crashes and an increase in non-severe crashes. Because of the low crash frequencies, however, the results should be used with caution.

Table 5-6: Sideswipe Crash Analysis Results for New Signal Installations

Sideswipe	Before/After Total Crash Frequency	Before/After Crash Frequency (cr/int/yr)	Before/After Posterior Mean (cr/int/yr)	CRF	CMF
Overall (1-5)	118/168	0.39/0.44	0.77/0.89	-15.1%	1.15
Non-Severe (1-3)	114/167	0.37/0.44	0.61/0.75	-22.7%	1.23
Severe (4-5)	4/1	0.02/0.00	0.08/0.05	36.2%	0.64

5.5 Speed Analysis

The 77 intersections that had a new signal installed were analyzed in two separate groups based on the speed limit at each intersection. There were 56 high speed (≥ 45 mph) intersections and 21 low speed (< 45 mph) intersections included in the analysis. The results from the hierarchical Bayesian model are shown in Table 5-7.

Similar to the overall and severe crash analyses in Section 5.2 and Section 5.3, the results show an overall increase in crashes, an increase in non-severe crashes and a decrease in severe crashes for both high and low speed intersections. For low speed intersections the increase in overall and non-severe crashes was approximately 15 percent. There was a slight decrease in severe crashes, but with the small number of crashes included in the analysis the resulting CMFs should be used with caution. High speed intersections, on the other hand, saw an increase and decrease of about 50 percent for both non-severe and severe crashes, respectively. The installation of a traffic signal appears to have more safety impacts at high speed intersections than at low speed intersections.

Table 5-7: Speed Analysis Results for New Signal Installations

	Speed (mph)	Before/After Total Crash Frequency	Before/After Crash Frequency (cr/int/yr)	Before/After Posterior Mean (cr/int/yr)	CRF	CMF
Overall (1-5)	< 45	407/587	5.10/5.37	13.48/15.49	-14.6%	1.15
	≥ 45	1036/1736	4.42/6.24	9.84/14.07	-43.0%	1.43
Non-Severe (1-3)	< 45	393/576	4.95/5.25	12.54/14.52	-15.5%	1.16
	≥ 45	963/1697	4.08/6.08	8.86/13.46	-52.1%	1.52
Severe (4-5)	< 45	14/11	0.15/0.12	0.62/0.59	6.1%	0.94
	≥ 45	73/39	0.34/0.16	0.82/0.42	49.6%	0.50

5.6 Functional Class Analysis

A functional class analysis was performed on the 77 intersections with a new signal installation as described in Section 4.1.5. There were 36 intersections analyzed in the "other" group and 41 intersections classified in the "minor arterial" group. The resulting CRFs and CMFs from the hierarchical Bayesian model are shown in Table 5-8.

Table 5-8: Functional Class Analysis Results for New Signal Installations

	Functional Class	Before/After Total Crash Frequency	Before/After Crash Frequency (cr/int/yr)	Before/After Posterior Mean (cr/int/yr)	CRF	CMF
Overall (1-5)	Other	709/1364	5.02/7.52	10.61/17.29	-63.0%	1.63
	Minor Arterial	734/959	4.24/4.67	12.95/14.18	-9.8%	1.10
Non-Severe (1-3)	Other	661/1337	4.70/7.36	9.41/16.14	-71.4%	1.71
	Minor Arterial	695/936	3.98/4.53	11.62/13.18	-13.7%	1.14
Severe (4-5)	Other	48/27	0.32/0.16	0.80/0.47	41.6%	0.58
	Minor Arterial	39/23	0.26/0.14	0.83/0.53	37.6%	0.62

The results of the functional class analysis show similar results as the previous analyses. An approximate 63 percent increase in overall crashes is expected for intersections in the "other" group, while those classified in the "minor arterial" group are only expected to have a 10 percent increase in overall crashes. There is an expected increase of non-severe crashes and a decrease in severe crashes expected for both functional class groups analyzed in this study. There is a greater change in the number of crashes for intersections classified in the "other" group than in the "minor arterial" group.

5.7 Benefit-to-Cost Analysis

A B/C analysis was conducted using the UDOT methodology as described in Section 4.3. The analysis was only done for the total list of new signals, not for each of the subsets that were analyzed in the crash type, speed, and functional class analyses. The CRFs and CMFs calculated by the hierarchical Bayesian model for each severity and corresponding frequency of before crashes are shown in Table 5-9. The corresponding CMF calculated using the traditional before-after method, as described in Section 4.2.3, is also shown in Table 5-9 to show the similarity of results using the two methods.

Table 5-9: B/C Analysis Parameters for New Signal Installations

Severity	Before/After Total Crash Frequency	Before/After Crash Frequency (cr/int/yr)	Hierarchical Bayes CRF	Hierarchical Bayes CMF	Traditional Before-After CMF
1	894/1493	2.87/3.83	-38%	1.38	1.33
2	301/504	0.94/1.32	-51%	1.51	1.41
3	161/276	0.51/0.70	-45%	1.45	1.39
4	80/45	0.27/0.13	49%	0.51	0.51
5	7/5	0.02/0.02	6%	0.94	1.18

A majority of the new traffic signals were installed in 2004 and therefore only had the minimum two years of before data to analyze. Because of this, there was a small sample size for the before crash frequency. Using the standard UDOT B/C methodology outlined in Section 4.3 the total annual benefit for year one was calculated to be $61,188. The total present worth benefits were calculated to be $453,325 during the 10 year project service life. Using a cost of $250,000, as discussed in Section 4.3, the B/C ratio was calculated to be 1.81. The spreadsheets used for calculations are shown in Appendix B, Section B.1.

The B/C ratio indicates that the installation of a traffic signal is cost effective over the 10 year project service life; it is beneficial to identify approximately how long it will take to recover the costs of installation. This was estimated by solving for n in Equation 4-11. It is anticipated, therefore, that the cost of a new signal installation may be recovered in approximately 5 years.

5.8 Chapter Summary

There were five analyses performed on the sites that had a new traffic signal installed. Overall there was a 36 percent increase in total crashes. The severe crash analysis indicated that non-severe crashes increased by 42 percent while severe crashes decreased by 45 percent. Other analyses were performed identifying specific crash types, but sample sizes were small so the results should be used cautiously. The speed and functional class analyses reflected similar results as the overall and severe crash analyses; there is an increase in overall and non-severe crashes and a decrease in severe crashes. The speed analysis indicated that traffic signals have a greater impact on safety for high speed intersections than low speed intersections. A B/C analysis was performed on the new signals. A B/C ratio of 1.81 was calculated and it is anticipated that the $250,000 average installation cost can be recovered in approximately 5 years, based on safety only.

6 MODIFIED SIGNAL RESULTS

Following the data collection and development of a hierarchical Bayesian model, the methodologies were applied to the study sites that had a traffic signal modification, to estimate the safety impacts of modified traffic signals, specifically left-turn improvements. This chapter presents the analysis methodology, the results for each of the analysis scenarios, and the resulting B/C analysis for the modification of a traffic signal.

6.1 Analysis Methodology

A hierarchical Bayesian analysis was performed using the methodology outlined in Chapter 4 on the data collected at the sites where existing traffic signals were modified. The modifications included in the analysis were all left-turn phasing improvements with the majority being the installation of a 5-section left-turn signal head. The purpose of left-turn phasing improvements is to reduce the number of LT angle crashes at an intersection. It is predicted, based on the Literature Review in Section 2.5.2, that left-turn signal modifications result in a decrease in overall and severe crashes.

A plot of the actual before and after crash data points and the mean of the posterior predictive distribution was produced for each analysis. This plot represents the mean regression line through the data points from a Bayesian perspective. The reduction in crashes was calculated by taking the mean of the posterior distribution of differences between the two intercepts. This plot is not displayed in the report for each of the analyses because the results are reflected in the corresponding output tables.

The hierarchical Bayesian model also provides output for each of the scenarios. The output includes the before and after posterior mean values with units of cr/int/yr and the projected reduction in crashes. These values are displayed in tables, where the reduction in crashes is displayed as a CRF with a positive number representing a decrease in crashes and a negative number representing an increase in crashes. The corresponding CMF was also calculated for each scenario where values less than 1.00 reflect a reduction in crashes and those greater than 1.00 reflect an increase in crashes. The average frequency of cr/int/yr was found for each analysis scenario to represent the sample size.

6.2 Overall Crash Analysis

The first analysis performed on the intersections with a signal modification was an overall crash analysis to identify the overall safety impacts of traffic signal modifications at intersections. An analysis of the 31 modified intersections was performed using the hierarchical Bayesian statistical model and included all severities. Figure 6-1 displays the before and after crash frequencies as a function of AADT. This figure indicates that there was an increase in overall crashes with the modification of existing traffic signals.

The overall CRF and CMF for modified traffic signals are shown in Table 6-1. The results show an approximate 15 percent increase in overall crashes after the modification of traffic signals. Since the modifications all involved left-turn phasing improvements, these results were not expected. Based on the Literature Review in Section 2.5.2, it was expected that there may be an overall decrease in crashes at intersections with a left-turn signal improvement.

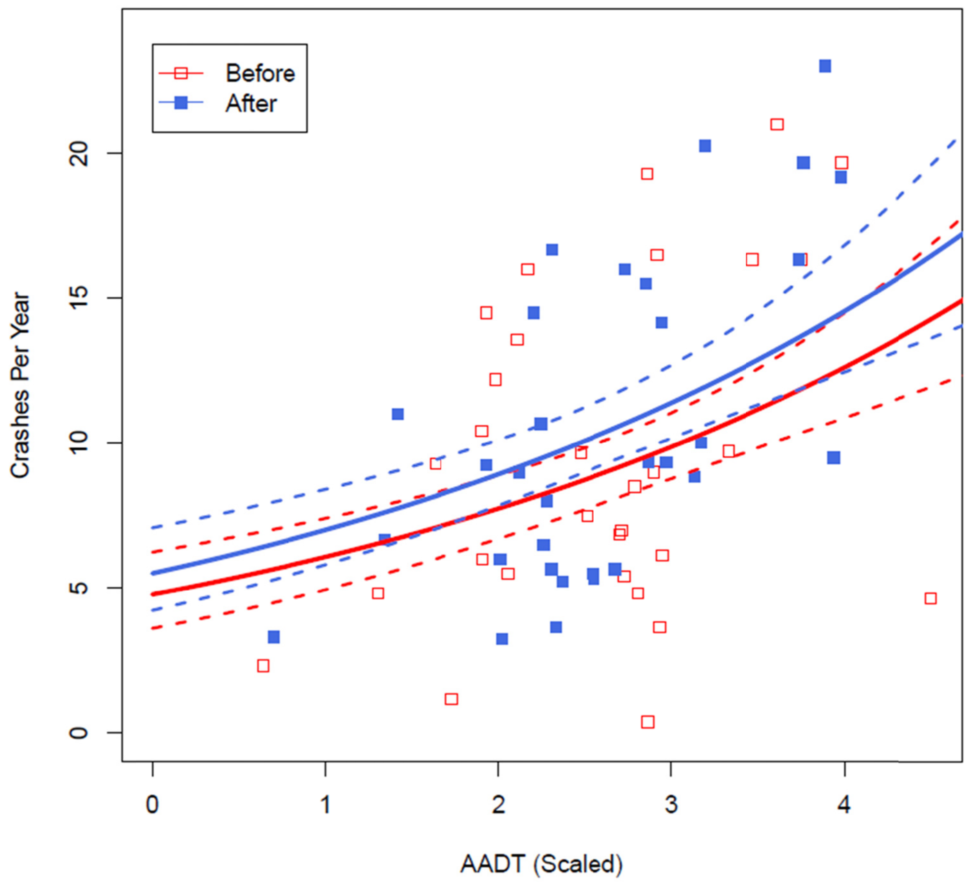


Figure 6-1: Overall crashes for modified traffic signals.

Table 6-1: Overall Crash Analysis Results for Signal Modifications

	Before/After Total Crash Frequency	Before/After Crash Frequency (cr/int/yr)	Before/After Posterior Mean (cr/int/yr)	CRF	CMF
Overall	1630/1218	9.56/10.58	10.81/12.48	-15.3%	1.15

There are several possible reasons that the results did not indicate a reduction in overall crashes after the modification of a traffic signal. One possible reason is that for a protected/permissive phase, turning vehicles may still be exposed to oncoming traffic at the end of the protected phase and at the end of the permissive phase. Drivers may attempt to sneak through the intersection at the end of the phases, thus leading to the potential for a crash. Another possible reason is that the green time for the left-turn phase comes at the expense of the through movement, thus there tends to be more stops and limited progression. This may cause red-light running, more aggressive driving, and a possible increase in crashes. One final possible reason for an increase in crashes could include a decrease in caution by drivers for turning vehicles with a protected phase; drivers may follow the vehicle in front of them without regards to the signal indication.

6.3 Severe Crash Analysis

A severe crash analysis was performed on the modified traffic signals using the methodology outlined in Section 4.1.2. The resulting CRFs and CMFs for both severe and non-severe crashes are shown in Table 6-2. The results show similar trends to the analyses on the new signal installations, namely an increase in non-severe crashes and a decrease in severe crashes.

Table 6-2: Crash Analysis Results by Severity for Signal Modifications

	Before/After Total Crash Frequency	Before/After Crash Frequency (cr/int/yr)	Before/After Posterior Mean (cr/int/yr)	CRF	CMF
Non-Severe (1-3)	1559/1195	9.13/10.39	10.22/12.11	-18.5%	1.19
Severe (4-5)	71/23	0.43/0.19	0.54/0.30	45.8%	0.54

6.4 Crash Type Analysis

Four analyses were performed to identify the effects that modified signals have on specific crash types: LT angle, head-on, rear-end, and sideswipe crashes. Based on the Literature Review in Section 2.5.2, it is anticipated that there may be a reduction in LT angle crashes and head-on crashes.

6.4.1 Left-Turn Angle Crashes

An analysis was performed on the 31 modified signals to identify the effects the improvements had on LT angle crashes. The purpose of left-turn phasing is to reduce the number of crashes involving left-turning vehicles, so it is expected that there may be a decrease in both severe and non-severe crashes. The resulting CRFs and CMFs are shown in Table 6-3.

Table 6-3: LT Angle Crash Analysis Results for Signal Modifications

LT Angle	Before/After Total Crash Frequency	Before/After Crash Frequency (cr/int/yr)	Before/After Posterior Mean (cr/int/yr)	CRF	CMF
Overall (1-5)	284/268	1.78/2.52	1.75/2.71	-55.1%	1.55
Non-Severe (1-3)	276/265	1.73/2.4/	1.47/2.37	-60.7%	1.61
Severe (4-5)	8/3	0.05/0.04	0.12/0.12	-2.4%	1.02

The results indicate an increase in both overall and non-severe crashes and relatively no change in severe crashes. These results do not reflect the findings of the Literature Review. Reasons for the different results are similar to those discussed in Section 6.2. The crash frequencies also indicate that there were very small sample sizes, especially for severe crashes. The resulting CMFs should be used with caution until more data are collected and the analysis performed again to verify these results.

6.4.2 Head-On Crashes

The 31 signal modifications were analyzed to identify the impacts on head-on crashes. The results are shown in Table 6-4. An estimated 78 percent reduction in overall and non-severe head-on crashes was found. There was an anticipated 58 percent reduction in severe head-on crashes as well. It should be noted again that the sample size of head-on crashes at the 31 modified signal locations was small and thus the results should be used with caution.

Table 6-4: Head-on Crash Analysis Results for Signal Modifications

Head-On	Before/After Total Crash Frequency	Before/After Crash Frequency (cr/int/yr)	Before/After Posterior Mean (cr/int/yr)	CRF	CMF
Overall (1-5)	262/37	1.44/0.36	1.71/0.39	77.6%	0.22
Non-Severe (1-3)	235/33	1.29/0.32	1.48/0.32	78.7%	0.21
Severe (4-5)	27/4	0.15/0.04	0.20/0.09	58.0%	0.42

6.4.3 Rear-End Crashes

An analysis identifying the impacts traffic signal modifications have on rear-end crashes was performed using the methodology outlined in Chapter 4. Table 6-5 displays the resulting CRFs and CMFs for overall, non-severe, and severe rear-end crashes. The results of the analysis show that there was an overall increase of crashes by approximately 29 percent. There was a 32 percent increase in non-severe rear-end crashes and a 33 percent decrease in severe rear-end crashes. The frequency of severe rear-end crashes at modified signal locations was very small for this study and thus the results should be used with caution.

Table 6-5: Rear-end Crash Analysis Results for Signal Modifications

Rear-End	Before/After Total Crash Frequency	Before/After Crash Frequency (cr/int/yr)	Before/After Posterior Mean (cr/int/yr)	CRF	CMF
Overall (1-5)	631/537	3.93/5.20	4.41/5.71	-29.4%	1.29
Non-Severe (1-3)	619/533	3.84/5.17	4.19/5.51	-31.5%	1.32
Severe (4-5)	12/4	0.09/0.03	0.17/0.12	32.8%	0.67

6.4.4 Sideswipe Crashes

The final crash type analysis for modified signals was performed for sideswipe crashes. The resulting CRFs and CMFs for non-severe and severe sideswipe crashes after the modification of a traffic signal are shown in Table 6-6. There was an increase in overall and non-severe sideswipe crashes by approximately 40 percent. There was relatively no change in severe sideswipe crashes. The sample size of sideswipe crashes was very small, especially for the severe crashes, and thus the results should again be used with caution.

Table 6-6: Sideswipe Crash Analysis Results for Signal Modifications

Sideswipe	Before/After Total Crash Frequency	Before/After Crash Frequency (cr/int/yr)	Before/After Posterior Mean (cr/int/yr)	CRF	CMF
Overall (1-5)	123/110	0.74/1.20	0.93/1.30	-40.6%	1.41
Non-Severe (1-3)	122/110	0.73/1.20	0.80/1.10	-38.1%	1.38
Severe (4-5)	1/0	0.01/0.00	0.07/0.07	-2.7%	1.03

6.5 Speed Analysis

Similar to the speed analysis described in Section 5.5, the 31 modified signals were analyzed based on high speed (≥ 45 mph) and low speed (< 45 mph) intersections. There were 18 and 13 high and low speed intersections, respectively included in the analyses. The resulting CRFs and CMFs calculated using the hierarchical Bayesian model are shown in Table 6-7.

Table 6-7: Speed Analysis Results for Signal Modifications

	Speed (mph)	Before/After Total Crash Frequency	Before/After Crash Frequency (cr/int/yr)	Before/After Posterior Mean (cr/int/yr)	CRF	CMF
Overall (1-5)	< 45	730/505	10.60/9.70	13.35/14.19	-5.7%	1.06
	≥ 45	900/713	8.82/11.22	10.13/13.01	-28.4%	1.28
Non-Severe (1-3)	< 45	703/494	10.20/9.51	9.00/10.02	-11.3%	1.11
	≥ 45	856/701	8.36/11.03	9.48/12.60	-33.0%	1.33
Severe (4-5)	< 45	27/11	0.40/0.19	0.52/0.37	30.2%	0.70
	≥ 45	44/12	0.46/0.19	0.61/0.35	44.2%	0.56

The results indicate that there may be a decrease in severe crashes and an increase in overall and non-severe crashes for both high and low speed intersections. The change in overall crashes at low speed intersections is less than 10 percent. Similar to the new signal installations, the signal modifications appear to have had a greater effect, both positive and negative, on the high speed intersections than on the low speed intersections.

6.6 Functional Class Analysis

A functional class analysis was performed on the 31 intersections with a signal modification as described in Section 4.1.5. There were 20 intersections classified in the "other" group and 11 intersections classified in the "minor arterials" group. The resulting CRFs and CMFs from the hierarchical Bayesian statistical model are shown in Table 6-8.

The results show an increase in overall and non-severe crashes at the intersections in the "other" category. There was a decrease in overall crashes and no change in non-severe crashes on the "minor arterial" intersections. Severe crashes were reduced on intersections for both functional classifications. Since only 11 intersections were included in the "minor arterials" group, the results should be used with caution until more data are collected for further analysis.

Table 6-8: Functional Class Analysis Results for Signal Modifications

	Functional Class	Before/After Total Crash Frequency	Before/After Crash Frequency (cr/int/yr)	Before/After Posterior Mean (cr/int/yr)	CRF	CMF
Overall (1-5)	Other	900/822	8.86/10.25	9.42/11.70	-24.1%	1.24
	Minor Arterial	730/396	10.84/11.19	18.95/18.31	3.2%	0.97
Non-Severe (1-3)	Other	865/806	8.49/10.06	8.93/11.30	-26.4%	1.26
	Minor Arterial	694/389	10.29/11.00	17.01/17.09	-0.7%	1.00
Severe (4-5)	Other	35/16	0.37/0.19	0.47/0.32	33.0%	0.67
	Minor Arterial	36/7	0.55/0.19	1.11/0.59	48.6%	0.51

6.7 Benefit-to-Cost Analysis

A B/C analysis was conducted using the UDOT methodology as described in Section 4.3. The analysis was only done for the total list of intersections that had a modification, not for each of the subsets that were analyzed in the crash type, speed, and functional class analyses. The CRFs and CMFs calculated with the hierarchical Bayesian model, the CMF calculated using the traditional before-after method for each severity, and corresponding crash frequencies are shown in Table 6-9.

Table 6-9: B/C Analysis Parameters for Signal Modifications

Severity	Before/After Total Crash Frequency	Before/After Crash Frequency (cr/int/yr)	Hierarchical Bayes CRF	Hierarchical Bayes CMF	Traditional Before/After CMF
1 (O)	1006/764	5.87/6.67	-19%	1.19	1.14
2 (C)	369/270	2.19/2.32	-12%	1.12	1.06
3 (B)	184/161	1.07/1.40	-33%	1.33	1.31
4 (A)	68/19	0.42/0.15	58%	0.42	0.36
5 (K)	3/4	0.02/0.04	-34%	1.34	2.45

The results of the analysis show an increase in fatalities after a signal modification; however, the very small crash frequency of 0.02 cr/int/yr should be noted. It is anticipated that with a larger sample size these results may change. Using the standard UDOT B/C methodology outlined in Section 4.3, the estimated annual benefit for year one was calculated to be $142,645. The total present worth benefits were calculated to be $1,056,819 during the 10 year project service life. Using a cost of $22,500, as discussed in Section 4.3, the B/C ratio was calculated to be 46.97. The spreadsheets used for the B/C analysis are shown in Appendix B, Section B.2.

The B/C ratio indicates that the modification of a traffic signal provides much more safety benefits than cost over the 10 year project service life; it is beneficial to identify approximately how long it will take to recover the costs of installation. This was estimated by solving for n in Equation 4-11 then converting the value into weeks. It is anticipated that the cost of a left-turn signal modification can be recovered in approximately 9 weeks.

6.8 Chapter Summary

There were five analyses performed on the sites that had an existing traffic signal modified to include a left-turn phase. Overall there was a 15 percent increase in total crashes. The severe crash analysis indicated that non-severe crashes increased by 19 percent while severe crashes decreased by 46 percent. Other analyses were performed identifying specific crash types, but sample sizes were small and thus the results should be used with caution. The speed analyses reflected similar results as the severe crash analysis; there is an increase in non-severe and a decrease in severe crashes. The speed analysis indicated that traffic signals have a greater safety impact on high speed intersections than low speed intersections. A B/C analysis was performed on the modified signals. A B/C ratio of 46.97 was calculated and it is anticipated that the $22,500 average signal modification cost can be recovered in approximately 9 weeks.

7 CONCLUSIONS

The purpose of this study was to determine the safety effects of signal improvements at intersections as a function of crash reduction. The preceding chapters have outlined the background of methods used in safety analysis. The analysis procedure using a hierarchical Bayesian model was utilized to analyze the safety impacts of signal improvements. The model was developed to estimate the reduction or increase in crash frequency as well as the corresponding reduction or increase in crashes at signalized intersections on Utah roadways. Multiple analyses were run based on different intersection characteristics such as crash type, speed, and functional class. Analyses identified the change in crashes for overall, severe, and non-severe crashes separately. The results of the study show an increase in overall crashes with an increase in non-severe crashes and a decrease in severe crashes for both new signal installations and signal modifications. This chapter summarizes the findings and conclusions of the research and provides suggestions for future research possibilities.

7.1 Findings and Conclusions

The analyses in this report were performed using a hierarchical Bayesian model that was developed in a previous research project and updated as part of the project. The model is a valuable tool that can be used for many different safety studies in the future. The model makes it possible to analyze different roadway segments and intersections where route and milepost data are available. It is also possible to analyze subsets of the crash database by simply creating a new spreadsheet to use as an input parameter. This study analyzed the effectiveness of installing a new traffic signal or modifying an existing signal and identified the effect each has on crash frequency and severity at selected locations. An analysis was performed for both new and modified signals separately. Multiple analyses were performed to identify the effects on overall crashes, severe and non-severe crashes, and for different subsets of the data based on speed at the intersection, functional class of the roadway, and crash type. A summary of the resulting CMFs for new signal installations are shown in Table 7-1. A summary of the resulting CMFs for modified signals are shown in Table 7-2.

Table 7-1: Summary of CMFs for New Signal Installations

	Overall (1-5)		**Non-Severe (1-3)**		**Severe (4-5)**	
	Before/After Total Crash Frequency	**CMF**	**Before/After Total Crash Frequency**	**CMF**	**Before/After Total Crash Frequency**	**CMF**
All Signals	1443/2323	1.36	1356/2273	1.42	87/50	0.56
LT Angle	266/426	1.33	240/418	1.63	26/8	0.52
Head-On	197/108	0.43	175/95	0.42	22/13	0.64
Rear-End	435/1104	2.16	425/1090	2.18	10/14	1.35
Sideswipe	118/168	1.15	114/167	1.23	4/1	0.64
High Speed	1036/1736	1.43	963/1697	1.52	73/39	0.50
Low Speed	407/587	1.15	393/576	1.16	14/11	0.94
Minor Arterial	734/959	1.10	695/936	1.14	39/23	0.62
Other	709/1364	1.63	661/1337	1.71	48/27	0.58

The results of the new signal installation analyses indicated a reduction in severe crashes, but an increase in non-severe and overall crashes. The increase in overall and non-severe crashes is anticipated to be primarily because of the crash types. As a result it is anticipated that the number of rear-end crashes may increase after the installation of a traffic signal. The analysis performed using the hierarchical Bayesian model validated this assumption and showed that the installation of a traffic signal may result in an increase in rear-end crashes and a decrease in head-on and severe LT angle crashes. This study provided evidence that installing a traffic signal is an effective technique to reduce the frequency of high severity crashes at intersections, but an increase in non-severe crashes can also be expected. The B/C analysis provided evidence that it is cost effective to install traffic signals, and the $250,000 cost of installation can be recovered in approximately 5 years.

Table 7-2: Summary of CMFs for Signal Modifications

	Overall (1-5)		Non-Severe (1-3)		Severe (4-5)	
	Before/After Total Crash Frequency	**CMF**	**Before/After Total Crash Frequency**	**CMF**	**Before/After Total Crash Frequency**	**CMF**
All Signals	1630/1218	1.15	1559/1195	1.19	71/23	0.54
LT Angle	284/268	1.55	276/265	1.61	8/3	1.02
Head-On	262/37	0.22	235/33	0.21	27/4	0.42
Rear-End	631/537	1.29	619/533	1.32	12/4	0.67
Sideswipe	123/110	1.41	122/110	1.38	1/0	1.03
High Speed	900/701	1.28	856/701	1.33	44/12	0.56
Low Speed	730/505	1.06	703/494	1.11	27/11	0.70
Minor Arterial	730/396	0.97	694/389	1.00	36/7	0.51
Other	900/822	1.24	865/806	1.26	35/16	0.67

The results of the signal modification analyses showed similar results as the new signal installations: an increase in overall crashes and non-severe crashes and a decrease in severe crashes. It was anticipated that LT angle crashes would be reduced by a signal modification, but the results did not reflect this assumption. There were 31 signals included in the analysis which is a small sample size when analyzing scenarios using subsets of the list of signals and subsets of the crash database. The results of these analyses provide evidence that modifying an existing signal to improve left-turn movements is effective at decreasing the frequency of severe crashes at signalized intersections. It is recommended that data at more intersections be collected and analyzed to improve the accuracy of the results, specifically for the crash type analyses. Although the analyses did not show the reductions in crashes that were expected, the B/C analysis indicates that there is a safety benefit to left-turn phasing improvements at signalized intersections. It is anticipated, based on the sample analyzed, that it may take approximately 9 weeks to recover the $22,500 installation cost of modifying the traffic signal.

Finally, the results of this study would indicate that there is a need for improved data collection for signal improvement projects in the future. The hierarchical Bayesian model that was developed for this project can be used in the future to develop CMFs and analyze other signal improvements, such as the FYA left-turn signals. To aid UDOT in future data collection, a one-page data collection form was created with all information needed to run the analyses. The front page of the data collection form is shown in Figure 7-1. The front of the form identifies the location of the intersection including the milepost and then asks questions about the changes made to signal timing and the intersection geometry. The beginning and end construction dates are also identified so that the data during that year can be discarded from the analysis. Finally the turn-on date, project cost, and room for additional comments are included. The back page of the data collection form, shown in Figure 7-2, includes two intersection diagrams to show the intersection configuration before and after the project is completed. The speed limit of the roadways, milepost, and the distance to the upstream and downstream intersections are also requested as part of the intersection diagram. Printable versions of the data collection form are provided in Appendix C.

Intersection Data Collection Form for Traffic Signal Improvement Projects

Intersection:________________________ **Date:**________________________

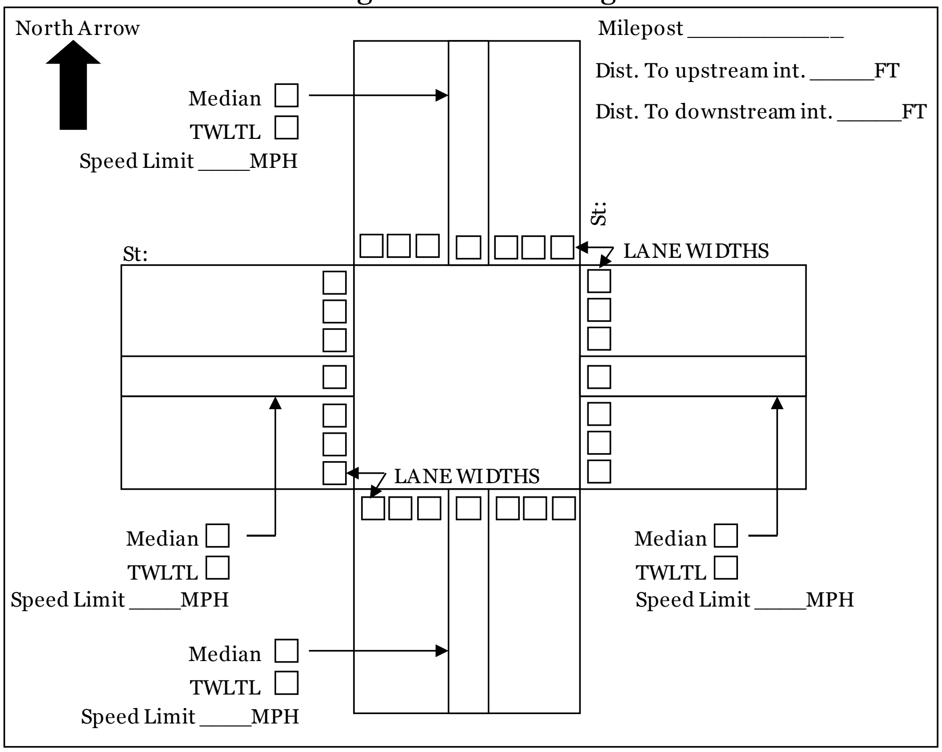
City:______________________________ **Analyst:**____________________

Milepost:__________ **Project No:**__________________

Data Collection	**Y**	**N**
Timing Changes? If Yes, provide details below		
Left Turn Changes? If Yes, provide details below		
New Signal Heads Added? If Yes, provide details below		
New lanes added? If Yes, show on configuration diagram on back of sheet		
New Right of Way added? If Yes, provide details including cost below		
Construction Start Date?		
Construction End Date?		
Signal Turn-On Date?		
Project Cost?		
Final comments & recommendations:		

Figure 7-1: Traffic signal improvement data collection form (front).

Existing Intersection Diagram[1]



New Intersection Diagram[1]

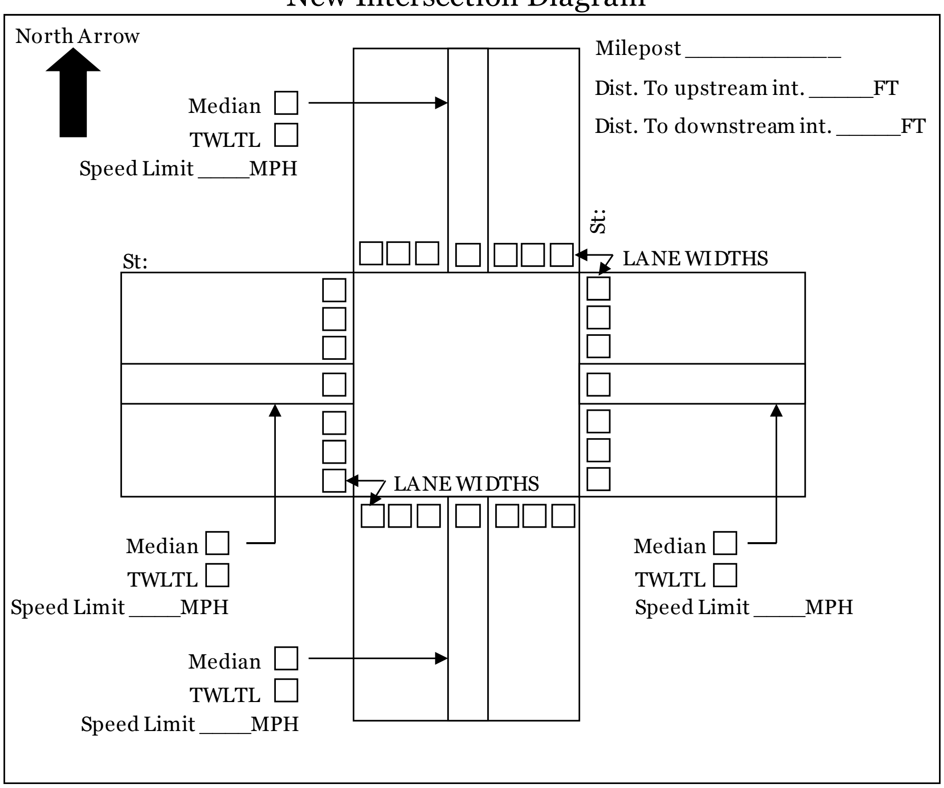


Figure 7-2: Traffic signal improvement data collection form (back).

7.2 Future Research

The methodology followed in this report is a valuable tool to be used in future transportation safety studies. It is recommended that this procedure be applied to future projects to determine CMFs for other types of intersection improvements. Potential intersection improvements to be analyzed include the safety effects of signal spacing, signal timing, and FYA left-turn signal installations. The model can also be used to analyze roadway segments rather than intersections; potential segment analyses include the safety effects of flex lanes on Utah roadways. The results of these studies would be beneficial to identify which improvements are most effective at reducing severe crash frequencies on Utah roadways.

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APPENDIX A MODELING CODE

This appendix presents the code utilized for the hierarchical Bayesian model used in this analysis. Code for the model is written in R.

A.1 Hierarchical Bayesian Model Code

```
### Model ###

### Read in Data ###

### Model

library(arm)

library(ggplot2)


poismod <- function(){

  for(i in 1:n){

    aadt2[i] <- aadt[i]/10000;

    crashes[i] ~ dpois(lambda[i]);

    log(lambda[i]) <-  b0 + b1*aadt2[i] + gam[tmt[i]];

  }

  b0 ~ dnorm(0,1);

  b1 ~ dnorm(1,1);

  gam[1] ~ dnorm(0,1);

  gam[2] ~ dnorm(0,1);

  gam[3] ~ dnorm(0,1);
```

```
  gam[4] ~ dnorm(0,1);
}
filename <- file.path(tempdir(),'poismod.bug')
write.model(poismod,filename)
crashes <- data2[,2]
aadt <- data2[,3]
tmt <- data2[,6]
n <- data2[,7][1]
data <- c('crashes','aadt','tmt','n')
parameters <- c('b0','b1','gam','lambda')
pois.sim <- bugs(data,inits=NULL,parameters,model.file='poismod.bug',
                n.iter=niter,n.burnin=1000,n.chains=1,n.thin=1,debug=F)
### Calculate Posteriors
attach(pois.sim$sims.list)
aadt1 <- seq(from=0,to=6,length.out=500)
#Before, Not Severe
post_bef_notsev <- exp(b0 + outer(b1,(aadt1),'*') + gam[,1])
#After, Not Severe
post_aft_notsev <- exp(b0 + outer(b1,(aadt1),'*') + gam[,3])
#Before, Severe
post_bef_sev <- exp(b0 + outer(b1,(aadt1),'*') + gam[,2])
#After, Severe
post_aft_sev <- exp(b0 + outer(b1,(aadt1),'*') + gam[,4])
### Plots
###Not Severe
pdf(paste(file,'_notsevere.pdf'))
plot((aadt[(n/n):(n/4)]/10000),crashes[(n/n):(n/4)],col='red',xlim=c(0,6),ylim=c(0,35),pch=0,main='Not
Severe',ylab='Crashes Per Year',xlab='AADT (Scaled)')
```

```
points((aadt[((n/2)+1):(3*n/4)]/10000),crashes[((n/2)+1):(3*n/4)],pch=15,col='royalblue')
lines(aadt1,apply(post_bef_notsev,2,mean),col='red',lwd=3)   # mean before
lines(aadt1,apply(post_bef_notsev,2,quantile,.025),lty=2,lwd=2,col='red')   # lower cred. interval before
lines(aadt1,apply(post_bef_notsev,2,quantile,.975),lty=2,lwd=2,col='red')   # upper cred. interval before
lines(aadt1,apply(post_aft_notsev,2,mean),col='royalblue',lwd=3)    # mean after
lines(aadt1,apply(post_aft_notsev,2,quantile,.025),lty=2,lwd=2,col='royalblue')   # lower cred. interval after
lines(aadt1,apply(post_aft_notsev,2,quantile,.975),lty=2,lwd=2,col='royalblue')   # upper cred. interval after
legend(0,35,c("Before, Not Severe","After, Not Severe"),pch=c(0,15),col=c('red','royalblue'),lty=c(1,1))
dev.off()
# Difference in Before-After
pdf(paste(file,'_notsevere_difference.pdf'))
diffnotsevere <- exp(gam[,3])-exp(gam[,1])
plot(density(diffnotsevere),lwd=3,xlim=c(-.5,1.5),main='Posterior Difference, After - Before',xlab='Difference')
cred_diffnotsevere <- quantile(diffnotsevere,c(.025,.975))
mean_diffnotsevere <- mean(diffnotsevere)
dev.off()
# Percent Reduction
pdf(paste(file,'_notsevere_percentreduction.pdf'))
rednotsevere <- exp(gam[,3])/exp(gam[,1])
plot(density(rednotsevere),lwd=3,main='Posterior For Percent Reduction',xlab='Percent Reduction')
abline(v=1,lwd=3,col='blue')
quantile(rednotsevere,c(.025,.975))
mean(rednotsevere)
dev.off()
percent_red_notsevere <- mean(rednotsevere<1)
mod_factornotsev1 <- median(rednotsevere)
if(mod_factornotsev1>1){
  mod_factornotsev <- mod_factornotsev1 - 1
```

```
} else{
  mod_factornotsev <- 1 - mod_factornotsev1
}
### SEVERE
pdf(paste(file,'_severe.pdf'))
plot((aadt[((n/4)+1):(n/2)]/10000),crashes[((n/4)+1):(n/2)],pch=2,col='red4',xlim=c(0,6),ylim=c(0,2),main='Severe',
ylab='Crashes Per Year',xlab='AADT (Scaled)')
points((aadt[((3*n/4)+1):n]/10000),crashes[((3*n/4)+1):n],pch=17,col='blue4')
lines(aadt1,apply(post_bef_sev,2,mean),col='red4',lwd=3)   # mean before
lines(aadt1,apply(post_bef_sev,2,quantile,.025),lty=2,lwd=2,col='red4')   # lower cred. interval before
lines(aadt1,apply(post_bef_sev,2,quantile,.975),lty=2,lwd=2,col='red4')   # upper cred. interval before
lines(aadt1,apply(post_aft_sev,2,mean),col='blue4',lwd=3)   # mean after
lines(aadt1,apply(post_aft_sev,2,quantile,.025),lty=2,lwd=2,col='blue4')   # lower cred. interval after
lines(aadt1,apply(post_aft_sev,2,quantile,.975),lty=2,lwd=2,col='blue4')   # upper cred. interval after
legend(0,2,c('Before, Severe','After, Severe'),bg='transparent',pch=c(2,17),col=c('red4','blue4'),lty=c(1,1))
dev.off()
# difference in before-after
pdf(paste(file,'_severe_difference.pdf'))
diffsevere <- exp(gam[,4])-exp(gam[,2])
plot(density(diffsevere),lwd=3,xlim=c(-3,1),main='Posterior Difference, After - Before',xlab='Difference')
cred_diffsevere <- quantile(diffsevere,c(.025,.975))
mean_diffsevere <- mean(diffsevere)
dev.off()
#percent reduction
pdf(paste(file,'_severe_percentreduction.pdf'))
redsevere <- exp(gam[,4])/exp(gam[,2])
plot(density(redsevere),lwd=3,xlim=c(0,1.5),main='Posterior For Percent Reduction',xlab='Percent Reduction')
abline(v=1,lwd=3,col='blue')
```

```
quantile(redsevere,c(.025,.975))
mean(redsevere)
dev.off()
percent_red_severe <- mean(redsevere<1)
mod_factorsev1 <- median(redsevere)
if(mod_factorsev1>1){
  mod_factorsev <- mod_factorsev1 - 1
} else{
  mod_factorsev <- 1 - mod_factorsev1
}
names <- c('Before, Not Severe, Posterior Mean','After, Not Severe, Posterior Mean',
      'Mean of Difference Between Before and After, Not Severe','95% Credible Interval on Difference',
      'Probability of a Reduction, Not Severe','Crash Modification Factor, Not Severe','Before, Severe, Posterior
Mean','After, Severe, Posterior Mean',
      'Mean of Difference Between Before and After, Severe','95% Credible Interval on Difference',
      'Probability of a Reduction, Severe','Crash Modification Factor, Severe')
crednot<-paste('(',round(cred_diffnotsevere[1],3),',',round(cred_diffnotsevere[2],3),')',sep='')
cred<-paste('(',round(cred_diffsevere[1],3),',',round(cred_diffsevere[2],3),')',sep='')
values <-
c(mean(post_bef_notsev),mean(post_aft_notsev),mean_diffnotsevere,crednot,percent_red_notsevere*100,mod_fact
ornotsev*100,
   mean(post_bef_sev),mean(post_aft_sev),mean_diffsevere,cred,percent_red_severe*100,mod_factorsev*100)
pdf(paste(file,'_output.pdf'))
par(oma=c(0,0,0,0),mar=c(0,0,0,0))
plot(seq(-2,2,length=14),(length(names)+2):1,type='n',xaxt='n',yaxt='n',xlab='',ylab='',bty='n')
mtext('Output',line=-2)
if(mod_factorsev1>1){
  text(.9,1,'Increase',adj=c(0,0))
```

```
} else {
  text(.9,1,'Decrease',adj=c(0,0))
}
if(mod_factornotsev1>1){
  text(.9,7,'Increase',adj=c(0,0))
} else {
  text(.9,7,'Decrease',adj=c(0,0))
}
text(-2,12:1,names,adj=c(0,0))
text(1.5,12:10,round(as.numeric(values[1:3]),3),adj=c(0,0))
text(1.25,9,values[4],adj=c(0,0))
text(1.5,8,paste(round(as.numeric(values[5]),3),'%',sep=''),adj=c(0,0))
text(1.5,7,paste(round(as.numeric(values[6]),1),'%',sep=''),adj=c(0,0))
text(1.5,6:4,round(as.numeric(values[7:9]),3),adj=c(0,0))
text(1.25,3,values[10],adj=c(0,0))
text(1.5,2,paste(round(as.numeric(values[11]),1),'%',sep=''),adj=c(0,0))
text(1.5,1,paste(round(as.numeric(values[12]),1),'%',sep=''),adj=c(0,0))
dev.off()
detach()
rm(list=ls())
cat('END')
timestamp()
}
```

APPENDIX B BENEFIT-TO-COST SPREADSHEETS

This appendix displays the completed spreadsheets used to calculate the B/C ratios for new and modified intersections. The spreadsheets were provided by UDOT.

B.1 New Signals

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Highway Safety Improvement Program (HSIP) Worksheet	State Route/ FAU Route/ FAS Route/ Local Route	Location	Beginning Accum. MP	Ending Accum. MP	Jurisdiction	Study Period Begins	Study Period Ends
	All		All	All	UDOT	1/1/2002	1/1/2003
	Description of Proposed Work	Install New Traffic Signal					

Crash Severity Distribution / Collision Description			Before Crashes per intersection per year								Total
Study Period: Number of Crashes (A)	Fatal	5	0.021	0	0	0	0	0	0	0	0.021
	Injury	4	0.27	0	0	0	0	0	0	0	0.27
		3	0.51	0	0	0	0	0	0	0	0.51
		2	0.94	0	0	0	0	0	0	0	0.94
	PDO	1	2.87	0	0	0	0	0	0	0	2.87
Total			4.611	0	0	0	0	0	0	0	4.611
Crash Reduction Factors (B)	Fatal	5	6%	0%	0%	0%	0%	0%	0%	0%	
	Injury	4	49%	0%	0%	0%	0%	0%	0%	0%	
		3	-45%	0%	0%	0%	0%	0%	0%	0%	
		2	-51%	0%	0%	0%	0%	0%	0%	0%	
	PDO	1	-38%	0%	0%	0%	0%	0%	0%	0%	
Estimated Reduction in Crashes (A x B)	Fatal	5	0.00								0.00
	Injury	4	0.13								0.13
		3	-0.23								-0.23
		2	-0.48								-0.48
	PDO	1	-1.08								-1.08
Total			-1.66	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.66

Year (HISP Project Construction)	2013	Crash Severity	Est. Red. of Crashes (Total)	Est. Annual Red. of Crashes	Average Cost per Crash (FHWA)	Estimated Annual Cost Saving (Benefit)
Project Cost (exclude Right of Way)	$ 250,000	5	0.00	0.00	$ 785,000	$ 956
Right of Way Costs	$ -	4	0.13	0.13	$ 785,000	$ 103,220
Traffic Growth Factor	1.5%	3	-0.23	-0.23	$ 80,000	$ (18,238)
CAPITAL RECOVERY		2	-0.48	-0.48	$ 42,000	$ (19,977)
Discount Rate	9.0%	1	-1.08	-1.08	$ 4,400	$ (4,773)
Project Service Life (yrs)	10	Total	-1.66	-1.66		$ 61,188

B/C= 1.81

Using present worth values:

Benefit = $ 453,325

Cost = $ 250,000

See "Calculations" tab for amortization information.

Change only yellow-shaded boxes. Crash reduction factors and Service Life values are from Utah Crash Reduction Factors spreadsheet. Contact W. Scott Jones if you have questions.

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Amortizing…

Year	Crash Benefits	Present Worth Benefits	Present Worth Costs
2013	$ 61,188	$ 61,188	$ 250,000
2014	$ 62,106	$ 56,978	
2015	$ 63,037	$ 53,057	
2016	$ 63,983	$ 49,407	
2017	$ 64,943	$ 46,007	
2018	$ 65,917	$ 42,841	
2019	$ 66,906	$ 39,894	
2020	$ 67,909	$ 37,149	
2021	$ 68,928	$ 34,593	
2022	$ 69,962	$ 32,212	
0	$ -	$ -	
0	$ -	$ -	
0	$ -	$ -	
0	$ -	$ -	
0	$ -	$ -	
0	$ -	$ -	
0	$ -	$ -	
0	$ -	$ -	
0	$ -	$ -	
0	$ -	$ -	
0	$ -	$ -	
0	$ -	$ -	
0	$ -	$ -	
0	$ -	$ -	
0	$ -	$ -	
0	$ -	$ -	
0	$ -	$ -	
0	$ -	$ -	
0	$ -	$ -	
0	$ -	$ -	
0	$ -	$ -	
	Totals =	**$ 453,325 (Benefit)**	**$ 250,000 (Cost)**

year (n)= 1, 2, 3,….

discount rate (i) = 9.00%

Crash Benefits (@ year n) = (Crash Benefits)$_{n-}$ X (1 + Traffic Growth Factor)

Present Worth Benefits (@ year n) = (Crash Benefits)$_n$ X 1/(1 + Discount Rate)^n

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B.2 Modified Signals

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Highway Safety Improvement Program (HSIP) Worksheet

State Route/ FAU Route/ FAS Route/ Local Route	Location	Beginning Accum. MP	Ending Accum. MP	Jurisdiction	Study Period Begins	Study Period Ends
All		0.00	All	UDOT	1/1/2002	1/1/2003

Description of Proposed Work	Install Modified Signal

Crash Severity Distribution / Collision Description			Before Crashes per intersection per year								Total
Study Period: Number of Crashes (A)	Fatal	5	0.02	0	0	0	0	0	0	0	0.02
	Injury	4	0.42	0	0	0	0	0	0	0	0.42
		3	1.07	0	0	0	0	0	0	0	1.07
		2	2.19	0	0	0	0	0	0	0	2.19
	PDO	1	5.87	0	0	0	0	0	0	0	5.87
		Total	9.57	0	0	0	0	0	0	0	9.57
Crash Reduction Factors (B)	Fatal	5	-34%	0%	0%	0%	0%	0%	0%	0%	
	Injury	4	58%	0%	0%	0%	0%	0%	0%	0%	
		3	-33%	0%	0%	0%	0%	0%	0%	0%	
		2	-12%	0%	0%	0%	0%	0%	0%	0%	
	PDO	1	-19%	0%	0%	0%	0%	0%	0%	0%	
Estimated Reduction in Crashes (A x B)	Fatal	5	-0.01								-0.01
	Injury	4	0.24								0.24
		3	-0.35								-0.35
		2	-0.26								-0.26
	PDO	1	-1.09								-1.09
		Total	-1.46	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-1.46

Year (HISP Project Construction)	2013	Crash Severity	Est. Red. of Crashes (Total)	Est. Annual Red. of Crashes	Average Cost per Crash (FHWA)	Estimated Annual Cost Saving (Benefit)
Project Cost (exclude Right of Way)	$ 22,500	5	-0.01	-0.01	$ 785,000	$ (5,354)
Right of Way Costs	$ -	4	0.24	0.24	$ 785,000	$ 191,556
Traffic Growth Factor	1.5%	3	-0.35	-0.35	$ 80,000	$ (27,991)
CAPITAL RECOVERY		2	-0.26	-0.26	$ 42,000	$ (10,762)
Discount Rate	9.0%	1	-1.09	-1.09	$ 4,400	$ (4,804)
Project Service Life (yrs)	10	Total	-1.46	-1.46		$ 142,645

B/C= 46.97

Using present worth values:

Benefit = $ 1,056,819

Cost = $ 22,500

See "Calculations" tab for amortization information.

Change only yellow-shaded boxes. Crash reduction factors and Service Life values are from Utah Crash Reduction Factors spreadsheet. Contact W. Scott Jones if you have questions.

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Amortizing…

Year	Crash Benefits	Present Worth Benefits	Present Worth Costs
2013	$ 142,645	$ 142,645	$ 22,500
2014	$ 144,785	$ 132,830	
2015	$ 146,957	$ 123,690	
2016	$ 149,161	$ 115,180	
2017	$ 151,398	$ 107,254	
2018	$ 153,669	$ 99,875	
2019	$ 155,974	$ 93,002	
2020	$ 158,314	$ 86,603	
2021	$ 160,689	$ 80,644	
2022	$ 163,099	$ 75,095	
0	$ -	$ -	
0	$ -	$ -	
0	$ -	$ -	
0	$ -	$ -	
0	$ -	$ -	
0	$ -	$ -	
0	$ -	$ -	
0	$ -	$ -	
0	$ -	$ -	
0	$ -	$ -	
0	$ -	$ -	
0	$ -	$ -	
0	$ -	$ -	
0	$ -	$ -	
0	$ -	$ -	
0	$ -	$ -	
0	$ -	$ -	
0	$ -	$ -	
0	$ -	$ -	
0	$ -	$ -	
0	$ -	$ -	
	Totals =	**$ 1,056,819 (Benefit)**	**$ 22,500 (Cost)**

year (n)= 1, 2, 3,….

discount rate (i) = 9.00%

Crash Benefits (@ year n) = $(\text{Crash Benefits})_{n-}$ X (1 + Traffic Growth Factor)

Present Worth Benefits (@ year n) = $(\text{Crash Benefits})_{n}$ X $1/(1 + \text{Discount Rate})^{n}$

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APPENDIX C DATA COLLECTION FORM

This appendix provides printable copies of the data collection form. This form should be used for all future intersection improvements to ensure there is adequate data to evaluate the safety effects of the improvement using the hierarchical Bayesian model developed in this report.

Intersection Data Collection Form for Traffic Signal Improvement Projects

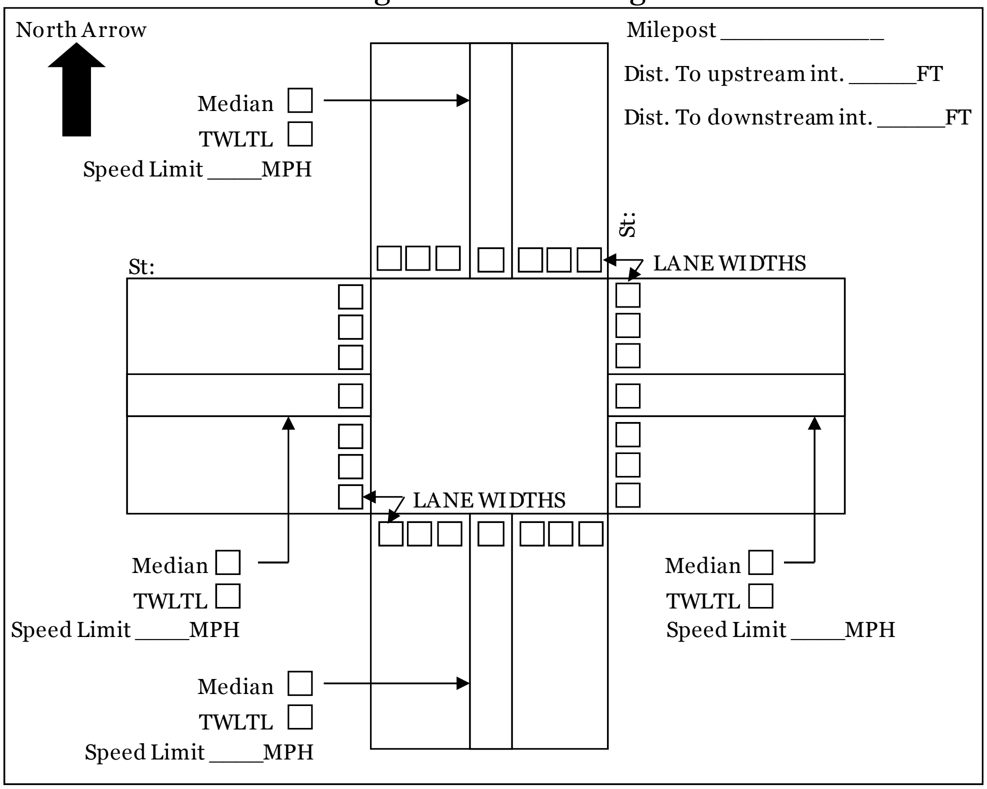
Intersection:____________________________ **Date:**________________________

City:____________________________________ **Analyst:**______________________

Milepost:__________ **Project No:**__________________

Data Collection	Y	N
Timing Changes? If Yes, provide details below		
Left Turn Changes? If Yes, provide details below		
New Signal Heads Added? If Yes, provide details below		
New lanes added? If Yes, show on configuration diagram on back of sheet		
New Right of Way added? If Yes, provide details including cost below		
Construction Start Date?		
Construction End Date?		
Signal Turn-On Date?		
Project Cost?		
Final comments & recommendations:		

Existing Intersection Diagram[1]



New Intersection Diagram[1]