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# TRANSPORTATION SAFETY DATA AND ANALYSIS Volume 1: Analyzing the Effectiveness of Safety Measures using Bayesian Methods

## Prepared For:

Utah Department of Transportation  
Traffic and Safety, Research Divisions

## Submitted By:

Brigham Young University  
Dept. of Civil & Environmental Engineering

## Authored By:

Grant G. Schultz, Ph.D., P.E., PTOE  
Associate Professor  
Daniel J. Thurgood, EIT  
Graduate Research Assistant  
Andrew N. Olsen  
Undergraduate Research Assistant  
C. Shane Reese, Ph.D.  
Professor, Department of Statistics

**December 2010**

**INSIDE COVER**

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## **EXECUTIVE SUMMARY**

Recent research suggests that traditional safety evaluation methods may be inadequate in accurately determining the effectiveness of roadway safety measures. In recent years, advanced statistical methods are being utilized in traffic safety studies to more accurately determine the effectiveness of roadway safety measures. These methods, particularly Bayesian statistical techniques, have the capabilities to account for the shortcomings of traditional methods. Hierarchical Bayesian modeling is a powerful tool that more fully identifies a given problem than a simpler model could.

This report explains the process wherein a hierarchical Bayesian model is developed as a tool to analyze the effectiveness of two types of road safety measures: raised medians and cable barrier. Several sites where these safety measures have been implemented in the last 10 years were evaluated using available crash data.

The results of this study show that the installation of a raised median is an effective technique to reduce the overall crash frequency and crash severity on Utah roadways. The analysis of cable barrier systems shows that they are effective in decreasing cross-median crashes and crash severity.

The tool developed through the research can now be utilized for additional analyses, including hot-spot analysis, before-after change, and general safety modeling. This tool will be an asset to the Utah Department of Transportation Traffic and Safety division for data analysis in the years to come.

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# **1 INTRODUCTION**

The importance of transportation safety continues to be highly emphasized by the United States Department of Transportation (USDOT) as well as state agencies. The number of deaths on highways in the United States has remained steady over the past 15 years at approximately 40,000 fatalities per year. The Utah Department of Transportation (UDOT) continues to make transportation safety a high priority. UDOT has introduced several campaigns and programs to increase traffic safety awareness and to reduce the number and severity of crashes on Utah roadways. While great strides have been made in traffic safety, there is still room for improvement.

## **1.1 Background**

Transportation safety analysis continues to play an important role in any state department of transportation (DOT) program. The Federal Highway Administration (FHWA) and the American Association of State Highway and Transportation Officials (AASHTO) are continually working to aid states in this analysis.

In recent years, advanced statistical methods have been utilized in traffic safety studies to more accurately determine the effectiveness of roadway safety measures. Traffic studies are not performed in a controlled environment such as a laboratory, but rather in the real world setting which has numerous variables including some that are difficult to account for. Traditional methods lack the capability to account for many of these variables. However, safety studies have continued to rely on these traditional methods with their limitations due to the complexity of more effective models. Fortunately, the development of advanced statistical software in recent years has overcome the complexity of advanced methods. These methods, particularly Bayesian statistical techniques, have the capabilities to account for the shortcomings of traditional methods.

One tool to aid in safety analysis is the Highway Safety Manual (HSM) published by AASHTO to aid in the analysis of transportation safety data (AASHTO 2010). The HSM represents a huge step in beginning to implement some of these advanced techniques in traffic safety studies. The HSM was developed to incorporate the explicit role of highway safety in making decisions on roadway planning, design, maintenance, construction, and operations. In the past, there were no such widely accepted tools available for agencies responsible for managing the safety of roadways. As a result, safety considerations had a diminished role in the decision making processes.

## **1.2 Problem Statement**

One element that can aid in transportation safety improvement is an increase in focused transportation safety data collection and analysis. The purpose of this research is to establish a procedure that can be used to analyze the effectiveness of various treatments in improving roadway safety. Such a procedure will emphasize transportation safety data and the statistical analysis of that data in the development and/or implementation of new or existing safety analytical tools in the state.

## **1.3 Objectives**

The objective of this research is to evaluate traffic safety data collection and analysis procedures and then establish a set procedure for this data collection and analysis. To accomplish this task, this study analyzes the effectiveness of two roadway safety treatments: raised medians and cable barrier systems. An initial step for this task will include identification of necessary tools for use in crash data collection and analysis for both evaluating the effectiveness of safety features and in identifying high proportion areas for further analyses. Such tools include standard before-after analyses, comparison group analyses, and Bayesian analyses. It will be critical to coordinate these efforts with ongoing efforts at the FHWA level by identifying ways to use new safety analysis tools such as the HSM.

The title of this report indicates that this is Volume 1 of this research report series. It is anticipated that two additional volumes will follow. Volume 2 will discuss the calibration of crash analysis models. Volume 3 will discuss the overall data analysis process and possible

training opportunities which will allow the methods discussed in this report to be more easily implemented.

## **1.4 Organization**

This report is organized into the following chapters: 1) Introduction; 2) Literature Review; 3) Site Selection; 4) Analysis Procedure; 5) Raised Median Results; 6) Cable Barrier Results; and 7) Conclusions. A References section and an Appendix follow the indicated chapters.

Chapter 2 is a literature review defining safety and how it is measured. Previous studies and methods for measuring safety are discussed, such as the simple before and after approach, the empirical Bayesian method, and the hierarchical Bayesian method.

Chapter 3 provides details on the types of safety measures that have been analyzed as well as background information on sites used in the analysis. The analysis will be performed on locations where raised medians and cable barrier systems have been installed on Utah roadways.

Chapter 4 documents the steps followed during the data collection and analysis of crash safety statistics. The steps are recorded in detail so that the procedure may be used in future analyses.

Chapter 5 presents the results of the raised median analyses. This includes the impacts of raised medians on overall and severe crash frequency where raised medians have been installed. Tables and figures are included to aid in the presentation of the results.

Chapter 6 presents the results of the cable barrier analyses. This includes the impacts of cable barrier systems on cross-median and severe crash frequency where cable barrier systems have been installed. Tables and figures are included to aid in the presentation of the results.

Chapter 7 provides the conclusions of the research as well as recommends future research possibilities.

Included in the Appendix section of the report is the modeling code used in the analysis.

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## **2 LITERATURE REVIEW**

A comprehensive literature review has been performed on current analysis methods used in safety evaluation. This process included researching recent safety analysis studies and determining the types of statistical tools utilized. The literature review covers several different topics. First, safety is defined and the methods used to measure safety are determined. Second, various crash statistic characteristics are discussed to determine their implication on evaluation statistical methods. Next, traditional safety analysis methods along with their benefits and limitations are reviewed. Finally, modern approaches that more accurately determine project effectiveness are discussed, including the use of the empirical Bayesian (EB) and hierarchical Bayesian methods.

### **2.1 Defining and Measuring Safety**

To be able to determine the safety of a site during analysis, it is important to determine what safety is and how it is measured. This section discusses the use of crash history as a method to quantify safety. Two methods used for measuring crashes are also presented.

#### *2.1.1 Characteristics of Crashes*

Safety has both qualitative and quantitative characteristics. Qualitative characteristics can refer to how safe a driver feels on a transportation facility and are difficult to measure and account for. Quantitative characteristics, such as number of crashes, are easier to measure than qualitative characteristics.

The HSM defines safety as “the crash frequency and/or crash severity and collision type for a specific time period, a given location, and a given set of geometric and operational conditions” (AASHTO 2010). Roadway safety is usually defined and evaluated in terms of the number of recorded crashes. Crash severity also plays an important role in understanding

roadway safety. For example, one site may experience considerably more crashes than another; however, the second site may have a much larger proportion of severe, particularly fatal, crashes. Therefore, both crash frequency and crash severity are essential in determining the safety of a facility. In order to understand how to reduce crash frequency and crash severity, it becomes important to first understand the factors behind crashes.

### *2.1.2 Causes of Crashes*

Crashes represent a very small proportion of all of the events that occur on a transportation system. There have been numerous proposed theories that try to explain the causes of crashes. The Handbook of Road Safety Measures (Elvik and Vaa 2004) provides a more in-depth look at various proposed theories. In this research, it is sufficient to emphasize four conclusions that can be made from these theories:

First, it is probable that all proposed crash theories have an element of truth in them. However, while crash cause theories do include portions of the truth, none of the theories provide a complete understanding or explanation of why crashes occur. One of the key reasons it is difficult to understand why crashes occur is because crashes are usually not the result of one factor, but the combination of multiple events, circumstances, and factors.

There are three categories of factors that contribute to crashes (AASHTO 2010):

1. Human – including age, judgment, driver skill, attention, fatigue, experience and sobriety, etc.
2. Vehicle – including design flaws, safety features, etc.
3. Roadway/Environment – including geometric alignment, cross-section, traffic control devices, surface friction, grade, signage, weather, visibility, etc.

The combination of multiple events can severely alter the amount of risk a driver may face. For example, imagine a deer runs in front of a driver on a rural highway. Driver A, driving during the daytime, is at considerably less risk than Driver B, driving at night during a snowstorm. Driver A may have to deal with factors such as reaction time, stopping distance, and brake wear. Driver B would be affected by the same factors in addition to reduced surface

friction and visibility. Understanding this point helps to understand that crashes are the outcome of a vastly complex random process.

Second, there are certain roadway, vehicle, and driver trends that make the occurrence of a crash more likely. The exact impact these trends have on roadway safety has long been the focus of research. Difficulty arises due to the fact that some are known, while others are not.

Third, it is also important to understand that even though improvements are continually made to reduce crash frequency, no system is entirely perfect. Drivers are fallible and thus still subject to error in judgment, whether recklessly or not. This provides great difficulty in determining the effectiveness of an improvement.

Finally, even if it were possible to account for all crash factors, the ability to predict a crash is not absolute. The reason is that crashes are still to some extent a random event.

The key principle is that understanding the nature of crashes is a vastly complex and random process when considering just the known factors. It is important to remember that there are factors that contribute to crashes that are unknown. The premature assumption might then be made that limited understanding of the contributing factors of crashes make it extremely difficult, if not impossible, to determine the proper remedy for crashes. The Handbook of Road Safety Measures provides valuable insight in understanding the concept of crash causes. The handbook states “the logic of the argument that you need to know the causes of a problem in order to solve it seems irresistible. Yet, 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). The complexity of known and unknown contributing factors can be overcome through the development and use of proper statistical tools that correctly model crash characteristics and behavior.

### *2.1.3 Crash Rate*

To model crashes, it first becomes necessary to define what exactly is being measured. Traditional practice has been to use crash rates as a measure of safety (Roess et al. 2004). The crash rate is the frequency of crashes adjusted to account for volume or exposure. The general relationship between crash frequency and crash rate is explained in Equation 2-1.

$$\text{Crash Rate} = \frac{\text{Average Crash Frequency in Period}}{\text{Exposure During Period}} \quad (2-1)$$

Crash rates for road segments are typically reported in crashes per million vehicle miles traveled (MVMT) or per hundred MVMT. Crash rates for intersections are typically reported in crashes per million entering vehicles (MEV). Equation 2-2 shows the crash rate equation for a section of roadway (Roess et al. 2004).

$$CR_{sec} = \frac{N}{V_{sec} \times 365 \times L} \times 10^6 \quad (2-2)$$

where:  $CR_{sec}$  = crash rate for section (in crashes per MVMT),  
 $N$  = number of crashes per year,  
 $V_{sec}$  = average annual daily traffic (AADT) of road section, and  
 $L$  = length of section (in miles)

Equation 2.3 shows the crash rate equation for intersections (Roess et al. 2004).

$$CR_{int} = \frac{N}{V_{int} \times 365} \times 10^6 \quad (2-3)$$

where:  $CR_{int}$  = crash rate for intersection (in crashes per MEV), and  
 $V_{int}$  = sum of average daily approach volumes of intersection.

When using crash rates, an assumption is often made that the relationship between frequency and exposure is linear. Recent studies have shown that this assumption is not always valid (Hauer et al. 2002). It has been determined that the use of crash frequency is a more accurate indicator of roadway safety than the use of crash rates. Research shows that the relationship between traffic volume and crash count is more complex and relates to quantities such as the distribution of traffic through the day and the types of crashes experienced. Some studies have indicated that there is indeed a relationship between the number of crashes and traffic volume (Miaou 1994). The exact form, however, is still unknown and likely depends on crash type. Models using aggregate data (not separated by crash type) and exposure as inputs ignore significant variation in highway crashes resulting from hourly volume changes and human

behavioral changes throughout the day. A study performed using disaggregate data (crashes broken down by type) revealed how the relationship between crashes and traffic volumes varies from location to location and by crash type (Qin et al. 2004). New approaches are also being developed for incorporating traffic volumes in crash rate analysis and forecasting studies (Ivan 2004).

#### *2.1.4 Crash Frequency*

One solution that overcomes the non-linear relationship between crash frequency and exposure associated with crash rates is to use crash frequency as the fundamental basis for safety analysis and measurement of treatment effectiveness (AASHTO 2010). The use of crash frequency as a measure of safety eliminates the inclusion of exposure altogether. A crash frequency is obtained by counting the number of crashes at a certain site of interest, usually a roadway segment or intersection, over a certain period of time. Crash frequency and crash severity are important elements of crash history and form the basis of quantifying and measuring safety. Along with understanding these elements of crash data, it is also important to understand trends exhibited within the data so that an appropriate statistical approach can be used in analysis of crashes.

## **2.2 Characteristics of Crash Statistics**

This section provides an understanding of the crash statistic characteristics used to determine proper statistical analysis tools. Misunderstanding of crash statistic characteristics has long been the source of great difficulty in accurately predicting crash frequency. Properly understanding the random nature of crashes, regression-to-the-mean (RTM) bias, and long and short-term trends, as discussed in this section, is fundamental to more accurately model crash behavior.

### *2.2.1 Crashes as Random Events*

In Section 2.1.2, various factors that contribute to crashes were examined. One of the key discoveries from that examination is that crashes are still not completely predictable, even

though there are trends and factors that increase the likelihood of crashes. One of the reasons crashes are not completely predictable is that crashes, by nature, are still random events. As such, crash frequencies will naturally fluctuate from year to year. The random nature of crashes must be considered during analysis because it presents a problem when performing studies using a short-term period. It would be nearly impossible to determine if short-term values are representative of the long-term behavior of the site (AASHTO 2010).

Fluctuations in crash frequency make it difficult to determine whether a reduction in the number of crashes is the result of a specific treatment, changes in site conditions over time, or simply the result of the natural fluctuations due to the random nature of crashes. This phenomenon is referred to as RTM bias.

### *2.2.2 Regression-to-the-Mean Bias*

The RTM phenomenon expects that a value that is determined to be extreme will tend to regress to the long-term average over time as illustrated in Figure 2-1. This means that it is statistically probable that a period of high crash frequency at a site will be followed by a period of low crash frequency (Hauer 1997). RTM bias refers to the selection of a site as a result of the short-term trend it exhibits, thus not taking into account the RTM. One of the primary limitations with many current safety analysis practices is that they do not account for RTM bias.

In Figure 2-1 the observed crash frequency of a specific site is plotted over the course of a long-term period, 13 years in this case. The long term (expected) average crash frequency line represents the actual crash behavior of the site. The short-term average crash lines represent the value of the crash frequency if only those respective short-term windows were used in the estimation. As is evident from the figure, the average crash frequency estimation could be considerably higher or lower than the long term (expected) average crash frequency if only short-term periods are used in the estimation (Hauer 1997).

If RTM bias is not accounted for, it could lead to an inaccurate overestimation or underestimation of the effectiveness of a treatment due to natural fluctuation in the long term statistical characteristics of a site. Figure 2-2 shows the difference between the perceived reduction in crashes when RTM bias is not accounted for and the actual reduction in crashes when RTM is accounted for.

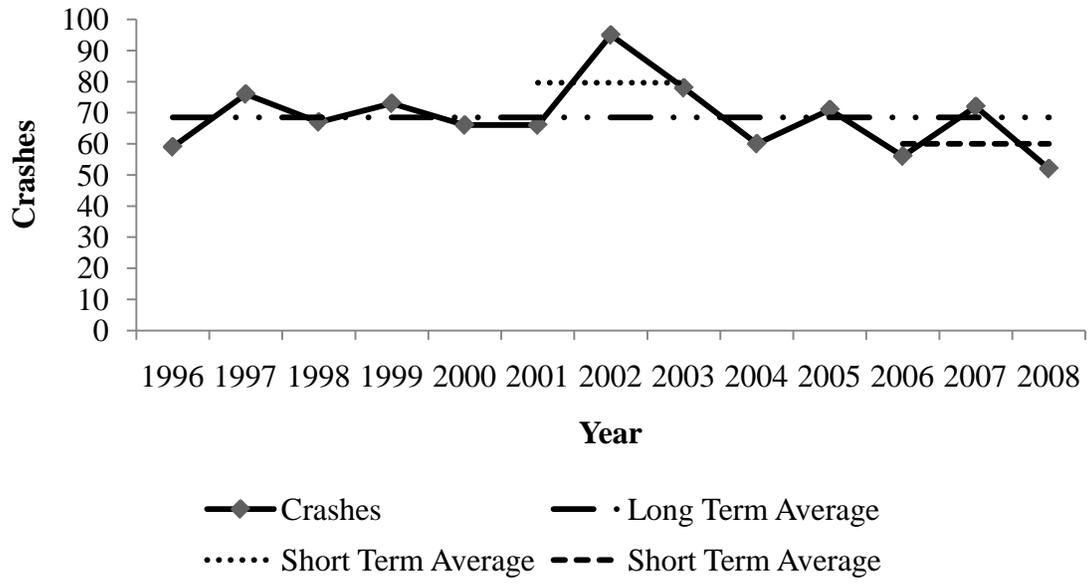


Figure 2-1. Variation in Short-Term and Long-Term Crash Frequency.

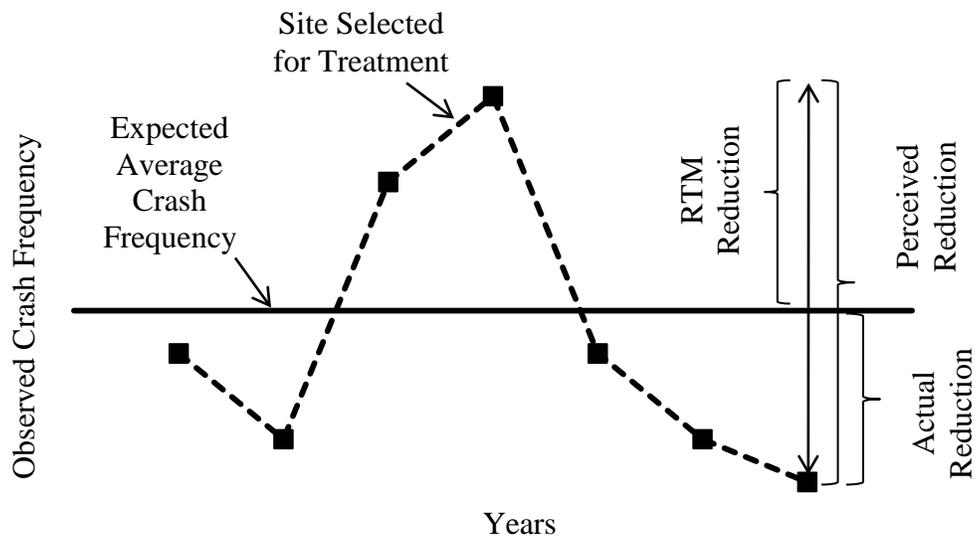


Figure 2-2. Perceived vs. Actual Reduction (adapted from AASHTO 2010).

### *2.2.3 Conflict between the Use of Short-Term and Long-Term Periods in Analysis*

The RTM bias provides evidence of limitations inherent in using short-term data for analysis. This leads to the assumption that using data from a longer period of time provides a better representation of crash behavior at a site. However, there are problems associated with this method as well. The characteristics of a site, such as traffic volume, weather, and pavement condition change over time. Some of these characteristics, such as weather, continually fluctuate with time. Other factors, such as pavement condition, roadway markings, etc. deteriorate gradually from use over time. These latter factors create a legitimate limitation of using long-term crash statistics for site analysis. If longer periods of time are studied to account for RTM bias and site variation characteristics, it is probable that site characteristics have changed during that time period (AASHTO 2010).

Difficulties exist in the use of both short-term and long-term periods to predict the average crash frequency of a site. Long-term crash statistics operate on the false assumption that all factors contributing to crashes remain constant over time; the use of short-term crash statistics fails to account for the RTM bias. If not properly accounted for, these characteristics may produce misleading results related to the effectiveness of a specific treatment. Fortunately, these issues have been addressed by improved statistical methods of analysis (Hauer 1997).

## **2.3 Distribution of Crash Statistics**

Traditional methods have used overly simple before and after approaches to analyze crash statistics. Such methods often involve nothing more than comparing the crash frequency at an entity immediately before an improvement was made to the crash frequency directly after the improvement to determine the effectiveness of the treatment (Hauer 1997).

### *2.3.1 Crashes as Counts*

A common mistake when performing a statistical crash analysis is to model crash data as continuous by using traditional methods such as standard least squares regression. This method is incorrect because such models can produce results that are non-integers or negative values that are inconsistent with crash data (Washington et al. 2003). Crash data are statistically classified

as count data and by nature are non-negative integers. Therefore generalized linear models for crash studies are insufficient because of the false assumption that the dependent variable is continuous (Liu et al. 2008). It then becomes essential to use a different type of analysis when analyzing crash data.

### *2.3.2 Poisson and Negative-Binomial Distribution*

Previous studies have suggested that the use of Poisson models or Negative-binomial models is more appropriate for crash statistics. However, one of the basic assumptions to the Poisson distribution is that both the mean and the variance are equal. Recent research has shown that in crash studies the variance often exceeds the mean (Liu et al. 2008). In this case, the data are said to be overdispersed, which is a major complication when using the Poisson assumption. One of the ways to address this complication is to use a variation of the Poisson distribution called the Negative-binomial distribution which accounts for the overdispersion parameter (Bonneson and McCoy 1993). The larger the overdispersion parameter, the more the crash data varies in comparison to the Poisson distribution. The various methods discussed further in this research are based on the assumption that crash statistics follow the Negative-binomial distribution.

## **2.4 Predicting Crash Frequency**

When performing any type of analysis related to the effectiveness of a treatment on the safety of an entity, it is relatively simple to determine the actual change in crashes between the before and after period through observational analysis. However, it is not only important to determine this change, but it is also important to consider what change in crashes would have occurred had the treatment not been implemented (AASHTO 2010). It is difficult to predict what effect a treatment would have on a site if it has not yet been implemented since no observation of the result can be made. Therefore, the use of statistical models is required. This section describes the types of statistical tools that are useful in creating the aforementioned estimation including the development of Safety Performance Functions (SPFs), Crash Modification Factors (CMFs), and local calibration factors.

### 2.4.1 *Safety Performance Functions*

One method of predicting the average crash frequency of an entity requires the development of SPFs. SPFs are developed through statistical regression modeling using historic crash data collected over a number of years at sites with similar roadway characteristics (AASHTO 2010). SPFs use characteristics particular to each site, such as Average Annual Daily Traffic (AADT) and segment length, to create an estimate of the average crash frequency for a specified facility type.

The regression coefficients used in SPFs are determined based on the assumption that the data follows a Negative-binomial distribution. As stated previously, the Negative-binomial distribution is an extension of the Poisson distribution that accounts for differences between the mean and variance. When the variance exceeds the mean, the data are said to be overdispersed. Studies have shown that this is often the case when dealing with crash data (Hauer et al. 2002). The degree of overdispersion is represented by an overdispersion parameter. This is estimated along with the regression coefficients in the Negative-binomial model. The larger the value of the overdispersion parameter, the more the data varies compared to the Poisson distribution.

Until recently one of the major deficiencies of SPFs is that they need to be derived for each site. Recent research has helped derive several of these for different facility types, some of which are covered in the HSM. In the first edition of the HSM SPFs have been developed for three facility types (AASHTO 2010):

1. Rural Two-Lane Two-Way Roads
2. Rural Multilane Highways
3. Urban and Suburban Arterials.

And for three site types:

1. Signalized Intersections
2. Unsignalized Intersections
3. Divided and Undivided Roadway Segments

Methods for additional facility types will be added to later editions of the HSM as future research is performed. As these become more widely available, the methods outlined in the HSM will become simpler to use. Agencies with sufficient expertise may develop SPFs unique to their jurisdiction but it is not a requirement for the method outlined in the HSM. Alternatively, the model can be calibrated to imitate local conditions using calibrations factors that will be discussed in later sections of the literature review.

#### 2.4.2 *Crash Modification Factors*

The CMF is the ratio of the expected crash frequencies associated with two different conditions and may serve as an estimate of the effectiveness of a specific type of design, control feature, or treatment. The expected average base condition crash frequency represents the expected crash frequency under the initial or base conditions of the site. The expected average condition ‘x’ crash frequency represents the expected crash frequency when a specific characteristic of interest differs from the base condition while all other characteristics remain constant. Therefore, the CMF represents the relative change in crash frequency due to a change in one specific characteristic, while all others are being held constant (AASHTO 2010). Equation 2-4 illustrates the calculation of a CMF.

$$CMF = \frac{\text{Expected Average Condition 'x' Crash Frequency}}{\text{Expected Average Base Condition Crash Frequency}} \quad (2-4)$$

To illustrate how a CMF is calculated, consider the following example: The CMF value is sought for the effect of increasing the lane width. For the purposes of this example, assume that the expected crash frequency before the change (under base conditions) was 100 crashes per year and that the expected crash frequency after the change (under condition ‘x’) was 90 crashes per year. Using equation 2-4, the value of the  $CMF = 90/100$  or 0.90.

If a particular site has a specific design feature or treatment that results in a CMF greater than 1, by definition the crash frequency of the site is greater than it would have been without that feature or treatment. Conversely, if the CMF is less than 1, then the site experiences a reduction in crash frequency as a result of the treatment. Finally, a CMF value equal to 1 implies that the treatment or feature had no effect.

The CMF can also be used to determine the expected percentage reduction (or increase) in crash frequency using Equation 2-5 (AASHTO 2010):

$$\text{Percent Reduction in Crashes} = 100 \times (1.0 - CMF) \quad (2-5)$$

Consider the previous example of a proposed change in lane width. Previously, the CMF was calculated to be 0.90 using equation 2-4. Inputting this value into equation 2-5 yields an expected percent change of  $100 \times (1.0 - 0.90) = 10$ , or a 10 percent reduction in the average crash frequency.

SPFs are multiplied by the CMFs to account for the unique characteristics of a specific site. The HSM assumes that CMFs can be multiplied together to estimate the effect of multiple treatments or characteristics. This is based upon the assumption that the effects of treatments or features are independent of each other. The HSM acknowledges that this assumption may or may not be valid. Due to limited research done regarding the independence of treatments, the HSM will follow this assumption until more research is performed. Various uses of CMFs are discussed in Chapter 3 of the HSM (AASHTO 2010).

### 2.4.3 Local Calibration Factor

One of the critical steps in the HSM method is to include locally calibrated factors to adjust the base model for each site type to local crash tendencies. Jurisdictions can vary widely in climate, driver demographics, crash reporting methods, etc. As a result, crash frequencies on similar facility types can vary from one jurisdiction to another. Calibration factors function in a similar fashion to CMFs. Multiplying local calibration factors with the crash frequency calculated by the SPF account for differences between the jurisdiction and time period for the site of interest from the facility type the models are based on (Bauer et al. 2004).

While the use of SPFs and the EB method correct for previously mentioned shortcoming of traditional methods such as correcting for the RTM bias, effects related to changes in demographics, weather, and other characteristics unique to each geographic jurisdiction (such as states) still need to be addressed (AASHTO 2010). This is accomplished by calibrating the model for the jurisdiction of interest using a local calibration factor, calculated according to

Equation 2-6, that compares the actual observed crash frequency of facility type with the frequency predicted using SPFs and CMFs.

$$C_i = \frac{\sum \text{observed crashes}}{\sum \text{predicted crashes}} \quad (2-6)$$

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

Crash frequencies, even with relatively similar characteristics, can vary widely between jurisdictions. This result was emphasized in research done on two-way left-turn lanes using the EB method (Lyon et al. 2008). The results of this study displayed a wide range of effects outlining a need to disaggregate analysis to determine if significant effects can be detected for specific conditions.

Roadways that experience higher crash frequencies than those the SPFs are based on will have calibration factor values greater than one; roadways that experience lower crash frequencies will have calibration factor values less than one. Methods for developing calibration factors to adjust SPFs to local conditions are included in the HSM. Equation 2-7 displays how local calibration factors and CMFs are combined with SPFs to more accurately predict crash frequency (AASHTO 2010).

$$N_{\text{predicted}} = N_{\text{spf}} \times (CMF_1 \times CMF_2 \times \dots \times CMF_n) \times C_i \quad (2-7)$$

where,  $C_i$  = local calibration factor,  
 $N_{\text{predicted}}$  = predicted crash frequency for a specific site type,  
 $N_{\text{spf}}$  = predicted crash frequency under base conditions, and  
 $CMF_i$  = Crash Modification factor.

Combining SPFs with factors such as CMFs to adjust for differences in site characteristics, and local calibration factors to adjust for differences within jurisdictions, creates a more accurate estimation of the crash frequency of a given site or facility. This approach helps to correct the uncertainty of both known and unknown factors that contribute to crashes and thereby reduce the amount of error.

## 2.5 Methods of Analysis

Several methods have been developed that more accurately determine the effectiveness of a safety measure by combining observed crash statistics with predicted values obtained by the use of SPFs, CMFs and local calibration factors. Some of those approaches include the EB approach and the HSM predictive method. In recent years, interest in the use of various Bayesian approaches in traffic safety studies have increased significantly. This section provides an overview of these different approaches.

### 2.5.1 Empirical Bayesian Approach

Several methods are available to model count data such as crash statistics. One of the more common methods being used in safety studies is the use of EB method of analysis. The EB approach has been demonstrably better suited to estimate safety than more traditional statistical methods (Hauer 1997).

The EB method combines an estimation of the study site crash frequency with characteristics of similar sites using SPFs to estimate the predicted number of crashes. This is combined, in Equation 2-8, with crash records at the site to create an estimate of the site-specific expected number of crashes.

$$N_{expected} = w \times N_{predicted} + (1 - w) \times N_{observed} \quad (2-8)$$

where,  $w$  = weighting factor,  
 $N_{expected}$  = estimate of expected average crash frequency,  
 $N_{predicted}$  = predicted value determined by Equation 2-7, and  
 $N_{observed}$  = observed crash frequency at the site.

The weighting factor is used to determine 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 site of interest. The overdispersion parameter that coincides with each SPF is used in the determination of the value of the weighting factor. Therefore, the reliability of the safety estimation depends greatly on the

strength of the crash record and on the reliability of the SPF used. The weighting factor is also used to reflect the statistical reliability of the model. The strength of the EB method is in the use of a weight that is based on sound logic and on real data (Hauer 1997). Equation 2-9 shows how the weighting factor is calculated.

$$w = \frac{1}{1+k \times (\sum_{all\ years} N_{predicted})} \quad (2-9)$$

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

$N_{predicted}$  = predictive model estimate determined using Equation 2-7.

The EB method addresses two problems encountered when performing safety estimation analysis: First, it corrects for the previously mentioned RTM bias by determining the expected crash frequency of an entity. The elimination of the RTM bias is important whenever the safety of a site is estimated partially or completely by crash history at the site. Second, it also can use crash data older than the traditionally used three year period (Hauer 1997).

The EB method does suffer from several deficiencies. Perhaps the most unfortunate among these is the need to spend time, resources, and effort on the development of SPFs required for implementation of the EB method. Another major disadvantage of the EB approach is that the SPF is estimated using an aggregate of more than one year of crash data. Therefore, to accurately apply this model, the units of crash frequencies per three years need to be maintained, (i.e., annual crash data cannot be used in place of three year aggregated data) (Powers and Carson 2004). Furthermore, the EB method is only applicable when both predicted and observed crash frequencies are available for a roadway network.

### 2.5.2 HSM Predictive Method

The HSM produces a step-by-step guide for estimating crash frequencies at a site using the EB method. The HSM predictive method uses functions that are based on a Negative-binomial crash distribution. This method combines the SPFs, CMFs, and local calibration factors to predict the expected crash frequency of an entity. These can then be used

independently or as part of the EB method. Various additional studies have been done to aid in developing methods for evaluating safety impacts of highway projects using the EB approach (Al Masaeid et al. 1993).

### *2.5.3 Hierarchical Bayesian Approach*

In recent years, a full or hierarchical Bayesian approach has been suggested as a useful alternative to the EB approach. Though more complex, the hierarchical Bayesian approach has several advantages over the EB approach such that it is believed to require less data for untreated reference sites, it better accounts for uncertainty in crash data, it provides more detailed causal inferences, and offers more flexibility in selecting crash count distributions (Persaud et al. 2010). Additionally, the EB approach has been criticized for its inability to incorporate uncertainties in the model parameters. The EB approach assumes the parameters are error free and can be replaced easily by their posterior analysis estimates. These limitations can be overcome with the use of the flexible modeling associated with the hierarchical Bayesian method (Sloboda 2009).

The hierarchical Bayesian approach has many advantages over the EB approach. In a hierarchical Bayesian analysis, prior information and all available data are integrated into posterior distributions from which inferences can be made. Therefore, all uncertainties are accounted for in the analyses. Hierarchical Bayesian methods might be less costly to implement and may result in safety estimates that have more realistic standard errors (Carriquiry and Pawlovich 2004). A study performed by Iowa State University argues that by using a hierarchical Bayesian approach at a site, it is possible to improve prediction of the expected number of crashes and simultaneously avoid the need to obtain estimates of SPFs or CMFs (Carriquiry and Pawlovich 2004).

Another important difference between hierarchical Bayesian and the EB approach is the manner by which the model parameters are determined. In the EB approach, model parameters depend only on the data. Model parameters are estimated using techniques that involve the use of crash data, such as the maximum likelihood technique. In the hierarchical Bayesian approach, the parameters of the prior distributions are fixed by modelers. The hierarchical Bayesian approach is normally implemented using hierarchical Poisson Bayesian models. There has been increased interest in this approach over the past few years due to the modeling flexibility associated with this approach (Sloboda 2009).

The hierarchical Bayesian method was applied to evaluate the safety effect of converting rural intersections in California from stop to signalized control. The results were then compared with those from the EB method and it was found that the hierarchical Bayesian method can provide similar or even better results than the EB approach (Lan et al. 2009).

## **2.6 Chapter Summary**

In summary, safety is measured by the frequency and severity of crashes on a roadway segment. There are many known and unknown factors that contribute to the difficulty in understanding why crashes occur. This difficulty can be overcome through the use of the proper statistical tools. In order to properly perform analysis on crash statistics, it is essential to analyze the characteristics of crash statistics so as to determine the proper statistical tools to use. The use of such statistical tools can allow the effectiveness of a safety measure to be properly evaluated.

Effectiveness evaluation is an important component of determining the overall impact that a treatment has on a project as well as assessing how well funds have been invested in safety improvements. Evaluating the change in crashes from implemented safety treatments provides an effectiveness assessment of a specific treatment on reducing crash frequency or severity. Traditional before and after analysis of crash data is usually insufficient to determine the actual effect of a treatment. Such studies are based on the incorrect assumption that all factors aside from the treatment remain unchanged over the course of the evaluation; they fail to take into consideration factors such as the RTM bias, changes in climate and land use that occur over time, and other factors that can impact results. Bayesian analysis methods overcome limitations of traditional analysis methods and greatly improve the capability of safety analyses to accurately determine the effectiveness of the treatment.

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### **3 SITE SELECTION**

In this report, the safety data collection and analysis techniques using a hierarchical Bayesian approach are applied to two types of safety mitigation devices: raised medians and cable barrier systems. Before conducting a detailed crash analysis, the study area must be defined. The raised median and cable barrier locations that have been selected for analysis are discussed in this section. For crash analysis purposes, the study area will be roadway segments where raised medians or cable barrier systems have been installed during the past 10 years. This section describes the background steps taken for the selection of these sites as well as a summary of sites selected for raised median and cable barrier analysis.

#### **3.1 Site Selection Background**

The process for site selection included identifying locations where raised medians and cable barrier systems have been installed on Utah roadways. The locations where raised medians and cable barrier systems have been installed were identified using previous safety studies (Schultz and Lewis 2006), UDOT project records, as well as online resources such as Google Maps (Google 2010). Possible sites were limited to locations where before and after crash data were available at the time of this study.

One of the difficulties in site selection was the accuracy of mileposts on Utah roadways. Mileposts on Utah roadways have been altered several times over the past 10 years to account for various roadway improvement and changes in alignment. UDOT is currently working to establish and maintain a continually updated database of mileposts on Utah roadways. Sites where uncertainty of reporting accuracy existed have been excluded from selection. For example, US-89 is a major north-south corridor through Utah that has raised medians installed on multiple segments. However, mileposts along the route have changed repeatedly over the

past 10 years and reliability of milepost data is insufficient. Mileposts in selected sites have been verified by UDOT to ensure any and all changes have been accounted for.

To perform an analysis on the impact of raised medians, the year in which the medians were installed needed to be determined. Installation dates at selected sites were determined by previous raised medians studies in the state, UDOT records, or by utilizing UDOT's Roadview Explorer tool (UDOT 2010). Data from both the current year and from past years were accessed with UDOT's Roadview Explorer tool.

### **3.2 Raised Medians**

A raised median is a physical barrier, such as a concrete or landscaped island, in the center portion of the roadway that separates opposing lanes of traffic and is not easily traversed. Raised medians are appropriate in some, though not all locations. Raised medians are most useful on high volume, high speed roads and are not always used to mitigate one specific type of crash or factor (CTRE 2005).

Raised medians have been installed as an access management technique, for beautification purposes, and various other purposes. The use of raised medians as an access management technique improves roadway safety in two ways: 1) raised medians reduce the number of conflict points by allowing turning movements to be made only at designed openings or at signalized intersections and 2) raised medians provide a physical barrier separating opposing traffic aimed at reducing the potential for head-on collisions (TRB 2003). Raised medians can be used to enhance the character of a street by providing space for landscaping which, in turn, may help reduce speeds. Raised medians also provide a pedestrian benefit, because they can serve as a place of refuge for pedestrians who cross a street midblock or at intersections. Regardless of the intended purpose, the installations of raised medians have had a positive impact on crash trends and patterns (TRB 2003).

Raised medians locations were selected based on previously conducted research (Schultz and Lewis 2006). An overview of each location is provided in the following subsections. Images were obtained utilizing Google Images (Google 2010).

### 3.2.1 *University Parkway (SR 265)*

University Parkway (SR 265) is a major east-west arterial located in the cities of Orem and Provo, UT. SR 265 begins on the west side of Interstate 15 at Geneva Road and terminates at 900 East in Provo. SR 265 provides access to important regional retail and office land uses as well as two of Utah's universities; Utah Valley University (UVU) and Brigham Young University (BYU). In 2002 a raised median was installed in a portion of the Orem section between 400 West and 200 East. Figure 3-1 shows a portion of the SR265 raised median that was installed in 2002 between 400 West and 200 East in Orem.



**Figure 3-1. Raised median on University Parkway (SR 265) (Google 2010).**

### 3.2.2 *Alpine Highway (SR 74)*

The Alpine Highway (SR 74), shown in Figure 3-2, is a major north-south highway providing access to the cities of Highland and Alpine, UT. SR 74 is a two-lane highway that mostly traverses residential areas. In 2002, a raised median was installed on the section from 9840 North to 11300 North in Highland.



**Figure 3-2. Raised median on Alpine Highway (SR 74) (Google 2010).**

### *3.2.3 400/500 South (SR 186)*

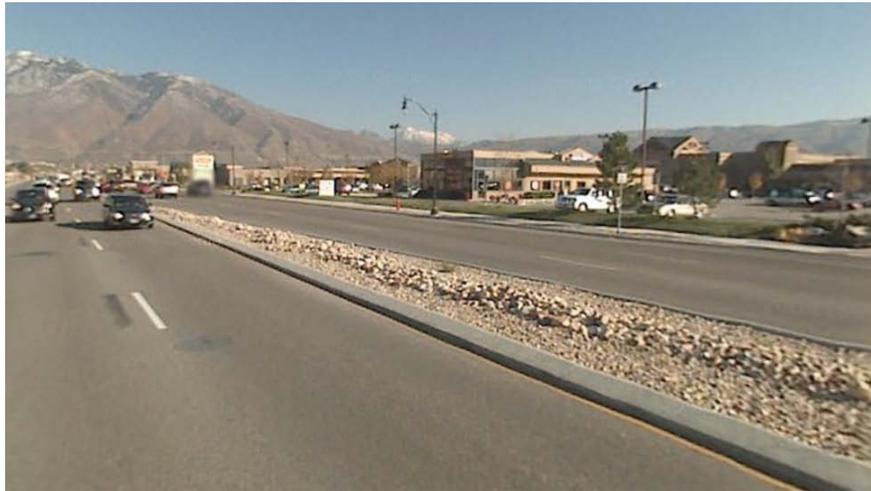
The 400/500 South segment of SR 186 is a six-lane east-west arterial in downtown Salt Lake City, UT. SR 186 curves from 400 South to 500 South between 900 East and 1100 East. A light rail transit line is located in the raised median of SR 186. Construction of the raised median and light rail transit line was completed in 2001. The segment of raised median used in analysis, shown in Figure 3-3, extends from Main Street to 1300 East in Salt Lake City.



**Figure 3-3. Raised median on 400/500 South (SR 186) (Google 2010).**

### 3.2.4 12300 South (SR 71)

12300 South (SR 71) is a major east-west arterial in Draper, UT and is shown in Figure 3-4. Due to a substantial growth of the surrounding area, this segment received major improvements in 2004 including widening to six lanes and the installation of a raised median. The raised median segment used for analysis extends from 300 East to 265 West. A short extension west from the south end to the new SR 154 was made in 2001. The extension caused a shift in the milepost, which was taken into consideration during analysis.



**Figure 3-4. Raised median on 12300 South (SR 71) (Google 2010).**

### 3.2.5 St. George Boulevard (SR 34)

St. George Boulevard (SR 34) is major arterial through the center of St. George, UT and is shown in Figure 3-5. Improvements to the road, including the installation of a raised median, were completed in 2006. The raised median extends over the entire length of the project from Bluff Street to 1000 East.



**Figure 3-5. Raised median on St. George Boulevard (SR 34) (Google 2010).**

### 3.2.6 SR 36

SR 36 is a major north-south arterial through Tooele County, UT and is shown in Figure 3-6. SR 36 serves as the major connector for communities within Tooele County as well as surrounding cities, including Salt Lake City. A project completed in 2005 widened the roadway to two lanes in each direction and installed a raised median for a short segment in the city of Erda, UT in north Tooele County.



**Figure 3-6. Raised median on SR 36 (Google 2010).**

### 3.3 Cable Barrier

Cable barrier is a type of roadside or median barrier. Although cable barrier systems have been in use since the 1960s it wasn't until the mid 1990s that many DOTs began to deploy them with any regularity.

The AASHTO *Roadside Design Guide* defines a cable barrier as a system of steel wire ropes mounted on weak posts. By far, the most accepted use of the cable barrier system occurs in the medians of divided highways, as cross median crashes are particularly severe. While median width plays a large role in the occurrence of these crashes, increased median width alone does not eliminate such crashes and often, the median must be shielded with a barrier. Cable barrier systems provide a cost-effective solution in reducing cross median crashes. The primary purpose of a cable barrier system is to prevent a vehicle from leaving the traveled way by capturing and/or redirecting the errant vehicle. Thus the errant vehicle is prevented from striking another object, particularly vehicles traveling in the opposite direction of travel. A cable barrier system is typically more forgiving than traditional concrete barrier or steel barriers. The flexibility of the system absorbs impact energy and dissipates it laterally, which reduces the forces transmitted to the vehicle occupants (AASHTO 2006).

Due to the fact that cable barrier is relatively inexpensive to install and highly effective at capturing vehicles, they are being used more frequently by state DOTs. In Utah, cable barrier has been installed primarily on the freeway system. Selected cable barrier locations are outlined in the following subsections. Images were obtained utilizing Google Images (Google 2010).

#### 3.3.1 I-15 Provo S-curves to University Parkway

The majority of the sites where cable barrier systems have been installed in the last few years are along Interstate 15 (I-15). I-15 is the one of the longest north-south transcontinental Interstate Highways in the United States, passing through the states of California, Nevada, Arizona, Utah, Idaho, and Montana. Over 400 miles of I-15 traverse Utah and serve as the main north-south connection in the state.

This specific site is a 2-mile segment along I-15 located between the Provo S-curve and University Parkway in Utah County, UT between mileposts 267 and 269. Cable barrier was installed along this segment in 2004. Originally 5 miles of cable barrier was installed, but 3

miles of the cable barrier was replaced with concrete barrier as part of a widening project in 2005. The remaining 2-mile segment, shown in Figure 3-7, retained the cable barrier system and was selected for analysis.



**Figure 3-7. Provo S-curves to University Parkway (Google 2010).**

### *3.3.2 I-15 between Pintura and Kolob Canyons*

This site is a 2-mile segment of I-15 located in the Southern part of Utah between Cedar City and St. George, UT. Cable barrier was installed between mileposts 36 and 38, as shown in Figure 3-8, in 2005. The population of cities in this portion of the State is relatively low. The majority of the traffic traveling this segment of I-15 is long distance travelers between St. George and the Wasatch Front.



**Figure 3-8. I-15 between Pintura and Kolob Canyons (Google 2010).**

### *3.3.3 I-15 Spanish Fork to SR 75*

The Wasatch Front is an urban area in the north-central part of the Utah. It consists of a chain of cities and towns stretched along the Wasatch Mountain Range from approximately Santaquin in the south to Brigham City in the north. Roughly 80 percent of Utah's population resides in this region, which includes the Salt Lake City, Provo and Ogden urban areas.

In 2005, cable barrier was installed in between Spanish Fork and SR 75 in the southern part of Utah County. This 4-mile segment of cable barrier on I-15 is located between mileposts 257 and 261 and is shown in Figure 3-9. This section of I-15 serves as the main connection between the communities south of Provo to the Provo-Orem area as well as various other destinations.



**Figure 3-9. I-15 between Spanish Fork and SR 75 (Google 2010).**

#### *3.3.4 I-15 South Layton to Syracuse*

This segment of I-15 is located just north of Salt Lake City, UT in Davis County. Congestion is a significant issue in the county, as north-south travel is confined to a narrow urban corridor between the Great Salt Lake and the Wasatch Front Mountains. Many residents of this area commute daily to Salt Lake County. In 2006, cable barrier was installed along this 4-mile segment of I-15 between mileposts 330 and 334 from South Layton to Syracuse as shown in Figure 3-10.



**Figure 3-10. I-15 between Layton and Syracuse (Google 2010).**

### 3.3.5 *I-15 600 North to 2300 North in Salt Lake*

In 2007, cable barrier was installed along a 3-mile segment of I-15 in the northern part of Salt Lake City, UT between 600 North and 2300 North (mileposts 309 and 312) and is shown in Figure 3-11. This section of I-15 is often one of the most congested in the state as it provides primary service for commuting traffic between Salt Lake County and Davis County.



**Figure 3-11. I-15 between 600 North and 2300 North in Salt Lake (Google 2010).**

### 3.3.6 *I-215E 3100 South to 3800 South in Salt Lake*

Interstate 215 (I-215) is an auxiliary interstate that forms a 270-degree loop around Salt Lake City, UT and many of its suburbs. In 2007, cable barrier was installed along the east portion of I-215 in Salt Lake County. This 1-mile segment of cable barrier is located between 3100 South and 3800 South. This cable barrier system was installed between mileposts 1.5 and 2.5 as is shown in Figure 3-12.



**Figure 3-12. I-215 East between 3100 South and 3800 South in Salt Lake (Google 2010).**

### *3.3.7 I-215W 2100 South to 4500 South Salt Lake*

In 2007, cable barrier was also installed along the west side of I-215 in Salt Lake. This section is a 2.5 mile segment located between 2100 South and 4500 South between mileposts 17 and 19.5 as illustrated in Figure 3-13.



**Figure 3-13. I-215 West between 2100 South and 4500 South in Salt Lake (Google 2010).**

### 3.4 Chapter Summary

This chapter provides a summary of selected raised median and cable barrier analysis sites from Utah roadways. The exact beginning and ending mileposts of each analysis segment were used to match the crashes that occurred at each selected site for each year of analysis. The year that a raised median or cable barrier system was installed at each site was also determined in order to separate the before and after periods used in analysis. Table 3-1 provides a summary of raised median sites that have been included in this analysis while Table 3-2 provides a summary of included cable barrier sites.

**Table 3-1. Raised Median Study Locations**

<b>Street</b>	<b>Route</b>	<b>Length (mi.)</b>	<b>Location</b>	<b>Year Installed</b>
University Parkway	265	0.76	400 West to 200 East	2002
Alpine Highway	74	1.89	9840 North to 11300 North	2002
400/500 South	186	2.05	Main Street to 1300 East	2001
12300 South	71	0.90	265 West to 300 East	2004
St. George Blvd.	34	1.74	Bluff Street to 1000 East	2006
SR 36	36	1.53	Erda Way to Bates Canyon Rd.	2005

**Table 3-2. Cable Barrier Study Locations**

<b>Site</b>	<b>Route</b>	<b>Length (mi.)</b>	<b>Location</b>	<b>Year Installed</b>
1	I-15	2.0	Provo S-curves to University Parkway	2004
2	I-15	2.0	Between Pintura and Kolob Canyons	2005
3	I-15	4.0	Spanish Fork to SR 75	2005
4	I-15	4.0	South Layton to Syracuse	2006
5	I-15	3.0	600 N to 2300 N – Salt Lake	2007
6	I-215 E	1.0	3100 S to 3800 S – Salt Lake	2007
7	I-215 W	2.5	2100 S to 4500 S – Salt Lake	2007

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## **4 ANALYSIS PROCEDURE**

This analysis provides an opportunity to estimate the safety impacts of the installation of raised medians and cable barrier in the state of Utah. Chapter 3 provides necessary background information on the sites selected for analysis.

As part of the analysis, a statistical model was developed to calculate crash frequency before and after the installation of raised medians or cable barrier. The model uses Bayesian techniques to account for RTM bias and thereby can more accurately determine the impacts of a safety mitigation measure than traditional before-after studies.

A set procedure was followed in the analysis of study site crash data. This chapter describes the analysis procedure including data collection, types of analysis performed, and an outline of how the model has been developed. This chapter also includes a description of the analysis steps taken to determine if the installation of a raised median or cable barrier system had an impact on the overall crash frequency as well as the severity of crashes at the selected critical sites.

### **4.1 Data Collection**

The analysis for this study was performed using data obtained from UDOT. This section describes the steps taken in the selection and collection of data used in the development of the model including crash data, AADT data, and milepost data.

#### *4.1.1 Crash Data*

Raw crash data was provided by the UDOT Traffic and Safety Division from the UDOT crash database. The UDOT crash database is comprised of records and statistics obtained from police reports of crashes that occurred on Utah roadways. At the time of this study, consistent data were available from 1996 to 2008.

The raw data needed to be refined for use in the analysis. The full data set was reduced to locations where either raised medians or cable barrier systems had been installed within the boundaries set by the mileposts indicated previously in Table 3-1. Duplicate records as well as crashes that occurred during the installation years were removed from the dataset.

#### 4.1.2 AADT Data

AADT data are used to measure total volume of vehicle traffic of a highway or road. Previous research has determined that a relationship exists between crashes and AADT. Although the exact relationship is still not entirely known, it is known that the relationship is generally non-linear (Hauer 1997). However, AADT is still an important parameter in predicting crash frequency and was used as a covariant in the development of the model.

From traffic counts, AADT is estimated for individual segments of Utah roadways. AADT values were obtained using the annual *Traffic on Utah Highways* reports available on the UDOT website (UDOT 2008). Each annual report provides AADT on Utah roadways for the corresponding year as well as AADT values for the two previous years. Each route is broken down into sections, the boundaries of which are usually defined by physical barriers (county or state boundaries) or where changes in roadway characteristics occur (such as intersections or interchanges). Annual reports are available on-line back to the year 2000. An example taken from the 2008 report (UDOT 2008) is shown in Figure 4-1.

#### 4.1.3 Milepost Data

Locations of crashes are reported as the milepost where the crash occurred on the corresponding route. However, mileposts on Utah highways have undergone several changes over the past 10 years. Shifts in mileposts are usually the result of either a realignment of the route, or an extension added onto either end of the route. Although the segments of each route of interest were held constant through each analysis year, corresponding mileposts have changed over the course of the study period. To ensure that data for the correct segment was used for each analysis year, correct mileposts were verified through UDOT. A summary of the changes in mileposts for each raised median analysis segment is displayed in Table 4-1.

ROUTE NAME	BEG. ACCUM. MILEAGE	END ACCUM. MILEAGE	LOCATION DESCRIPTION	2008 AADT	2007 AADT	2006 AADT
0013	24.956	31.057	SR 30 Riverside	835	860	2,470
0013	31.057	31.641	20000 North Plymouth	665	670	665
0013	31.641	32.224	20400 North Plymouth	650	670	665
0013	32.224	32.841	Road to Nucor Steel Plant - I 15	820	840	1,920
0014	0.000	0.546	SR 130 Main Street Cedar City	3,010	3,165	2,745
0014	0.546	4.961	580 East Cedar City	2,170	2,455	2,390
0014	4.961	18.172	Scenic Backway to Kolob Reservoir	1,575	1,780	860
0014	18.172	25.711	SR 148 Road to Cedar Breaks National Monument	840	890	850
0014	25.711	40.995	Navajo Lake Rd - SR 89 Long Valley	855	905	850
0015	0.000	4.660	Arizona State Line	20,415	22,505	21,930
0015	4.660	6.310	Bloomington	32,235	35,540	34,640
0015	6.310	8.660	SR 18 Bluff Street St George	24,615	27,140	40,750
0015	8.660	10.930	SR 34 St. George Boulevard	43,260	44,230	42,145
0015	10.930	13.378	SR 212 Washington	38,285	40,995	39,955
0015	13.378	15.910	Washington Parkway Interchange	36,645	40,405	39,380
0015	15.910	22.580	SR 9 Hurricane Zion National Park	19,820	21,075	20,495
0015	22.580	23.720	SR 228 South Leeds Silver Reef	19,365	20,600	20,040
0015	23.720	27.480	SR 228 North Leeds Silver Reef	20,655	21,975	21,375
0015	27.480	30.680	SR 17 Anderson Jct. Toquerville	21,170	22,520	20,725
0015	30.680	31.870	Browse Interchange	21,125	22,490	21,310
0015	31.870	33.440	Pintura	20,940	22,275	21,670
0015	33.440	36.770	Ranch Exit (Snowfield)	20,950	22,285	21,675
0015	36.770	40.270	Ranch Exit (Black Ridge)	20,835	21,105	20,530
0015	40.270	42.170	Kolob Canyons Interchange	20,415	21,580	20,990
0015	42.170	51.160	New Harmony/Kanarrville Interchange	20,610	21,785	21,190

Figure 4-1. Example of UDOT 2008 Traffic on Utah Highways Annual Report (UDOT 2008).

Table 4-1. Summary of Raised Median Milepost Changes

Route	Year	Beg. MP	End MP
265	1995-2001	1.21	1.97
	2002-2009	1.20	1.96
74	1995-2009	2.40	4.29
186	1995-2001	5.50	7.55
	2002-2005	5.54	7.59
	2006-2007	5.48	7.53
71	1995-2001	2.17	3.07
	2002-2005	4.56	5.46
	2006-2009	4.55	5.45
34	1995-2009	0.00	1.74
36	1995-2001	59.31	60.84
	2002-2005	59.43	60.96
	2006-2008	59.29	60.82

The mileposts for all cable barrier segments remained unchanged during the study period. The segment lengths for each site were summarized previously in Table 3-2.

## **4.2 Type of Analysis**

This section describes the types of analysis that have been performed on locations where raised medians and cable barrier have been installed in the state of Utah. An overall analysis on all crashes and a severe crash analysis on only severe crashes were performed for both raised median and cable barrier sites. An additional analysis was performed on cross-median crashes at cable barrier sites.

### *4.2.1 Overall Crash Analysis*

An overall crash analysis was conducted on all crashes that occurred at sites before and after the installation of cable barrier systems and raised medians. The roadway safety assessment of a segment should consider the roadway elements (roadway type, weather), the driver (age, fatigue) and the vehicle (type, volume, speed). These safety characteristics need to be reviewed whenever a roadway analysis is performed. The crash data should be analyzed to determine the current crash trends and related traffic issues should be identified. Changes in types of crashes or contributing factors that can be attributed to the specific mitigation technique used need to be identified. These factors have been considered as part of this analysis.

### *4.2.2 Severe Crash Analysis*

An analysis was also performed on severe crashes that occurred where raised medians and cable barrier systems have been installed. According to the National Safety Council (NSC), “there are five mutually exclusive categories of injury severity for classification of road vehicle (crashes)” (NSC 1996). The five categories are fatal, incapacitating injury, non-incapacitating evident injury, possible injury, and non-injury. A common abbreviation for these severity levels is referred to as the KABCO scale, with each letter, “K” through “O”, representing fatal through non-injury levels of severity, respectively. The five severity classifications are mutually exclusive because a crash is classified based on the most severe of injuries sustained as a result

of a crash (e.g., a crash with a fatality and a minor injury is classified only as a fatal crash, not a fatal crash and a minor injury crash).

Crash severity is coded into a police report by the reporting officer as one of the five categories explained above. The police reports, along with corresponding crash severity ratings, are then entered into the UDOT database. Initially fatal crashes were an area of interest in the analysis. However, due to the limited availability of data, fatal crashes were expanded to severe crashes. Severe crashes were determined to be crashes indicated on the report as “fatal” or “incapacitating injury.”

One of the main goals in the installation of both raised median and cable barrier is to reduce severe crashes as is described in Chapter 3. The primary purpose of cable barrier is to eliminate median crossover crashes. Median crossover crashes often result in fatalities or severe injuries to occupants of the errant vehicle and the motorists in the opposing traffic lanes. Similarly, raised medians reduce sideswipe and head-on collisions by limiting turning movements and providing a physical barrier from opposing traffic.

#### *4.2.3 Cross-Median Crash Analysis*

An analysis was also performed on cross-median crashes. The cross-median analysis was performed only on locations where cable barrier systems have been installed. As described in Chapter 3, the primary purpose of cable barrier is to eliminate cross-median crashes. Cross-median crashes often result in fatalities or severe injuries.

### **4.3 Development of Model**

A set procedure was followed in the analysis of crash data for the selected sites. A hierarchical Bayesian model was constructed to perform the analysis. The development of the model was necessary to more accurately determine the impact of raised medians and cable barrier systems on crashes. The analysis procedure presents an opportunity to estimate the safety impacts of various types of treatments, particularly raised medians and cable barrier systems. This section outlines the development of the model by first outlining the background of the hierarchical Bayesian model, and then identifying model specification and estimation.

### 4.3.1 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):

$$p(\theta, y) = p(y)p(\theta|y) \quad (4-1)$$

where,  $y$  = crashes per mile, and  
 $\theta$  = mean number of crashes per mile

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

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

The distribution  $p(\theta)$  denotes the prior distribution for  $\theta$ . 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  $\theta$ . The conditional distribution  $p(\theta|y)$  is the posterior distribution of  $\theta$  given the data. The posterior distribution is used to draw conclusions in this study.

### 4.3.2 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:

$$y_i \sim \text{Poisson}(\theta_i) \quad (4-3)$$

The Poisson distribution is utilized due to crash data being classified as count data, as discussed in Chapter 2. 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 per mile is then calculated using Equation 4-4.

This result is the consideration of two intercepts: one for the before data and one for the after data. AADT is constrained to be the same for either time period. The log transform was chosen as part of the standard Poisson regression procedures.

The prior for each  $\beta_j$  where  $j \in \{A, B, 1\}$  is normally distributed as defined in Equation 4-5 where  $A$  represents the after period and  $B$  represents the before period. These priors are quite uninformative, which reflects the lack of convincing evidence to suggest more specific priors.

$$\log(\theta_i) = \beta_A I(A_i) + \beta_B (1 - I(A_i)) + \beta_1 \text{AADT}_i, \quad (4-4)$$

where,  $\theta_i$  = the mean number of crashes per mile,  
 $\text{AADT}_i$  = AADT for the  $i^{\text{th}}$  observation, and  
 $I(A_i)$  = an indicator variable stating whether or not the  $i^{\text{th}}$  observation was in the after period of data collection (equal to 0 for before period and 1 for after period).

$$\beta_j \sim \text{Normal}(0,1) \quad (4-5)$$

The posterior distribution for the  $\beta$  parameters is expressed in Equation 4-6.

$$\pi(\beta|y) \propto P(y|\beta)\pi(\beta_A)\pi(\beta_B)\pi(\beta_1) = \frac{\exp(\sum_{i=1}^n \exp(X_i\beta))}{\prod_{i=1}^n y_i!} \times \frac{1}{(\sqrt{2\pi})^3} \exp\left[-\frac{1}{2}(\beta_A^2 + \beta_B^2 + \beta_1^2)\right] \quad (4-6)$$

where,  $X_i$  = matrix containing appropriate covariates to satisfy the model, and  
 $n$  = 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 Metropolis Hastings under the Markov Chain Monte Carlo (MCMC) methodology. This involves beginning with initial values and sampling each of the  $\beta_k$  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  $\beta_k$  parameters. In this study, each site is modeled with its own set of  $\beta$  parameters for both overall and severe crashes. The modeling code developed for the analysis is included in Appendix A.

#### **4.4 Chapter Summary**

This chapter outlines the process used in the analysis. This process includes the collection of needed data, development of the model, and understanding the types of analysis performed. Data collected for the study include crash histories, AADT data, and milepost data of Utah roadways. The milepost data were used to identify locations where raised medians and cable barrier systems have been installed. A hierarchical Bayesian model was constructed for the analysis. Using the model, an analysis was performed on both the overall and severe crashes that occurred where raised medians and cable barrier systems have been installed. The overall crash analysis included all crashes that occurred at each site before and after the installation of the specific treatment. Severe crashes were determined to be crashes indicated on the report as “fatal” or “incapacitating injury.” Severity of each crash is available from police reports that crash data is based on.

## **5 RAISED MEDIAN RESULTS**

A hierarchical Bayesian analysis was performed at selected sites where raised medians have been installed following the procedure outlined in Chapter 4. This analysis was performed for both overall crash frequency and severe crash frequency at each site.

Two types of plots are produced for each analysis performed. The first is a plot of the actual data. These plots display the actual data points along with the mean of the posterior (after) predictive distribution. Essentially it represents the mean regression line through the points from a Bayesian perspective. The reduction is calculated by taking the mean of the differences between the two intercepts in the posterior distribution. This is a percent reduction because  $\log(\text{after/before}) = \log(\text{after}) - \log(\text{before})$ , and the intercepts are on a log scale. This is essentially equivalent to dividing the after curve by the before curve and getting the percent reduction.

The second plot produced shows the distribution of the differences between the before and after periods. The differences plots display the posterior distributions of differences between the before and after intercepts of the model. Negative values indicate that the after period saw a reduction in crashes. As the exact form of those posterior distributions is unknown, the model uses simulated draws from the posterior with MCMC; since those draws represent the actual posterior distribution, the proportion of the draws that are less than zero represents the probability that there was a decrease in crashes from the before period to the after period.

### **5.1 Raised Median Individual Site Results**

The safety impacts of raised medians at the individual study sites are discussed in this section. Details about each location are provided in Chapter 3. The analysis procedure is described in Chapter 4. The following sections summarize the results of the analysis performed at each individual site where raised medians were installed based on crash data provided by

UDOT as well as an overall analysis performed on all sites. Sites selected for analysis were shown previously in Table 3-1, but are repeated for convenience in Table 5-1.

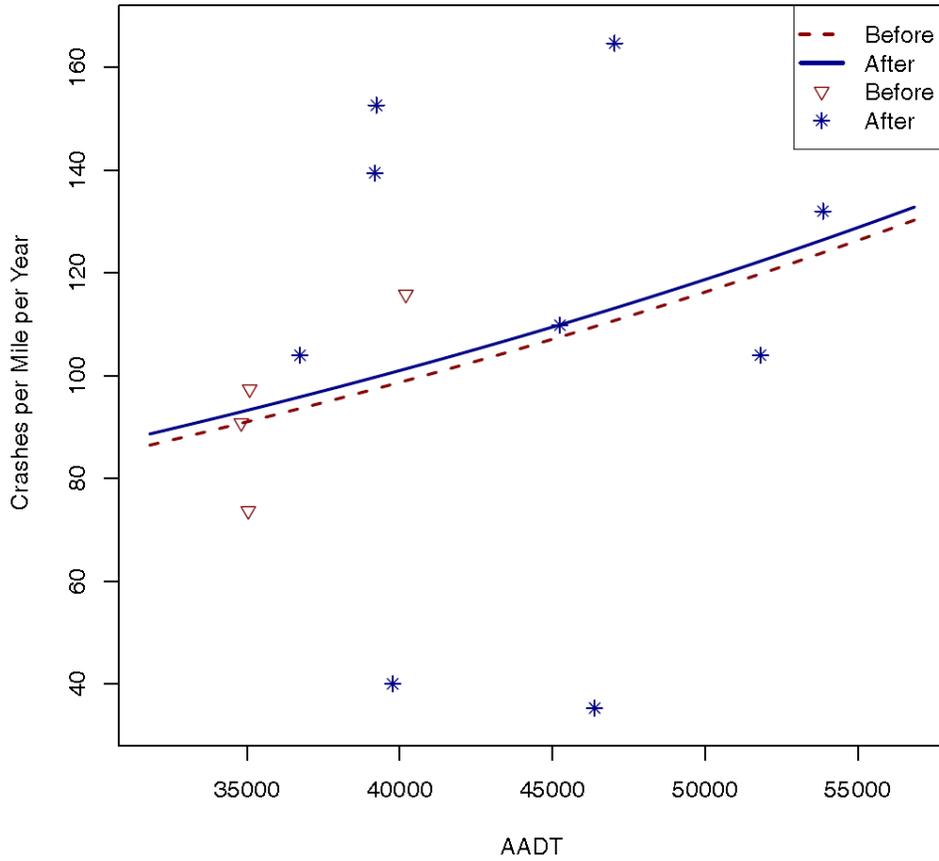
**Table 5-1. Raised Median Study Locations**

<b>Street</b>	<b>Route</b>	<b>Length (mi.)</b>	<b>Location</b>	<b>Year Installed</b>
University Parkway	265	0.76	400 West to 200 East	2002
Alpine Highway	74	1.89	9840 North to 11300 North	2002
400/500 South	186	2.05	Main Street to 1300 East	2001
12300 South	71	0.90	265 West to 300 East	2004
St. George Blvd.	34	1.74	Bluff Street to 1000 East	2006
SR 36	36	1.53	Erda Way to Bates Canyon Rd.	2005

*5.1.1 University Parkway (SR 265)*

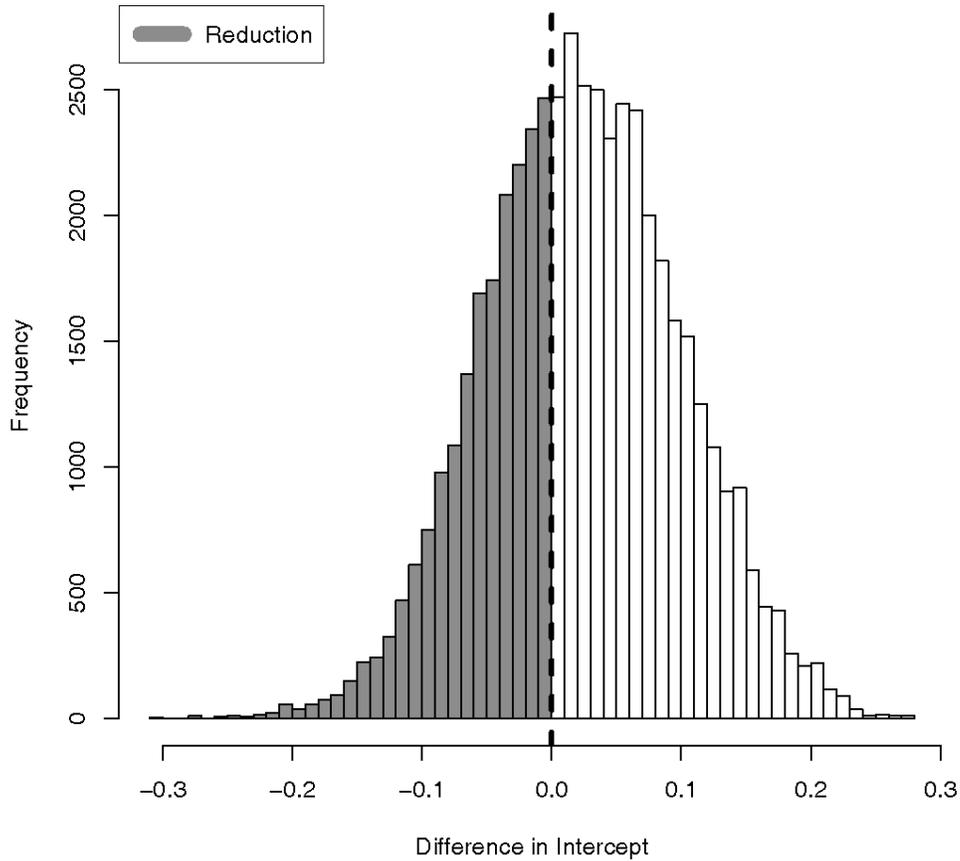
In 2002 a raised median was installed in a segment of SR 265 between 400 West and 200 East in Orem, UT. This section summarizes the results of the analysis performed before and after the raised median was installed. The before period used in the analysis is from 1998 to 2001 and the after period is from 2003 to 2008.

The results of the analysis in Figure 5-1 show the results of the model on overall crash frequency for SR 265. The plot displays the crash frequency of all crashes for the before and after periods as a function of AADT. The results of the analysis indicated the expected percent change after the raised median was installed was a 2.70 percent increase as can be seen in Figure 5-1.



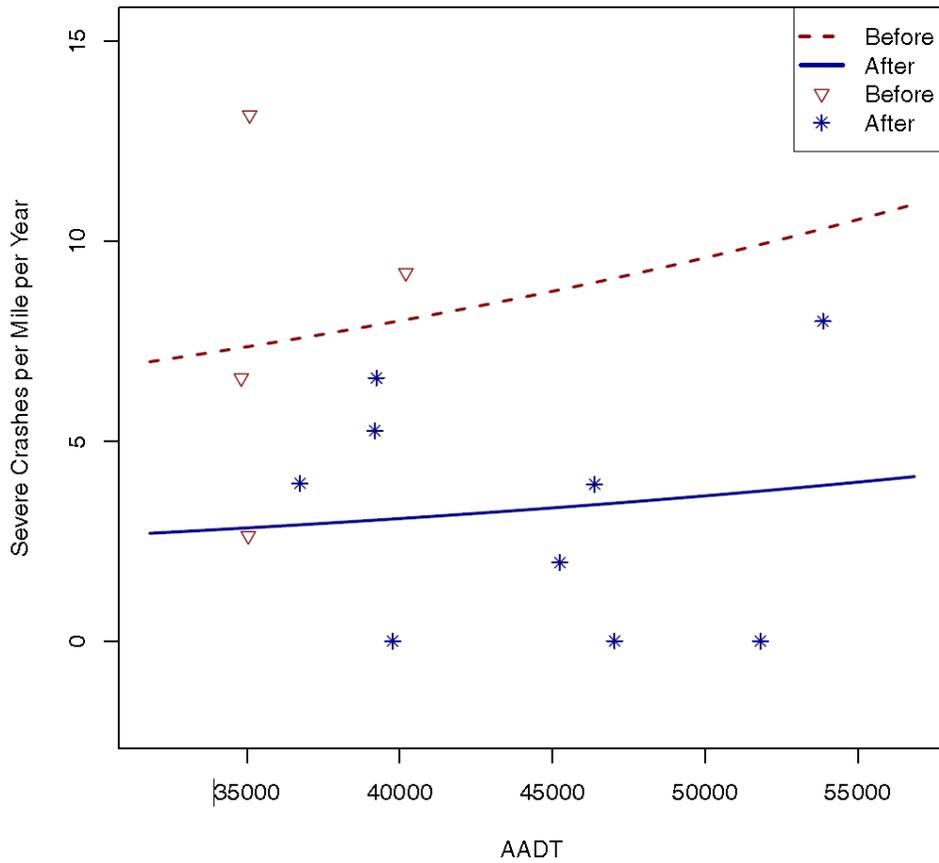
**Figure 5-1. Overall Crashes on SR 265.**

Figure 5-2 shows the corresponding probability distribution of the differences between the before and after periods for overall crashes for SR 265. The gray portion of the distribution represents the probability that a decrease in overall crashes occurred. The probability a decrease in overall crash frequency occurred was 38.24 percent as is represented by the gray portion of Figure 5-2. Therefore it is possible that this segment of University Parkway experienced no difference in overall crash frequency after the installation of the raised median.



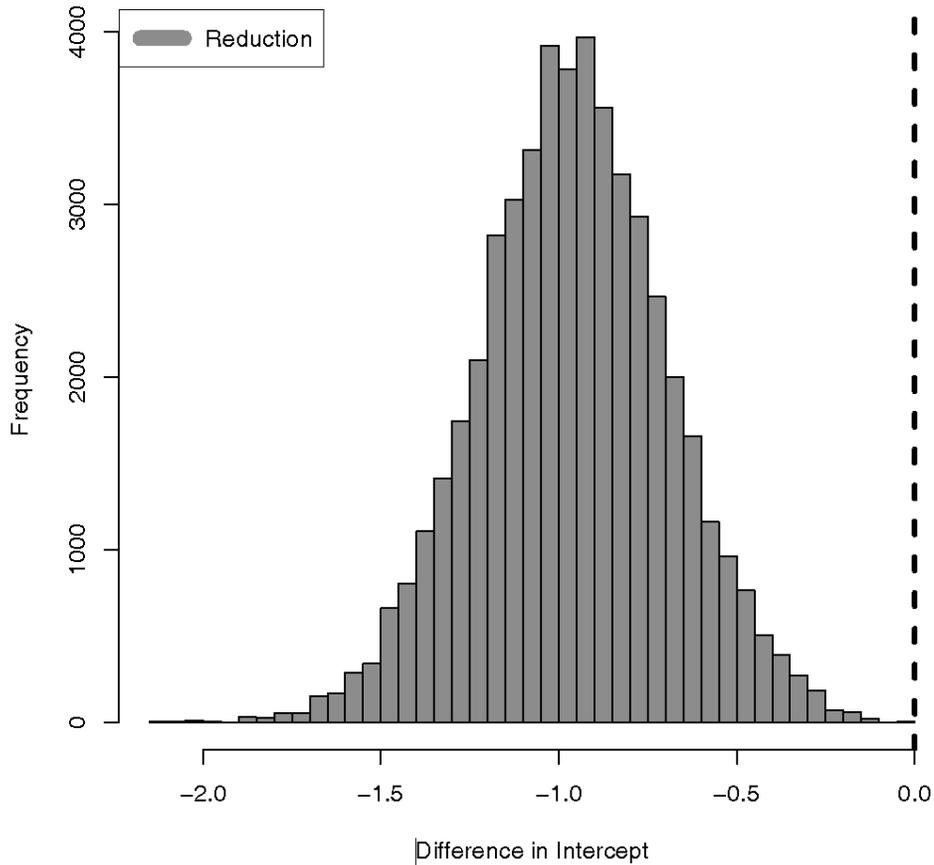
**Figure 5-2. Distribution of differences in overall crashes on SR 265.**

The severe crash frequency analysis provided different results. Figure 5-3 displays the results of the severe crash analysis on SR 265. The figure shows the crash frequency of severe crashes for the before and after periods as a function of AADT. The expected difference was a 60.37 percent average reduction in severe crash frequency after a raised median was installed, as can be seen in Figure 5-3.



**Figure 5-3. Severe Crashes on SR 265.**

Figure 5-4 shows the corresponding probability distribution of the difference between the before and after periods for severe crashes for SR 265. In Figure 5-4, the entire distribution of differences was less than zero, indicating a 100 percent probability a reduction in severe crash frequency occurred after the raised median was installed.

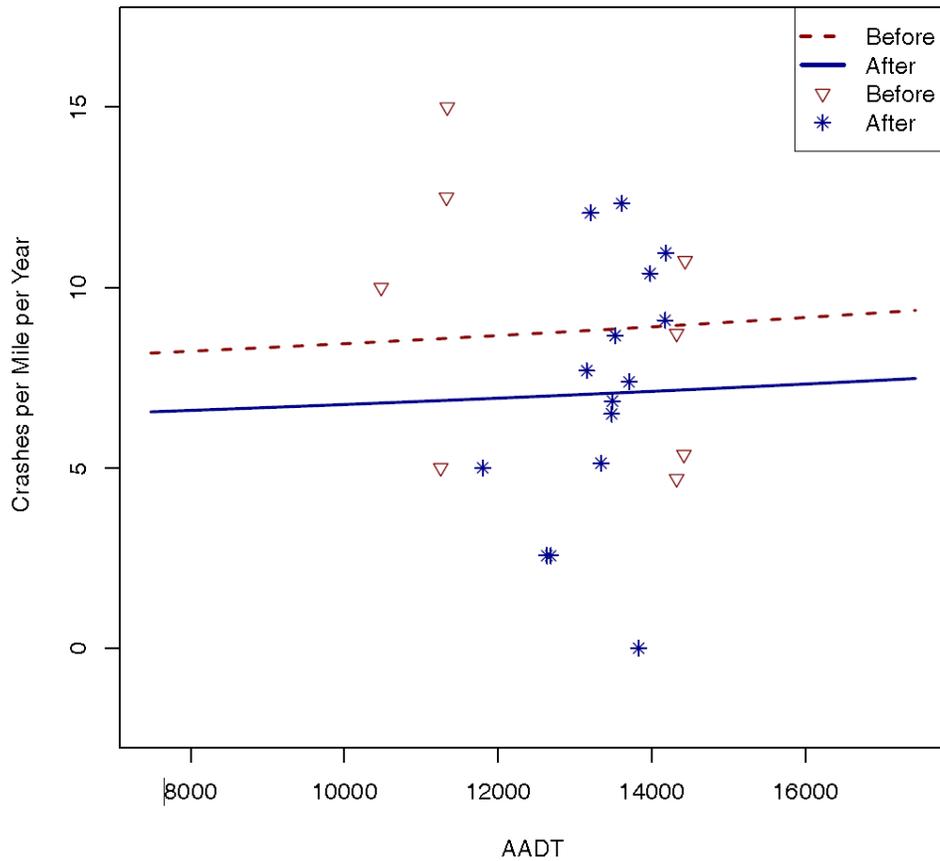


**Figure 5-4. Distribution of differences in severe crashes on SR 265.**

### 5.1.2 Alpine Highway (SR 74)

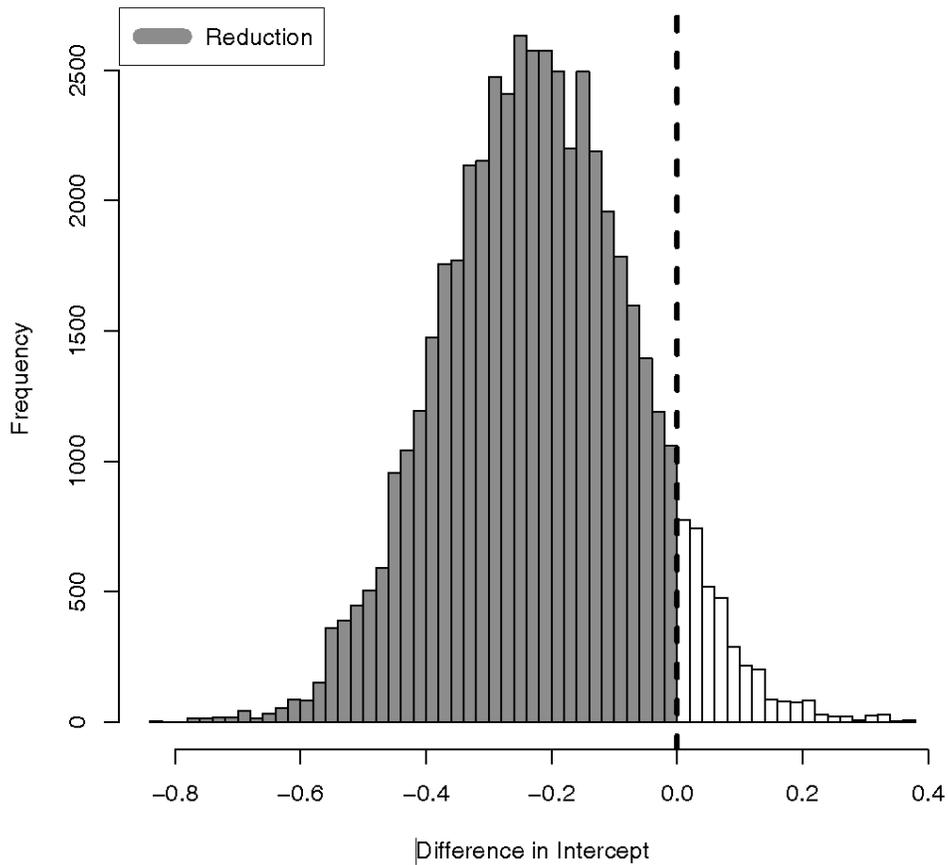
In 2002, a raised median was installed on the section of SR 74 from 9840 North to 11300 North in Highland, UT. This section summarizes the results of the analysis performed before and after the raised median was installed. The before period used in the analysis is from 1998 to 2001 and the after period is from 2003 to 2008.

Figure 5-5 displays the crash frequency of all crashes for the before and after periods as a function of AADT for this segment of SR 74. The overall analysis for this segment of SR 74 showed some improvement. The results indicated the overall crash frequency decreased by 18.92 percent after the installation of the raised median.



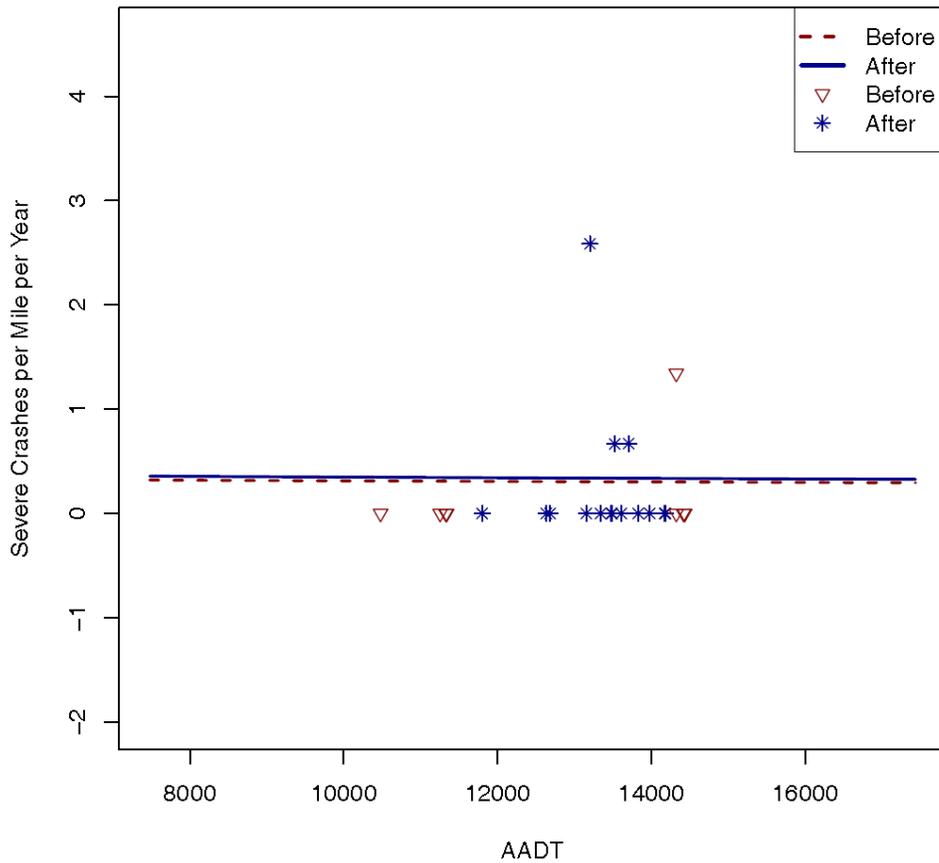
**Figure 5-5. Overall crashes on SR 74.**

Figure 5-6 shows the corresponding probability distribution of the differences between the before and after periods for all crashes for SR 74. The results of the analysis indicated there was a 92.64 percent probability a decrease in the overall crash frequency occurred along this segment of SR 74 after the installation of the raised median. This is represented as the gray portion of the distribution shown in Figure 5-6.



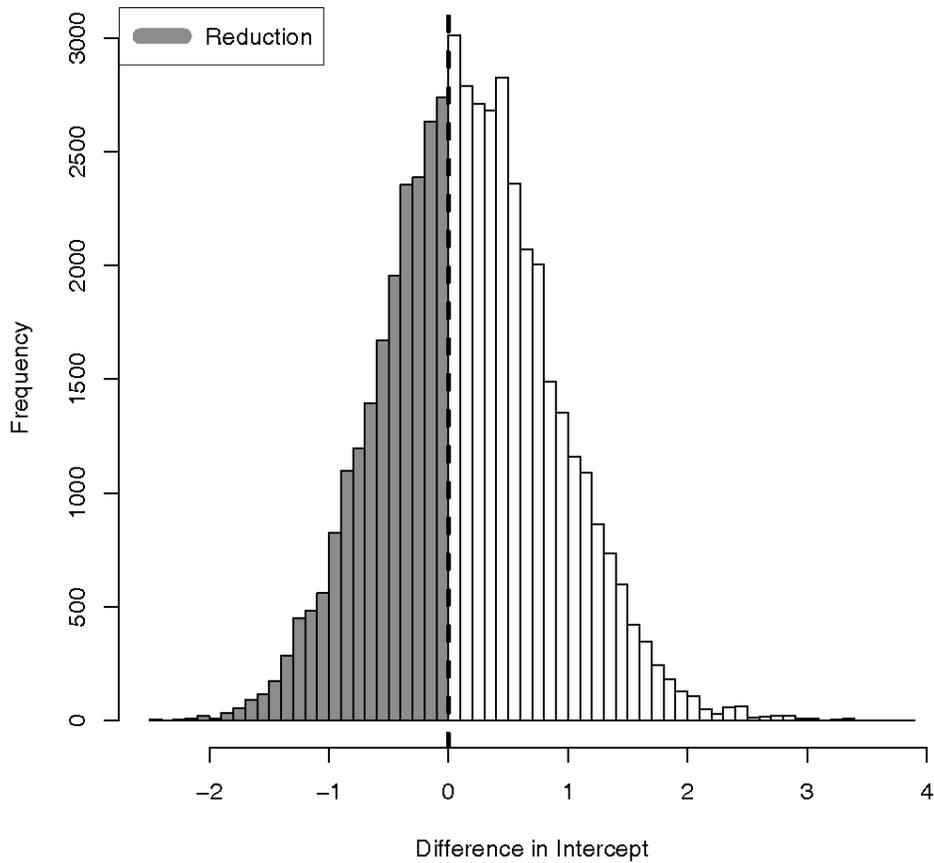
**Figure 5-6. Distribution of differences in overall crashes on SR 74.**

The severe crash analysis results showed differing results. Figure 5-7 displays the crash frequency of severe crashes on SR 74 for the before and after periods as a function of AADT. The severe crash frequency for this segment of SR 74 experienced an increase after the installation of the raised median by 55.27 percent.



**Figure 5-7. Severe crashes on SR 74.**

This increase in severe crashes is unexpected. However, the distribution of the difference for the severe crash analysis shown in Figure 5-8, indicates a 58.93 percent chance an increase occurred (or 41.07 percent chance of decrease), as represented by the gray portion of the distribution in Figure 5-8. However, a large degree of uncertainty still exists in whether or not an increase occurred. Figure 5-7 also revealed an outlier that occurred after the installation of the raised median. Further research should be done to identify reasons why this unusually high frequency occurred.



**Figure 5-8. Distribution of differences in severe crashes on SR 74.**

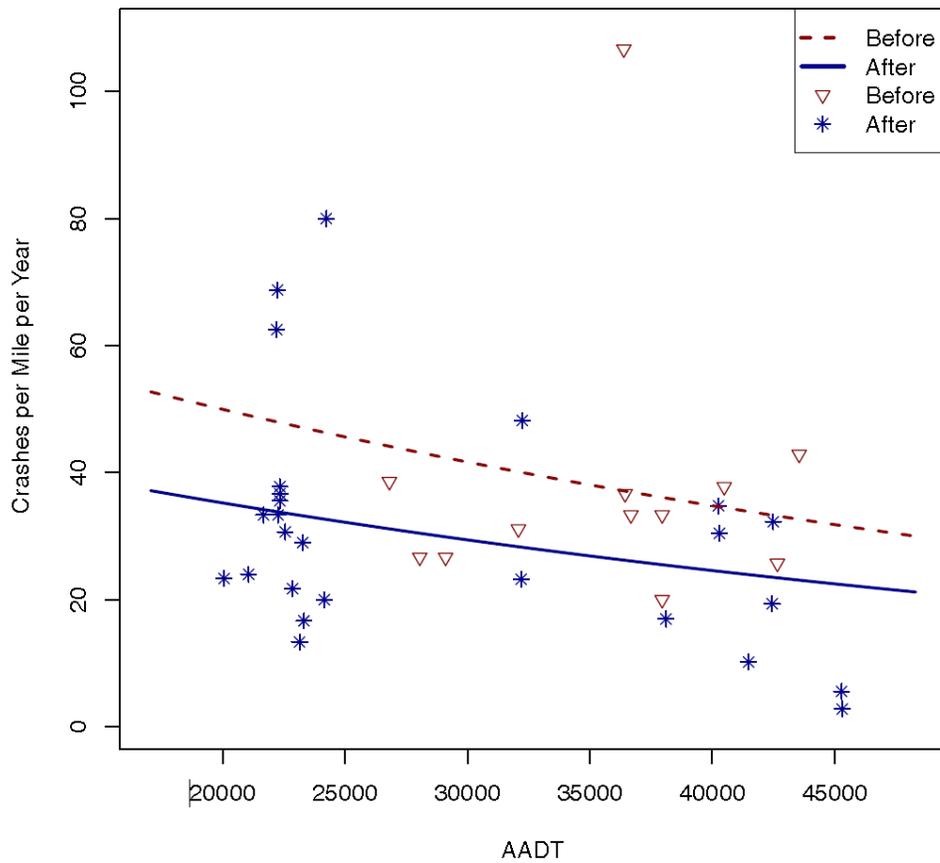
Even if an increase in severe crashes did occur at this site, there are a few possible explanations that could contribute to the significant increase in severe crashes. First, it appears the raised median was installed for beautification purposes rather than as a safety technique. Second, this area has experienced continual increases in residential growth over the past 10 years which may contribute to the increase in severe crash frequency.

### 5.1.3 400/500 South (SR 186)

Construction of the light rail/raised median project on SR 186 between Main Street and 1300 East in Salt Lake City, UT was completed in 2001. This section summarizes the results of

the analysis performed before and after the raised median was installed. The before period used in the analysis is from 1998 to 2000 and the after period is from 2002 to 2007. In 2007, SR-186 was realigned to cover all of former SR-184; therefore data for 2008 was not used in the analysis.

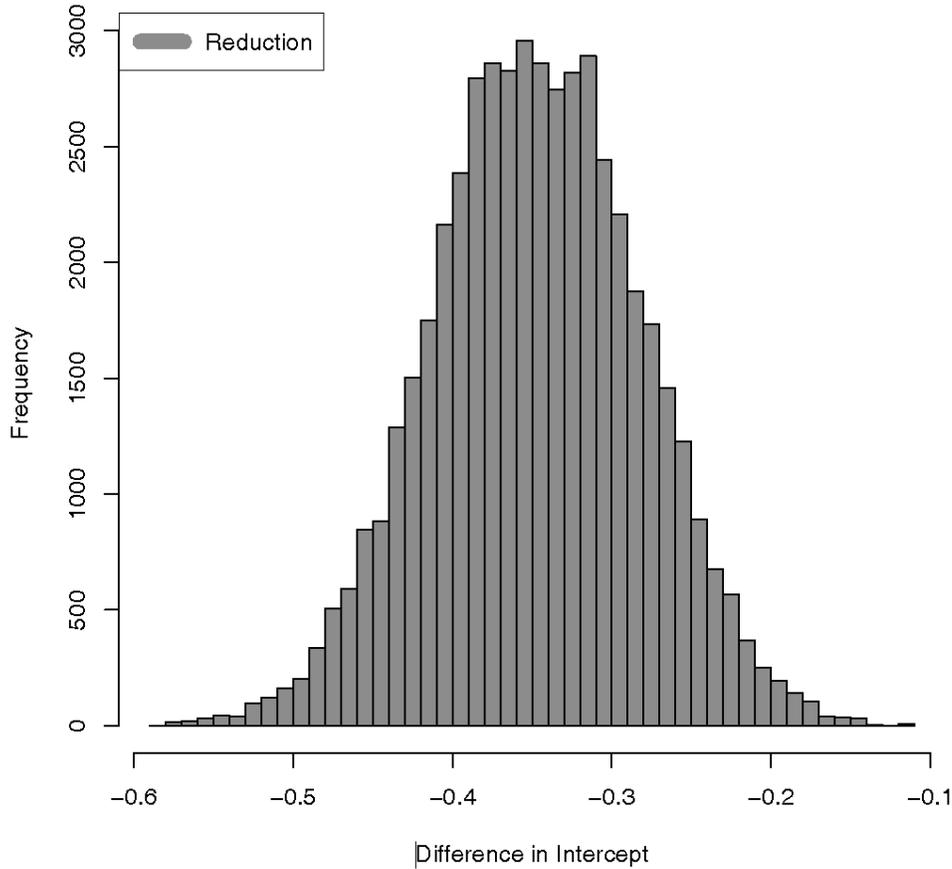
Figure 5-9 displays the results of the overall crash analysis. The overall crash frequency for this segment of SR 186 decreased 29.22 percent after the installation of the raised median.



**Figure 5-9. Overall crashes on SR 186.**

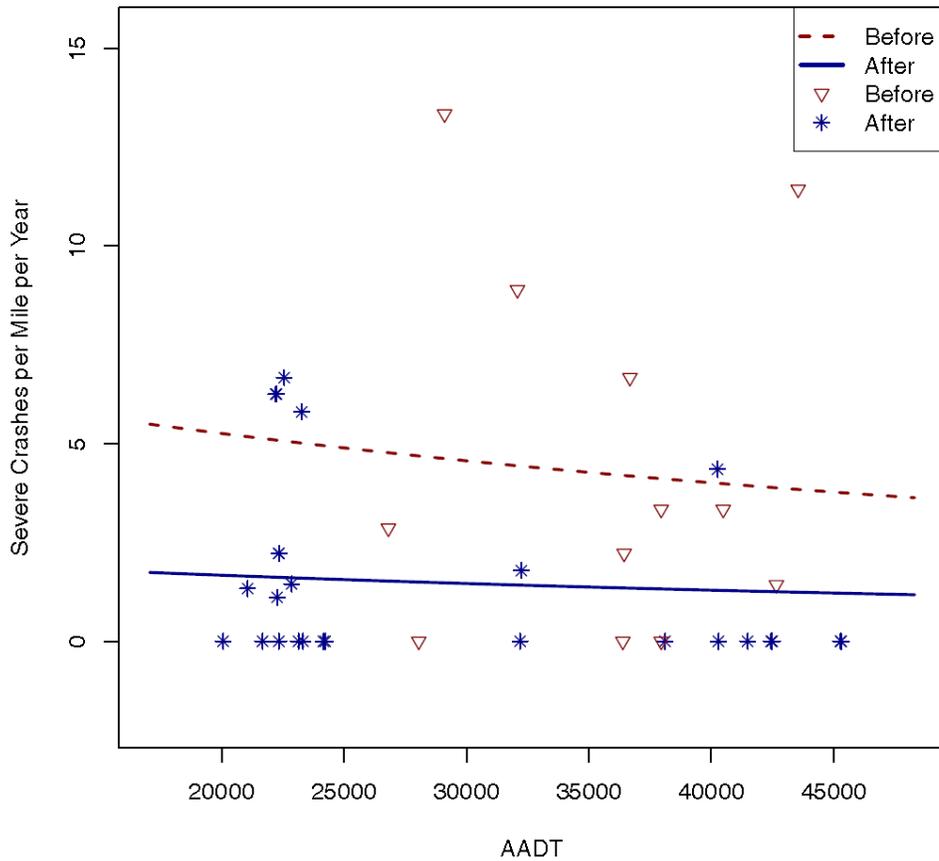
Figure 5-10 shows the corresponding probability distribution of the difference between the before and after periods for all crashes. The probability of a decrease in crash frequency occurring is represented by the gray portion of the distribution. The entire distribution of differences, shown in Figure 5-10, is less than zero indicating a 100 percent probability that a decrease occurred. The analysis also revealed a few outliers that experienced an unusually high

crash frequency after the raised median was installed. Further research should be performed to identify contributing factors that could be mitigated.



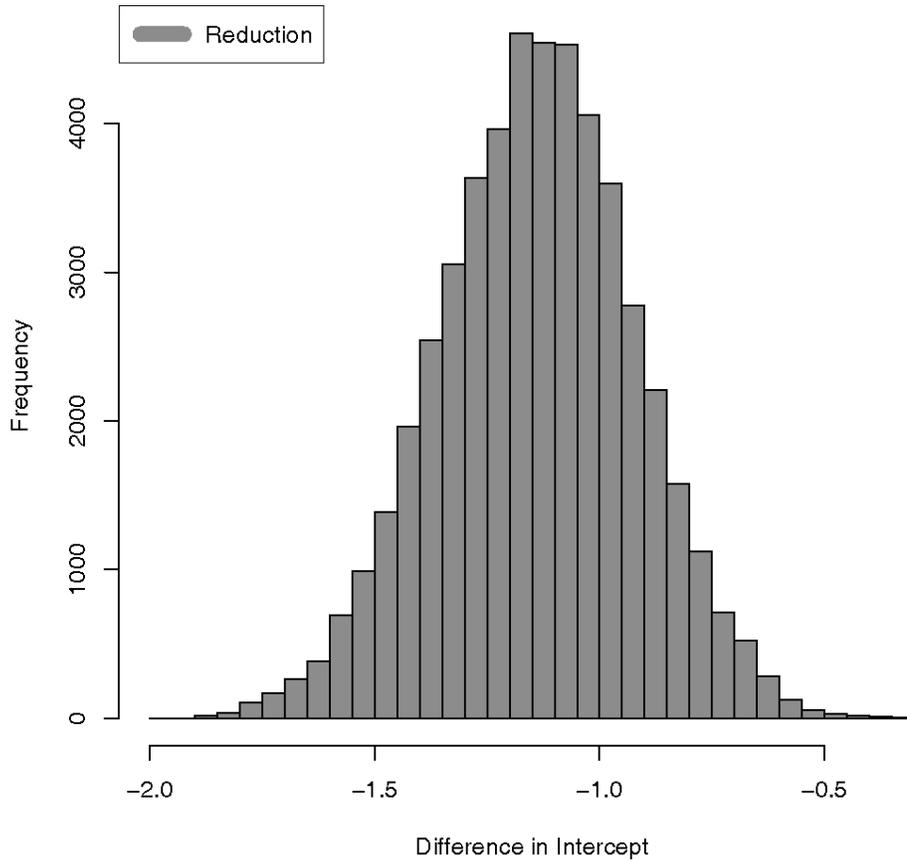
**Figure 5-10. Distribution of differences in overall crashes on SR 186.**

The severe crash analysis for this segment provided similar results. The severe crash frequency for this segment of SR 186 decreased after the installation of the raised median by 67.27 percent. Figure 5-11 displays the crash frequency of severe crashes on SR 186 for the before and after periods as a function of AADT.



**Figure 5-11. Severe crashes on SR 186.**

Figure 5-12 shows the probability distribution of the difference between the before and after periods for severe crashes. Again, the entire distribution of differences, shown in Figure 5-12, is less than zero indicating a 100 percent probability that a decrease occurred. Of all of the study sites, SR 186 showed the largest decrease in severe crashes. It is highly probable that a decrease in both overall crashes and severe crashes occurred on SR 186 as a result of installing a raised median.

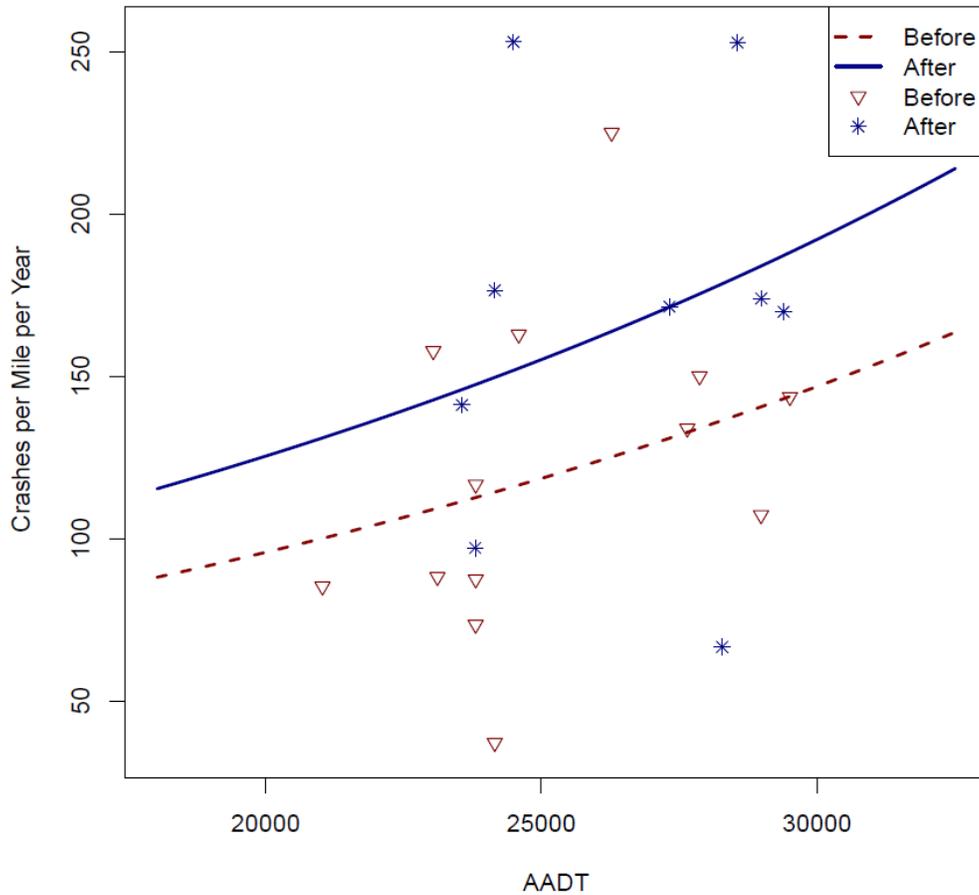


**Figure 5-12. Distribution of differences in severe crashes on SR 186.**

#### 5.1.4 12300 South (SR 71)

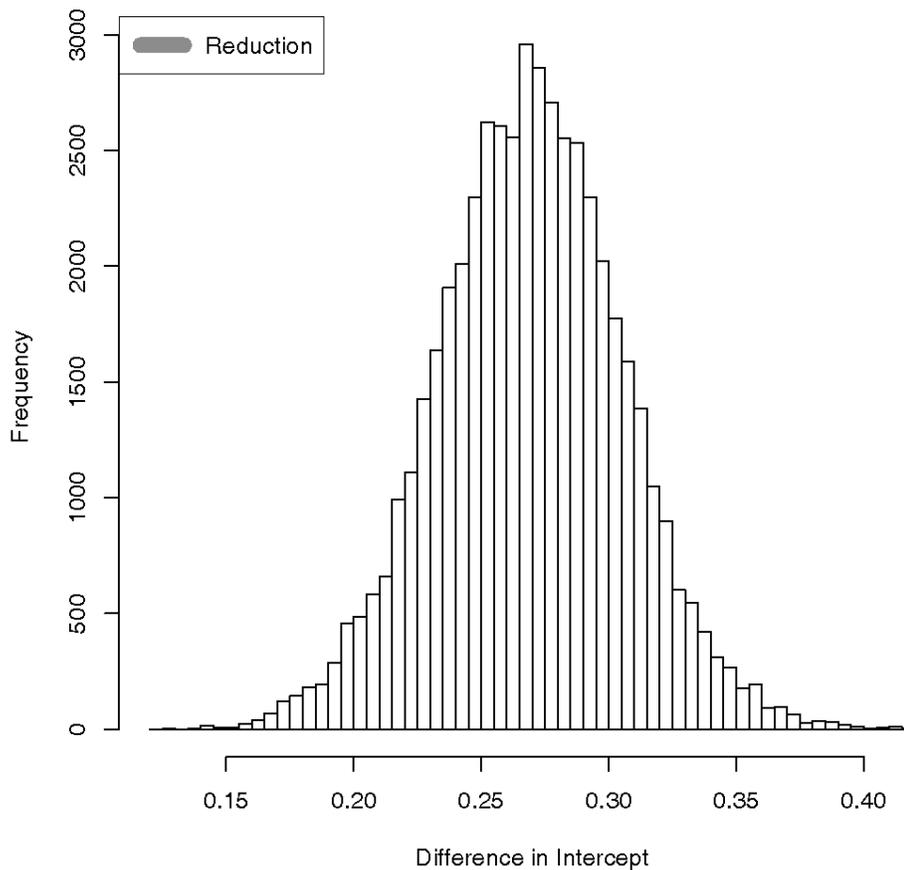
In 2004, SR 71 received some major improvements including widening to six lanes and the installation of a raised median. The raised median segment used in the analysis extends from 300 East to 265 West in Draper, UT. This section summarizes the results of the analysis performed before and after the raised median was installed. The before period used in the analysis is from 1998 to 2003 and the after period is from 2005 to 2008.

Figure 5-13 displays the results of the overall crash analysis. The overall crash results of this site differed from other sites. The analysis showed this segment of SR 71 experienced an increase of 30.98 percent in overall crash frequency after the installation of the raised median.



**Figure 5-13. Overall crashes on SR 71.**

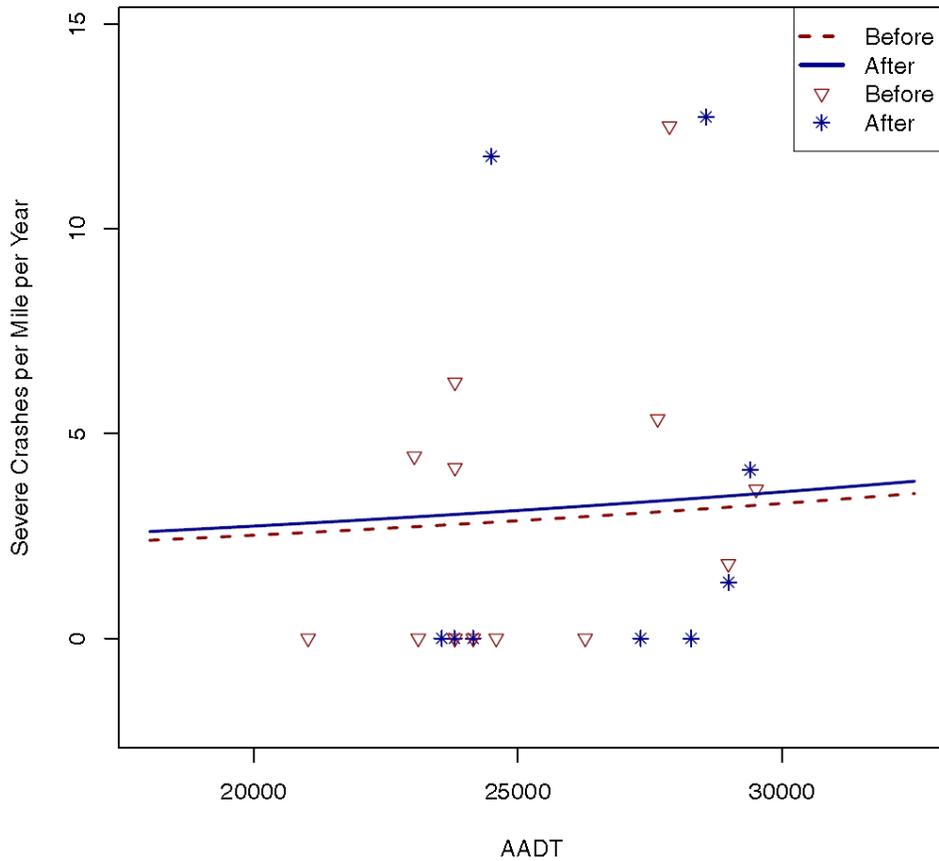
Figure 5-14 shows the corresponding probability distribution of the differences between the before and after periods for all crashes. The entire corresponding distribution of differences is greater than zero, indicating a 100 percent probability that an increase in overall crashes occurred at this site after the raised median was installed (0 percent probability that a decrease occurred).



**Figure 5-14. Distribution of differences in overall crashes on SR 71.**

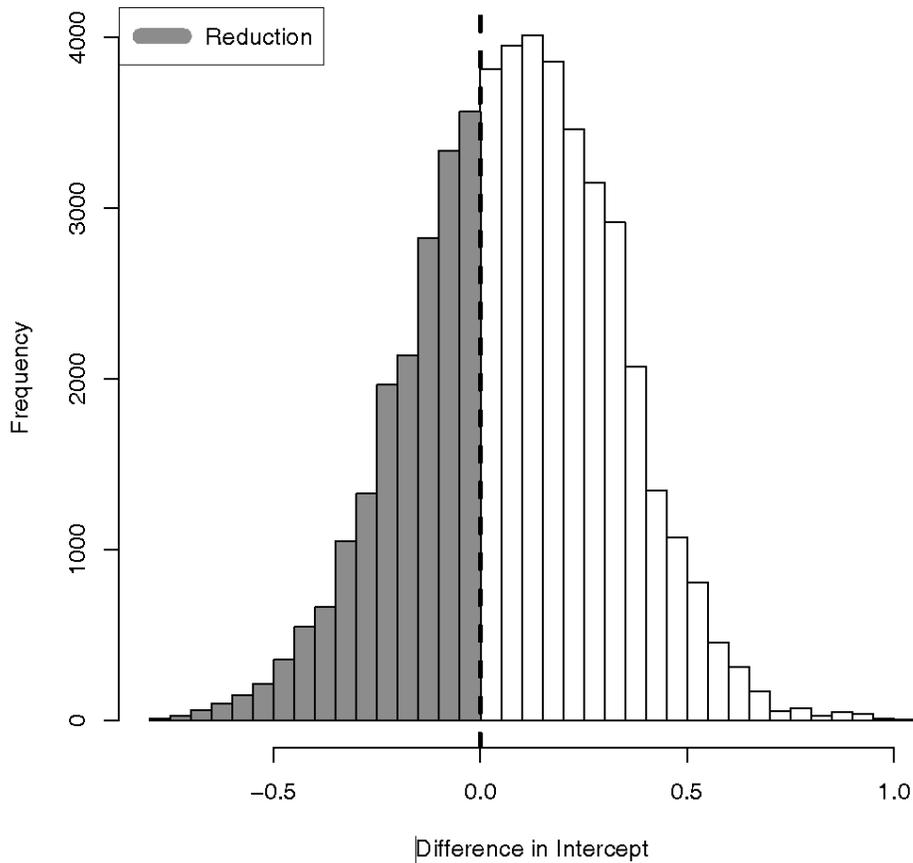
This increase in overall crash frequency is somewhat unexpected. The most likely contributing factor to this result has to do with the widening of this segment of SR 71 to six lanes that occurred as part of the raised median installation project. As noted in Chapter 3, rapid growth in the surrounding area warranted the need for widening. However, the increase in number of lanes increases weaving complexity and conflict points which could have had a significant impact on the overall crash results.

The severe crash analysis of SR 71 showed similar results. Figure 5-15 displays the crash frequency of severe crashes for the before and after periods of SR 71 as a function of AADT. The analysis showed that the severe crash frequency of SR 71 also showed an increase of 11.73 percent.



**Figure 5-15. Severe crashes on SR 71.**

Figure 5-16 shows the corresponding distribution of differences for the severe crash analysis. The portion of the difference that was less than zero was only 36.67 percent, as represented by the gray portion of the distribution in shown in Figure 5-16. This means that there was almost a 37 percent probability that a decrease occurred. Therefore, it cannot be definitively concluded that SR 71 experienced any change in severe crash frequency after the raised median was installed.

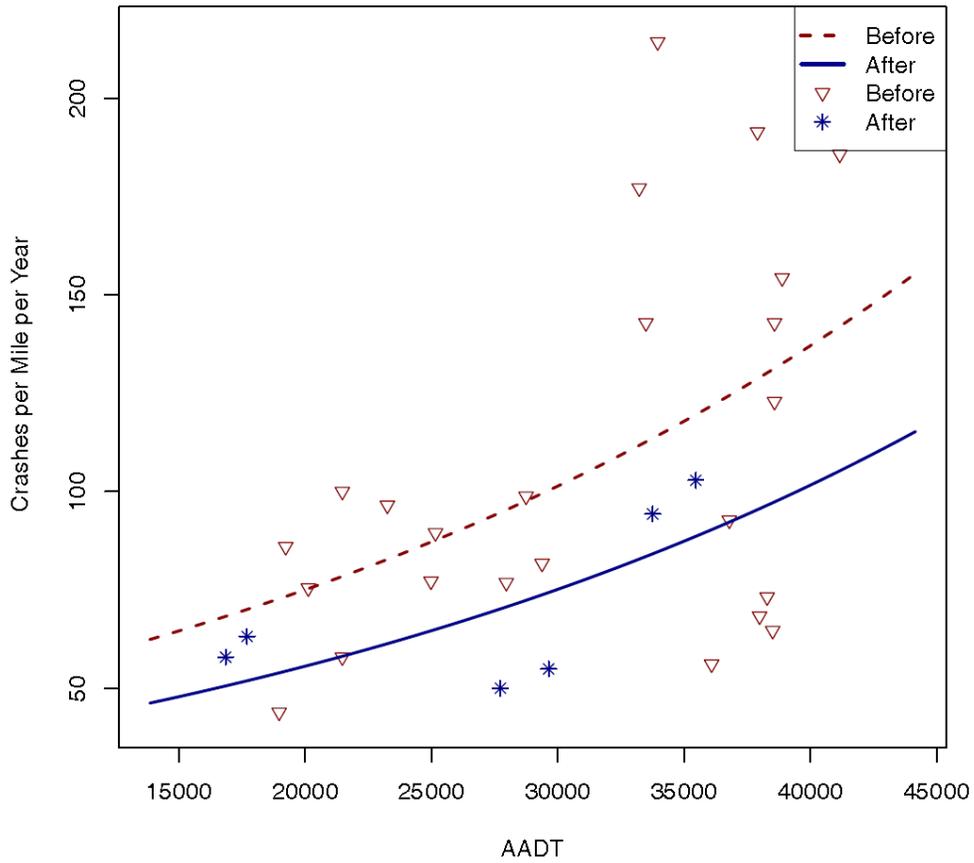


**Figure 5-16. Distribution of differences in severe crashes on SR 71.**

### 5.1.5 St. George Boulevard (SR 34)

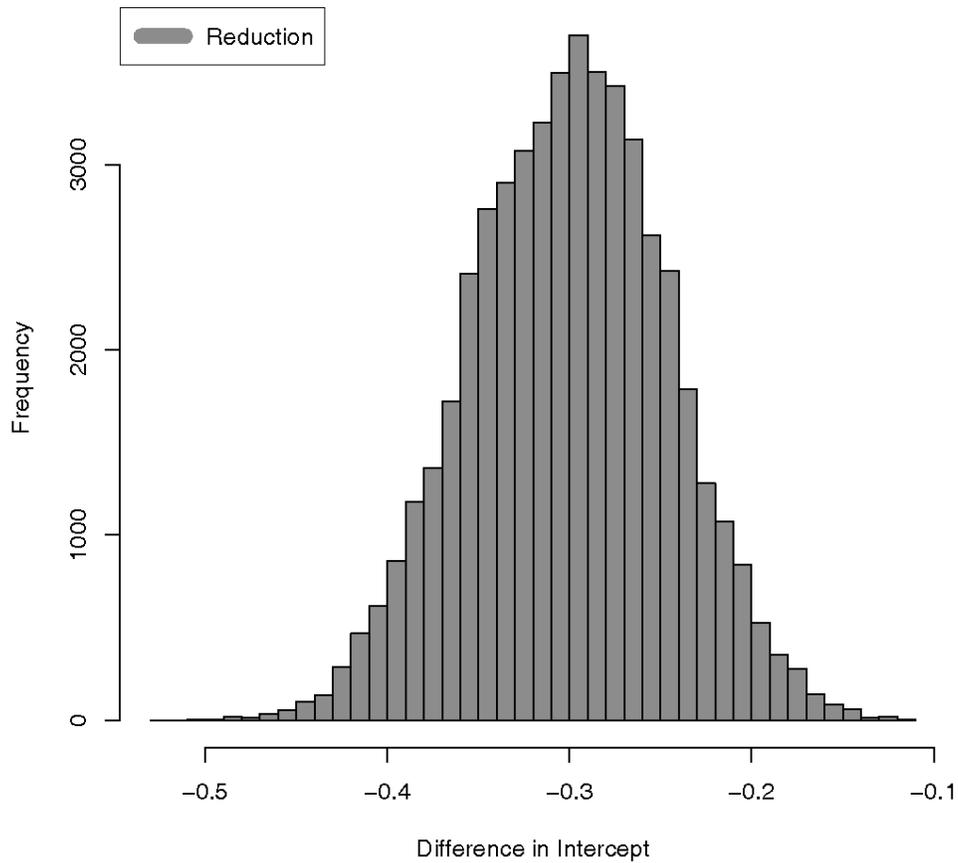
A raised median was installed over the entire length of the St. George Boulevard from Bluff Street to 1000 East in St. George, UT. The project was completed in 2006. This section summarizes the results of the analysis performed before and after the raised median was installed. The before period used in the analysis is from 1998 to 2005 and the after period is from 2007 to 2008.

Figure 5-17 displays the crash frequency for the before and after periods as a function of AADT for this segment of SR 34. The overall crash frequency for this segment of SR 34 decreased after the installation of the raised median by 25.85 percent.



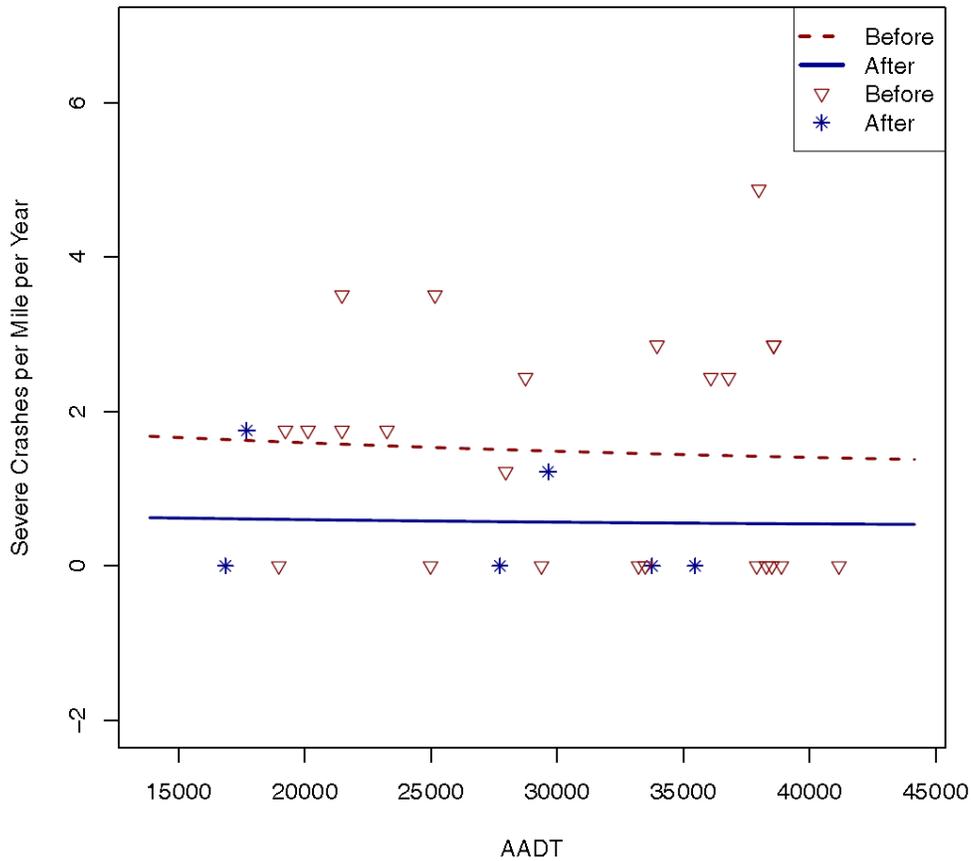
**Figure 5-17. Overall crashes on SR 34.**

Figure 5-18 shows the corresponding probability distribution of the differences between the before and after periods for all crashes. The entire distribution of differences, shown in Figure 5-18, is greater than zero indicating a 100 percent probability that a decrease occurred.



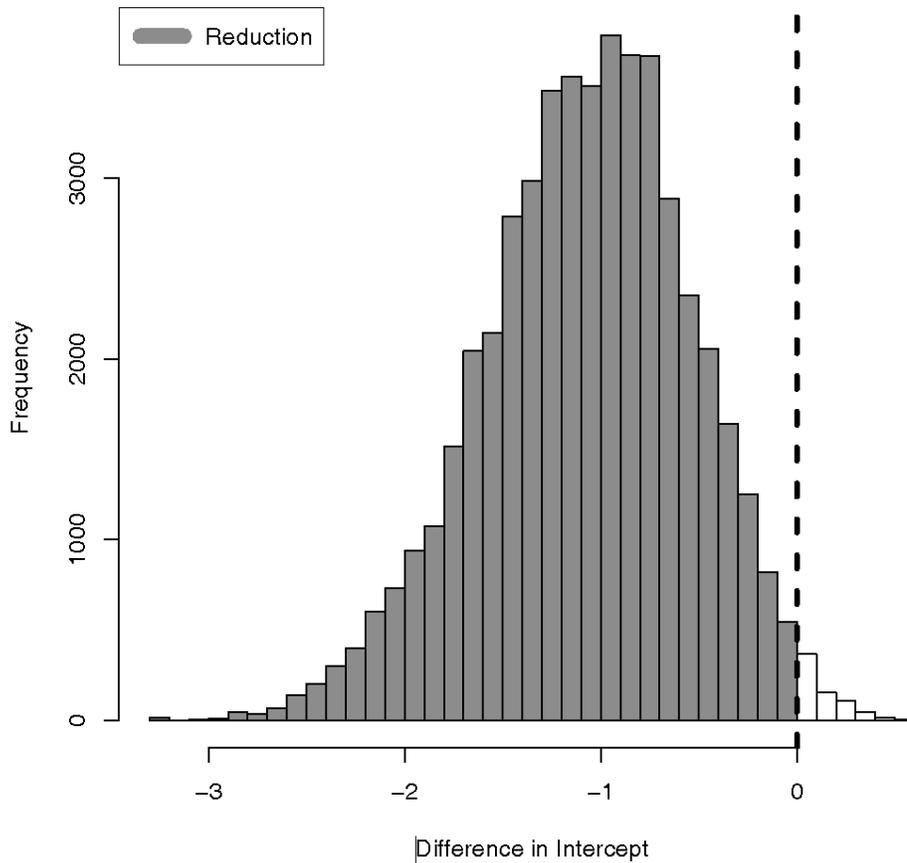
**Figure 5-18. Distribution of differences in overall crashes on SR 34.**

The results of the severe crash analysis showed similar results. The results showed the severe crash frequency for SR 34 also decreased an estimated 60.85 percent after the raised median was installed. Figure 5-19 displays the crash frequency of severe crashes on SR 34 for the before and after periods as a function of AADT.



**Figure 5-19. Severe crashes on SR 34.**

Figure 5-20 shows the probability distribution of the differences between the before and after periods for severe crashes. Almost the entire distribution of differences shown in Figure 5-20 is less than zero, indicating a 98.62 percent probability that SR 34 also experienced a decrease in the frequency of severe crashes after the installation of a raised median. SR 34 showed the second largest reduction in severe crashes among all the study sites.



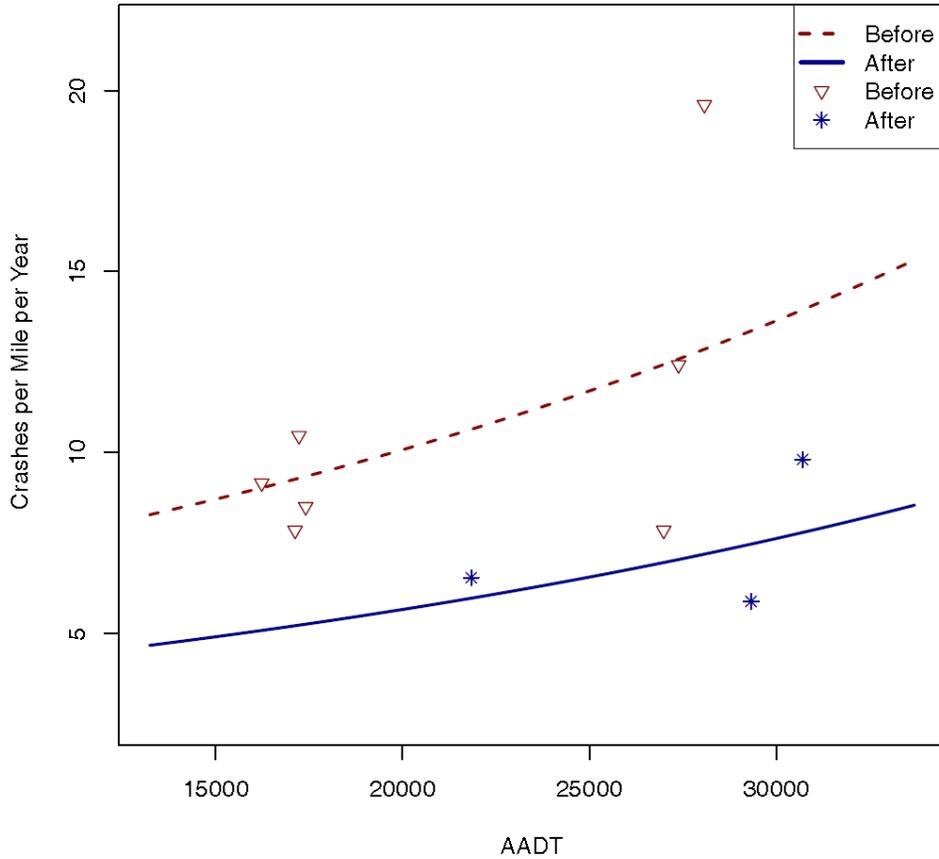
**Figure 5-20. Distribution of differences in severe crashes on SR 34.**

### 5.1.6 SR 36

A project completed in 2005 widened SR 36 to two lanes in each direction and installed a raised median for a short segment of SR 36 in the city of Erda, UT in north Tooele County. This section summarizes the results of the analysis performed before and after the raised median was installed. The before period used in the analysis is from 1998 to 2004 and the after period is from 2006 to 2008.

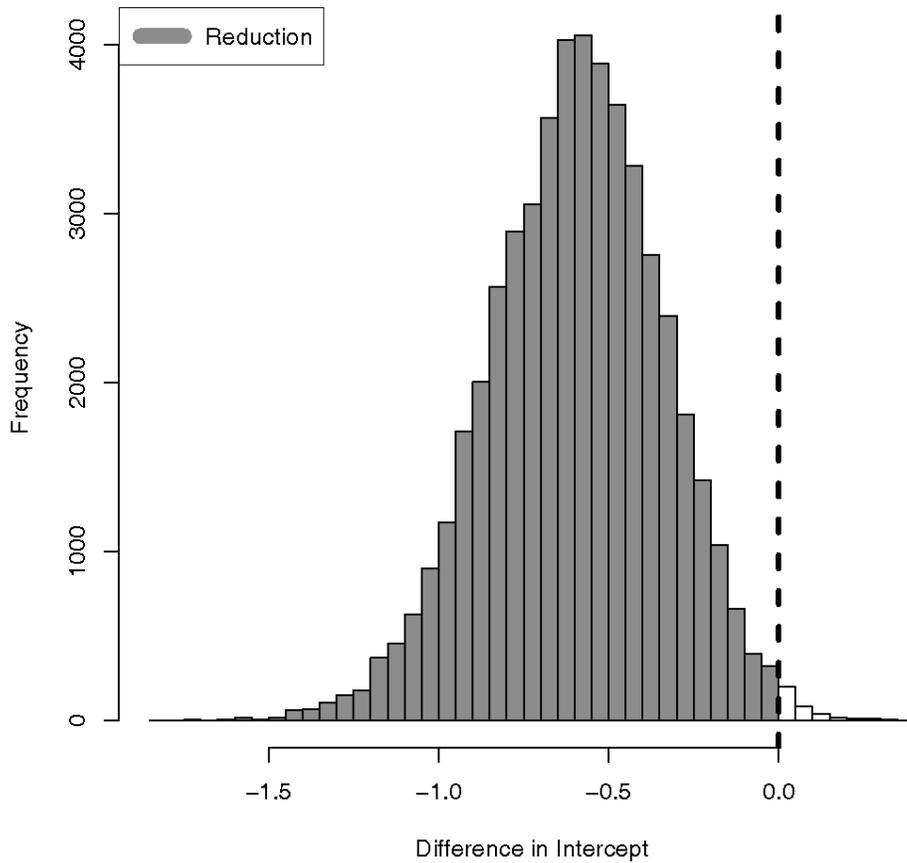
Figure 5-21 displays the crash frequency of all crashes for the before and after periods as a function of AADT. The overall crash frequency for this segment of SR 36 decreased by an

estimated 43.03 percent after the installation of the raised median. Overall, SR 36 showed the largest decrease in overall crashes among study sites.



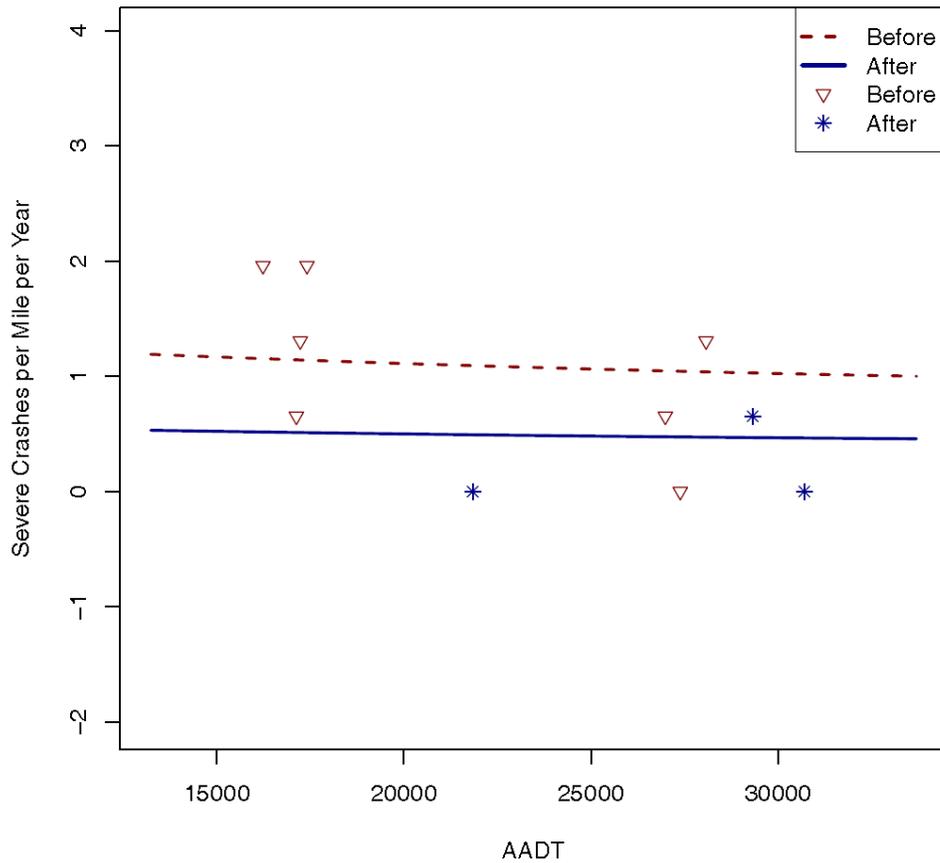
**Figure 5-21. Overall crashes on SR 36.**

Figure 5-22 shows the corresponding probability distribution of the differences between the before and after periods for all crashes. Nearly the entire distribution of the differences for this site was less than zero. Overall this segment experienced a 99.27 percent probability that a decrease occurred after the raised median was installed.



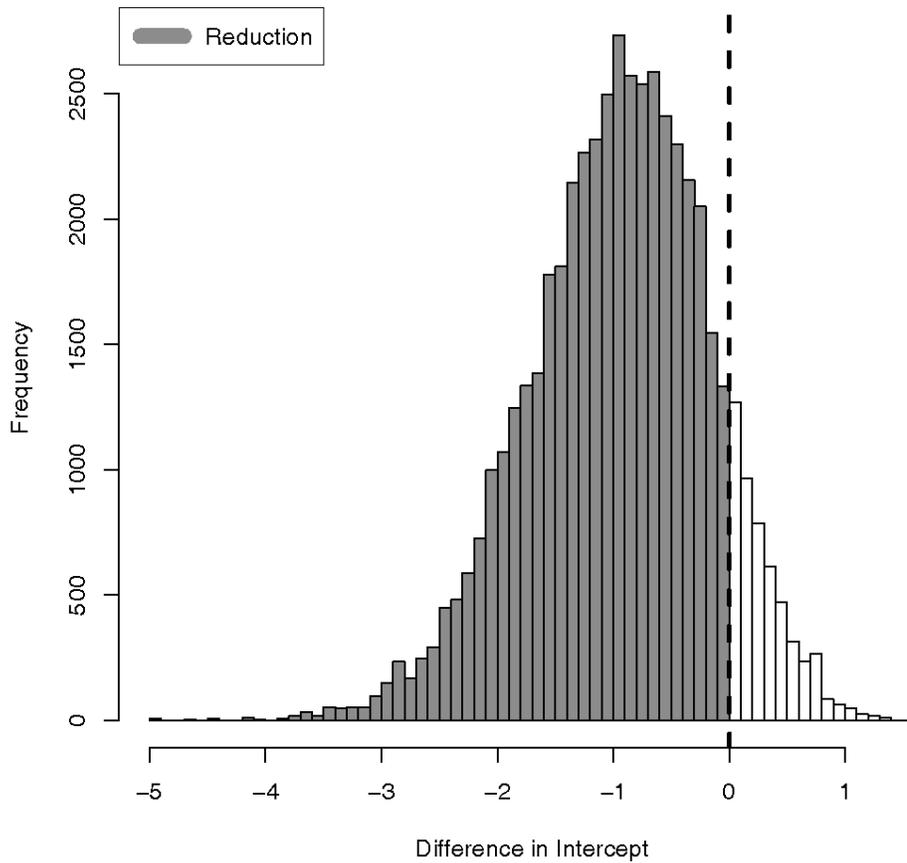
**Figure 5-22. Distribution of differences in overall crashes on SR 36.**

The severe crash analysis provided similar results. Figure 5-23 displays the crash frequency of severe crashes for the before and after periods as a function of AADT. The analysis showed SR 36 experienced a significant decrease in severe crash frequency. The results indicate the segment experienced a 49.02 percent decrease in severe crash frequency after the raised median was installed.



**Figure 5-23. Severe crashes on SR 36.**

Figure 5-24 shows the probability distribution of the differences between the before and after periods for severe crashes. Approximately 90 percent of the distribution of differences shown in Figure 5-24 is less than zero, indicating a 90 percent probability that a decrease in severe crash frequency occurred on SR 36 after the raised median was installed.

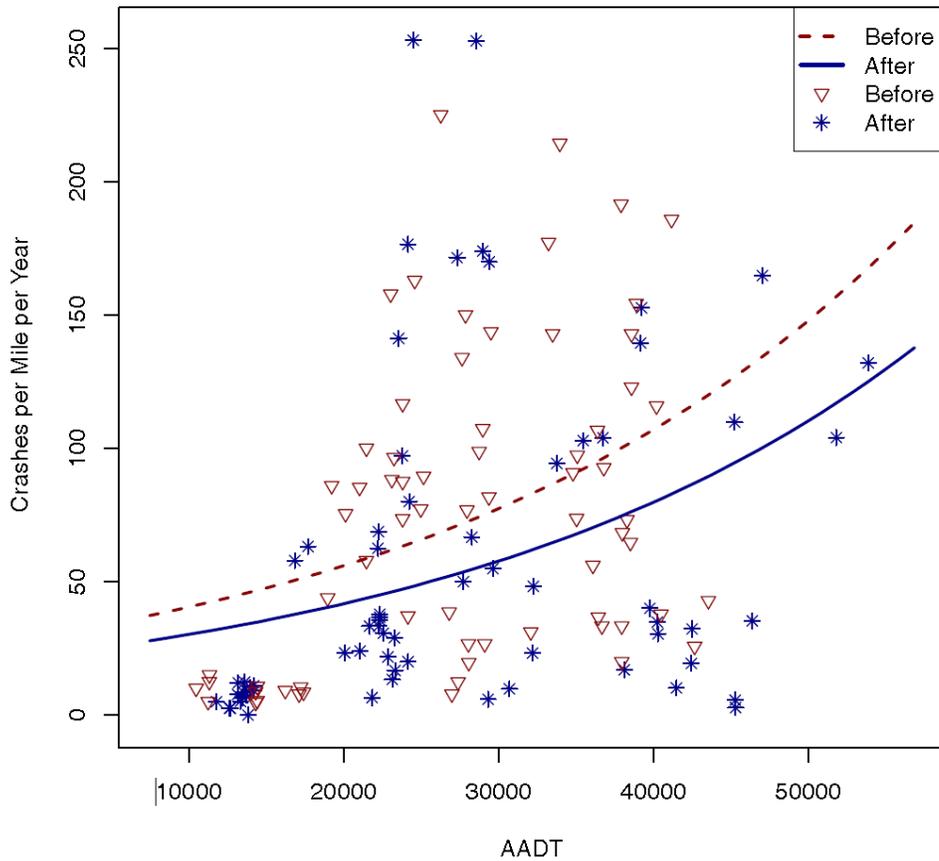


**Figure 5-24. Distribution of differences for severe crashes on SR 36.**

## 5.2 Overall Raised Median Results

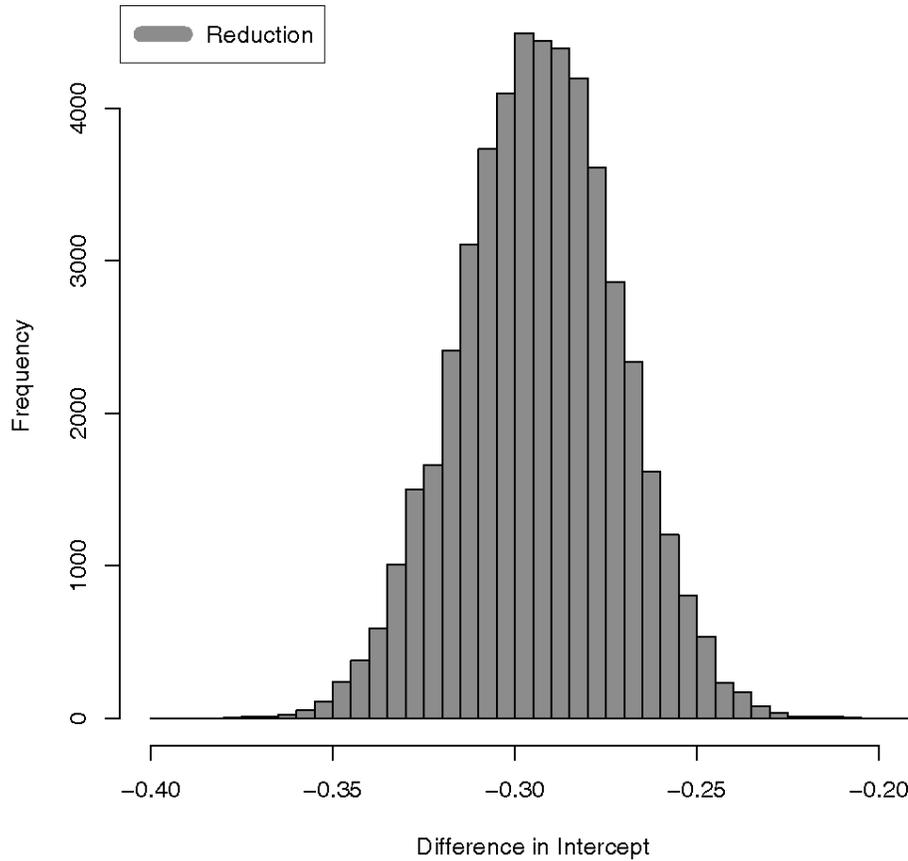
The overall safety impacts of raised medians on all of the study sites have undergone analysis and are discussed in this section. Data from all study sites were grouped together for analysis.

Figure 5-25 displays the overall crash frequency for the before and after periods as a function of AADT. The overall analysis results indicate 25.41 percent decrease in overall crash frequency after the raised medians were installed.



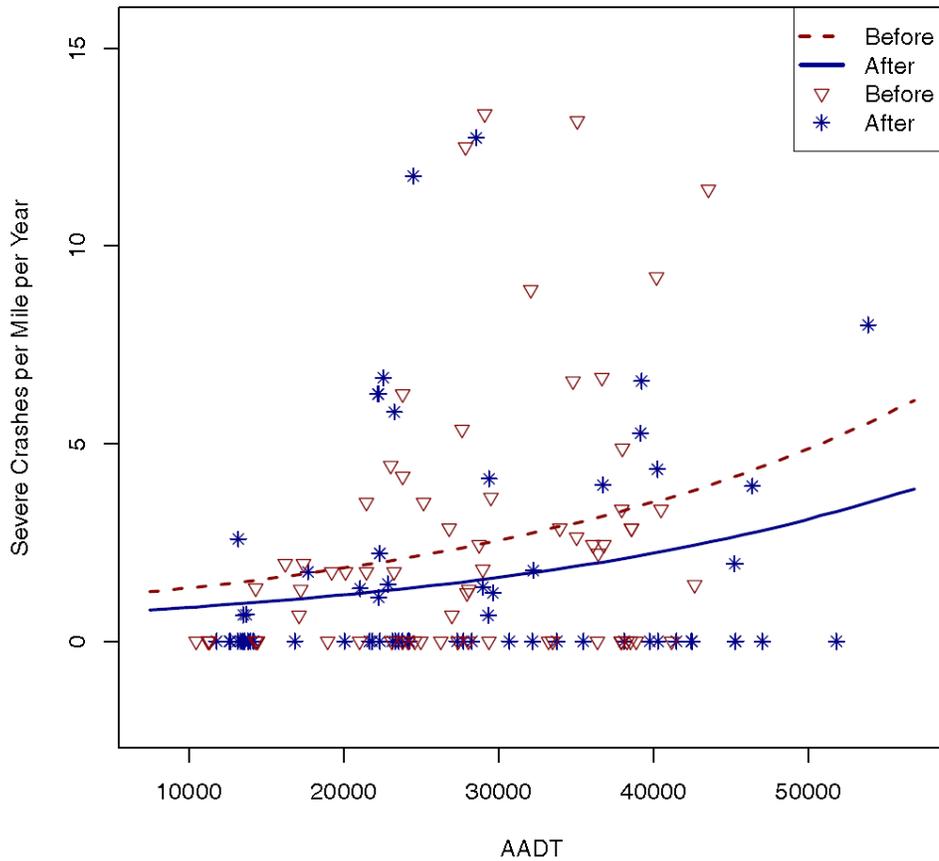
**Figure 5-25. Overall crashes on all raised median study sites.**

Figure 5-26 shows the corresponding probability distribution of the differences between the before and after periods for overall crashes. The gray portion of the distribution represents the probability that a decrease was detected from the before to the after period. The entire distribution of differences shown in Figure 5-26 is less than zero, indicating a 100 percent probability that a decrease in overall crash frequency occurred after raised medians were installed.



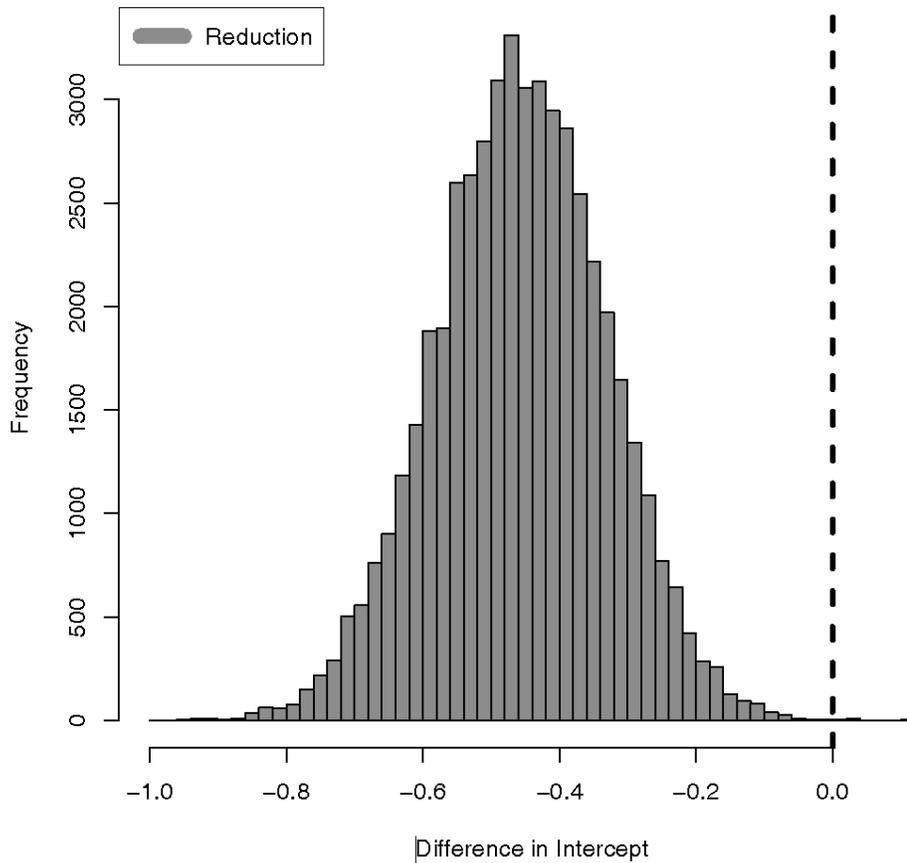
**Figure 5-26. Distribution of differences for overall crashes on all raised median study sites.**

The severe analysis results display an even greater reduction. Figure 5-27 displays the results of the severe crash analysis for all raised median locations. The severe crash analysis results on all sites show a 36.16 percent reduction in severe crash frequency after raised median installation.



**Figure 5-27. Severe crashes for all raised median study sites.**

Figure 5-28 shows the corresponding probability distribution of the differences between the before and after periods for severe crashes. The gray portion of the distribution represents the probability that a decrease was detected from the before to the after period. The results of the analysis indicate a 99.97 percent chance of decrease in severe crash frequency occurred after raised medians were installed.



**Figure 5-28. Distribution of differences of severe crashes for all raised median study sites.**

### 5.3 Chapter Summary

A summary of the raised median analysis results are presented in this chapter. An analysis was performed on individual raised median locations. A crash data analysis for all locations grouped together was also performed. In each case, a decrease or an increase in overall and severe crash frequency was presented. Additionally, the corresponding distribution of differences was presented.

The analysis of the individual locations where raised medians have been installed show interesting results. Based on the probability of decrease, the analysis showed three of the six study sites experienced a significant (greater than 95 percent probability) decrease in the overall

crash frequency while the SR 71 segment experienced an increase in the overall crash frequency. The probability of decrease for the remaining sites (SR 265 and SR 74) was too low to confidently determine if a reduction or increase occurred (although the results on SR 74 were close to significant at 92.64 percent probability of decrease). Table 5-2 provides a summary of the impact of raised medians on all crashes.

**Table 5-2. Summary of Overall Crashes at Raised Median Study Sites**

<b>Location</b>	<b>State Route</b>	<b>Year Installed</b>	<b>Probability of Decrease</b>	<b>Percent Change Expected</b>
University Parkway	265	2002	38.24%	2.70%
Alpine Highway	74	2002	92.64%	-18.92%
400/500 South	186	2001	100.00%	-29.22%
12300 South	71	2004	0.00%	30.98%
St. George Blvd.	34	2006	100.00%	-25.85%
SR 36	36	2005	99.27%	-43.03%

Similarly, many of the sites also showed a decrease in the severity of crashes. Table 5-3 provides a summary of the impact of raised medians on severe crashes. The results indicate that three of the six study sites experienced a significant decrease in the frequency of severe crashes after raised medians were installed. The analysis indicated that a decrease in severe crashes may have occurred at SR 36 and that an increase may have occurred at the two remaining sites (SR 74 and SR 71). However, the probability of a difference at these sites was too low to make any definite conclusions.

Data from all analysis sites grouped together also provided interesting results. The combined analysis showed 100 percent probability of a reduction of 25.41 percent in overall crash frequency. The severe crash analysis results on all sites showed an even better increase in safety as the analysis showed an almost 100 percent probability that severe crashes reduced by 36.16 percent. These results are summarized in Table 5-4.

**Table 5-3. Summary of Severe Crashes at Raised Median Study Sites**

<b>Location</b>	<b>State Route</b>	<b>Year Installed</b>	<b>Probability of Decrease</b>	<b>Percent Change Expected</b>
University Parkway	265	2002	100.00%	-60.37%
Alpine Highway	74	2002	41.07%	55.27%
400/500 South	186	2001	100.00%	-67.27%
12300 South	71	2004	36.67%	11.73%
St. George Blvd.	34	2006	98.62%	-60.85%
SR 36	36	2005	89.66%	-49.02%

**Table 5-4. Results for All Raised Median Study Sites**

<b>Type of Analysis</b>	<b>Probability of Decrease</b>	<b>Percent Change Expected</b>
Overall	100.00%	-25.41%
Severe	99.97%	-36.16%

Additionally, the analysis revealed several outliers that experienced an unusually high frequency of either overall or severe crashes. Further research should be performed to identify factors that may contribute to the high crash frequency.

## 6 CABLE BARRIER RESULTS

A hierarchical Bayesian analysis was performed at selected sites where cable barrier systems have been installed following the procedure outlined in Chapter 4. An analysis was performed on overall crash frequency, severe crash frequency, and cross-median crash frequency at locations where cable barrier systems have been installed. It was predicted that cable barrier would have no impact on overall crash frequency since cable barrier is designed to decrease severity and is not a preventative measure. The overall crash frequency analysis is included to provide background information for each location.

Two types of plots are produced for each analysis performed. The first plot is a plot of the actual data. These plots display the actual data points along with the mean of the posterior (after) predictive distribution. Essentially it represents the mean regression line through the points from a Bayesian perspective. The reduction is calculated by taking the mean of differences between the two intercepts in the posterior distribution. This is a percent reduction because  $\log(\text{after}/\text{before}) = \log(\text{after}) - \log(\text{before})$ , and the intercepts are on the log scale. This is essentially equivalent to dividing the after curve by the before curve and getting the percent reduction.

The second plot produced shows the distribution of the differences between the before and after periods. The differences plots display the posterior distributions of differences between the before and after intercepts of the model. Negative values indicate that the after period saw a reduction in crashes. As the exact form of those posterior distributions is unknown, the model uses simulated draws from the posterior with MCMC; since those draws represent the actual posterior distribution, the proportion of the draws less than zero represents the probability that there was a decrease in crashes from the before period to the after period.

## 6.1 Cable Barrier Individual Site Results

The safety impacts of cable barrier at the individual study sites are discussed in this section. Details about each location are provided in Chapter 3. The analysis procedure is described in Chapter 4. Sites selected for analysis were shown previously in Table 3-2, but are repeated for convenience in Table 6-1. Analyses were performed on overall crashes, severe crashes, and cross-median crashes that occurred at each site, along with an overall analysis for all sites grouped together. The following sections summarize the results of the analysis performed at each individual site as well as an overall analysis performed on all cable barrier study sites. UDOT provided the crash data used for analysis.

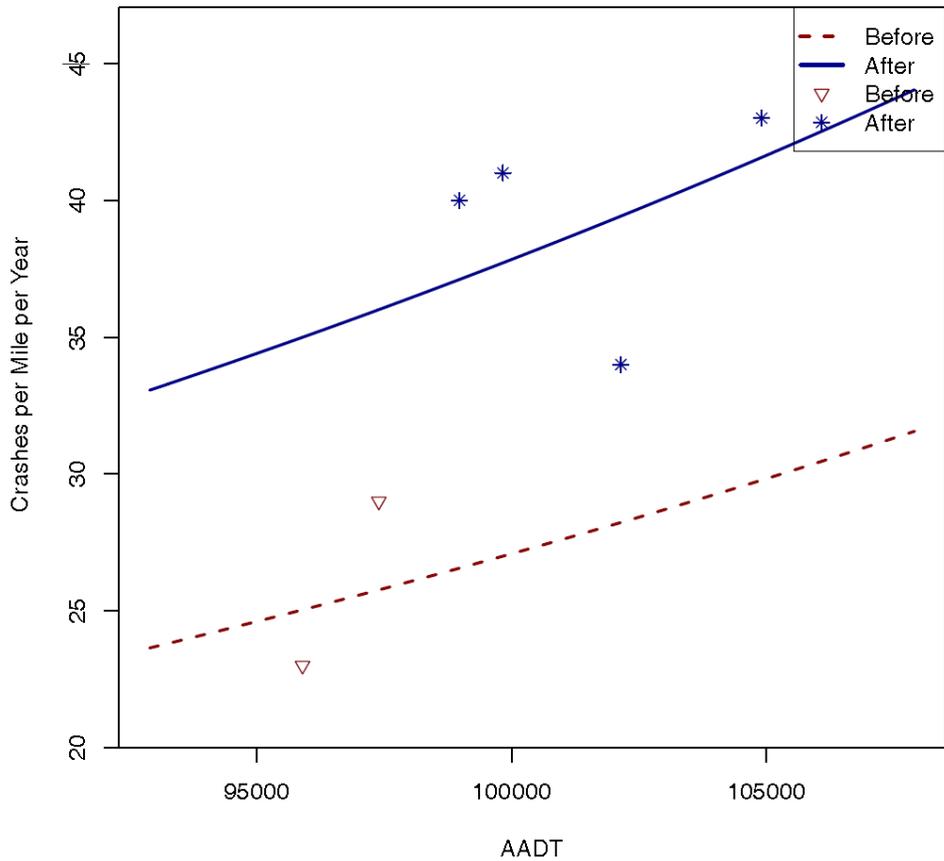
**Table 6-1. Cable Barrier Study Locations**

<b>Site</b>	<b>Route</b>	<b>Begin MP</b>	<b>End MP</b>	<b>Length (mi.)</b>	<b>Location</b>	<b>Year Installed</b>
1	I-15	267	269	2.0	Provo S-curves to University Parkway	2004
2	I-15	36	38	2.0	Between Pintura and Kolob Canyons	2005
3	I-15	257	261	4.0	Spanish Fork to SR 75	2005
4	I-15	330	334	4.0	South Layton to Syracuse	2006
5	I-15	309	312	3.0	600 N to 2300 N – Salt Lake	2007
6	I-215 E	1.5	2.5	1.0	3100 S to 3800 S – Salt Lake	2007
7	I-215 W	17	19.5	2.5	2100 S to 4500 S – Salt Lake	2007

### 6.1.1 I-15 Provo S-curves to University Parkway

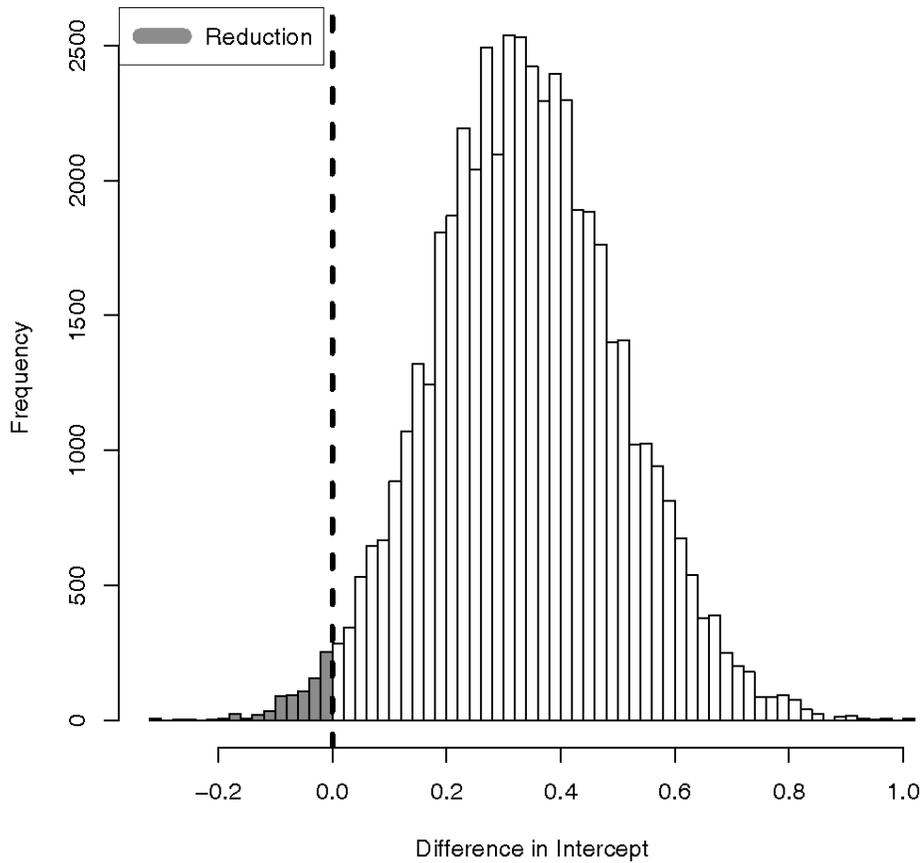
Cable barrier was installed along a 2-mile segment of I-15 between Provo Center Street and University Parkway in 2004 near Provo, UT. This section summarizes the results of the analysis performed before and after the cable barrier was installed. The before period used in the analysis is from 2002 to 2003 and the after period is from 2005 to 2008.

Figure 6-1 displays the crash frequency of overall crashes for the before and after periods as a function of AADT. The analysis indicates that the overall crash frequency increased by 42.56 percent after the installation of the cable barrier.



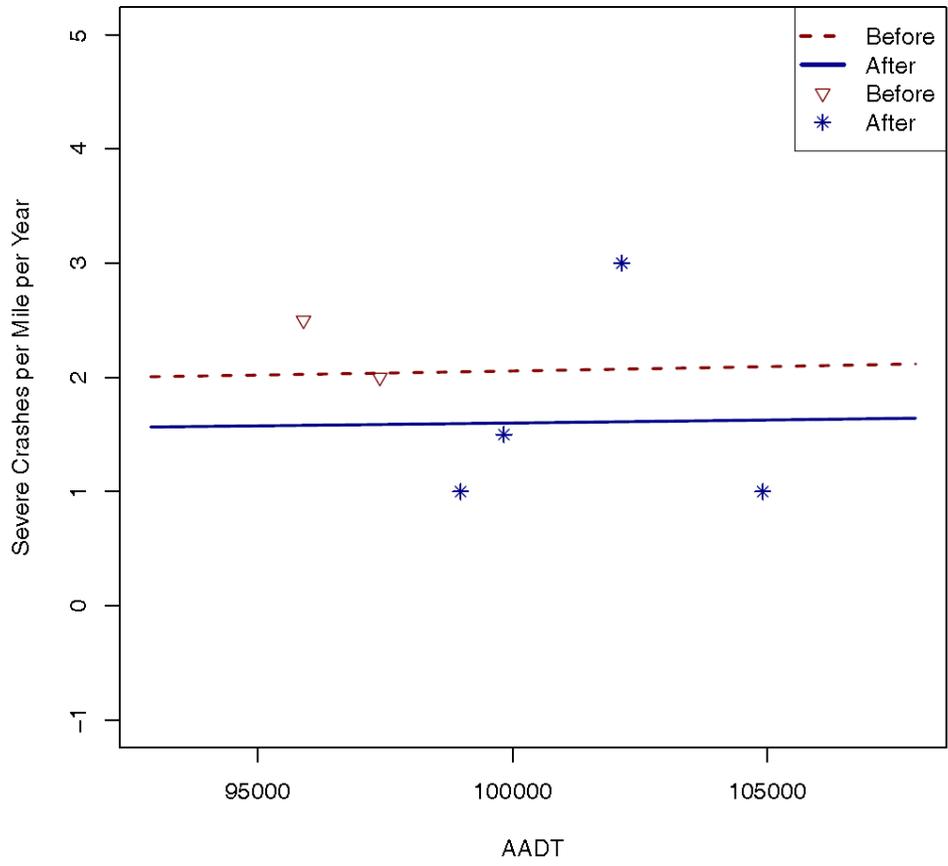
**Figure 6-1. Overall crashes on I-15 between Provo S-curves to University Parkway.**

Figure 6-2 shows the corresponding probability distribution of the difference between the before and after periods for all crashes. More than 98 percent of the distribution of differences is greater than zero, indicating an almost 100 percent probability that an increase in overall crashes occurred after the cable barrier system was installed. However, it is anticipated the increase is likely the result of an increase in traffic volumes or other factors other than the cable barrier system. As noted previously, cable barrier is not generally designed as a preventative measure for crashes.

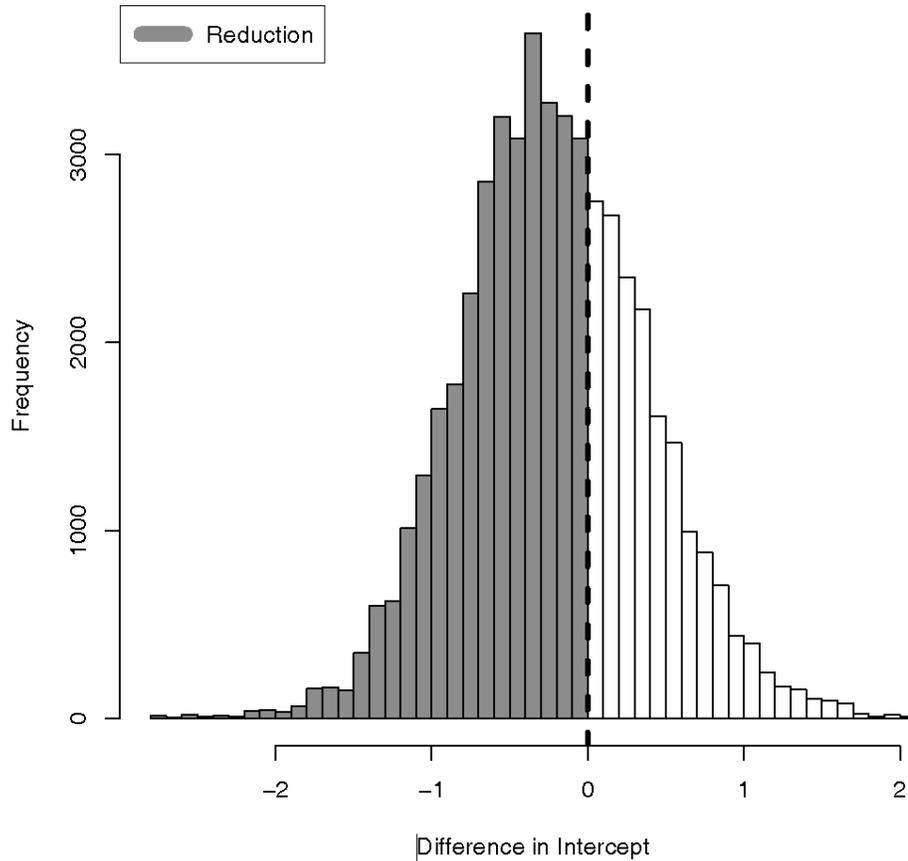


**Figure 6-2. Distribution of differences for overall crashes on I-15 between Provo S-curves and University Parkway.**

Figure 6-3 displays the crash frequency of severe crashes for the before and after periods. The severe crash analysis for this segment of I-15 suggest the possibility that severe crashes decreased by 3.15 percent after the installation of the cable barrier system. However, the probability of a decrease, approximately 65 percent as illustrated in Figure 6-4 by the percent of the distribution greater than zero, was determined to be too low to confidently conclude a decrease occurred.

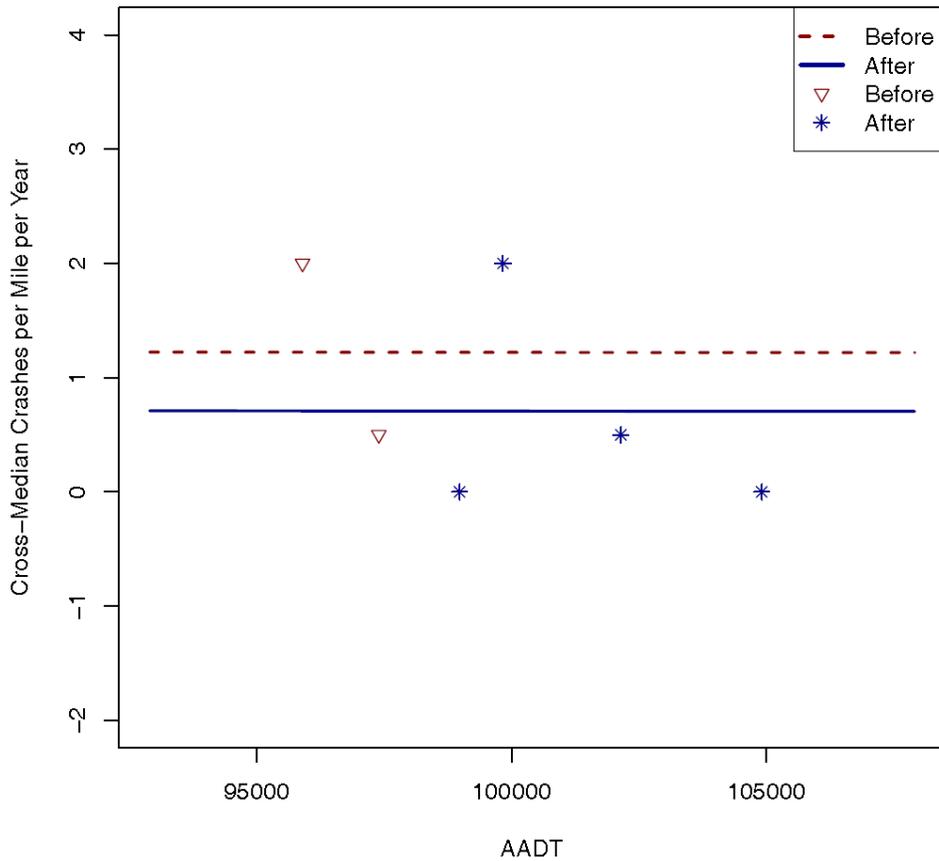


**Figure 6-3. Severe crashes on I-15 between Provo S-curves and University Parkway.**



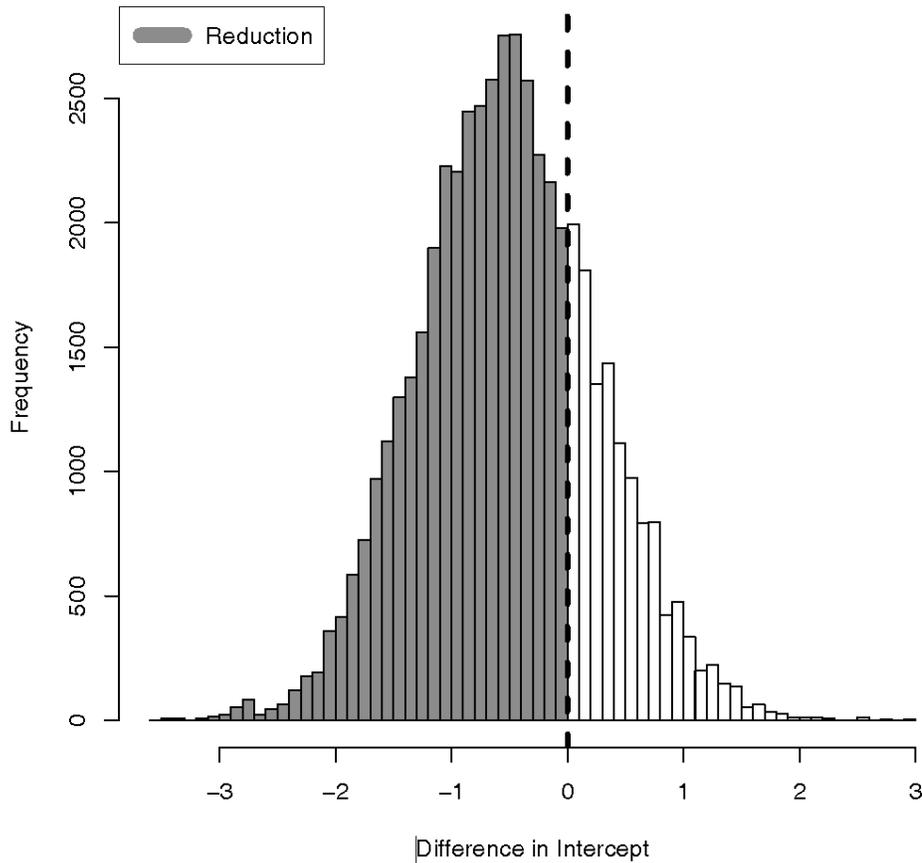
**Figure 6-4. Distribution of differences for severe crashes on I-15 between Provo S-curves and University Parkway.**

The results of the cross-median analysis for this segment of I-15 were similar to the severe crash analysis results. The cross-median crash analysis for this segment of I-15 suggest the possibility that severe crashes decreased by 19.59 percent after the installation of the cable barrier system. The results of the analysis are represented graphically in Figure 6-5.



**Figure 6-5. Cross-median crashes on I-15 between Provo S-curves and University Parkway.**

Figure 6-6 shows the probability distribution of the difference between the before and after periods for cross-median crashes. The grayed portion of the plot shows the portion of the distribution that was less than zero. Approximately 75 percent of the distribution of cross-median crashes for this segment of I-15 was less than zero. This can be interpreted to mean a 75 percent probability a decrease occurred. While the probability is suggestive a decrease occurred, the probability was determined to be too low to confidently conclude a decrease occurred.



**Figure 6-6. Distribution of differences for cross-median crashes on I-15 between Provo S-curves and University Parkway.**

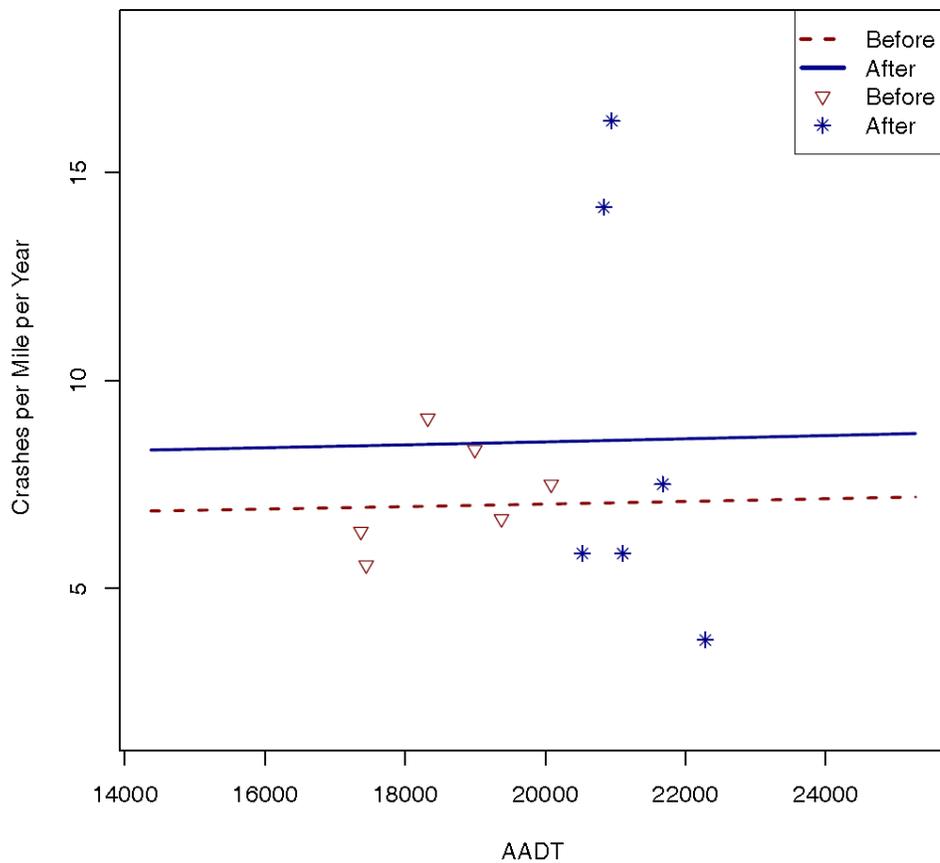
### 6.1.2 I-15 between Pintura and Kolob Canyons

This analysis site is a 2-mile segment of I-15 located in the Southern part of Utah between Cedar City and St. George, UT. Cable barrier was installed along this segment in 2005. This section summarizes the results of the analysis performed before and after the cable barrier system was installed. The before period used in the analysis is from 2002 to 2004 and the after period is from 2006 to 2008.

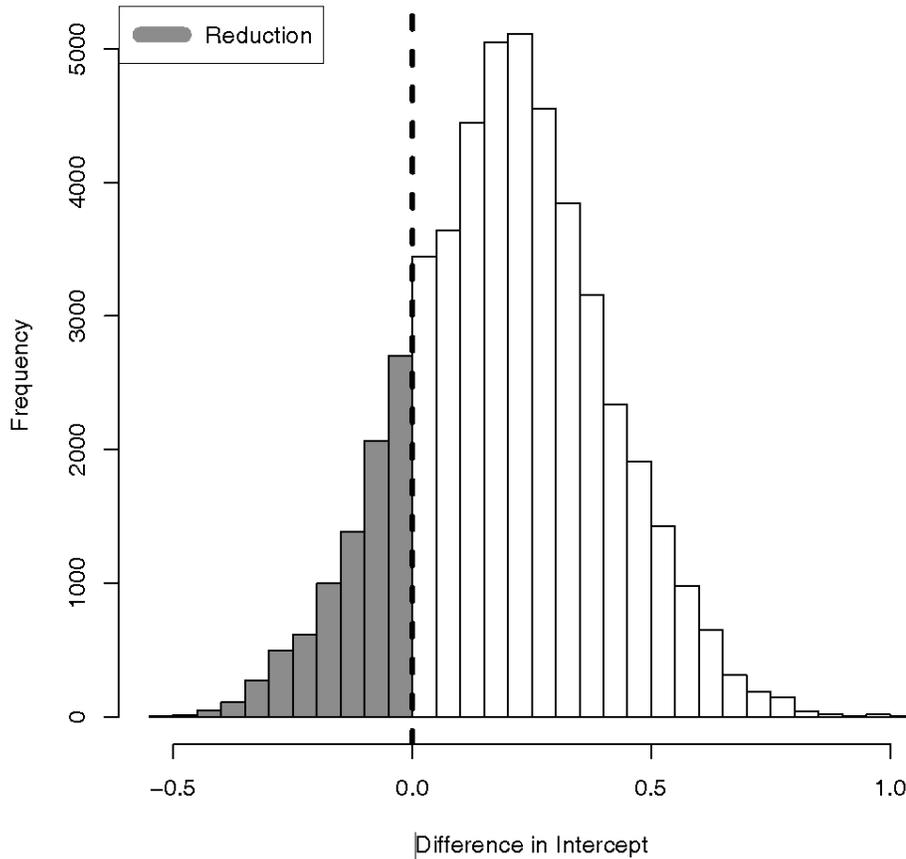
The results of the overall crash analysis for this segment of I-15 are displayed graphically in Figure 6-7. The results of the analysis indicated that overall crashes increased 24.29 percent

after the installation of the cable barrier system. Figure 6-8 shows the probability distribution of the difference between the before and after periods for the overall crash analysis.

The distribution of differences for this site indicate that there is a 82.56 percent chance that the number of overall crashes increased in the after period. Although this probability is high, it is still too low to confidently claim any change occurred (there is a 17.44 percent chance of decrease). Several outlier sites were also revealed that need to be explored further in future research.

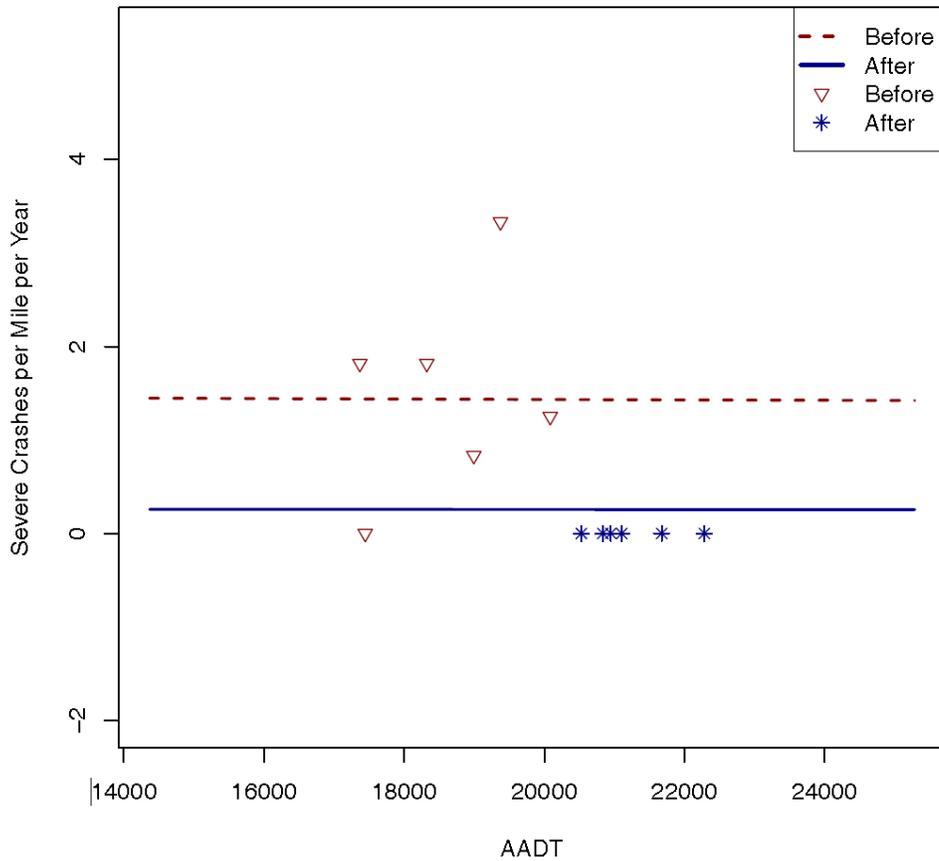


**Figure 6-7. Overall crashes on I-15 between Pintura and Kolob Canyons.**



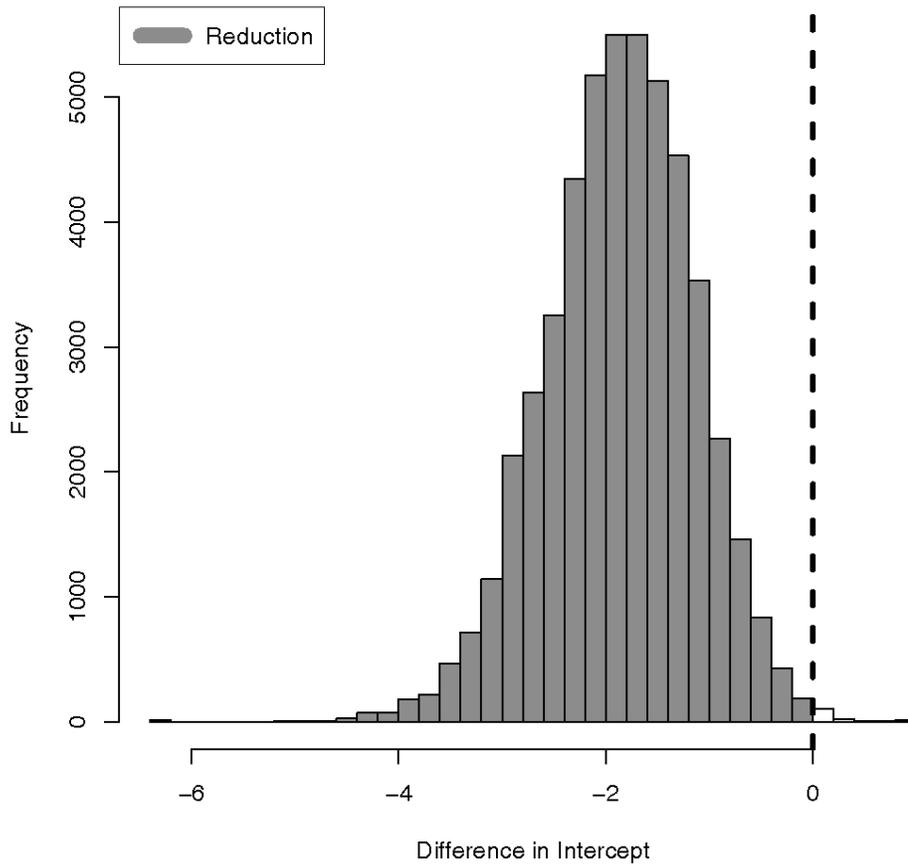
**Figure 6-8. Distribution of differences for overall crashes on I-15 between Pintura and Kolob Canyons.**

The severe crash analysis results for this segment showed promising results. The results indicated that severe crashes decreased by 80.08 percent after the installation of the cable barrier system. Figure 6-9 displays the crash frequency of severe crashes for the before and after periods.



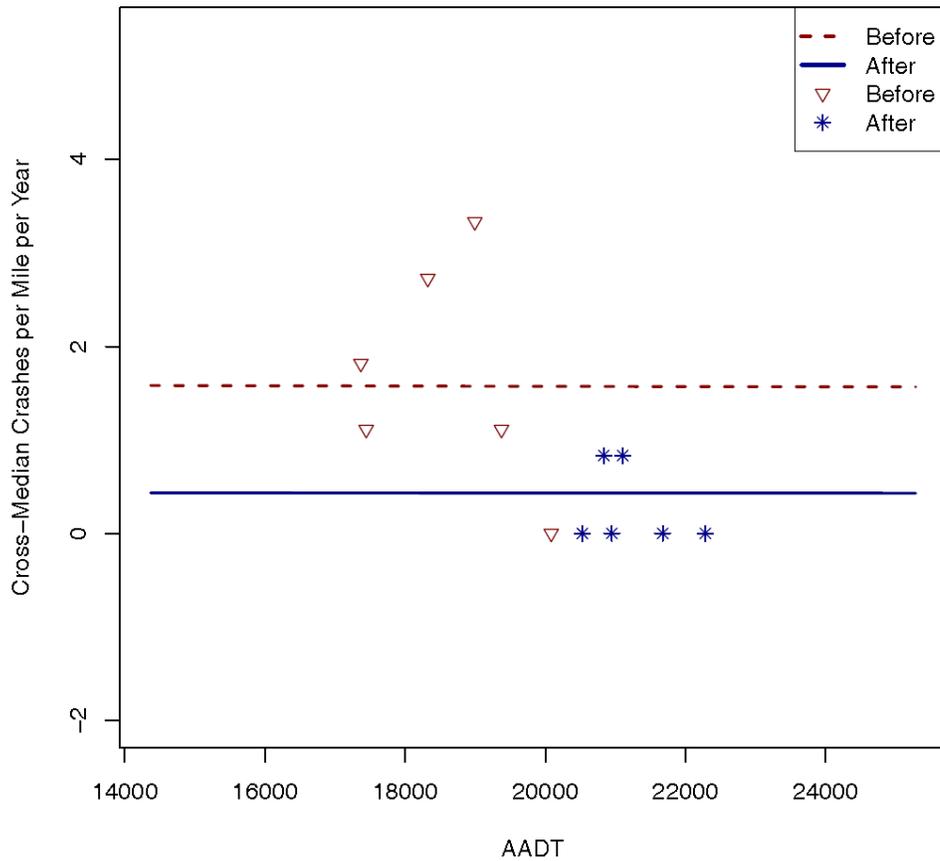
**Figure 6-9. Severe crashes on I-15 between Pintura and Kolob Canyons.**

Figure 6-10 shows the probability distribution of the difference between the before and after periods for the severe crash analysis for this segment of I-15. The probability a decrease occurred at this site was 99.69 percent, as represented by the gray portion of the distribution shown in Figure 6-10. These results provide convincing evidence that a decrease in severe crash frequency occurred at this site after the installation of the cable barrier system.



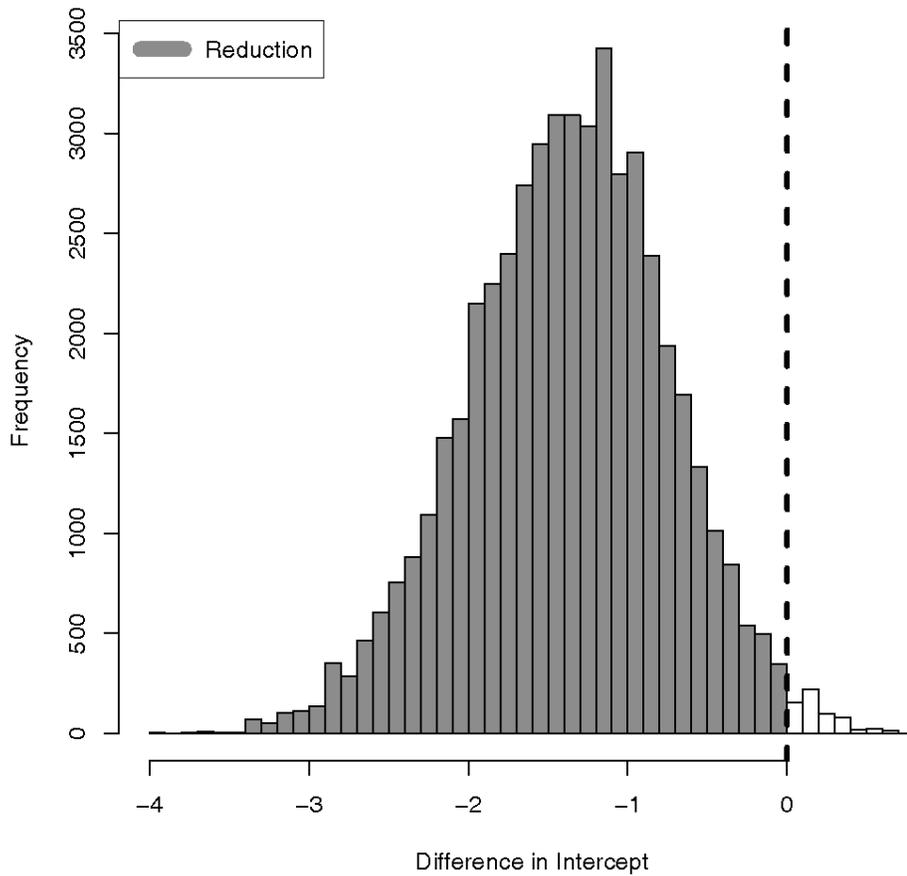
**Figure 6-10. Distribution of differences for severe crashes on I-15 between Pintura and Kolob Canyons.**

The cross-median crash analysis results for this segment were also very promising. The results indicated that cross-median crash frequency decreased by 69.31 percent after the installation of cable barrier. Figure 6-11 displays the crash frequency of cross-median crashes for the before and after periods.



**Figure 6-11. Cross-median crashes on I-15 between Pintura and Kolob Canyons.**

Figure 6-12 shows the probability distribution of the difference between the before and after periods for the cross-median crash analysis for this segment of I-15. The probability a decrease occurred at this site was 98.79 percent, as represented by the gray portion of the distribution shown in Figure 6-12. These results provide convincing evidence that a decrease in cross-median crash frequency also occurred at this site after the installation of the cable barrier system.



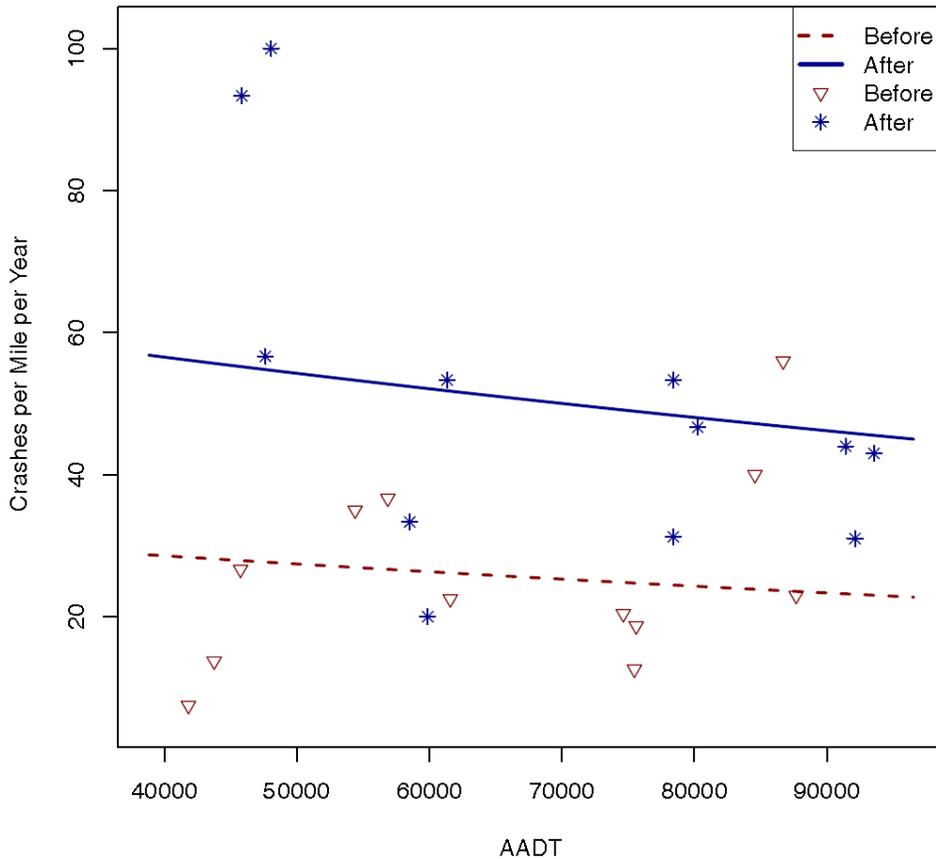
**Figure 6-12. Distribution of differences for cross-median crashes on I-15 between Pintura and Kolob Canyons.**

### 6.1.3 I-15 Spanish Fork to SR 75

In 2005, cable barrier was installed along the section of I-15 between Spanish Fork, UT and SR 75. This section is a 4-mile segment of I-15 located in the south end of Utah County. This section of the report summarizes the results of the analysis performed before and after the cable barrier was installed. The before period used in the analysis is from 2002 to 2004 and the after period is from 2006 to 2008.

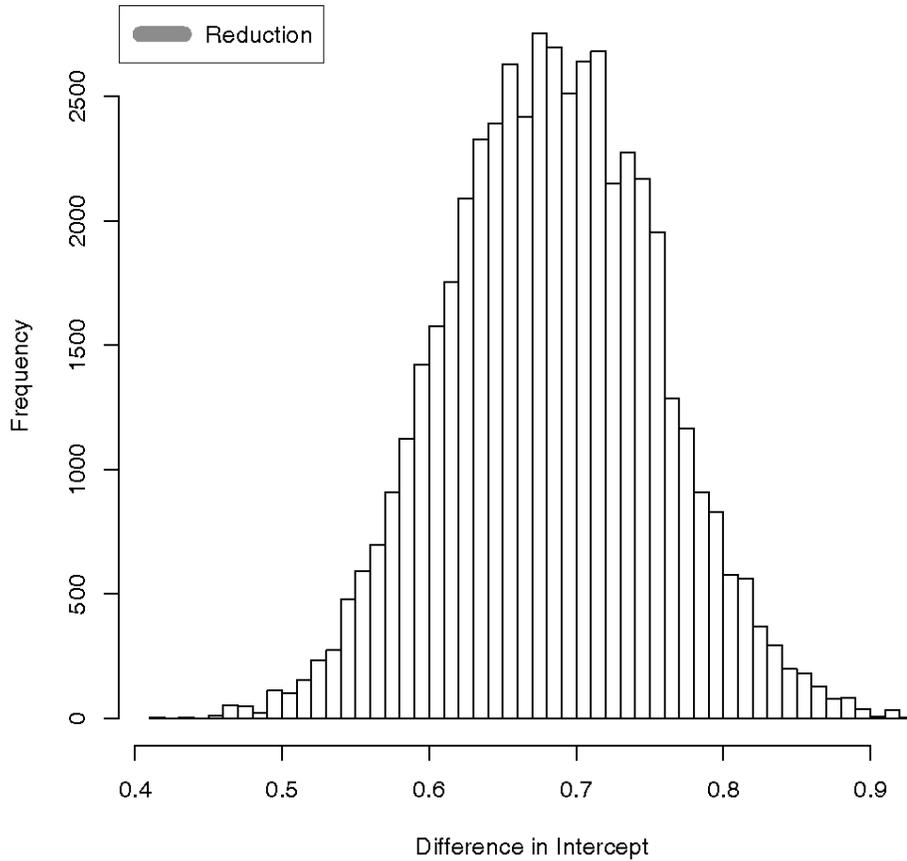
The results of the overall crash analysis are displayed graphically in Figure 6-13. The results of the overall crash analysis for this segment show a 98.50 percent increase in the overall

crash frequency after the cable barrier was installed. The corresponding distribution of the differences for the overall crash analysis are shown in Figure 6-14.



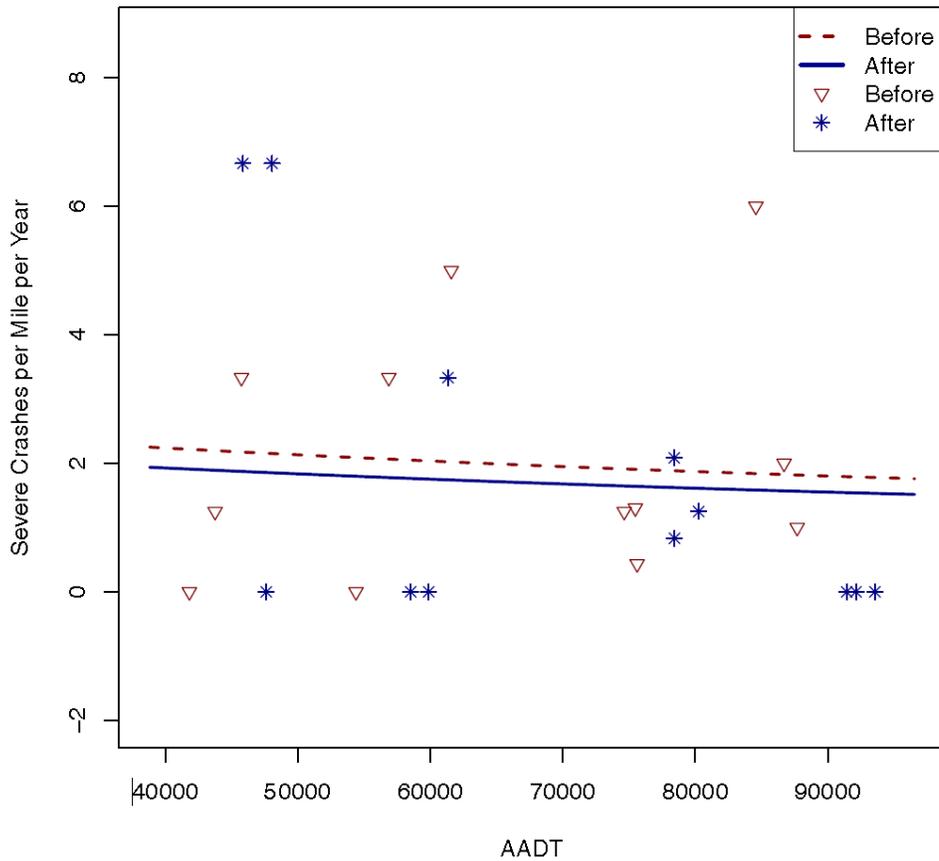
**Figure 6-13. Overall crashes on I-15 between Spanish Fork and SR 75.**

The entire distribution was greater than zero, indicating a 100 percent probability that an increase in the overall crash frequency occurred after the installation of cable barrier (0 percent probability of a decrease). However, it is unlikely the increase is a direct result of the cable barrier system. It is more likely that the increase in overall crashes is the product of increased traffic volumes and other contributing factors. The results are useful as background information to show an increase in crashes overall.



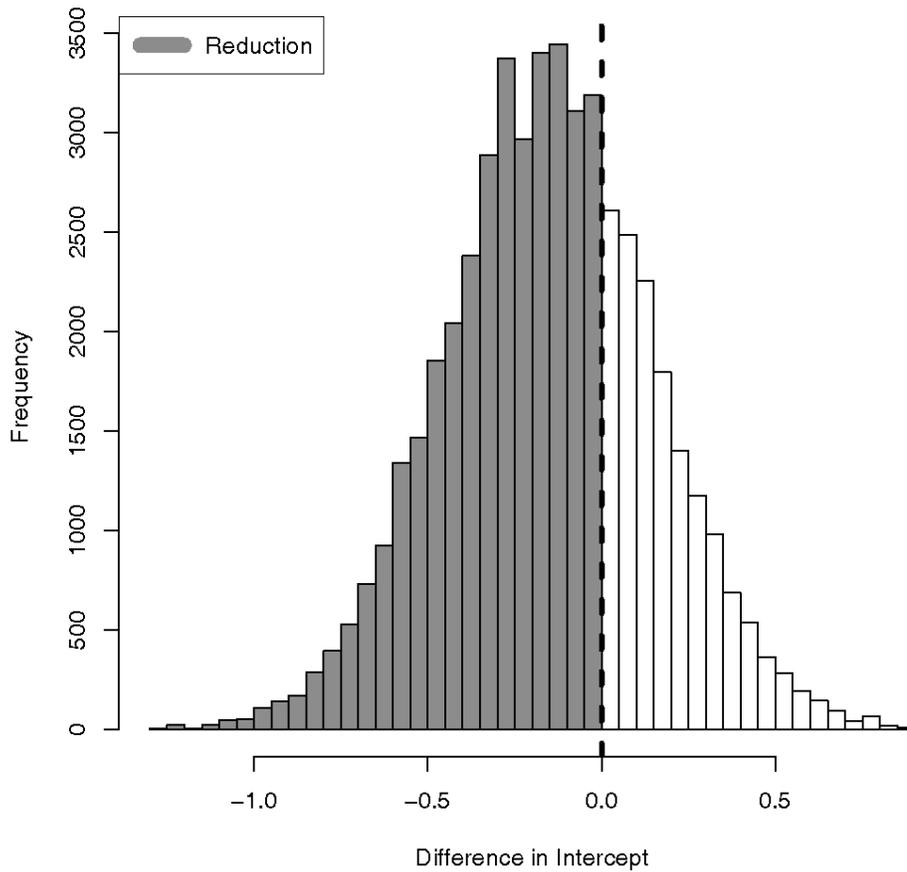
**Figure 6-14. Distribution of differences for overall crashes on I-15 between Spanish Fork and SR 75.**

The results of the severe crash analysis for this segment of I-15 indicate that the installation of the cable barrier had only minimal impact on severe crash frequency for this segment. These results are displayed in Figure 6-15. The analysis indicated a 10.07 percent decrease in severe crash frequency after the installation of the cable barrier system.



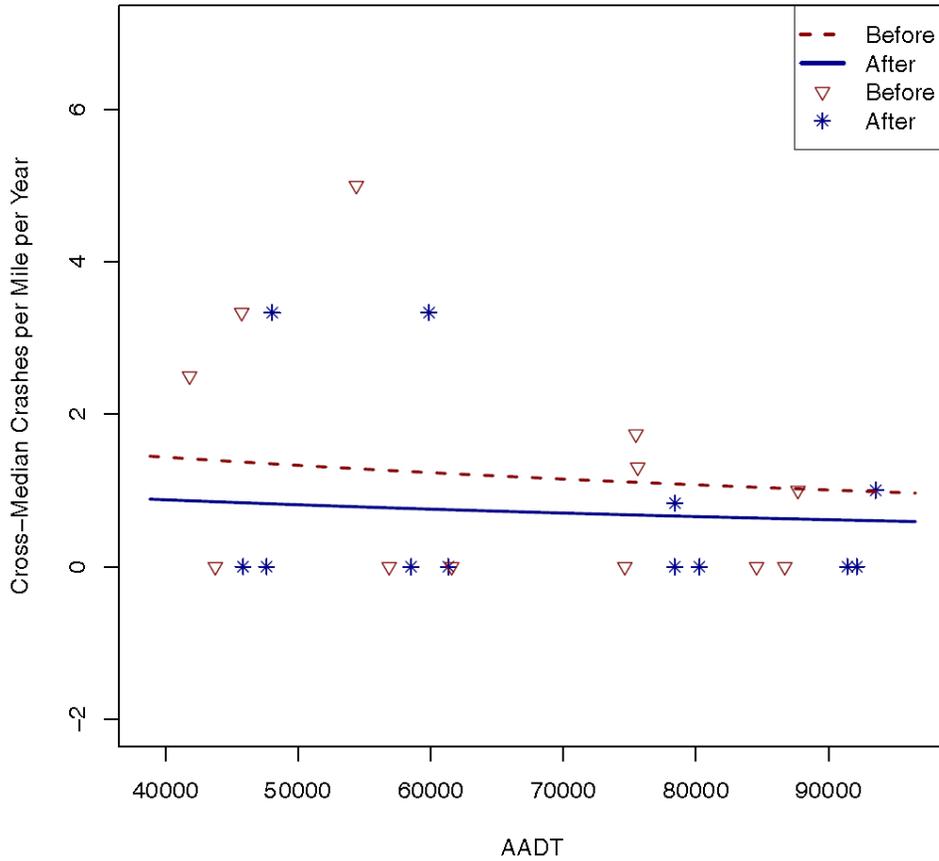
**Figure 6-15. Severe crashes on I-15 between Spanish Fork and SR 75.**

Figure 6-16 shows the corresponding distribution of differences for the severe crash analysis for this segment of I-15. The results of the analysis indicate a 69.73 percent probability a decrease in severe crash frequency occurred after the installation of the cable barrier system. Therefore, even though the analysis results suggest a decrease may have occurred, the probability was determined to be too low to be conclusive.



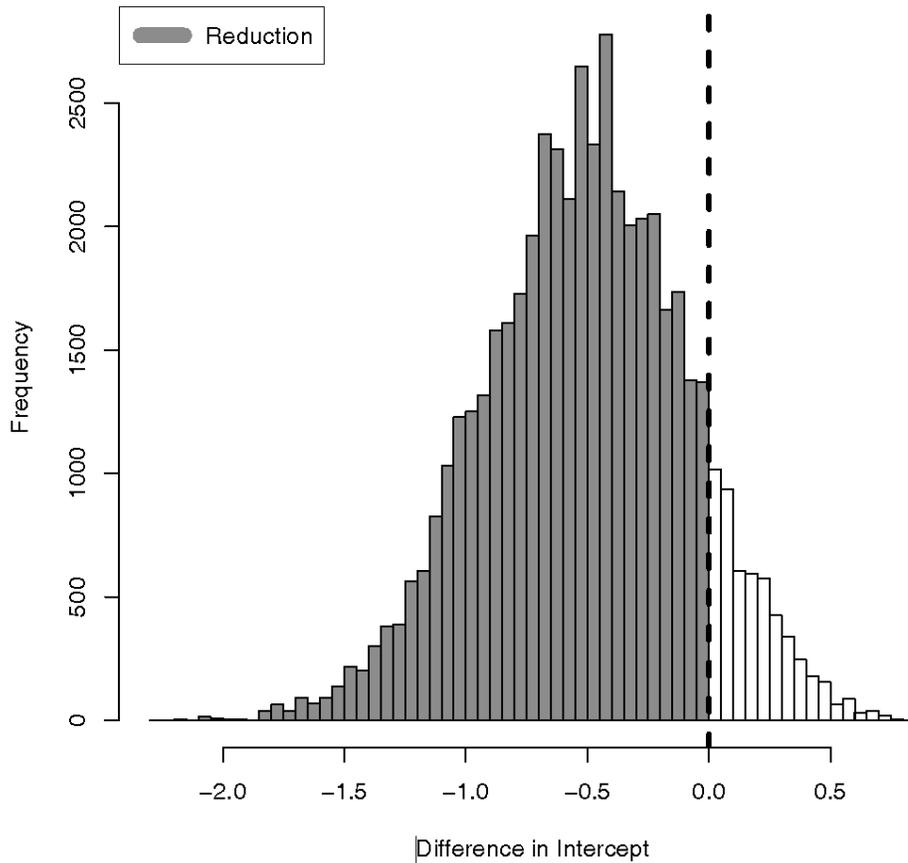
**Figure 6-16. Distribution of differences of severe crashes on I-15 between Spanish Fork and SR 75.**

The results of the cross-median analysis were more promising than the severe crash analysis for this segment. Figure 6-17 displays the crash frequency of cross-median crashes for the before and after periods as a function of AADT. The analysis results indicate that cross-median crash frequency decreased by 34.74 percent after the cable barrier system was installed.



**Figure 6-17. Cross-median crashes on I-15 between Spanish Fork and SR 75.**

Figure 6-18 shows the corresponding probability distribution of the difference between the before and after periods for cross-median crashes for this segment. An estimated 89.39 percent of the probability distribution for this site was less than zero. This can be interpreted to mean that there was nearly a 90 percent probability that a decrease in cross-median crashes occurred.



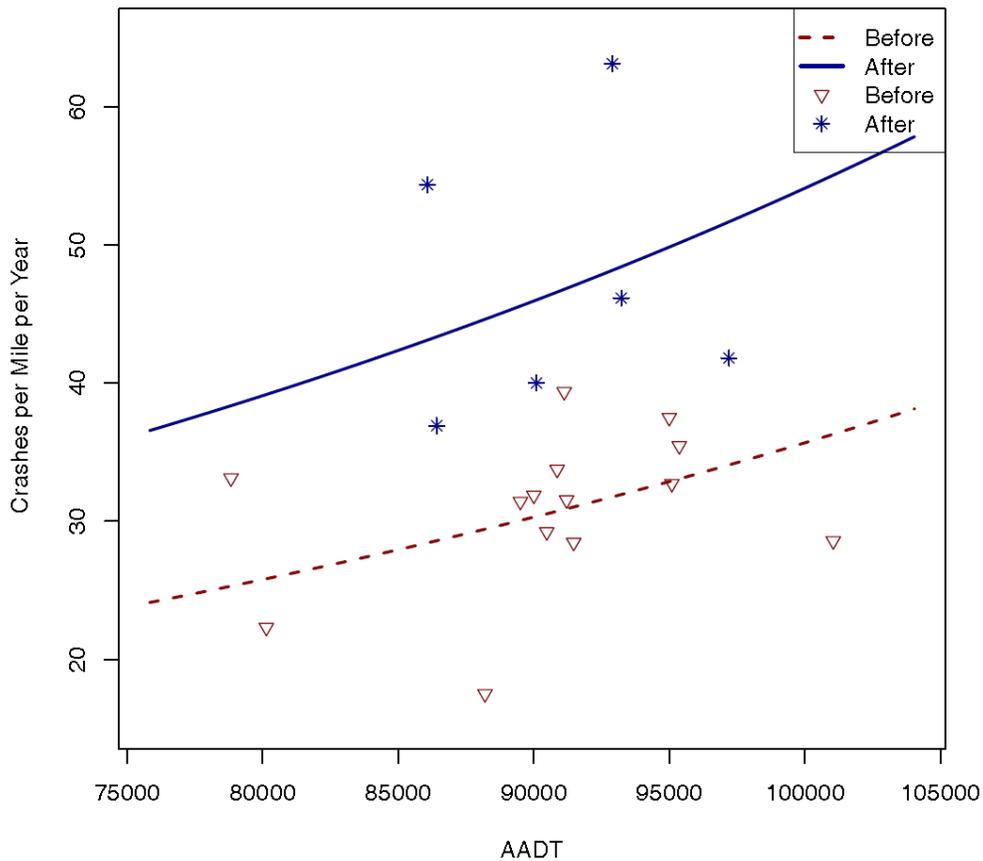
**Figure 6-18. Distribution of differences for cross-median crashes on I-15 between Spanish Fork and SR 75.**

#### 6.1.4 I-15 South Layton to Syracuse

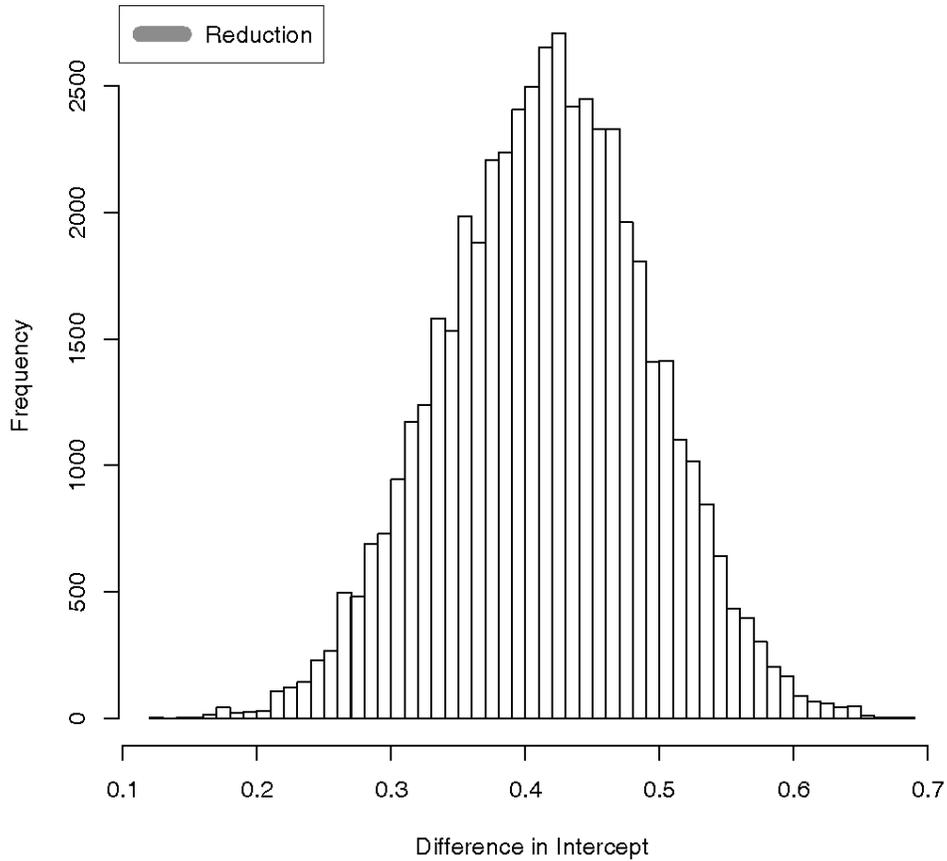
This site is a segment of I-15 located in Davis County, just north of Salt Lake City, UT. Cable barrier was installed on a 4-mile segment between South Layton and Syracuse. The project was completed in 2006. This section summarizes the results of the analysis performed before and after the cable barrier system was installed. The before period used in the analysis is from 2002 to 2005 and the after period is from 2007 to 2008.

Figure 6-19 displays the crash frequency of the overall crash analysis for the before and after periods as a function of AADT. Figure 6-20 shows the probability distribution of the difference between the before and after periods for overall crashes.

The entire distribution of the differences for the overall analysis was greater than zero, as shown in Figure 6-20. This can be interpreted as a 100 percent probability that an increase occurred after the installation of the cable barrier system (0 percent probability of decrease). The corresponding increase in overall crash frequency was 52.00 percent. As noted previously, it is anticipated the increase in overall crash frequency is most likely the result of an increase in traffic volumes or factors other than the cable barrier system. The analysis also revealed an outlier for both the before and after periods. These two sites should be analyzed in the future using the analysis procedure developed in this research to address the specific causes of the crashes.

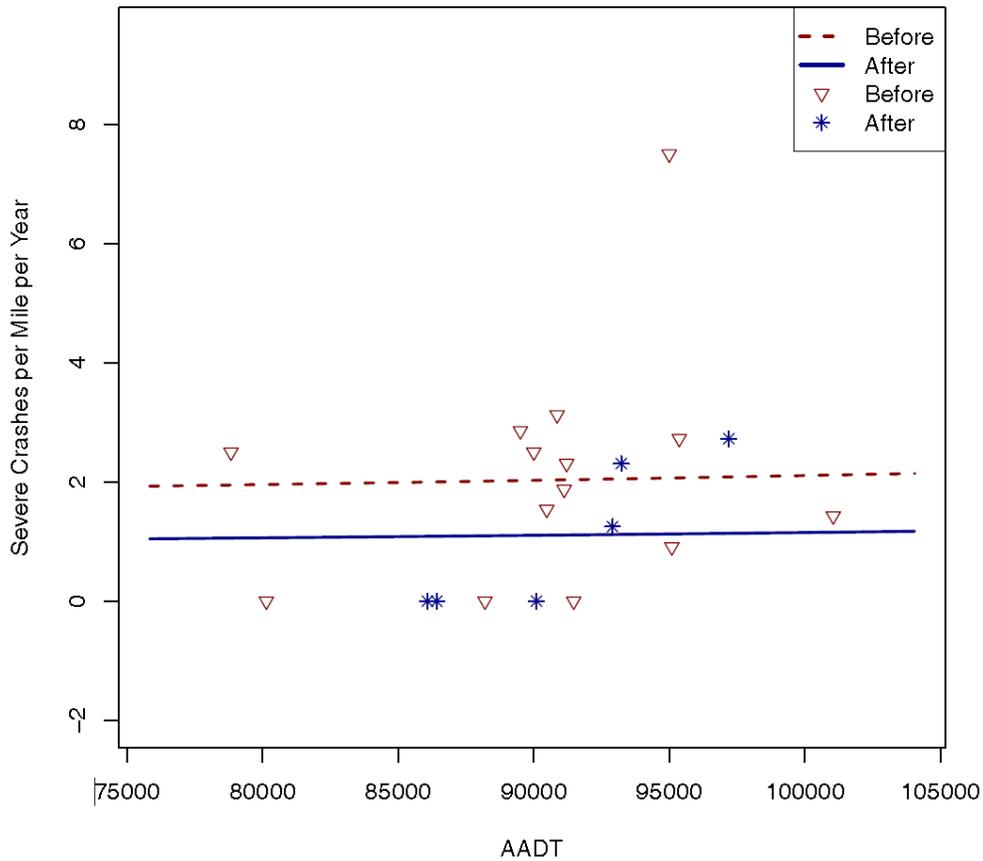


**Figure 6-19. Overall crashes on I-15 from South Layton to Syracuse.**



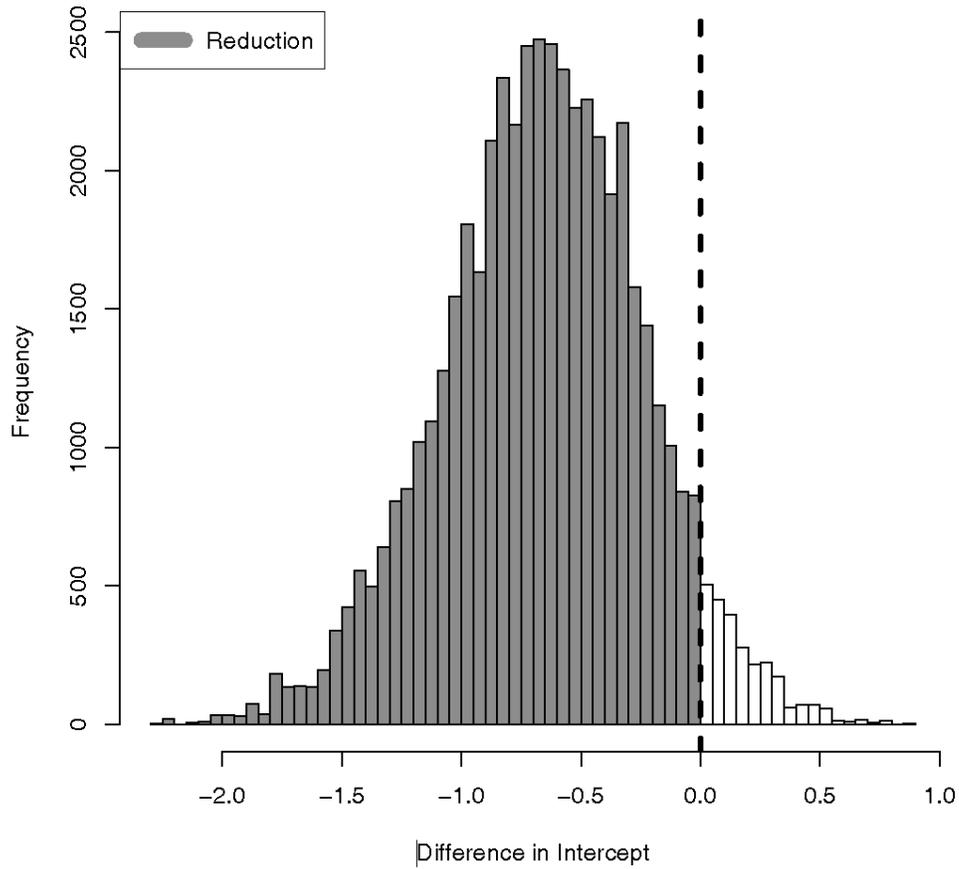
**Figure 6-20. Distribution of differences for overall crashes on I-15 between South Layton and Syracuse.**

The results of the severe crash analysis for this segment provide more promising results. Figure 6-21 displays the crash frequency of severe crashes for the before and after periods as a function of AADT. The results of the analysis indicate that the severe crash frequency decreased by 43.70 percent for this segment after a cable barrier system was installed.



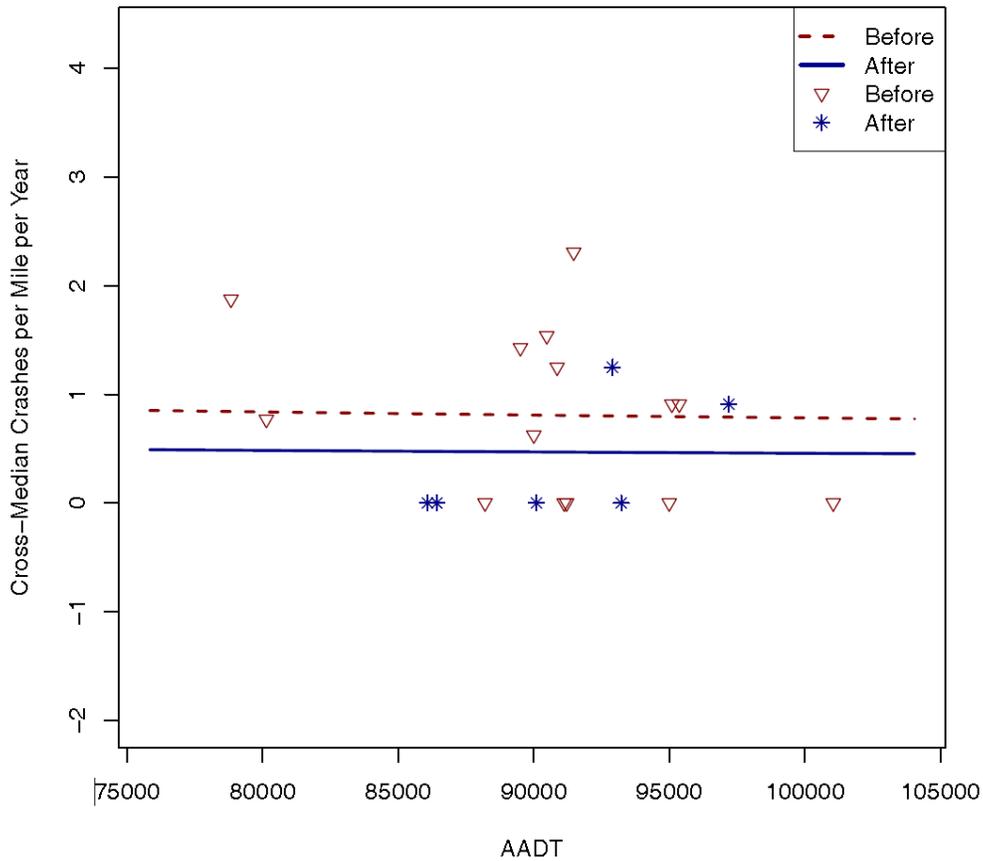
**Figure 6-21. Severe crashes on I-15 from South Layton to Syracuse.**

Figure 6-22 shows the probability distribution of the difference between the before and after periods for severe crashes. The results of the analysis indicate a strong probability that the installation of the cable barrier system had impact on severe crashes at this site. The probability that a decrease occurred was 94.88 percent as represented by the grayed portion of Figure 6-22.



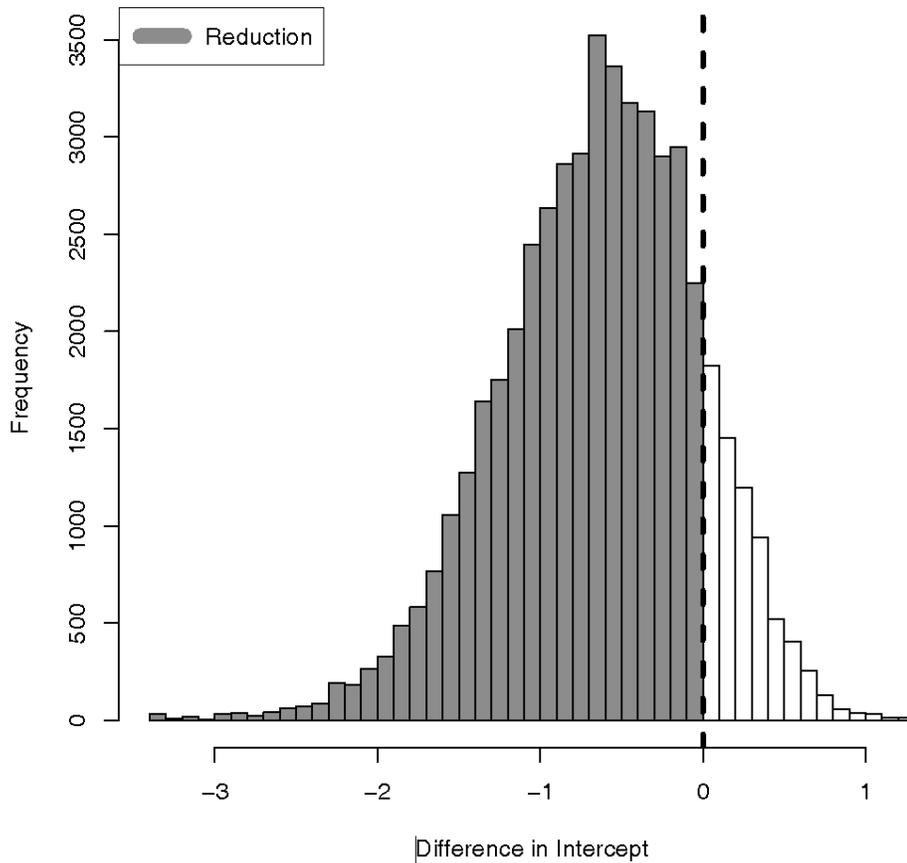
**Figure 6-22. Distribution of differences for severe crashes on I-15 between South Layton and Syracuse.**

Figure 6-23 displays the crash frequency of cross-median crashes for the before and after periods for this segment. The results of the analysis showed that cross-median crash frequency decreased by 37.70 percent after the cable barrier system was installed.



**Figure 6-23. Cross-median crashes on I-15 from South Layton to Syracuse.**

Figure 6-24 shows the corresponding probability distribution of the difference between the before and after periods for cross-median crashes. The results of the cross-median analysis indicate an 86.24 percent probability that the installation of the cable barrier system decreased cross median crashes at this site. The probability that a decrease occurred is represented by the grayed portion of Figure 6-24.

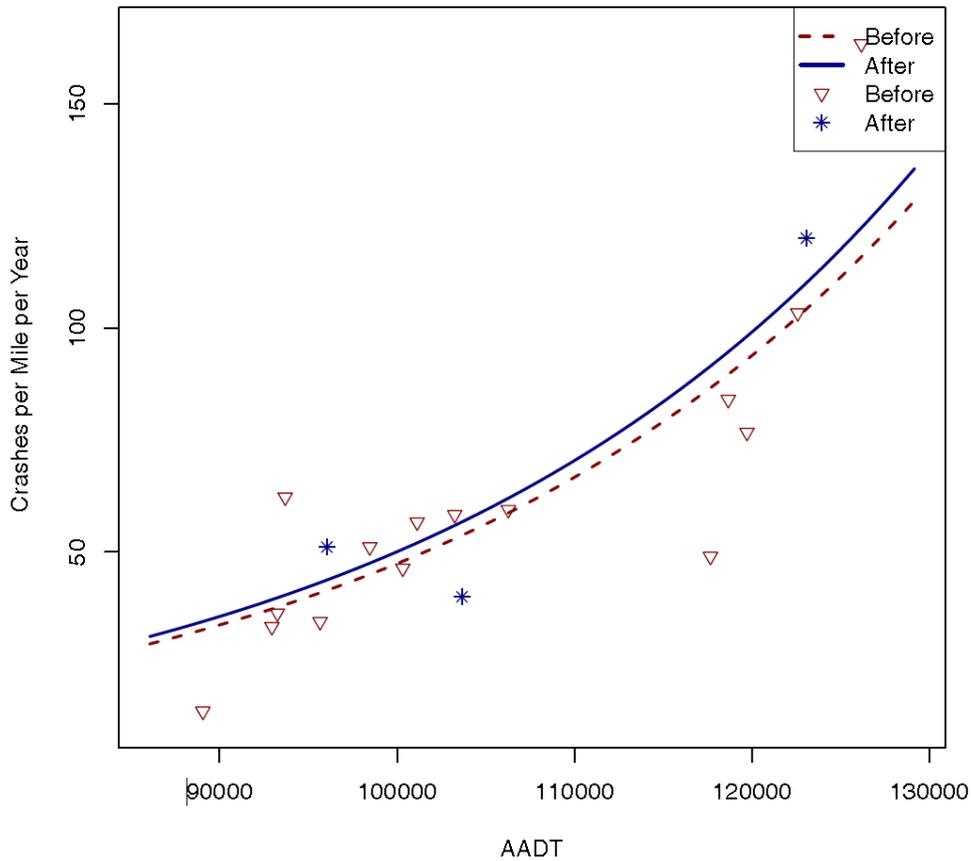


**Figure 6-24. Distribution of differences for cross-median crashes on I-15 between South Layton and Syracuse.**

### 6.1.5 I-15 600 North to 2300 North in Salt Lake

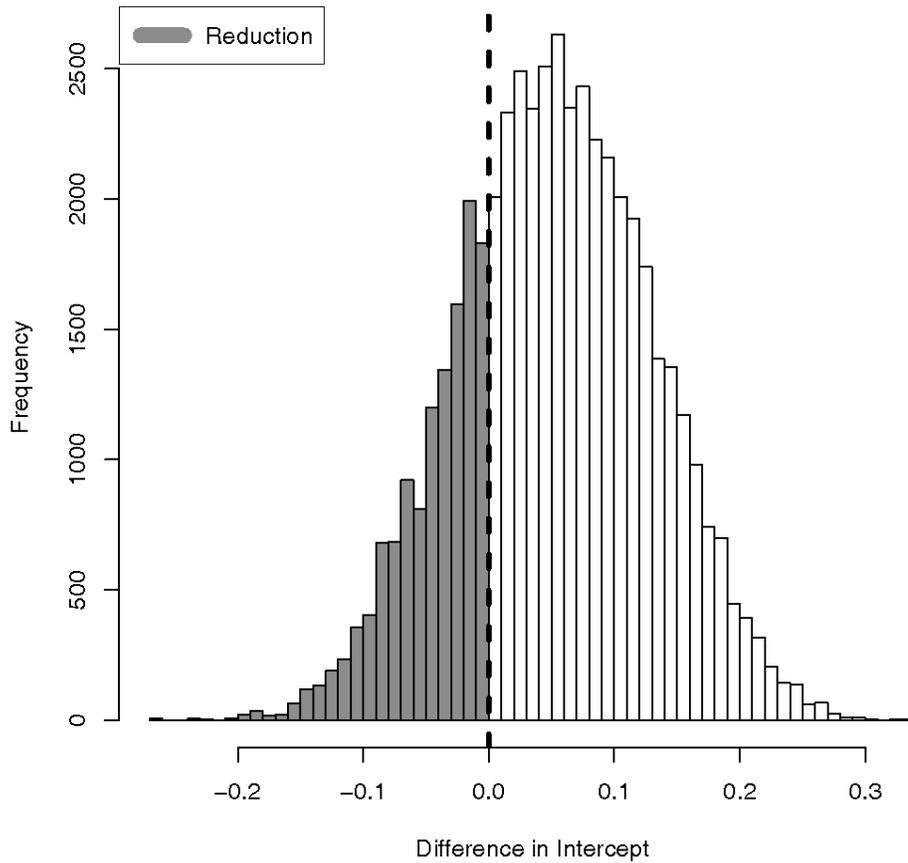
In 2007, cable barrier was installed along a 3-mile segment of I-15 located just north of Salt Lake, UT between 600 North and 2300 North. This section summarizes the results of the analysis performed before and after the cable barrier system was installed. The before period used in the analysis is from 2002 to 2006. Only one year of after data were available, 2008.

Figure 6-25 displays the crash frequency of all crashes for the before and after periods as a function of AADT. Figure 6-26 shows the corresponding probability distribution of the difference between the before and after periods for all crashes.



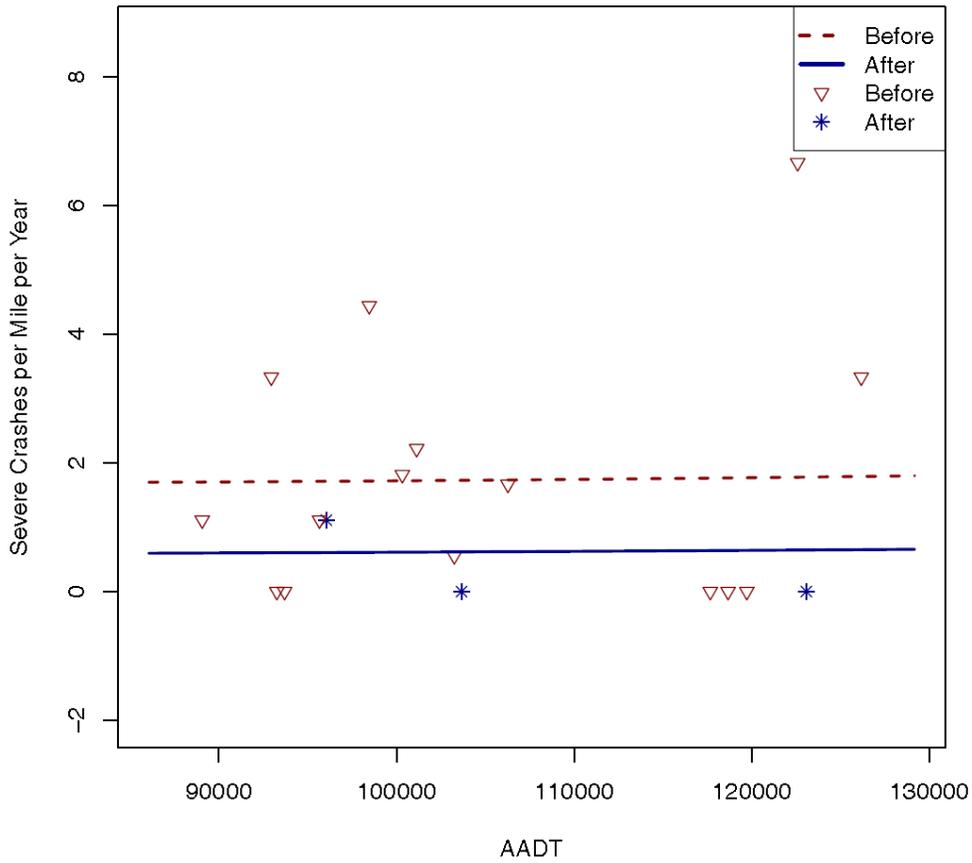
**Figure 6-25. Overall crashes on I-15 between 600 North and 2300 North.**

The analysis of this segment showed the probability of a decrease was only 25.37 percent. Therefore there is a high probability that an increase in overall crashes occurred after the cable barrier system was installed. The corresponding increase in overall crash frequency was 5.71 percent. However, it cannot be confidently concluded that there was an increase in overall crashes. Furthermore, it is highly unlikely that the installation of cable barrier caused any increase in the overall crash frequency.



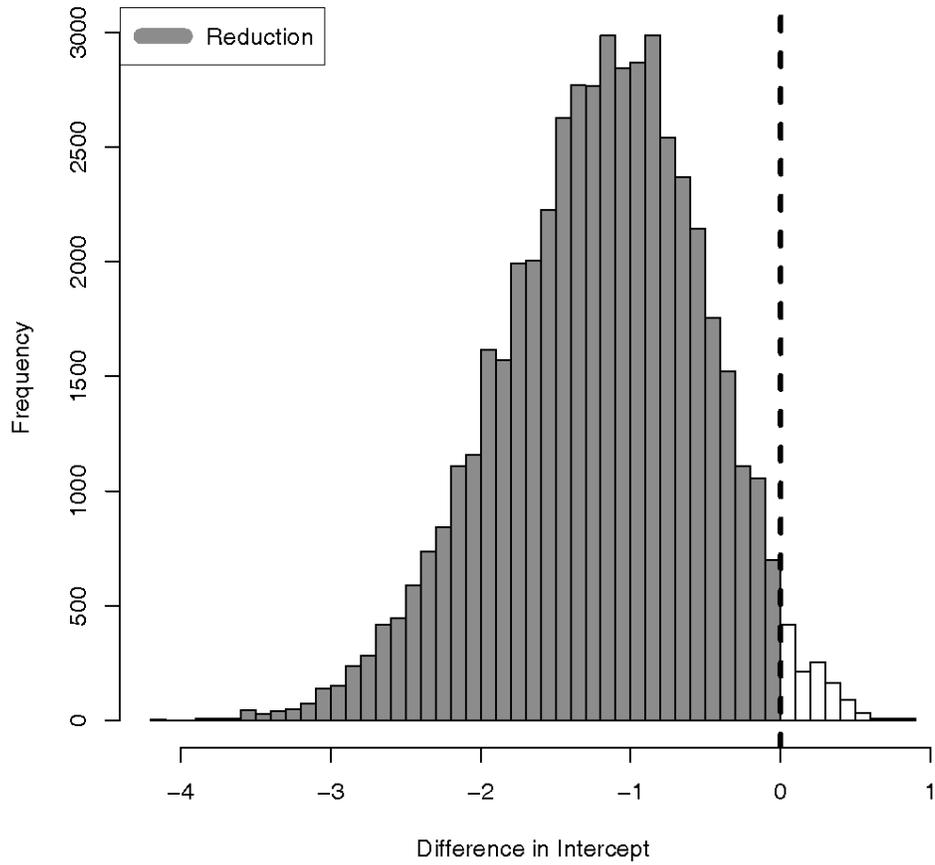
**Figure 6-26. Distribution of differences for overall crashes on I-15 between 600 North and 2300 North.**

Figure 6-27 displays the crash frequency of severe crashes for the before and after periods as a function of AADT. The results of the analysis indicate that the severe crash frequency of this segment decreased by 62.97 percent after a cable barrier system was installed.



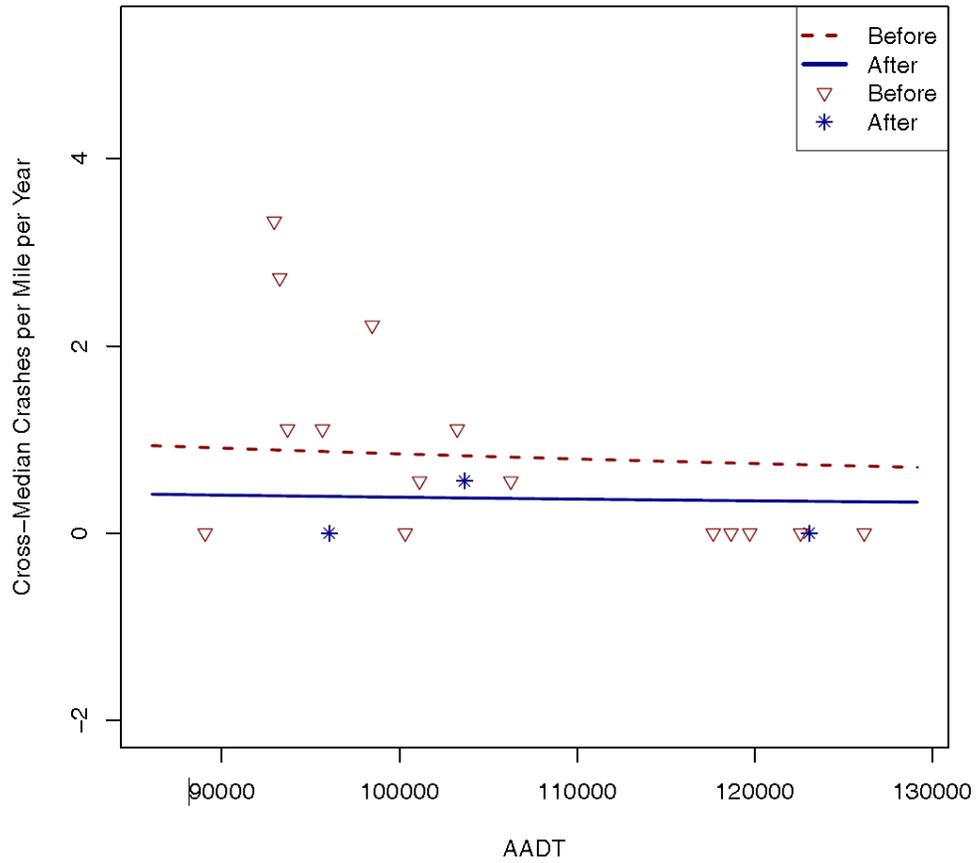
**Figure 6-27. Severe crashes on I-15 between 600 North and 2300 North.**

Figure 6-28 shows the probability distribution of the difference between the before and after periods for severe crashes. The probability a decrease in severe crash frequency occurred at this site was 97.62 percent, which is represented by the gray portion of the distribution shown in Figure 6-28.



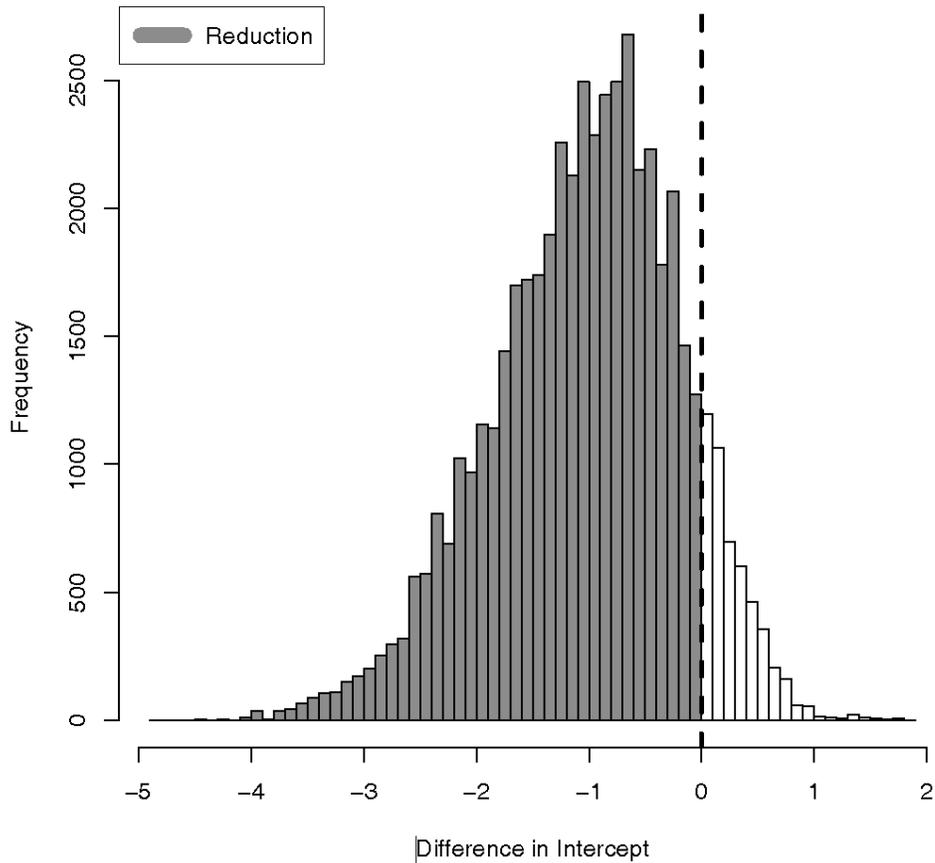
**Figure 6-28. Distribution of differences for severe crashes on I-15 between 600 North and 2300 North.**

The cross-median analysis showed a similar reduction in frequency. Figure 6-29 displays the crash frequency of cross-median crashes for the before and after periods as a function of AADT.



**Figure 6-29. Cross-median crashes on I-15 between 600 North and 2300 North.**

The analysis indicated that this segment experienced a 51.30 percent reduction in cross-median crash frequency. The corresponding probability was strong at 90.14 percent, which is represented by the gray portion of the probability distribution shown in Figure 6-30.



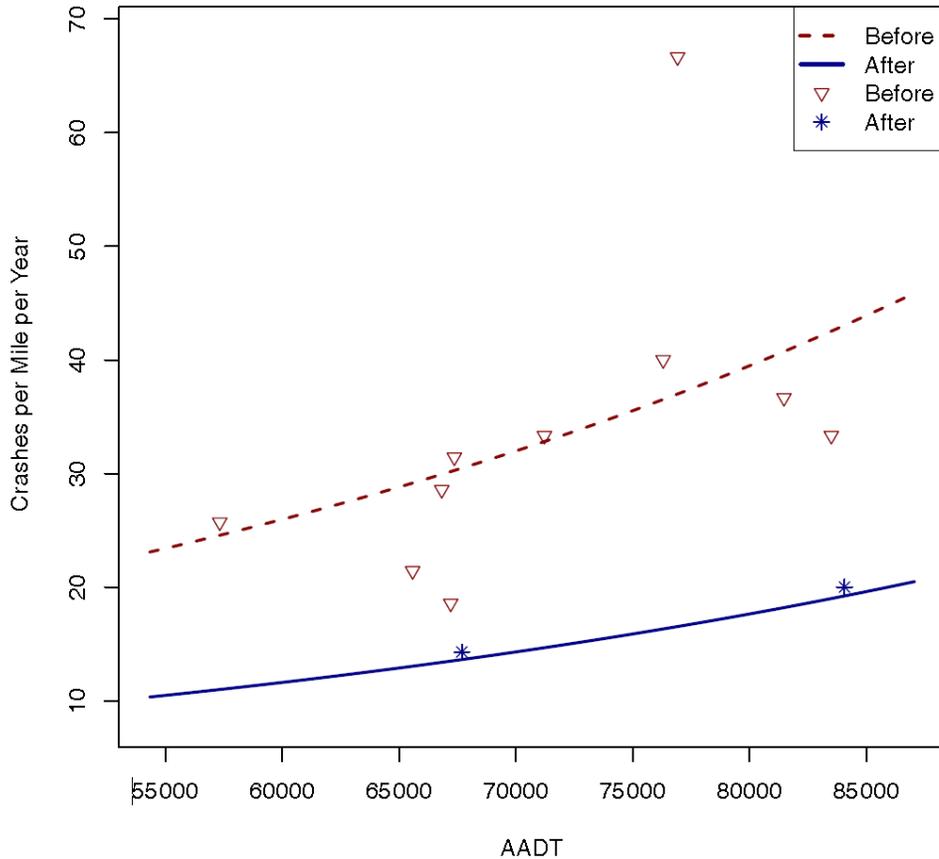
**Figure 6-30. Distribution of differences for cross-median crashes on I-15 between 600 North and 2300 North.**

### 6.1.6 I-215E 3100 South to 3800 South in Salt Lake

In 2007 a cable barrier was installed along the east side of I-215 in Salt Lake County, UT. This section is a 1 mile segment located between 3100 South and 3800 South. This section summarizes the results of the analysis performed before and after the raised median was installed. The before period used in the analysis is from 2002 to 2006. Only one year of after data was available, 2008.

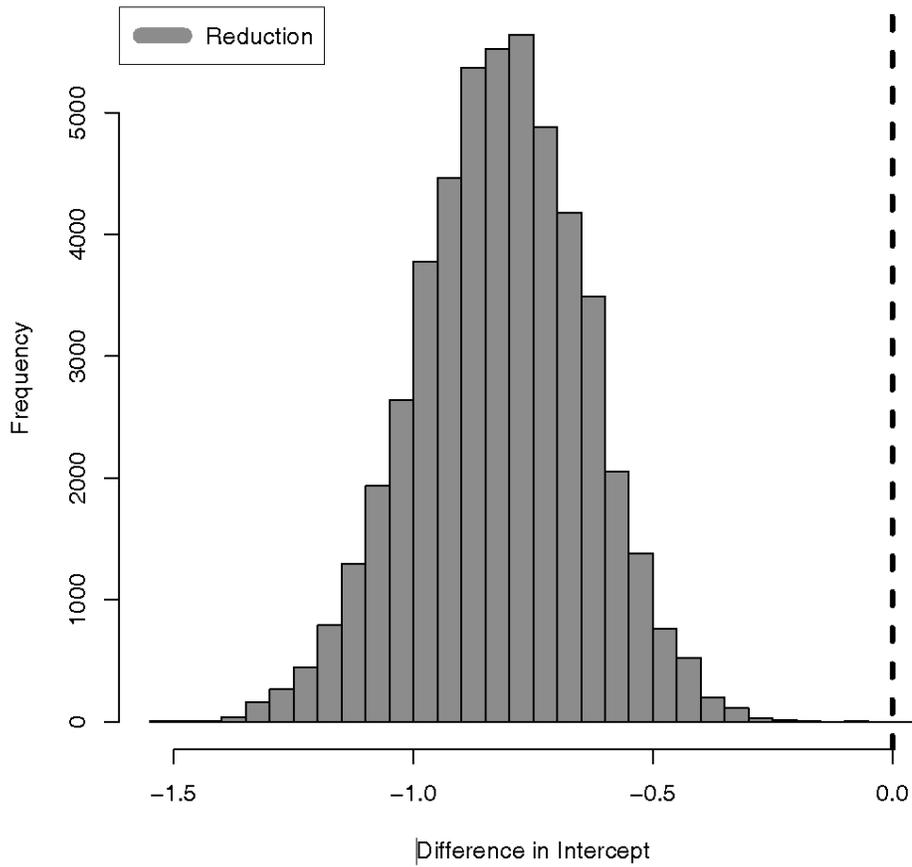
Figure 6-31 displays the crash frequency of all crashes for the before and after periods as a function of AADT. The results of the analysis of this segment provide results that differ from

most other sites. The results indicate that the overall crash frequency decreased for this segment after the cable barrier system was installed.



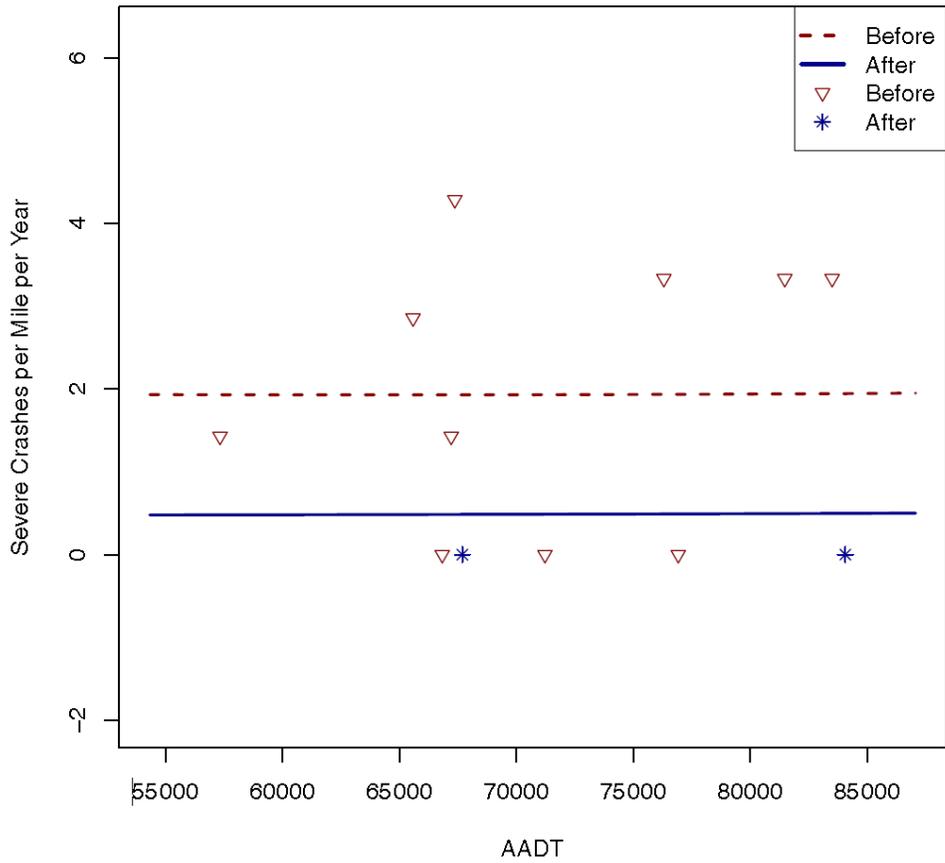
**Figure 6-31. Overall crashes on I-215 East.**

Figure 6-32 shows the corresponding probability distribution of the difference between the before and after periods for all crashes. The analysis showed this segment had a 100 percent probability that a decrease in overall crashes occurred, which is represented by the entire distribution of differences being gray in Figure 6-32. The corresponding reduction was a 55.20 percent decrease in overall crash frequency. While it is probable that the decrease in overall crash frequency was possibly the result of other factors, the cable barrier system installation may have contributed to the reduction in overall crash frequency.



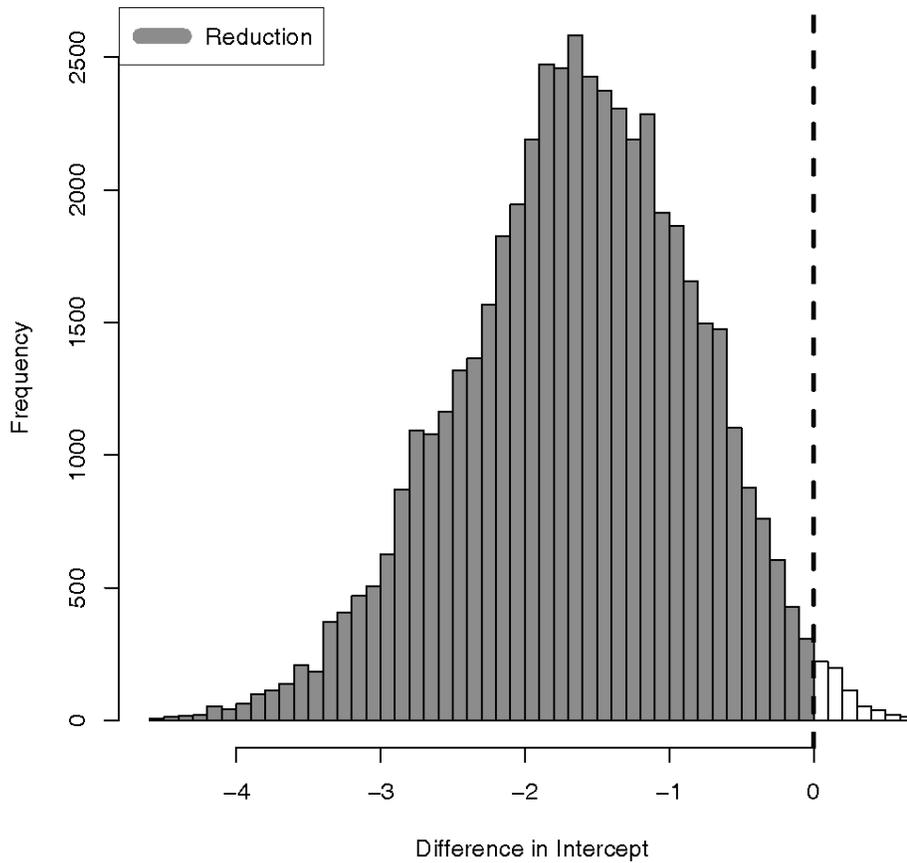
**Figure 6-32. Distribution of differences in overall crashes for I-215 East.**

Figure 6-33 displays the crash frequency of severe crashes for the before and after periods as a function of AADT. Figure 6-34 shows the corresponding probability distribution of the differences between the before and after periods for severe crashes.



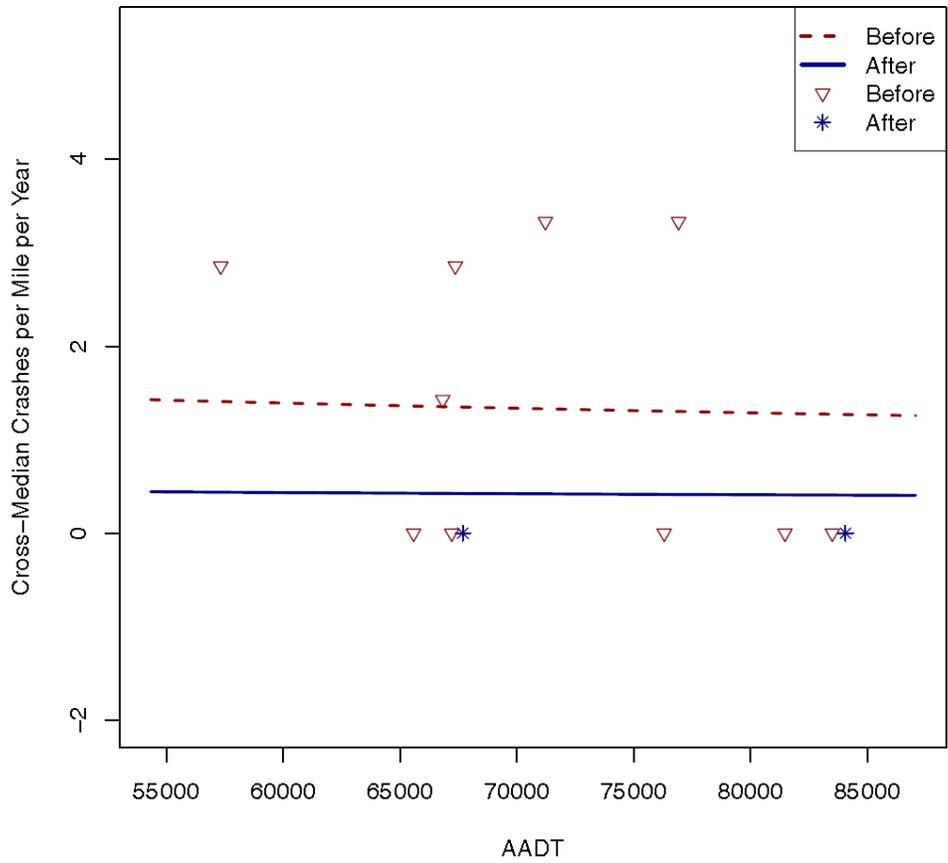
**Figure 6-33. Severe crashes on I-215 East.**

The results of the analysis indicate that there was a 98.68 percent probability that severe crashes decreased by 73.65 percent after the installation of the cable barrier system, as is represented by the grayed portion of Figure 6-34. However, due to the limitations of the available data, all severe crashes were considered in the analysis and not just those directly related to cable barrier. Therefore, while it is likely that the cable barrier system contributed in part to the reduction in severe crashes at this site, it is unlikely it was solely responsible for the decrease.

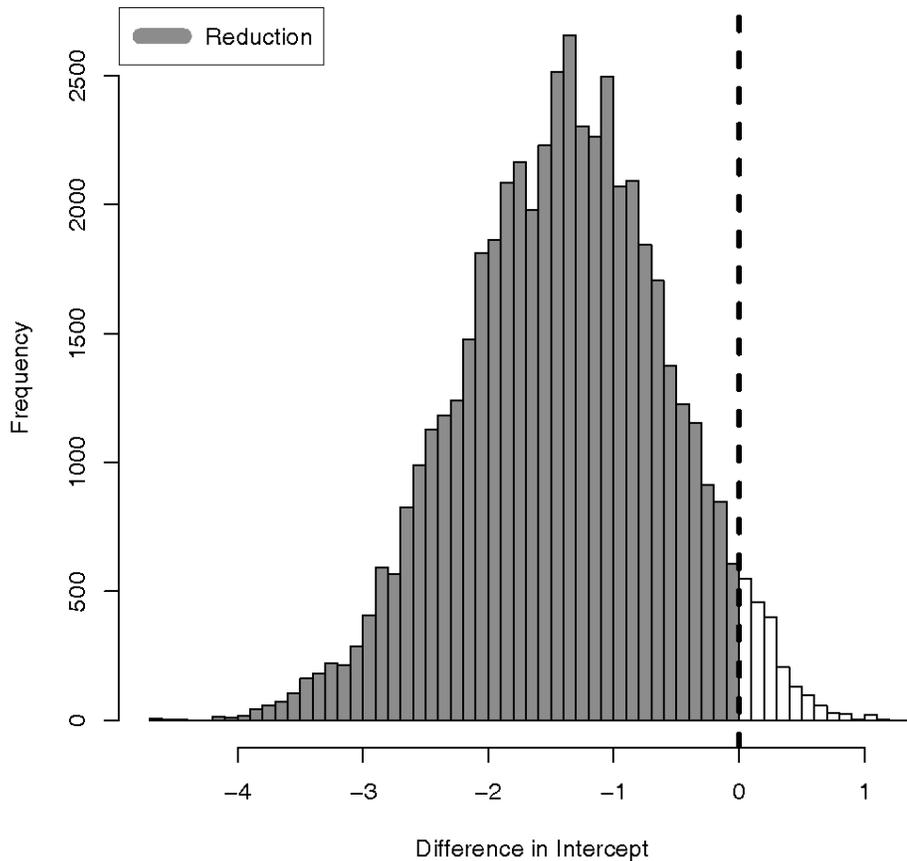


**Figure 6-34. Distribution of differences in severe crashes for I-215 East.**

The results of the cross-median analysis provide similarly promising results. Figure 6-35 displays the crash frequency of cross-median crashes for the before and after periods as a function of AADT. The results show that cross-median crash frequency decreased by 66.34 percent for this segment. The corresponding probability was 96.04 percent as represented by the gray portion of the distribution shown in Figure 6-36.



**Figure 6-35. Cross-median crashes on I-215 East.**



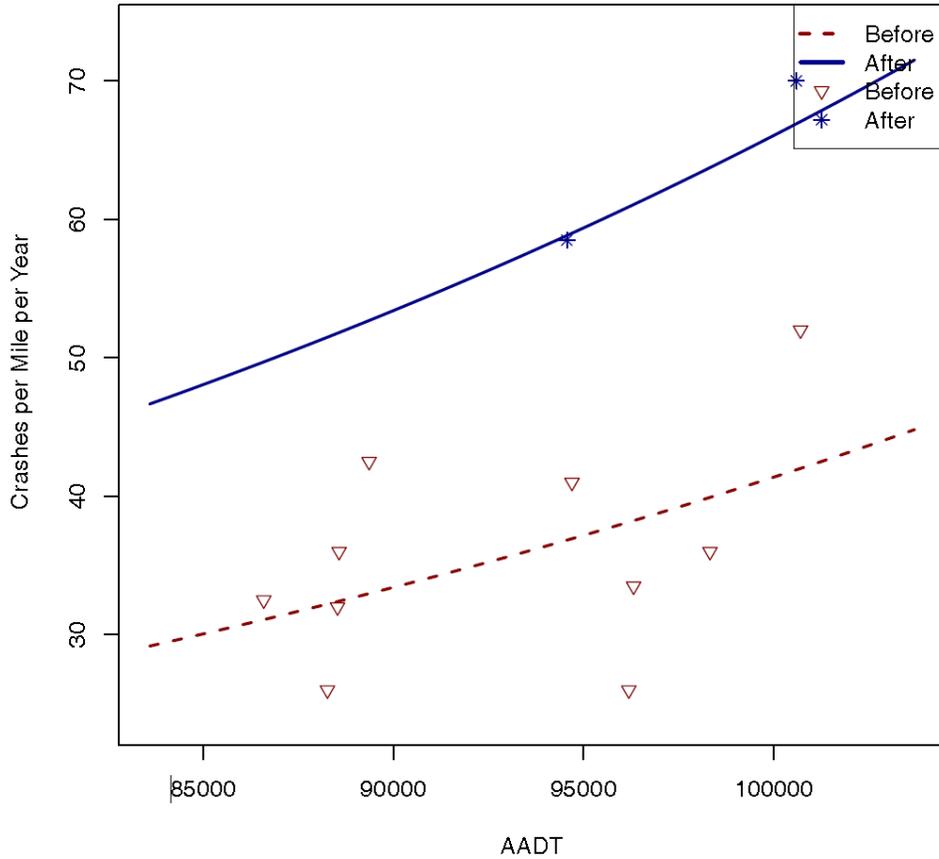
**Figure 6-36. Distribution of differences in cross-median crashes for I-215 East.**

### 6.1.7 I-215W 2100 South to 4500 South Salt Lake

In 2007, cable barrier was also installed along the west side of I-215 in Salt Lake County, UT. This 2.5-mile segment is located between 2100 South and 4500 South. This section of the report summarizes the results of the analysis performed before and after the cable barrier system was installed. The before period used in the analysis is from 2002 to 2006. Only one year of after data was available, 2008.

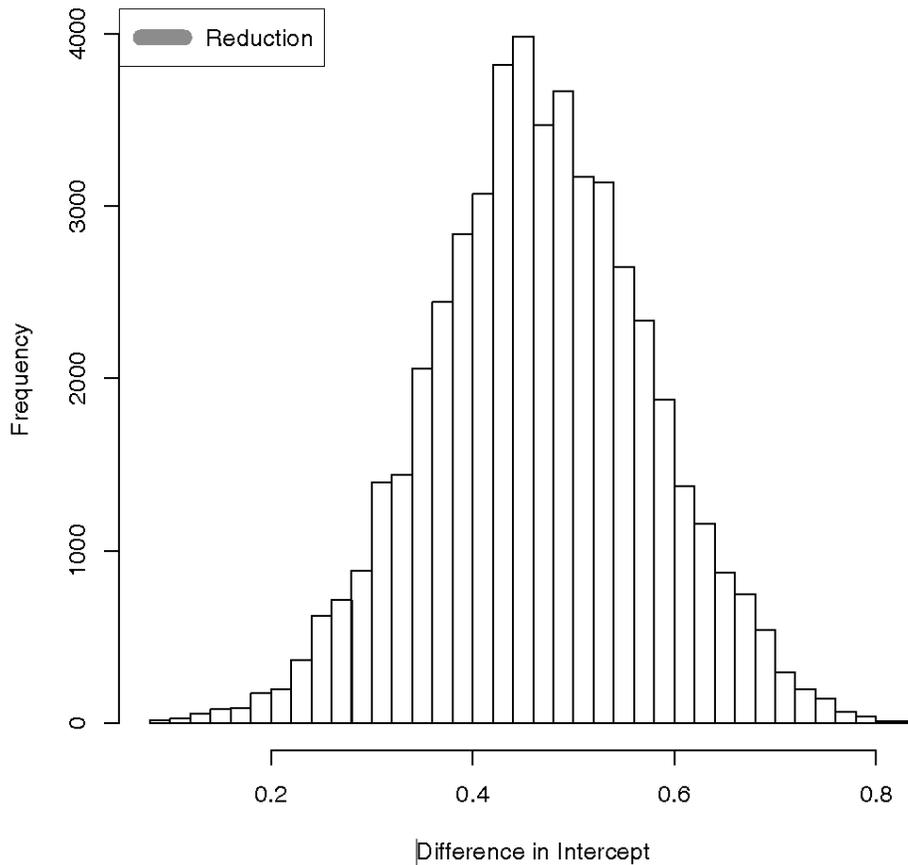
Figure 6-37 displays the crash frequency of all crashes for the before and after periods as a function of AADT. The results of the analysis indicate that the overall crash frequency increased by 60.27 percent after the cable barrier system was installed. As stated previously, it is

anticipated that this increase is the product of other contributing factors rather than the cable barrier system installation. The results are included here strictly for background information.



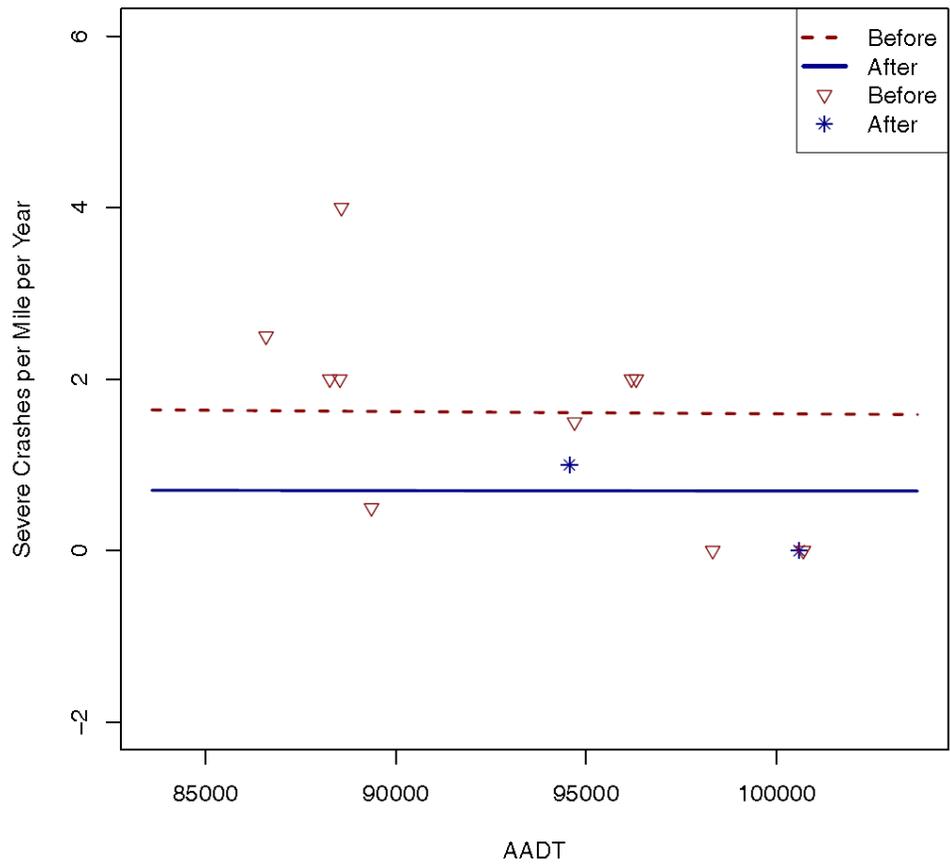
**Figure 6-37. Overall crashes on I-215 West.**

Figure 6-38 shows the probability distribution of the difference between the before and after periods for all crashes. The entire distribution for the differences for the overall crashes for this segment is greater than zero indicating a 100 percent probability of an increase (0 percent probability of a decrease) occurred after the cable barrier system was installed.



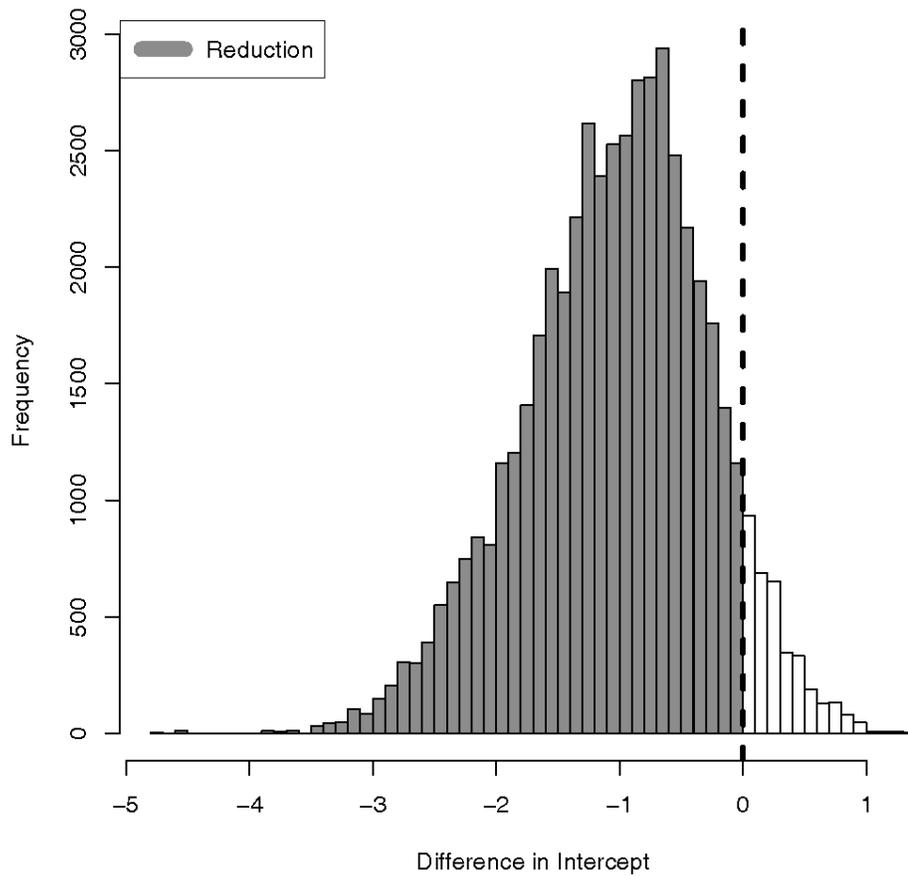
**Figure 6-38. Distribution of differences for overall crashes on I-215 West.**

The results of the severe crash analysis show much more promising results. Figure 6-39 displays the crash frequency of severe crashes for the before and after periods as a function of AADT. The analysis results indicate that this segment experienced a 53.94 percent reduction in severe crash frequency after the cable barrier system was installed. Since the analysis considered all severe crashes and not just those impacted by the cable barrier system, it would be inappropriate to assume the cable barrier system had an impact on all severe crashes. However, it is likely the cable barrier system contributed to the reduction in severe crashes.



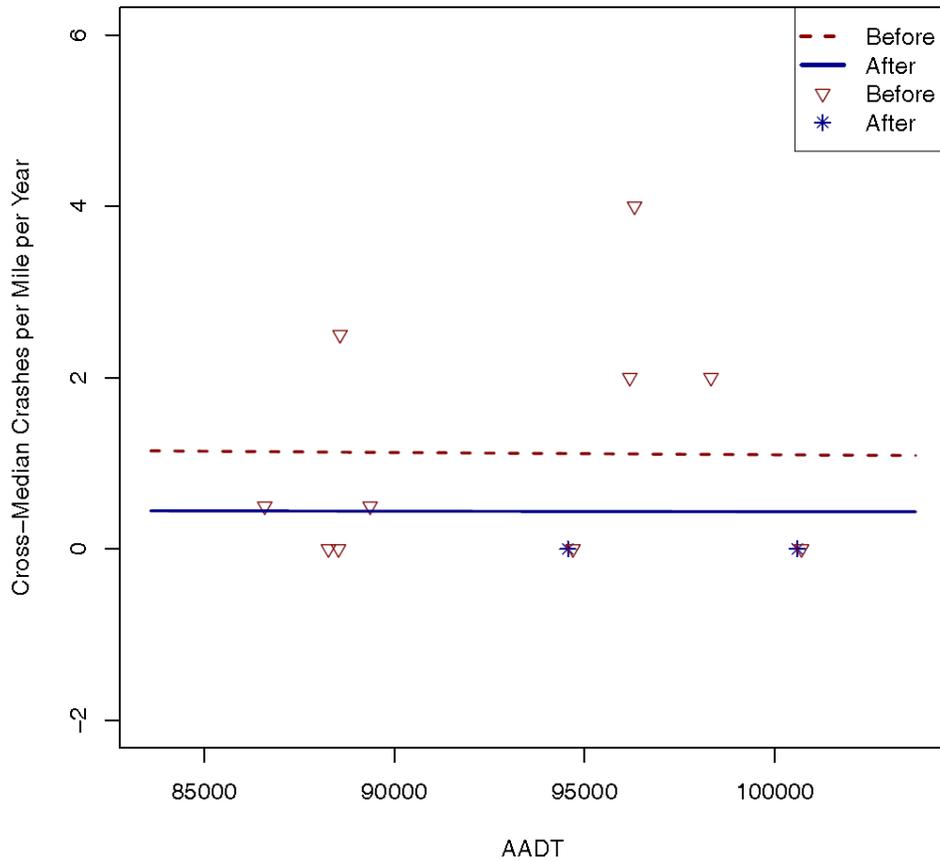
**Figure 6-39. Severe crashes on I-215 West.**

Figure 6-40 shows the probability distribution of the differences between the before and after periods for severe crashes. The probability that a decrease occurred along this segment was 92.90 percent as represented by the grayed portion of Figure 6-40.



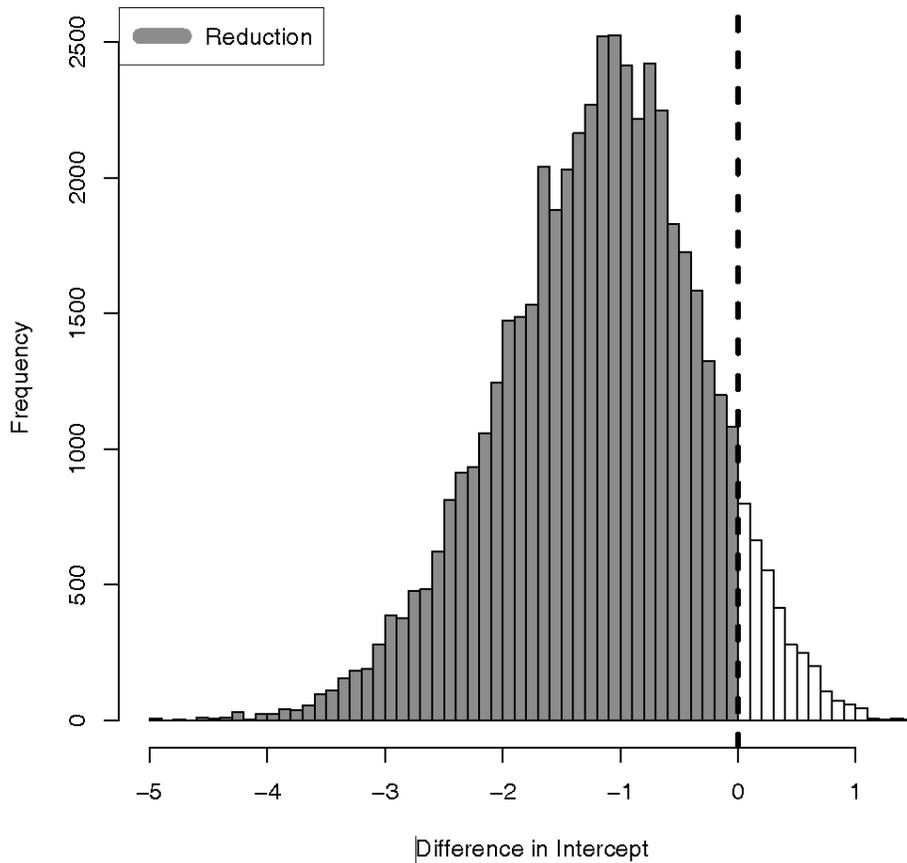
**Figure 6-40. Distribution of differences for severe crashes on I-215 West.**

The analysis of the cross-median crashes for this segment provided similarly promising results. Figure 6-41 displays the crash frequency of cross-median crashes for the before and after periods as a function of AADT.



**Figure 6-41. Cross-median crashes on I-215 West.**

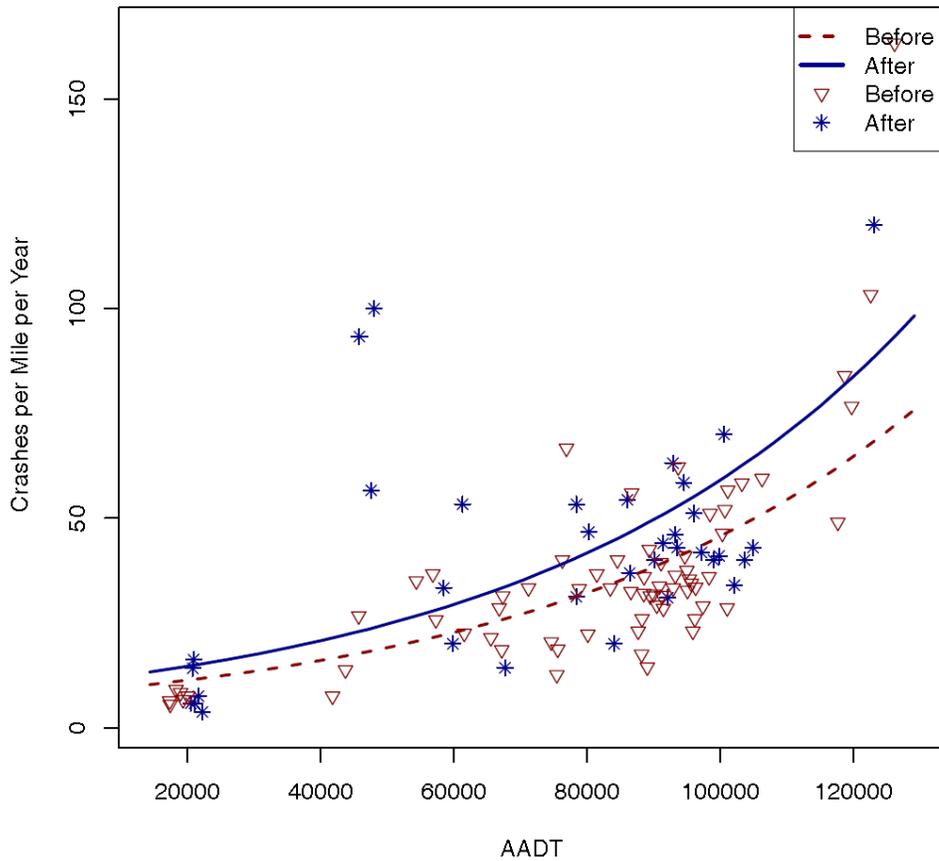
The results of the analysis indicated that cross-median crash frequency decreased by 57.87 percent following the installation of the cable barrier system. The probability that a decrease occurred was 93.08 percent as represented by the grayed portion of the corresponding probability distribution shown in Figure 6-42.



**Figure 6-42. Distribution of differences for cross-median crashes on I-215 West.**

## 6.2 Overall Cable Barrier Results

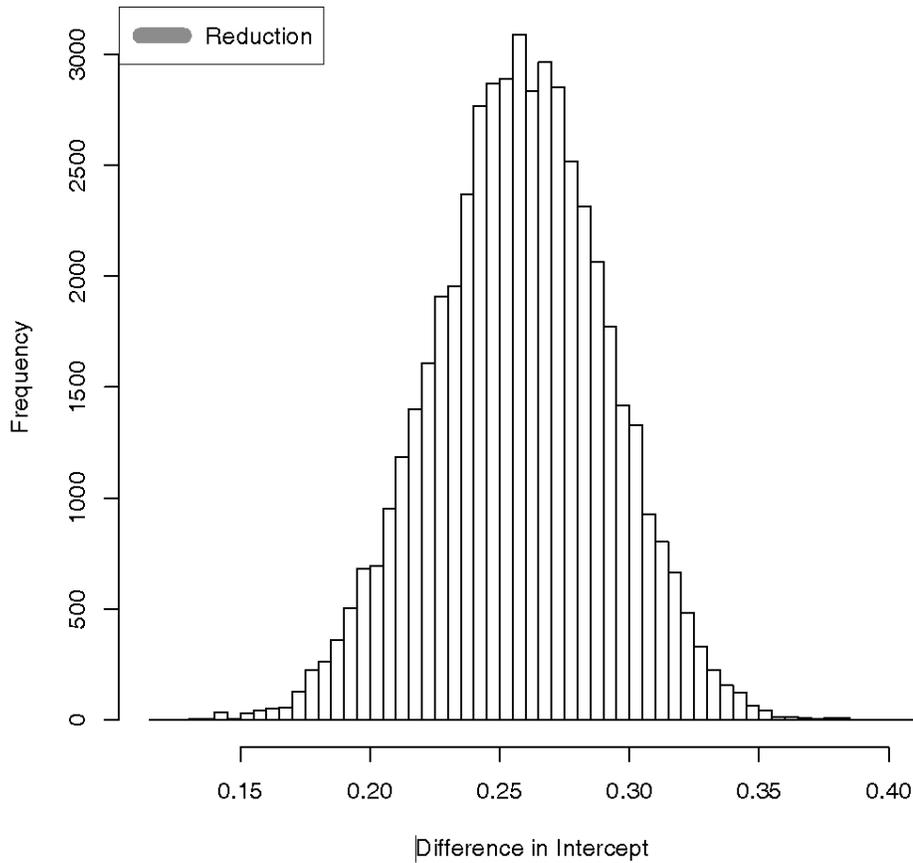
This section summarizes the results of the overall analysis performed on all cable barrier analysis sites. Figure 6-43 displays the crash frequency of overall crashes for the before and after periods as a function of AADT. Figure 6-44 shows the corresponding probability distribution of the differences between the before and after periods for overall crashes.



**Figure 6-43. Overall crashes on all cable barrier study sites.**

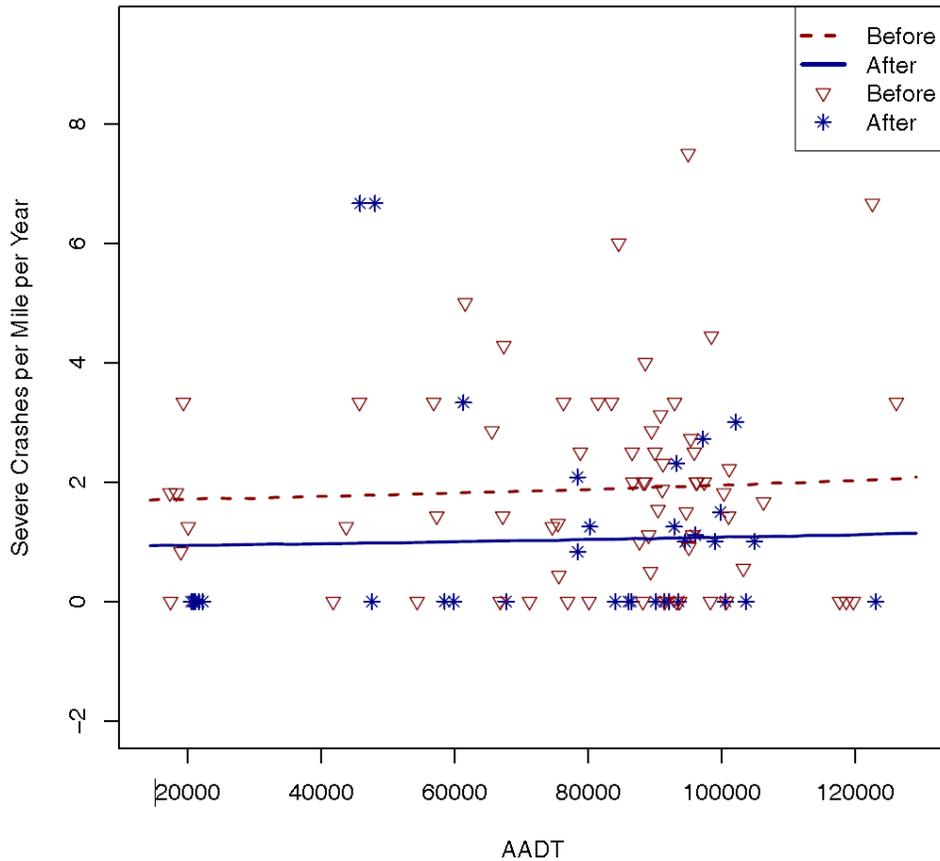
The analysis of overall crashes at sites where cable barrier systems have been installed provides interesting results. As shown in Figure 6-43, the analysis indicates that the overall crash frequency increased by 29.49 percent after the installation of cable barrier. The entire distribution of the differences, shown in Figure 6-44, is greater than zero, indicating a 100 percent probability there was an increase in overall crashes after cable barrier was installed (0 percent probability of decrease). However, since the analysis considers all crashes and not just those impacted by cable barrier, the increase in overall crash frequency is not likely caused by cable barrier systems. It is more likely the result of an increase in traffic volumes or other factors. Several outlier locations with an unusually high crash frequency are also revealed in

Figure 6-43, warranting further analysis on each of those sites to determine improvements that could be made.



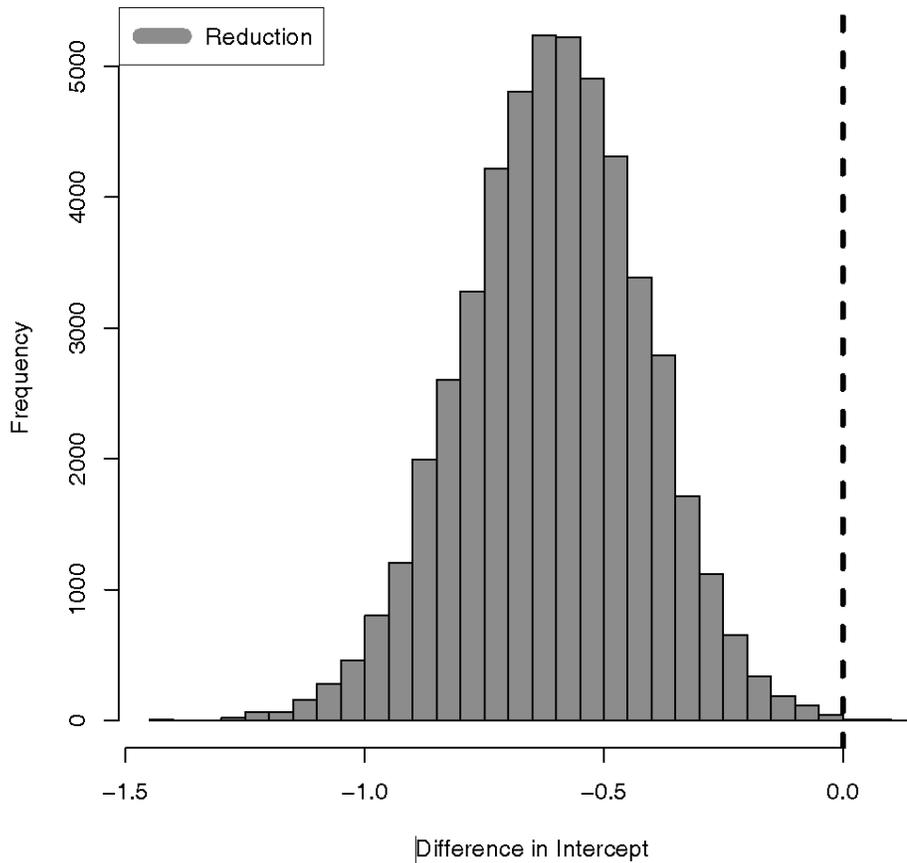
**Figure 6-44. Distribution of differences for overall crashes on all cable barrier study sites.**

Figure 6-45 displays the crash frequency of severe crashes for the before and after periods as a function of AADT. Figure 6-46 shows the corresponding probability distribution of the differences between the before and after periods for severe crashes.



**Figure 6-45. Severe crashes on all cable barrier study sites.**

The results of the analysis indicate that the severe crash frequency decreased by 44.43 percent after the installation of cable barrier systems. The probability that a decrease occurred was 99.97 percent as represented by the grayed portion of Figure 6-46. This high probability of decrease indicates that the frequency of severe crashes decreased after cable barrier were installed. Since all severe crashes were considered, the installation of cable barrier is likely not the sole contributing factor to the decrease. However, cable barrier likely significantly contributed to the reduction in severe crashes. Figure 6-45 also reveals possible outliers for both the before and after analysis periods that experienced an unusually high severe crash frequency. Further analysis should be performed to determine causes for these data points and any improvements that could be made.

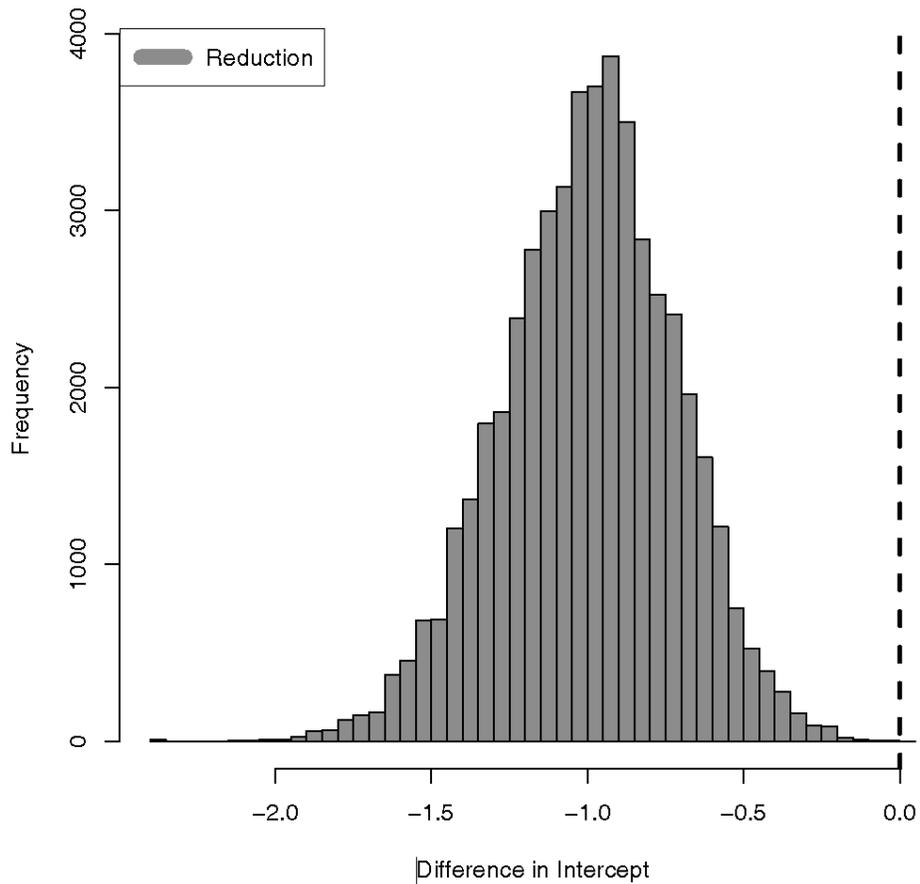


**Figure 6-46. Distribution of differences for severe crashes on all cable barrier study sites.**

Figure 6-47 displays the crash frequency of cross-median crashes for the before and after periods as a function of AADT. The results of the analysis indicate that the cross-median crash frequency decreased by 61.69 percent after the installation of cable barrier systems.

Figure 6-48 shows the corresponding probability distribution of the differences between the before and after periods for cross-median crashes. The entire distribution of differences was less than zero indicating a 100 percent probability a decrease occurred as represented by the grayed portion of Figure 6-48.





**Figure 6-48. Distribution of differences for cross-median crashes on all cable barrier study sites.**

### 6.3 Chapter Summary

A summary of cable barrier analysis results are presented here. An analysis was performed on individual cable barrier locations. A crash data analysis of all locations grouped together was also performed. In each case a decrease or an increase in overall, severe, and cross-median crash frequency and corresponding distribution of differences is presented.

The analysis showed a high probability that the overall crash frequency increased after the installation of a cable barrier system at four of seven study sites. These results were expected since cable barrier systems are designed only to reduce crash severity, not prevent crashes. Table 6-2 provides a summary of the impact of cable barrier systems on overall crash frequency.

**Table 6-2. Summary of Overall Crashes at Cable Barrier Study Sites**

<b>Location</b>	<b>State Route</b>	<b>Year Installed</b>	<b>Probability of Decrease</b>	<b>Percent Change Expected</b>
Provo S-curves to University Parkway	I-15	2004	1.63%	42.56%
Between Pintura and Kolob Canyons	I-15	2005	17.44%	24.29%
Spanish Fork to SR 75	I-15	2005	0.00%	98.50%
South Layton to Syracuse	I-15	2006	0.00%	52.00%
600 N to 2300 N – Salt Lake	I-15	2007	25.37%	5.71%
3100 S to 3800 S – Salt Lake	I-215 E	2007	100.00%	-55.20%
2100 S to 4500 S – Salt Lake	I-215 W	2007	0.00%	60.27%

In contrast, the severe crash analyses of the individual locations where cable barrier systems have been installed show promising results. The analysis showed a significant (greater than 95 percent) probability that the severe crash frequency after the installation of cable barrier systems decreased at four of the seven sites while the remaining sites also experienced a decrease, however the probability of decrease was not as significant. Although the installation of cable barrier may not be the only factor in reducing the crash severity, it certainly contributed. Table 6-3 provides a summary of the impact of cable barrier on severe crashes for each site.

The cross-median crash analysis of the individual locations where cable barrier has been installed also shows promising results. The analysis showed a significant probability that cross-median crash frequency decreased after the installation of a cable barrier system at two of the seven sites and that the remaining sites may also have experienced a decrease. It is anticipated that the reduction in cross-median crashes contributed to the aforementioned reduction in crash severity. Table 6-4 provides a summary of the impact of cable barrier systems on cross-median crashes for each site.

The combined analysis for all study sites grouped together showed a 100 percent probability that overall crashes increased by 29.49 percent. The severe crash analysis results on all sites showed promising results indicating a 99.97 percent probability that severe crashes were reduced by 44.43 percent. The cross-median crash analysis indicated cross-median crashes were reduced by 61.69 percent after a cable barrier system was installed with a 100 percent probability of decrease. These results are summarized in Table 6-5.

**Table 6-3. Summary of Severe Crashes at Cable Barrier Study Sites**

<b>Location</b>	<b>State Route</b>	<b>Year Installed</b>	<b>Probability of Decrease</b>	<b>Percent Change Expected</b>
Provo S-curves to University Parkway	I-15	2004	65.28%	-3.15%
Between Pintura and Kolob Canyons	I-15	2005	99.69%	-80.03%
Spanish Fork to SR 75	I-15	2005	69.73%	-10.07%
South Layton to Syracuse	I-15	2006	94.88%	-43.70%
600 N to 2300 N – Salt Lake	I-15	2007	97.62%	-62.97%
3100 S to 3800 S – Salt Lake	I-215 E	2007	98.68%	-73.65%
2100 S to 4500 S – Salt Lake	I-215 W	2007	92.90%	-53.94%

**Table 6-4. Summary of Cross-median Crashes at Cable Barrier Study Sites**

<b>Location</b>	<b>State Route</b>	<b>Year Installed</b>	<b>Probability of Decrease</b>	<b>Percent Change Expected</b>
Provo S-curves to University Parkway	I-15	2004	75.13%	-19.59%
Between Pintura and Kolob Canyons	I-15	2005	98.79%	-69.31%
Spanish Fork to SR 75	I-15	2005	89.39%	-34.74%
South Layton to Syracuse	I-15	2006	86.24%	-37.70%
600 N to 2300 N – Salt Lake	I-15	2007	90.14%	-51.30%
3100 S to 3800 S – Salt Lake	I-215 E	2007	96.04%	-66.34%
2100 S to 4500 S – Salt Lake	I-215 W	2007	93.08%	-57.87%

**Table 6-5. Results for All Cable Barrier Study Sites**

<b>Type of Analysis</b>	<b>Probability of Decrease</b>	<b>Percent Change Expected</b>
Overall	0.00%	29.49%
Severe	99.97%	-44.43%
Cross-median	100.00%	-61.69%

## **7 CONCLUSIONS**

The purpose of this study was to develop a procedure for data collection and analysis that could be used to determine the effectiveness of roadway safety measures. The preceding chapters have outlined the background of safety analysis methods. An analysis procedure using a hierarchical Bayesian statistical model has been set forth that can analyze the impact of safety improvements. The model is able to estimate the reduction or increase in crash frequency as well as the corresponding probability that a change occurred. The procedure developed in this report was applied to sites where raised medians or cable barrier systems have been installed to determine the effectiveness that each had on overall crash frequency and crash severity. The results of the study show a reduction in the overall frequency and severity of crashes. This chapter summarizes the findings and conclusions of the research and provides suggestions for future research possibilities.

### **7.1 Findings and Conclusions**

The analysis in this report was performed using a hierarchical Bayesian model developed as part of the project. The model is a valuable tool with many potential applications in traffic safety studies. As part of this project, the model was applied to raised median and cable barrier locations throughout the state of Utah. This study analyzed the effectiveness of raised medians and cable barrier systems on roadway safety by determining the effect that each has on crash frequency and severity at selected locations. An analysis was performed on individual locations where these treatments have been applied as well as on combined crash data from all of the study sites grouped together.

The results of the raised median analysis indicate a statistically significant improvement on both crash frequency and crash severity where a raised median has been installed. Results from all sites combined show that the overall crash frequency was reduced by 25.41 percent and

crash severity was reduced by 36.16 percent where raised medians were installed. The reduction in crash severity is anticipated to be a result of a change in the type of collisions occurring. This study provides evidence that installing raised medians is an effective technique to reduce crash frequency, particularly severe crashes caused by sideswipes or head on collisions.

The results of the cable barrier analysis indicated that the installation of cable barrier has a statistically significant impact on crash severity and cross-median crashes. The analysis results indicate that crash severity was reduced by 44.43 percent and that cross-median crashes were reduced by 61.69 percent at locations where cable barrier systems have been installed. However, the analysis showed that cable barrier was not effective in reducing overall crash frequency. Analysis results showed that the overall crash frequency increased by 29.49 percent after cable barrier systems were installed. These results were somewhat expected since cable barrier systems are not designed to prevent crashes but are designed rather to reduce crash severity. It is anticipated that the increase in overall crash frequency is the result of increased traffic volumes or other factors. These results provide evidence that installing cable barrier is an effective safety measure in preventing cross-median crashes and reducing crash severity, but have little influence in overall crash frequency.

In this study, the impact of raised medians and cable barrier systems on overall and severe crash frequency was analyzed using a hierarchical Bayesian statistical model. The usefulness of this model is shown through its application to these two types of road safety measures. However, the model can also be used to determine the impact of other safety measures on various crash frequencies. Furthermore, only AADT and crash data were used as covariates for this study. Additional covariates may be included in the model. Selection of appropriate covariates for the model depends on the scope of the study being performed.

Finally, an important element of transportation safety planning is identifying locations that experience an unusually high crash frequency. The model set forth in this report can be used to identify outlier sites for various types of crashes. The cable barrier and raised median analyses revealed several outlier locations that experienced an unusually high crash frequency in either overall or severe crashes. As such sites are discovered, further research can be conducted to identify additional factors contributing to unusually high crash frequency and methods that can mitigate these factors.

## **7.2 Future Research**

The procedure outlined in this report is a valuable tool that can be used in transportation safety studies. It is recommended that this procedure be applied to future projects to estimate the effectiveness of other safety measures. It is also recommended that future research be performed to expand the model to identify areas of interest where unusually high proportions of particular crash types may occur. The results of such a study would be beneficial to identify and prioritize sites where safety improvements need to be made.

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## APPENDIX A. MODELING CODE

```
# Median Analysis
# Perform the analysis for Overall Crashes
posterior <- myMCMCpoisson(I(crash/nmil) ~ site : I(aadt/maxaad)
+ site:I(ba==0) + site : ba - 1, data=newdata,
burnin=10000,mcmc=50000, b0=0, B0=precision )
# Perform the analysis for Severe Crashes
posteriorfatal <- myMCMCpoisson(I(fatal/nmil) ~ site :
I(aadt/maxaad) + site:I(ba==0) + site : ba - 1 , data=newdata,
burnin=1000,mcmc=50000, b0=0, B0=precision )
posterioroverall <- myMCMCpoisson(I(crash/nmil) ~ I(aadt/maxaad)
+ I(1-ba) + ba - 1 , data=newdata, burnin=10000,mcmc=50000, b0=0,
B0=precision )
posterioroverallfatal <- myMCMCpoisson(I(fatal/nmil) ~
I(aadt/maxaad) + I(1-ba) +ba - 1, data=newdata,
burnin=10000,mcmc=50000, b0=0, B0=precision )
plotposterior(posterior,"",newdata,offset=0,z=1)
plotposterior(posteriorfatal,"Severe",newdata,offset=2,z=16)
plotposterior(posterioroverall,titlename='',newdata,overall=TRUE,
z=1)
plotposterior(posterioroverallfatal,titlename='Severe',newdata,ov
erall=TRUE,z=16)
# Cable Barrier Analysis
# Perform the analysis for Overall Crashes
posterior <- myMCMCpoisson(I(crash/nmil) ~ site : I(aadt/maxaad)
+ site:I(ba==0) + site : ba - 1 , data=newdata,
burnin=10000,mcmc=50000, b0=0, B0=precision )
# Perform the analysis for Severe and Cross Median Crashes
posteriorfatal <- myMCMCpoisson(I(fatal/nmil) ~ site :
I(aadt/maxaad) + site:I(ba==0) + site : ba - 1 , data=newdata,
burnin=10000,mcmc=50000, b0=0, B0=precision )
posteriorheadon<- myMCMCpoisson(I(headon/nmil) ~ site :
I(aadt/maxaad) +site:I(ba==0) + site : ba - 1 , data=newdata,
burnin=10000,mcmc=50000, b0=0, B0=precision )
posterioroverall <- myMCMCpoisson(I(crash/nmil) ~ I(aadt/maxaad)
+ ba - 1 , data=newdata, burnin=10000,mcmc=50000, b0=0,
B0=precision )
posterioroverallfatal <- myMCMCpoisson(I(fatal/nmil) ~
I(aadt/maxaad) + ba - 1, data=newdata, burnin=10000,mcmc=50000,
b0=0, B0=precision )
posterioroverallheadon<- myMCMCpoisson(I(headon/nmil) ~
I(aadt/maxaad) + ba - 1, data=newdata, burnin=10000,mcmc=50000,
b0=0, B0=precision )
plotposterior(posterior,"",newdata,offset=0,z=1)
plotposterior(posteriorfatal,"Severe",newdata,offset=2,z=14)
plotposterior(posteriorheadon,"Cross-
Median",newdata,offset=4,z=13)
```

```
plotposterior(posterioroverall,titlename='',newdata,overall=TRUE,
z=1)
plotposterior(posterioroverallfatal,titlename='Severe',newdata,ov
erall=TRUE,z=14)
plotposterior(posterioroverallheadon,titlename='Cross-
Median',newdata,overall=TRUE,z=13)
```