IDAHO TRANSPORTATION DEPARTMENT

RESEARCH REPORT

RP 191A

Potential Crash Reduction Benefits of Safety Improvement Projects – Part A: Shoulder Rumble Strips

By
Ahmed Abdel-Rahim
Mubassira Khan
University of Idaho

Prepared for
Idaho Transportation Department
Research Program
Division of Highways, Resource Center
http://itd.idaho.gov/highways/research/

June 2012

DISCLAIMER

1. Report No. FHWA-ID-12-191A	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Potential Crash Reduction Benefits of Safety Improvement Projects – Part A: Shoulder Rumble Strips		5. Report Date June 2012 6. Performing Organization Code KLK556
7. Author(s) Ahmed Abdel-Rahim and Mubassira Khan		8. Performing Organization Report
9. Performing Organization Name and Address National Institute for Advanced Transportation Technology (NIATT) P.O. Box 440901 University of Idaho Moscow, Idaho 83844-0901		10. Work Unit No. (TRAIS) 11. Contract or Grant No. RP191A
12. Sponsoring Agency Name and Address Research Program, Resource Center Division of Highways Idaho Transportation Department 3311 West State Street Boise, ID 83707-5881		13. Type of Report and Period Covered Final Report 01/14/09-06/30/12 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

This research provides a comprehensive evaluation of the safety benefits of shoulder rumble strips in rural highways in Idaho. The effectiveness of shoulder rumble strips in reducing the number and severity of run-off-the-road (ROR) crashes was examined based on Idaho's crash experience for 3 different roadway types: 2-lane rural highways, 4-lane rural highways and rural freeways. All ROR, severe ROR crashes, and truck ROR crashes were analyzed as part of this study. The evaluation was done using two different evaluation methods: Comparison Groups (CG) before-and-after analysis and Empirical Bayes (EB) before-and-after analysis. For cases where control section data was limited or not available, naïve before-and-after analysis was used. Based on Idaho's crash data, the installation of shoulder rumble strips on 2-lane rural highways resulted in a 15 percent reduction in all ROR crashes and a 74 percent reduction in severe ROR crashes. The benefits seem higher in roadway segments that have little to moderate roadway curvature. For rural freeways, the percent reduction in all ROR crashes and severe ROR crashes was 29 percent and 67 percent, respectively. The big difference between the two numbers is because there seems to be a higher percentage of minor (less severe) crashes on the freeway segments tested. The percent reduction in all ROR crashes and severe ROR crashes when shoulder rumple strips were installed in 4-lane rural highways were 60 percent and 45 percent, respectively, which is statistically significant. Truck crashes in all rural highways also decreased after shoulder rumble strips installation by a range of 42 to 62 percent.

17. Key Word: Highway Safety Improvement Program, Crash Reduction Factor, Rumble Strips	18. Distribution Statement Unrestricted. This document is available to the public at http://itd.idaho.gov/highways/research/archived/closed.htm and http://www.webs1.uidaho.ed/niatt		
19. Security Classif. (of this report) Unrestricted	20. Security Classif. (of this page) Unrestricted	21. No. of Pages 90	22. Price

METRIC (SI*) CONVERSION FACTORS									
APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH					LENGTH		
in	inches	25.4		mm	mm	millimeters	0.039	inches	in
ft	feet	0.3048		m	m	meters	3.28	feet	ft
yd	yards	0.914		m	m	meters	1.09	yards	yd
mi	Miles (statute)	1.61		km	km	kilometers	0.621	Miles (statute)	mi
		AREA					AREA		
in^2	square inches	645.2	millimeters squared	cm^2	mm^2	millimeters squared	0.0016	square inches	in^2
ft^2	square feet	0.0929	meters squared	m^2	m^2	meters squared	10.764	square feet	ft^2
yd^2	square yards	0.836	meters squared	m^2	km^2	kilometers squared	0.39	square miles	mi^2
mi^2	square miles	2.59	kilometers squared	km^2	ha	hectares (10,000 m^2)	2.471	acres	ac
ac	acres	0.4046	hectares	ha					
		MASS (weight)					MASS (weight)		
oz	Ounces (avdp)	28.35	grams	g	g	grams	0.0353	Ounces (avdp)	oz
lb	Pounds (avdp)	0.454	kilograms	kg	kg	kilograms	2.205	Pounds (avdp)	lb
T	Short tons (2000 lb)	0.907	megagrams	mg	mg	megagrams (1000 kg)	1.103	short tons	T
		VOLUME					VOLUME		
fl oz	fluid ounces (US)	29.57	milliliters	mL	mL	milliliters	0.034	fluid ounces (US)	fl oz
gal	Gallons (liq)	3.785	liters	liters	liters	liters	0.264	Gallons (liq)	gal
ft^3	cubic feet	0.0283	meters cubed	m^3	m^3	meters cubed	35.315	cubic feet	ft^3
yd^3	cubic yards	0.765	meters cubed	m^3	m^3	meters cubed	1.308	cubic yards	yd^3
Note: Volumes greater than 1000 L shall be shown in m^3									
		TEMPERATURE (exact)					TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (°F-32)	Celsius temperature	°C	°C	Celsius temperature	9/5 °C+32	Fahrenheit temperature	°F
		ILLUMINATION					ILLUMINATION		
fc	Foot-candles	10.76	lux	lx	lx	lux	0.0929	foot-candles	fc
fl	foot-lamberts	3.426	candela/m^2	cd/cm^2	cd/cm^2	candela/m^2	0.2919	foot-lamberts	fl
		FORCE and PRESSURE or STRESS					FORCE and PRESSURE or STRESS		
lbf	pound-force	4.45	newtons	N	N	newtons	0.225	pound-force	lbf
psi	pound-force per square inch	6.89	kilopascals	kPa	kPa	kilopascals	0.145	pound-force per square inch	psi

Acknowledgements

The authors would like to acknowledge the Idaho Transportation Department's Office of Highway Safety staff for their continuing support and guidance throughout this study and for providing the data used in the analysis.

Table of Contents

List of Tables

List of Figures

Notations and Symbols Used

E{ } = Expected value of the variable inside {}.

VAR{ } = Variance of the variable inside {}.

K = Count of target crashes during the “before period” on the treatment group sites.

L = Count of target crashes during the “after period” on the treatment group sites.

M = Count of target crashes during the “before period” on the control group sites.

N = Count of target crashes during the “before period” on the control group sites.

V = Annual Average Daily Volume of Traffic.

d = Length of road segment in miles.

b = Parameter of the Gamma probability density function.

r_c = Ratio of the expected number of crashes for the comparison group sites.

r_d = Ratio of duration.

r_j = Road curvature type parameter of safety performance function.

r_T = Ratio of the expected number of crashes for the treatment group sites.

psw_k = Paved right shoulder width parameter of safety performance function.

α_y = Yearly factor parameter of safety performance function.

β = Traffic flow parameter for safety performance function.

δ = Reduction in expected frequency of target crashes.

θ = Index of Effectiveness.

κ = Estimate of the expected number of before crash counts for treatment group sites.

λ = Estimate of the expected number of after crash counts for treatment group sites.

μ = Estimate of the expected number of before crash counts for comparison group sites.

ν = Estimate of the expected number of after crash counts for comparison group sites

π = Expected number of Crashes in “after period” for the Treatment Site if there had not been any Treatment.

ω = Parameter weight of Empirical Bayes Estimate.

Executive Summary

Idaho Transportation Department (ITD) uses shoulder rumble strips as a cost effective safety improvement to all roadways. A rumble strip is a longitudinal roadway design feature installed on a paved shoulder near the roadway. ITD started installing shoulder rumble strips in two-lane rural highways on 2000. Since then shoulder rumble strips have been installed in approximately 580 miles of two-lane rural highways. ITD requested the study to assess the safety benefits and provide information to determine the need for additional shoulder rumble strips.

This study examined the effectiveness of shoulder rumble strips in reducing the number and severity of Idaho's run-off-the-road (ROR) crashes for three different roadway types: two-lane rural highways, four-lane rural highways and rural freeways. Treatment sites were selected from 5, two-lane rural highways in Idaho: SH-3, SH-21, US-12, US-30 and US-95. From 2004 through 2007, shoulder rumble strips were installed along 260.15-miles of two-lane rural highway segments in Idaho. This included studying all ROR crashes, severe ROR crashes, and truck ROR crashes. The severe crash category included fatal crashes and severe-injury crashes. The evaluation utilized two different evaluation methods: Comparison Groups (CG) before-and-after analysis and Empirical Bayes (EB) before-and-after analysis. For cases where the control section data was limited or not available, Naïve before-and-after analysis was used.

Overall Impact of Shoulder Rumble Strips for Two-Lane Rural Highways

- For two-lane rural highways, using CG analysis, the average safety effect of shoulder rumble strips resulted in an estimated reduction of ROR crashes of 23 percent. This estimate was statistically significant at the 0.05 level (95 percent confidence level). EB analysis estimated an average of 15 percent reduction in ROR crashes as a result of shoulder rumble strips treatment. Using EB estimates, the results were statistically significant at the 0.05 level.

Impact of Shoulder Rumble Strips on Severe Crashes

- For two-lane rural highways, shoulder rumble strips reduced severe (fatal and severe injury) ROR crashes by 74 percent, with a standard deviation estimate of 15 percent. The estimated reduction in ROR truck crashes was 56 percent. However, this reduction in ROR truck crashes was not statistically significant because of its high standard deviation due to the small number of truck crashes (sample size) on the treatment and control sections. Even though this is not statistically significant, it is still worth mentioning. Most studies with a small number of crashes yield results that are not statistically significant. Yet there is still a value in reporting them.

Impact of Shoulder Rumble Strips by Road Curvature Type

- The effect of road geometry, defined here as degree of roadway curvature, on the effectiveness of shoulder rumble strips was considered in the analysis. Three different road curvature types were considered in the analysis:

- Road Curvature Type 1 (relatively straight roadway segments).
- Road Curvature Type 2 (horizontal curves with a design speed of 50 mph or more).
- Road Curvature Type 3 (sharp horizontal curves with a design speed of 45 mph or lower).

- Shoulder rumble strips reduced all ROR crashes under the 3 road curvature types. Type 1 was reduced by 22 percent, Type 2 by 29 percent, and Type 3 by 8 percent. This evidence indicates shoulder rumble strips were less effective in reducing ROR crashes in Type 3 road curvatures.

Impact of Shoulder Rumble Strips by Traffic Volume Level

- This study examined the percent reduction in ROR crashes under different Average Annual Daily Traffic (AADT) levels. Shoulder rumble strips were more effective in reducing ROR crashes in low-volume road sections (AADT less than 1,000) than in moderate- and/or high-volume road sections. Low-volume road sections showed an estimated 33 percent reduction in ROR crashes after the installation of shoulder rumble strips. Road sections with AADT values of around 2,500 showed a marginal reduction in ROR crashes (3 percent) as a result of shoulder rumble strips installation. Road sections with AADT values that ranged from 3,500 to approximately 4,000 showed a 16 percent reduction in ROR crashes with the installation of shoulder rumble strips. Road sections with relatively high volumes (AADT values around 6,700) experienced a 24 percent reduction in ROR crashes after the installation of shoulder rumble strips. Although the estimates were not statistically significant at the 0.05-level, the results provide an idea about the potential benefits of shoulder rumble strips for different road traffic volume.

Impact of Shoulder Rumble Strips on Four-Lane Rural Highways

- The research showed that the safety effect of shoulder rumble strips installed on four-lane rural highways reduced ROR crashes by an average of 60 percent with a standard deviation of 10 percent. The estimated results were statistically significant at the 0.05 level. Using the naïve before-and-after comparison, the average reduction in severe ROR crashes and truck ROR crashes resulting from the installation of rumble strips on four-lane rural highways was 45 percent and 62 percent, respectively, with a standard deviation of 21 percent and 23 percent. The results of the Naïve study were statistically significant at the 0.05-level; however, they may be subject to regression-to-the-mean bias that can make natural variation in repeated data look like real change.

Impact of Shoulder Rumble Strips on Rural Freeways

- For rural freeways, the EB method estimated that the installation of shoulder rumble strips resulted in a reduction of 29 percent and 67 percent for all ROR crashes and severe ROR crashes, respectively. The corresponding standard deviation was estimated respectively at 9 percent and 14 percent. These estimates were significant at the 0.05 level. The reduction in truck ROR crashes as a result of shoulder rumble strip installation in rural freeway was estimated at 42 percent. Due to the limited number of truck crashes on the test and control sections, this estimate was not statistically significant at the 0.05 confidence level. It is however beneficial to report the information.

Recommendations

When conducting a cost/benefit analysis for shoulder rumble strips installation projects on rural Idaho highways, the crash reduction factors determined through this research, (see Table 1) should be used. The sensitivity of these reduction factors to the geometric characteristics of the roadway segments should be factored in the analysis using the results documented in this report.

Table 1. Crash Reduction Factors for Rural Highways in Idaho

Roadway Type	Crash Type	Crash Reduction Factor	
		Average	Standard Deviation
Two-Lane Highways	All ROR Crashes	15%	10%
	Most Severe ROR Crashes	74%	15%
Four-Lane Highways	All ROR Crashes	60%	10%
	Most Severe ROR Crashes	45%	21%
	Truck ROR Crashes	62%	23%
Rural Freeways	All ROR Crashes	29%	9%
	Most Severe ROR Crashes	67%	14%

Chapter 1
Introduction

Overview

The Idaho Transportation Department (ITD) and the U.S. Department of Transportation (USDOT) have identified priorities in the area of safety as expressed in ITD's *Strategic Highway Safety Plan* and in USDOT's *Department of Transportation Strategic Plan 2003-2008.*[1,2] As stated in its strategic plan, USDOT aims to "work . . . with stakeholders to build safety into the transportation infrastructure and into operational procedures through research, planning, design, engineering, incentives, and incorporation of safety-enhancing technologies" as well as to "increase the implementation of infrastructure and operational improvements focused on enhancing the ability of drivers to remain on the roadway, reducing the adverse consequences of roadway departure, improving intersection safety and protecting pedestrians in the roadway environment."[2]

ITD's safety improvement program allocates funds in order to maximize the benefits of safety improvement projects that target specific high-crash locations and highway sections. Currently, no system tracks safety investments and documents their results to ensure the most cost-effective use of limited ITD resources. Since SAFETEA-LU calls for a data-driven decision process, there is a need for systematic research to aid ITD in assessing safety investments using a performance-measure-based system.[3] This report is Part A of a two-part study of the effect of safety improvement projects on highway safety. Part A provides a comprehensive evaluation of the effectiveness of shoulder rumble strips in reducing run-off-the-road (ROR) crashes in Idaho's rural highways. Part B will evaluate centerline rumble strips, durable pavement markings, advances warning signs at high-speed intersections, and provide information about the characteristics of vehicle-animal crashes, railroad crashes, and crashes involving older drivers.

The results of Part A's safety evaluation allows ITD to determine the potential safety benefit of shoulder rumble strips in reducing the number and severity of ROR crashes on Idaho's rural highways. The data provided by this research enable ITD to make informed safety improvement decisions by revealing the characteristics of crashes and assessing the safety impacts and cost-effectiveness of shoulder rumble strip installation projects.

Research Objectives

This research had the following objectives:

1. Evaluate the effectiveness of shoulder rumble strips in reducing the number and severity of ROR crashes on rural highways in Idaho.
2. Investigate the effect of the roadway's degree of curvature on the crash reduction benefits of shoulder rumble strips in two-lane rural highways.

Primarily, two statistical methods were employed in this study: CG before-and-after analysis and EB before-and-after analysis. For cases where control section data was limited or not available, Naïve before-and-after analysis was used.

Report Organization

This report is organized in four chapters. After the introduction, Chapter 2 documents the research methodology and statistical analysis used. Chapter 3 summarizes the results of the rumble strips effectiveness and crash reduction analysis. Chapter 4 includes the conclusions and recommendations followed by a list of references used in the analysis. A list of references used in this report is provided.

Chapter 2
Research Methodology

Overview

This chapter focuses on the research methodology and data analysis. The chapter provides information regarding the sources of data used in the analysis, data analysis procedures, as well as the statistical methods used in the analysis. Primarily two statistical methods were employed in this study: CG before-and-after analysis and EB before-and-after analysis. For cases where control section data was limited or not available, naïve before-and-after analysis was used.

Crash Reduction Factors

A crash reduction factor (CRF) can be defined as the percent change attributable to the implementation of a specific crash countermeasure or a combination of countermeasures. The crash modification factor (CMF), however, is the factor applied to crash counts to estimate the expected number of crashes after the implementation of crash countermeasures.[4] A CMF can be expressed as:

$$CMF = 1 - CRF$$

Figure 1. Crash Modification Factor Equation

Several factors can influence the value of CRFs that result from the countermeasure evaluation process. Some of these factors are:

- The selection criteria for before and after periods affect the number of observations included in the analysis. This may change the outcome of the evaluation process.

- It can sometimes be difficult to isolate the safety effect of one particular countermeasure because other countermeasures may also be implemented to improve safety. A typical example would be the installation of shoulder or centerline rumble strips as part of road and shoulder widening projects.

  The effect of other changes in the road environment (such as enforcement or education campaigns) may also change driver behavior and influence the measured difference.

- The effect of countermeasures may not be uniform across different crash types and may lead to an increase in the occurrence of certain crash types. This makes it complex to draw conclusions about the effectiveness of the countermeasures that would adequately reflect the average expected effect of a particular countermeasure without conducting in-depth analysis of different crash types.

The National Cooperative Highway Research Program's (NCHRP) *Research Results Digest 299* presented some of the issues related to the development of CRFs and CMFs in safety studies.[4] The authors pointed out that collision migration may occur because of a particular measure; however this is rarely considered in the development and provisions of CRFs. They noted that the quality of the available data used for the development of CRFs/CMFs varied. CRF/CMF values may be affected by publication bias (publishing only when results indicated that a particular measure is beneficial) and selective reporting of results (reporting only the positive effects of a particular measure without referencing adverse effects).

The effect of a countermeasure may vary within the same district. In many cases, results from countermeasure evaluations may appear to be significantly different due to changes in crash environment from location to location. The generalization of CRFs and the transferability of the results across regions and states are influenced by differences such as the difference in the crash reporting threshold. Bonneson and Lord reported that lower crash reporting thresholds would result in higher reported collision frequencies and higher likelihood of larger observed CRFs.[5]

The calculation of CRFs involves the use of safety prediction models that require significant data resources to obtain the desired predictive capability. Small sample sizes (i.e. low observed collision frequencies) can limit the ability to determine statistically significant results. The EB methodology is generally regarded as a more appropriate statistical methodology compared to traditional simple before-and-after analysis when one considers correction for the regression-to-the-mean effect. EB methodology requires a minimum level of observed collisions to measure statistically significant differences and therefore may limit the ability of the scientist to measure the effect on particular collision types or more severe collision categories. For this reason, alternative before-and-after methodologies are still used. Note that the absence of a statistically significant CRF does not imply that a particular measure would not improve safety.[6]

Sources of Data Used in the Study

A Vehicle Collision Report (VCR) is filled out for every crash that involves a motor vehicle, occurs on public property, and results in more than $1,500 of property damage for any one vehicle involved in the crash or results in an injury to any person involved. Prior to January 1, 2006 the damage amount was set at $750. All law enforcement agencies in Idaho are required to send VCR forms to ITD's Office of Highway Safety (OHS), which maintains and archives the data. Crash data for this project was obtained from WebCARS, a web-based crash analysis reporting system developed and maintained by OHS.[7] The Office of Highway Safety (OHS) provided all the data regarding the installation year and location of shoulder rumble strips. Shoulder width and lane width data were also provided by OHS. Vehicle exposure data, in the form of Average Annual Daily Traffic (AADT), was obtained from ITD Automatic Traffic Recorders (ATR) data published by ITD's Roadway Data Section.[8]

Road curvature data were obtained from two sources: Google Earth's satellite images and speed advisory signs from ITD's sign inventory database. Three different degrees of road curvature were used in the analysis:

1. Road Curvature Type 1 - No or slight curvature.
2. Road Curvature Type 2 - Moderate curvature.
3. Road Curvature Type 3 - Sharp curvature.

Rural highways included in the analysis were divided into segments with lengths ranging from 3 to 5 miles. Each highway segment was consistent in:

- Geometry (degree of curvature, lane number, and lane and shoulder width).
- Terrain (rural, suburban, urban).
- Traffic flow levels.

Data Analysis and Statistical Methods Used

The underlying concept of a before-and-after analysis is to compare the actual number of crashes which occurred in the "after period" at the treatment sites with the expected number of crashes that would have occurred during the "after period" had the treatment not been installed. Different methods are used to estimate the expected number of crashes during the "after period." Three statistical methods were employed in the analysis conducted in this study: 1) CG method, 2) EB method and 3) Naïve before-and-after analysis.

In Naïve before-and-after analysis, the crash counts for a location before and after a treatment are compared to assess the safety benefit attributed to a treatment. The crash data for the treatment sites are assumed to follow the Poisson distribution.

The CG Method uses an untreated comparison site, or group of sites, that has similar road geographic and traffic volume characteristics as the treatment site. In the CG Method comparison site(s) crash data are used to estimate crashes that would have occurred at the treatment sites, during the after period if treatments were not in place. The CG Method is based on two assumptions: first, the causal factors change similarly from "before period" to "after period" for both the treatment sites and comparison group sites. Second, the changes in the causal factor affect safety of treatment site and comparison sites in a similar way.

The EB Method can overcome the limitation of the Naïve and CG Methods by accounting for the regression-to-the-mean effect, a statistical phenomenon that can make natural variation in repeated data look like real change. It happens when unusually large or small measurements tend to be followed by measurements that are closer to the mean. The EB method also accounts for traffic volume changes and factors that change with time that affect crash occurrence. Such factors can be weather, crash reporting practices, and driving habits. The EB Method for estimating safety increases the precision of estimation and corrects for the regression-to-the-mean bias. This method is based on the recognition that crash counts are not the only measure of safety for an entity. To estimate the expected number of crashes in the treatment site without treatment (π), two trends are considered with the EB Method: the crash trend at the treatment site prior to the treatment installation and the safety performance or crash trends at similar sites, referred to as control sites that did not have any treatment during the analysis period. A full description of these methods is presented in Appendix A. A literature review that covers the use of the EB method in safety analysis is provided in the following section.

Use of Empirical Bayes Method in Safety Analysis

A literature review was performed to identify the available resources related to the use of the EB Method in road safety analysis. A number of publications clearly indicate that EB methodology is one of the most widely used and reliable methods for before-and-after road safety evaluation.

The before-and-after study method investigates a treatment site to estimate the change in safety within a certain period of analysis. To estimate the change in safety that is attributed to a treatment, it is necessary to estimate the safety at treatment sites in the “after-period” as if no treatments have been made. This is then compared to what actually happened after the treatment was installed.

Literature suggests there are shortcomings associated with the naïve and CG methods for before-and-after analysis. In the Naïve method, the crash counts for a location before and after a treatment are compared in order to assess the safety benefit attributed to a treatment. The assumption for this simple before-and-after analysis is that the passage of time from the before and after periods is not associated with the changes that affect the safety of the entity.[9] Unfortunately, this simple before-and-after comparison often leads to two misleading conclusions:

1. Regression-to-the-mean bias.
2. External factors.[10]

Regression-to-the-mean bias results when a nonrandom sample is selected from a population. This is the most cited problem in literature of the before-and-after study, as it results in an overestimation of the safety benefit of a crash countermeasure. A location may be selected for treatment because it has too many crashes. In simple before-and-after studies, the expected crash frequency of an entity in the “after period” without treatments is estimated as the same crash frequency in the “before period.” However, the expected crash frequency without a crash countermeasure cannot be estimated from an unusual scenario. It may happen that the crash frequency in the “after period” shows a reduction in crash frequency not only because of the treatment, but because crashes at the treatment site tend to regress or return to the long-term mean number of crashes.

At the same time, crash counts before and after a treatment are not the only factors that contribute to the story of the safety of an entity. There are changes over time that can affect the safety characteristics of a site, such as changes in traffic volume, driver behavior, and weather. Therefore, safety estimated using simple before-and-after methodology cannot distinguish between what is caused by the treatment and what is caused by other changes.[9]

To take into account different causal factors that change with time, a CG study is developed.[10] A comparison group is a selected site(s) that has similar traffic volume and geographic characteristics to the treatment site but no treatments installed during the analysis period. The CG Method is based on two assumptions stated by Hauer:

1. The causal factors change similarly from the “before period” to the “after period” for both the treatment sites and comparison group sites.
2. The changes in causal factors affect safety of the treatment site and comparison site(s) in similar ways.[9]

The expected crash frequency of the treatment site in the “after period” without the treatment is estimated using the crash data of the comparison group in the “after period.” Safety estimation using this method depends on the selection of the comparison group. Although this method considers different causal factors that change with time, it has limitations in overcoming the regression-to-the-mean bias.

The EB before-and-after study method increases the precision of estimation and corrects for the regression-to-the-mean bias.[9] This method estimates the number of crashes in the “after period” if there had not been any treatment at the site using two measures: crash history of the treatment site and safety performance of the control or comparison site. Then the actual number of crashes of the treatment site in the “after period” is compared with the expected number of crashes without the treatment.

The theory of EB Method is well developed by Hauer and Hauer, et al.[9, 10] This method is currently used in road safety analysis to a greater extent for evaluating the effectiveness of different crash countermeasures. According to *NCHRP Report 641*, “The EB method is now the most widely used method to evaluate the safety effectiveness of a countermeasure given a set of matched before and after sites and a set of reference sites.”[11] Interactive Highway Safety Design Model (IHSDM) also applied this method for road safety estimation.[12]

Syed et al. used the EB Method to discover the impact of rumble strips on highways in British Columbia, Canada.[13] Patel et al. used the EB before-and-after study method to evaluate the safety benefit of shoulder rumble strips on two-lane rural highways in Minnesota.[14] Persaud et al. employed this study method to estimate the crash reduction benefit for centerline rumble strips on two-lane rural highways.[15] To evaluate the safety benefit of transverse rumble strips on stop controlled intersection approaches, Srinivasan et al. applied EB methodology.[16] Srinivasan et al. also used this analysis methodology to evaluate the safety of improved curve delineation with signing enhancements.[17] Feldman et al. had used this method to evaluate the safety effect of high-visibility school (yellow) crosswalks in San Francisco.[18]

Chapter 3
Safety Performance of Shoulder Rumble Strips

Overview

This chapter presents the results of the safety evaluation of the effect of shoulder rumble strips in reducing ROR crashes. The chapter summarizes previous studies that examined the safety performance of shoulder rumble strips. The results of the Naïve before-and-after analysis, CG analysis, and EB before-and-after analysis are presented for three different road categories: two-lane rural highways, four-lane rural highways, and rural freeways.

Literature Review

Significant past efforts have been directed towards ROR crashes related to road safety problems. However, the target collision type, methodology, and the range of obtained results are dissimilar in different studies. This section provides a review of available resources related to the use of shoulder rumble strips to reduce the number and severity of single-vehicle ROR crashes while preserving safe use of the roadway by other road users.

Safety Effect of Rumble Strips

NCHRP Report 641: Guidance for the Design and Application of Shoulder and Centerline Rumble Strips summarizes the 2005 crash statistics for the United States from Fatality Analysis Reporting System (FARS) and General Estimates System (GES).[(11)] The statistics show that 40.3 percent of fatal crashes, 21 percent of total injury crashes and 16.5 percent of property damage only crashes are single-vehicle crashes that occurred off the roadway, on the shoulder, or within the median. Although 18 percent of the total crashes are single-vehicle crashes, these crashes are of high severity in nature. *NCHRP Report 641* also shows that single-vehicle collisions with fixed objects resulted in 31.7 percent of the fatal crashes in the United States.

Inattentive driving is a significant factor identified for many of these ROR crashes. Driver inattention comes in many forms, including distraction, daydreaming, competing thoughts, fatigue, drowsiness, and impaired driving.[(17)] As a safety measure, rumble strips can alert drivers when they are drifting off the roadway and address the class of crashes related to driver inattention. The Federal Highway Administration (FHWA) suggests that shoulder rumble strips are very effective in warning drivers that they are about to drive off of the road.[(19)]

In 1999, Griffith conducted a study on California and Illinois freeways to evaluate the safety benefit of continuous shoulder rumble strips.[(20)] This researcher used the CG before-and-after study method for the evaluation. The results for the Illinois dataset indicated an 18.3 percent reduction of single-vehicle ROR crashes on all freeways and a 21.1 percent reduction on rural freeways. The results for the California dataset indicated a 7.3 percent reduction of ROR crashes, but this dataset was not statistically significant because of high standard deviation.

Marvin and Clark in 2003, evaluated the effectiveness of shoulder rumble strips in reducing the number and severity of ROR crashes on interstate and primary highways in the State of Montana.[21] Crash data was collected throughout Montana for 3 years before and after rumble strip implementation on 393 miles of National Highway Interstate System and 213 miles of National Highway Non-Interstate System and State Primary Routes. Descriptive and comparative statistical analyses showed a 14 percent reduction for ROR crashes on the interstates and 23.5 percent reduction in collision severity. A benefit/cost (B/C) analysis, based on the reduction of off-road crashes, was conducted for Interstates and found as high as 19.5 percent. However, this study used a simple before-and-after study to find the safety effectiveness; as such the results of this study may be subject to regression-to-the-mean bias. A study conducted by Smith and Ivan in 2005 also used the CG before-and-after study to find the effectiveness of shoulder rumble strips to reduce single-vehicle and fixed object crashes in Connecticut.[22] Only freeways crash data were analyzed for the target crash type. The study concluded that rumble strips reduced target crashes by 33 percent.

In 2006, Garder and Davies studied the effectiveness of continuous shoulder rumble strips in preventing ROR crashes on rural interstates in Maine.[23] The CG before-and-after analysis method was used to evaluate the safety benefit of continuous shoulder rumble strips. The results of this study on Maine's rural interstates indicated a reduction of approximately 58 percent with sleep related ROR crashes and 43 percent for dry road ROR crashes after the installation of continuous shoulder rumble strips. The overall effectiveness of continuous shoulder rumble strips installations was estimated to be a 27 percent reduction with respect to all ROR crashes.

A 2007 study by Patel, et al. performed a before-and-after analysis on crash data of two-lane rural highways in Minnesota.[14] The EB before-and-after method was used in this study. The results of this analysis revealed that after the installation of continuous shoulder rumble strips there was a 13 percent reduction in all ROR crashes and 18 percent reduction in injury-related ROR crashes.

In 2010, Sayed, et al. conducted a study using a British Columbia dataset to ascertain the impact of shoulder rumble strips on two-lane undivided highways and rural freeways.[13] The author used the EB method for the study. The results indicated a 22.5 percent reduction of ROR crashes after the installation of shoulder rumble strips.

Literature Review Summary

Several states conducted studies to evaluate the safety benefit of shoulder rumble strips and found that it is an effective crash countermeasure to reduce single-vehicle ROR crashes. For freeway facilities many different studies are available, but for two-lane rural highways, the availability of published research is very limited. The effectiveness of shoulder rumble strips for different road geometries can vary considerably and needs to be addressed. The road geometry can lead to inattention. For example, a straight segment of road increases the probability of falling asleep while driving. A discussion on the effectiveness of shoulder rumble strips specifically on curvy roads was not found in the literature.

Description of Treatment Sites

Two-Lane Rural Highways

Treatment sites were selected from 5, two-lane rural highways in Idaho: SH-3, SH-21, US-12, US-30 and US-95. From 2004 through 2007, shoulder rumble strips were installed along 260.15-miles of two-lane rural highway segments in Idaho. Among these sections, 66.52-segment miles were not considered in the analysis for 2 primary reasons. First, some of these segments were very close to the city limits and thus have significantly different operational limits. Second, some segments underwent major geometric changes, such as changing from two-lane to four-lane segments or widening of the paved right shoulder during the analysis period. Treatment sites on 41, two-lane rural highway segments were used to evaluate the safety effectiveness of shoulder rumble strips. These sites include 193.63-miles where rumble strips were installed between 2004 and 2007. Lane width for all the test sites was a standard 12 feet. Table 2 and Table 3 summarize the crash and geometric characteristics of the test sites. The tables list all ROR crashes as well as the severe ROR crashes. Truck crashes are shown in parenthesis.

Road curvature data is described for these segments in Table 2 and Table 3. Sections were divided into 3 broad categories: road curvature Types 1, 2 and 3. Test sites were broken into the following categories:

- Road Curvature Type 1 (straight segments)
  - 4 test sites (24.6 miles)
- Road Curvature Type 2 (horizontal curves with large radius curves)
  - 14 test sites (61.37 miles)
- Road Curvature Type 3 (sharp horizontal curves with reduction in speed)
  - 23 test sites (110.66 miles)

Table 2. Treatment Sites Details for All ROR Crashes on Two-Lane Highways

Segment Number	Length (mile)	Installation year	Number of Years		Crash Counts Passenger Car(Truck)		AADT		Road Curvature Type
			Before	After	Before	After	Before	After	
1	4.03	2006	5	3	7(0)	1(0)	5875	5470	2
2	5.00	2004	3	5	12(0)	30(1)	3497	3254	3
3	5.00	2004	3	5	8(0)	10(1)	3497	3254	3
4	5.00	2004	3	5	12(3)	8(0)	3497	3254	3
5	5.00	2004	3	5	6(1)	5(0)	3242	3024	2
6	5.00	2004	3	5	9(1)	8(1)	2124	1981	3
7	5.00	2004	3	5	3(0)	7(1)	2124	1981	2
8	3.64	2004	3	5	8(0)	8(1)	2124	1981	3
9	5.00	2004	3	5	9(2)	8(1)	3149	3081	3
10	5.00	2004	3	5	9(2)	3(1)	1005	843	3
11	5.00	2007	6	2	5(0)	0(0)	638	559	2
12	5.00	2007	6	2	4(1)	1(0)	638	559	3
13	5.00	2007	6	2	26(7)	8(0)	638	559	3
14	5.00	2007	6	2	6(1)	2(0)	638	559	3
15	5.00	2007	6	2	9(9)	2(1)	638	559	3
16	5.00	2007	6	2	4(2)	0(0)	638	559	3
17	5.00	2007	6	2	8(0)	0(0)	638	559	3
18	5.00	2007	6	2	8(6)	1(0)	638	559	3
19	5.00	2007	6	2	6(4)	0(0)	677	545	3
20	5.00	2007	6	2	5(4)	2(1)	677	545	3
21	5.00	2007	6	2	5(2)	0(0)	677	545	2
22	5.00	2007	6	2	4(1)	2(0)	677	545	2
23	2.45	2007	6	2	2(0)	1(0)	677	545	3
24	6.60	2007	6	2	3(0)	1(0)	3731	3894	1
25	5.00	2007	6	2	3(2)	0(0)	2778	2541	1
26	5.00	2007	6	2	2(0)	1(0)	2778	2541	1
27	2.99	2007	6	2	0(0)	0(1)	2778	2541	2
28	2.63	2007	6	2	3(1)	0(0)	2778	2541	2
29	4.22	2007	6	2	0(0)	1(0)	2224	1949	2
30	4.57	2007	6	2	3(1)	0(0)	1946	1888	3
31	5.00	2007	6	2	7(0)	1(0)	2918	2859	3
32	5.00	2005	4	4	5(0)	0(0)	2902	2910	3
33	5.00	2005	4	4	3(0)	4(0)	2842	2837	3
34	5.00	2005	4	4	10(0)	6(0)	2842	2837	3
35	5.00	2007	6	2	12(0)	4(1)	7135	7228	2
36	5.00	2007	6	2	10(0)	4(0)	7135	7228	2
37	5.00	2007	6	2	10(1)	3(0)	7135	7228	1
38	5.00	2007	6	2	9(1)	0(0)	7135	7228	2
39	5.00	2007	6	2	3(0)	0(1)	974	1020	2
40	5.00	2007	6	2	0(2)	0(0)	974	1020	3
41	2.51	2007	6	2	1(1)	0(0)	974	1020	2

Table 3. Treatment Sites Details for Severe ROR Crashes on Two-Lane Highways

Segment Number	Length (mile)	Installation Year	Number of Years		Crash Counts		AADT		Road Curvature Type
			Before	After	Passenger Car(Truck)		Before	After	
					Before	After			
1	4.03	2006	5	3	0 (0)	0 (0)	5875	5470	2
2	5.00	2004	3	5	1 (0)	3 (0)	3497	3254	3
3	5.00	2004	3	5	0 (0)	1(0)	3497	3254	3
4	5.00	2004	3	5	3 (0)	0 (0)	3497	3254	3
5	5.00	2004	3	5	0 (0)	0 (0)	3242	3024	2
6	5.00	2004	3	5	0 (0)	3 (0)	2124	1981	3
7	5.00	2004	3	5	1 (0)	1 (0)	2124	1981	2
8	3.64	2004	3	5	1 (0)	0 (0)	2124	1981	3
9	5.00	2004	3	5	4 (0)	1 (0)	3149	3081	3
10	5.00	2004	3	5	1 (0)	0 (0)	1005	843	3
11	5.00	2007	6	2	0 (0)	0 (0)	638	559	2
12	5.00	2007	6	2	1 (0)	0 (0)	638	559	3
13	5.00	2007	6	2	4 (1)	1 (0)	638	559	3
14	5.00	2007	6	2	0 (0)	0 (0)	638	559	3
15	5.00	2007	6	2	0 (0)	1 (0)	638	559	3
16	5.00	2007	6	2	0 (0)	0 (0)	638	559	3
17	5.00	2007	6	2	2 (0)	0 (0)	638	559	3
18	5.00	2007	6	2	3 (0)	0 (0)	638	559	3
19	5.00	2007	6	2	3 (0)	0 (0)	677	545	3
20	5.00	2007	6	2	0 (0)	0 (0)	677	545	3
21	5.00	2007	6	2	1 (0)	0 (0)	677	545	2
22	5.00	2007	6	2	1 (1)	1 (0)	677	545	2
23	2.45	2007	6	2	0 (0)	1 (0)	677	545	3
24	6.60	2007	6	2	1 (0)	1 (0)	3731	3894	1
25	5.00	2007	6	2	0 (0)	0 (0)	2778	2541	1
26	5.00	2007	6	2	0 (0)	1 (0)	2778	2541	1
27	2.99	2007	6	2	1 (0)	0 (0)	2778	2541	2
28	2.63	2007	6	2	0 (0)	0 (0)	2778	2541	2
29	4.22	2007	6	2	0 (0)	2 (0)	2224	1949	2
30	4.57	2007	6	2	0 (0)	0 (0)	1946	1888	3
31	5.00	2007	6	2	2 (0)	0 (0)	2918	2859	3
32	5.00	2005	4	4	1 (0)	0 (0)	2902	2910	3
33	5.00	2005	4	4	0 (0)	0 (0)	2842	2837	3
34	5.00	2005	4	4	2 (0)	0 (0)	2842	2837	3
35	5.00	2007	6	2	1 (0)	0 (0)	7135	7228	2
36	5.00	2007	6	2	1 (0)	0 (0)	7135	7228	2
37	5.00	2007	6	2	1 (0)	0 (0)	7135	7228	1
38	5.00	2007	6	2	1 (0)	0 (0)	7135	7228	2
39	5.00	2007	6	2	0 (0)	0 (0)	974	1020	2
40	5.00	2007	6	2	0 (1)	0 (0)	974	1020	3
41	2.51	2007	6	2	1 (0)	0 (0)	974	1020	2

The before-and-after average yearly crashes per five mile segments were determined for these three types of road curvature. The weighted average AADT for the “before period” and the “after period” was also calculated for these segments.

Table 4 and Table 5 summarize the before-and-after annual change in crashes per 5-mile segments for all ROR and severe ROR crashes, respectively. The change in AADT for these road sections are also listed in the tables. The before-and-after annual change in crash rates for all ROR and severe ROR crashes are shown in Figure 2 and Figure 3, respectively. Road curvature Type 1 showed an 11 percent reduction in all ROR crashes and a 21 percent reduction in fatal and severe injury crashes and after the installation of shoulder rumble strips. These roads experienced a 1 percent increase in traffic volume during the “after installation” periods. After the installation of rumble strips, road curvature Type 2 and Type 3 roadways showed 36 percent and 32 percent reduction in all ROR crashes and 29 percent and 47 percent reduction in severe ROR crashes respectively. Traffic volumes also were reduced for road curvature Type 2 and Type 3 road sections after the installation of rumble strips.

Table 4. Before-and-After Data for All ROR Crashes on Two-Lane Highway Treatment Sites

Road Curvature Type	Number of Sites	Length (mile)	Yearly Crashes / 5 Miles			AADT		
			Before	After	Percent Reduction	Before	After	Percent Change
1	4	21.60	0.694	0.579	17%	4078	4039	-1%
2	14	61.37	1.064	0.671	37%	3255	3158	-3%
3	23	110.66	1.875	1.197	36%	1750	1652	-6%
Average			1.486	0.961	35%	2487	2396	-4%

Table 5. Before-and-After Data for Severe ROR Crashes on Two-Lane Highway Treatment Sites

Road Curvature Type	Number of Sites	Length (mile)	Yearly Crashes / 5 mile			AADT		
			Before	After	Percent Reduction	Before	After	Percent Change
1	4	21.60	0.077	0.061	21%	4078	4039	-1%
2	14	61.37	0.163	0.116	29%	3255	3158	-3%
3	23	110.66	0.275	0.147	47%	1750	1652	-6%
Average			0.217	0.128	41%	2487	2396	-4%

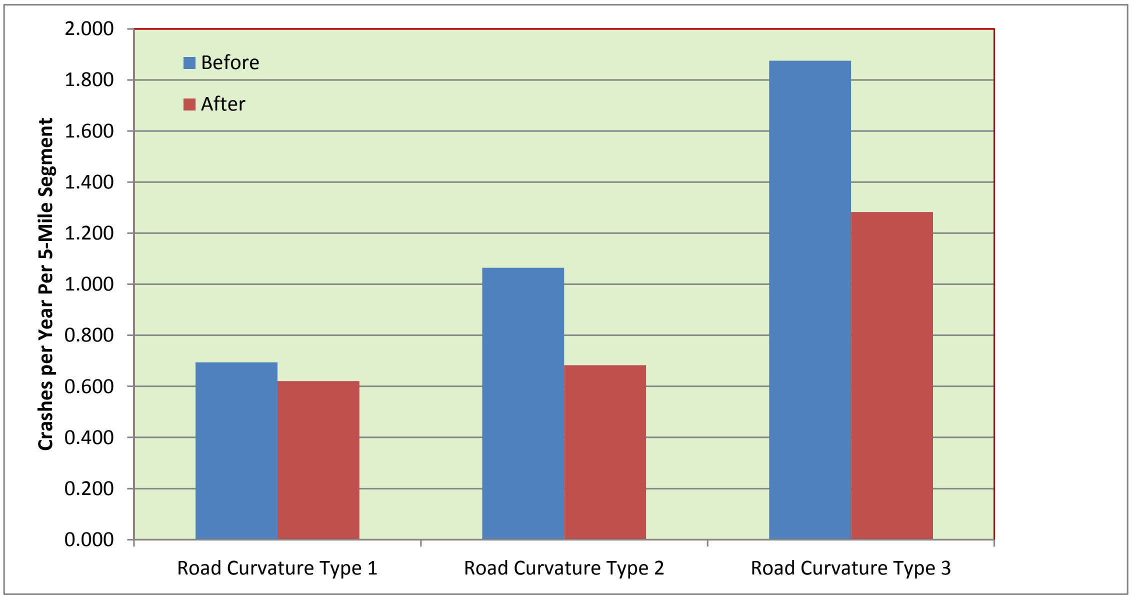

Figure 2. Before-and-After Data for All ROR Crashes on Two-Lane Highway Treatment Sites

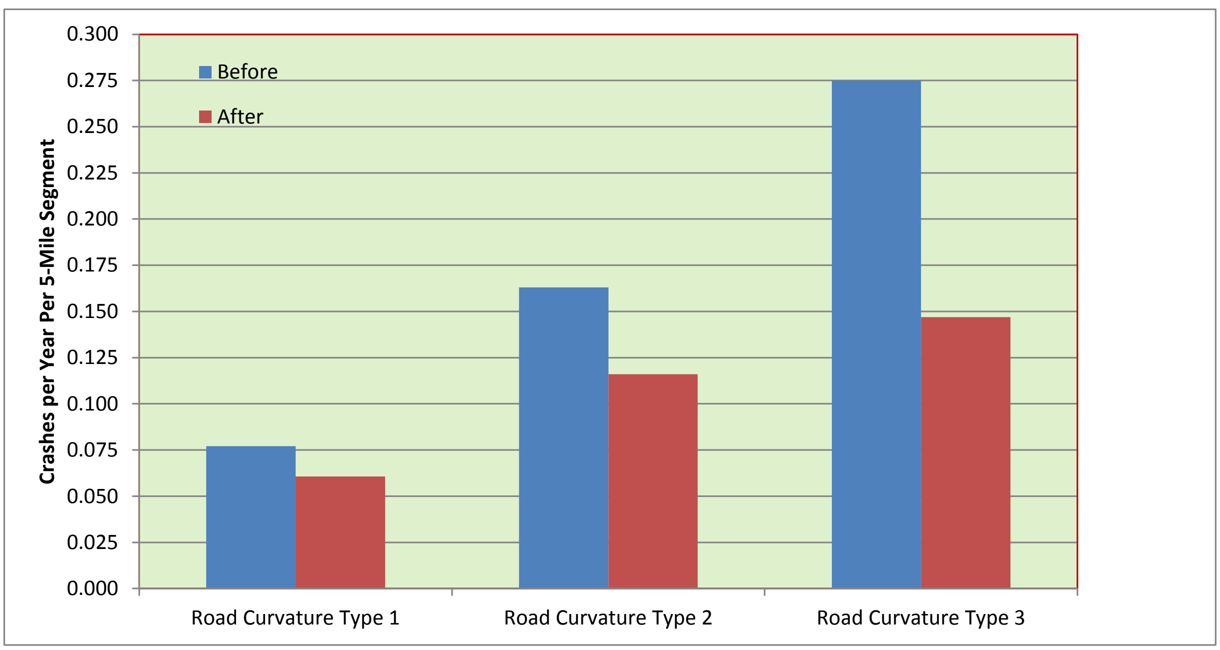

Figure 3. Before-and-After Data for Severe ROR Crashes on Two-Lane Highway Treatment Sites

The annual average number of crashes per 5-mile segment for all treatment sites dropped from 1.486 crashes to 1.019 crashes. This demonstrates a 31 percent reduction in all ROR crashes after the treatment. The annual average number of truck crashes per 5-mile segment for all treatment sites also dropped from 0.275 crashes to 0.101 crashes. This shows an overall reduction of 63 percent. Similarly, the severe ROR crashes during the “before period” averaged annually 0.217 crashes per 5-mile segment.

This value changed to 0.128 crashes after the rumble strips were installed, approximately a 41 percent reduction. Truck severe crashes also dropped from an annual average of 0.022 crashes per 5-mile segment to 0.013 crashes annually per 5-mile road segment, a 40 percent reduction post-treatment.

The weighted average AADT for all treatment sites changed from 2,487 vehicles to 2,502 vehicles during the before-and-after period, a 1 percent increase as shown in Figure 4.

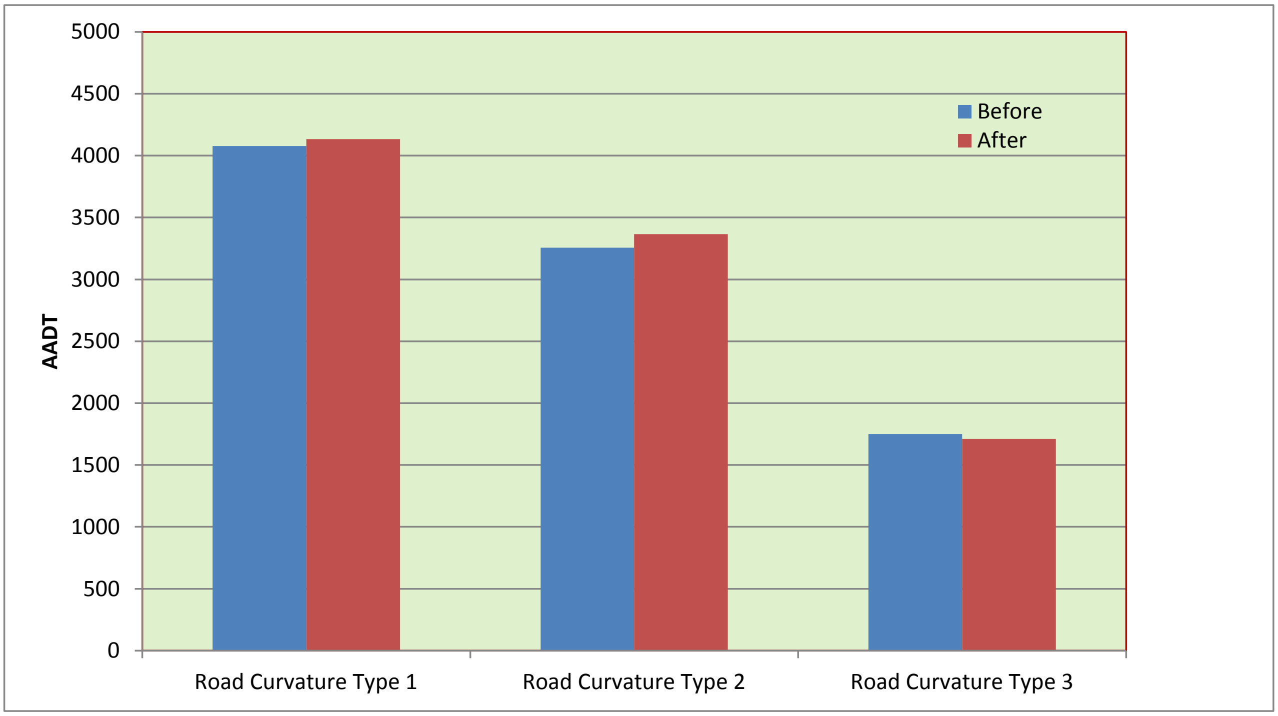

Figure 4. Before-and-After Average AADT Values of Two-lane Highway Treatment Sites

Four-Lane Rural Highways

A total of 11 four-lane rural highway treatment sites, with total length of 45.54 miles, were selected for the analysis. Shoulder rumble strips were installed at these sites between 2003 and 2008. All four-lane rural highway treatment sites had a lane width of 12 feet, with a right paved shoulder width that varied from 2 feet to more than 7 feet. All selected sites had a degree of curvature Type 1 which is defined as having no horizontal curves or having horizontal curves with a radius larger than that required for the road's design speed. Crash data for 10 years (2001-2010) were used in the analysis.

Table 6 and Table 7 provide information about the four-lane highway treatment sites for all ROR crashes and truck ROR crashes, respectively. Figure 5 shows the before-and-after changes in average number of crashes per year per 5-mile segments for all crashes and severe crashes on four-lane rural highways.

Table 6. Characteristics of Four-Lane Highway Treatment Sites

Segment	Length (mile)	Installation year	Number of Years		Crash Counts				AADT	
					All ROR Crash		Most Severe ROR Crash			
			Before	After	Before	After	Before	After	Before	After
1	5.00	2008	7	1	9	4	1	1	4966	5028
2	5.00	2007	6	2	26	2	2	0	31922	29543
3	2.49	2007	6	2	10	2	0	0	31922	29543
4	5.00	2003	2	6	8	4	1	1	30307	31673
5	2.44	2003	2	6	5	8	1	1	30307	31673
6	3.87	2006	5	3	8	6	1	0	14285	15139
7	5.00	2006	5	3	18	12	1	1	14285	15139
8	5.00	2006	5	3	27	5	5	1	14285	15139
9	1.75	2006	5	3	5	2	0	0	14285	15139
10	5.00	2007	6	2	9	2	2	1	7685	7788
11	5.00	2007	6	2	2	2	0	1	7685	7788

Table 7. Characteristics of Four-Lane Highway Treatment Sites (Truck Crashes)

Segment	Length (mile)	Installation year	Number of Years		Crash Counts				AADT	
					All ROR Crash		Most Severe ROR Crash			
			Before	After	Before	After	Before	After	Before	After
1	5.00	2008	7	1	0	0	0	0	4966	5028
2	5.00	2007	6	2	5	0	0	0	31922	29543
3	2.49	2007	6	2	1	0	0	0	31922	29543
4	5.00	2003	2	6	1	0	0	0	30307	31673
5	2.44	2003	2	6	0	1	0	0	30307	31673
6	3.87	2006	5	3	0	1	0	0	14285	15139
7	5.00	2006	5	3	2	1	0	0	14285	15139
8	5.00	2006	5	3	1	0	0	0	14285	15139
9	1.75	2006	5	3	0	0	0	0	14285	15139
10	5.00	2007	6	2	0	0	0	0	7685	7788
11	5.00	2007	6	2	0	0	0	0	7685	7788

Comparing the average number of crashes for all treatment sites during the “before treatment” to the “after treatment” periods shows a reduction from 2.988 crashes to 2.013 crashes annually per 5-mile segment. The severe crashes declined from 0.352 crashes to 0.329 crashes annually per 5-mile segment during the “before treatment” to “after treatment” period. This shows a reduction of about 33 percent for all ROR crashes and 7 percent for severe ROR crashes. The weighted average AADT for the selected treatment sites for the “before treatment” period was 17,330 vehicles compared to 17,484 vehicles during the “after treatment” period, an increase of about 1 percent. Since the yearly number of crashes were reduced after installing shoulder rumble strips and traffic volumes increased slightly, it is probable that the safety of the treatment sites were improved primarily as a result of the shoulder rumble strip installation.

The average annual number of truck ROR crashes for all treatment sites during the “before treatment” period was 0.231 crashes. This value declined to 0.091 crashes during the “after treatment” period, approximately a 60 percent reduction. No injury Type A (serious injury) and/or fatal crashes were found for trucks during the before-and-after period for the selected treatment sites.

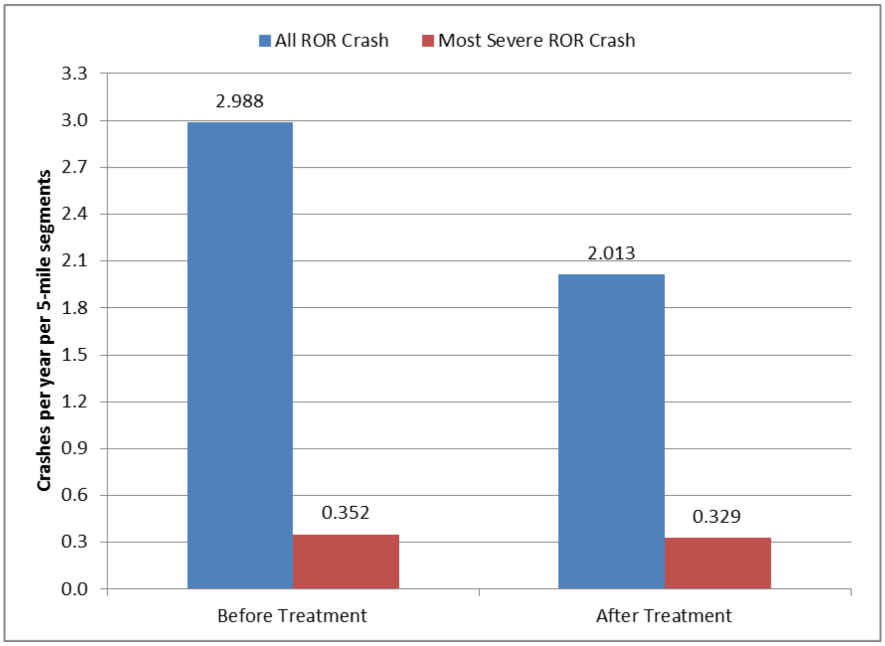

Figure 5. Before-and-After Data for ROR Crashes on Four-Lane Highway Treatment Sites

Rural Freeways

A total of 16 rural freeway treatment sites on I-84, I-86 and I-90 were selected for analysis. Shoulder rumble strips were installed at these sites in 2007. The total length of the selected treatment sites was 73.36 miles. All of these segments had 4-lanes (2 lanes in each direction) with a standard lane width of 12 feet. The shoulder width of the selected test sections varied from 10 feet to 12 feet. Road curvature of the selected test sites was not considered because all treatment sites have either no curves or curves with very large radii. Table 8 summarizes the geometric and crash characteristics of the freeway treatment sites.

The average annual number of crashes per 5-mile segment for all rural freeway treatment sites declined from 3.749 crashes per segment during the “before treatment” period to 1.909 crashes during the “after treatment” period. This represents a 49 percent reduction in ROR crashes after treatment. Similarly, the average number of severe ROR crashes declined from an annual average of 0.295 crashes per 5-mile segment during the “before treatment” period to 0.135 crashes during the “after treatment” period. This represents a 53 percent reduction. Figure 6 shows the before-and-after changes in the average number of crashes for treatment sites on rural freeways. The average AADT at all rural freeway treatment sites changed from 11,069 vehicles during the “before treatment” period to 10,781 vehicles during the “after treatment” period, a 3 percent reduction. Though a reduction in crash rates was demonstrated in the “after treatment” period, there is a probability that part of this reduction can be attributed to the reduction in traffic volume.

Table 8. Characteristics of Freeway Treatment Sites

Segment	Length (mile)	Installation Year	Crash Counts				AADT	
			All ROR Crash		Most Severe ROR Crash			
			Before	After	Before	After	Before	After
1	5.00	2007	16	9	0	2	18393	17905
2	5.00	2007	13	5	3	1	18109	17807
3	5.00	2007	3	5	0	0	6342	6289
4	5.00	2007	5	6	0	0	6342	6289
5	5.00	2007	6	0	1	0	6342	6289
6	5.00	2007	1	0	0	0	6342	6289
7	5.00	2007	6	3	1	0	6342	6289
8	5.00	2007	9	3	1	0	12003	11612
9	5.00	2007	6	4	1	0	12003	11612
10	5.00	2007	7	7	0	0	12003	11612
11	5.00	2007	13	7	1	1	10980	10627
12	3.10	2007	14	9	2	2	21807	22070
13	4.00	2007	16	5	2	0	11341	10733
14	4.51	2007	19	8	0	0	11341	10733
15	4.27	2007	23	9	1	0	11341	10733
16	2.47	2007	8	4	1	0	9453	8946

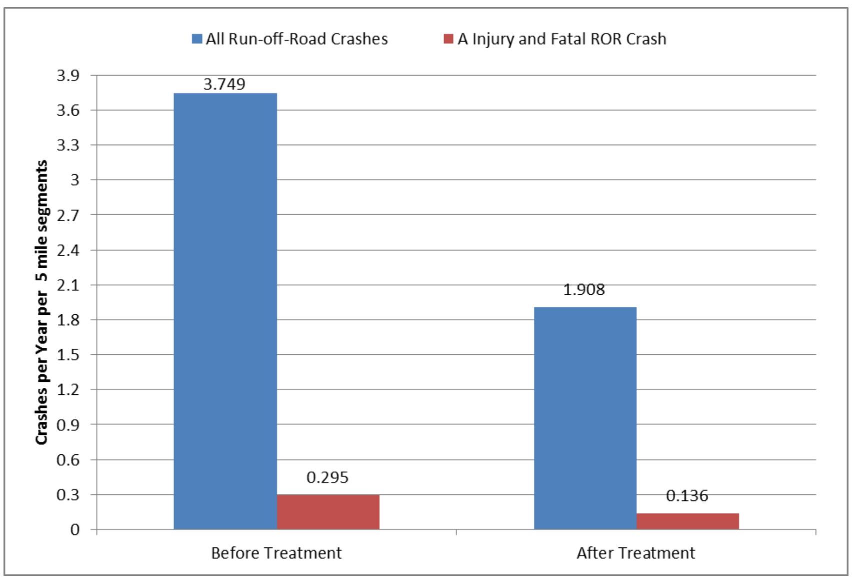

Figure 6. Before-and-After Data for ROR Crashes on Freeway Treatment Sites

Table 9 summarizes the characteristics of the truck crashes for the rural freeway treatment sites. The average annual number of truck ROR crashes during the “before treatment” period per 5-mile segment for all treatment sites was 0.750 crashes. This value dropped to 0.239 crashes annually per 5-mile segment during the “after treatment” period, approximately a 68 percent reduction. No fatal or Type A (serious) injury truck crashes occurred on the rural freeway treatment sites during either treatment periods.

Table 9. Characteristics of Freeway Treatment Sites (Truck Crashes)

Segment	Length (mile)	Installation Year	Crash Counts				AADT	
			All ROR Crash		Most Severe ROR Crash			
			Before	After	Before	After	Before	After
1	5.00	2007	1	1	0	0	18393	17905
2	5.00	2007	4	0	0	0	18109	17807
3	5.00	2007	2	0	0	0	6342	6289
4	5.00	2007	0	1	0	0	6342	6289
5	5.00	2007	0	0	0	0	6342	6289
6	5.00	2007	0	1	0	0	6342	6289
7	5.00	2007	2	0	0	0	6342	6289
8	5.00	2007	3	3	0	0	12003	11612
9	5.00	2007	0	0	0	0	12003	11612
10	5.00	2007	1	1	0	0	12003	11612
11	5.00	2007	1	0	0	0	10980	10627
12	3.10	2007	1	0	0	0	21807	22070
13	4.00	2007	1	0	0	0	11341	10733
14	4.51	2007	0	0	0	0	11341	10733
15	4.27	2007	3	0	0	0	11341	10733
16	2.47	2007	3	0	0	0	9453	8946

Description of Control Sites

As part of the study, we also reviewed crash data for road segments that did not have shoulder rumble strips. These control group sites were similar to the treatment sites in terms of traffic volume and geometric characteristics. Crash rates at treatment and control sites were compared to assess the safety impact of the shoulder rumble strips.

Two-Lane Rural Highways

A total of 58 sites were selected as control group sites in the CG analysis for the two-lane rural highways. The same control sites were also used to develop the safety performance function of the EB analysis. The total length of these 58 sites was 277.04 miles. Detail control site data of all ROR crashes and severe ROR crashes are presented in Appendix B. All truck ROR crashes data are also presented in Appendix B in Tables 30, 31, and 32.

Four-Lane Rural Highways

A total of 6 four-lane rural highway control sites were selected for analysis. The total length of these control sites was 23.53 miles. Selected control sites had a 12-feet lane width with shoulder widths ranging from 4 feet to more than 7 feet. The number of available control sites was sufficient for CG analysis. However, for EB analysis these segments were found to be insufficient to develop safety performance functions for treatment sites. The available data for four-lane rural highway control sites were under dispersed and did not fit the negative binomial distribution (i.e. negative dispersion parameter). The characteristics of the control sites for four-lane rural highways are presented in Appendix B in Tables 33, 34, and 35.

Rural Freeways

A total of 23 control sites from I-15, I-84 and I-90 were selected as control sites for two purposes: to act as the rural freeway CG analysis sites and to develop the safety performance function of EB analysis for rural freeways. The total length of the control sites was 80.91 miles. All of the selected control sites were within close proximity to the selected treatment sites so that the traffic volume and road geometric characteristics were similar. The characteristics of the rural freeway control sites are presented in Appendix B in Tables 36, 37, and 38.

Comparison Group Analysis

In this part of the study, the effect of shoulder rumble strips in reducing ROR crashes was evaluated using CG before-and-after crash data analysis. The comparison ratio term (r_c) of CG Method incorporates the before and after crash counts of the control site(s). The results of CG analysis are described in the following sections.

Two-Lane Rural Highway Comparison Group Analysis

For two-lane rural highway treatment sites, comparison groups were matched based on road curvature type, traffic volume, and paved right shoulder width. The results of the CG analysis are presented in Table 10. Of the 41 test sites, 3 were excluded from the analysis as their comparison sites reported zero crashes during the “after treatment” period. The actual crash counts (λ) for the remaining treatment sites “after treatment” was 95.00 crashes and the CG estimates of expected crashes for the same period without the treatment was 116.35. The unbiased estimate of safety effectiveness (θ) and its variance were computed following the method described in Appendix A. This result was statistically significant at the 0.05 level. The average reduction in ROR crashes due to the installation of shoulder rumble strips was estimated to be a 23 percent with a standard deviation of 7 percent. The 95th percentile confidence interval is 23 percent ± 14 percent. This means that the expected reduction of all ROR crashes due to the installation of shoulder rumble strips on two-lane rural highways ranges from a lower limit of 9 percent to an upper limit of 37 percent.

The results of the CG analysis for severe ROR truck crashes at the treatment sites are presented in Table 11. All truck ROR crashes were analyzed for 19 treatment sites to evaluate the effectiveness of shoulder rumble strips. Shoulder rumble strips reduced all ROR truck crashes for most treatment sites. However, an increase in crashes was observed after the treatment at some sites. The average safety effect of shoulder rumble strips was estimated to be a reduction in all ROR truck crashes of 56 percent with a standard deviation of 32 percent. Due to the small number of truck crashes and the high standard deviation of the estimate, the result was not statistically significant at the 0.05 level. However, the result was statistically significant at the 0.07 level.

Results of the CG analysis for severe ROR crashes at the treatment sites are presented in Table 12. Out of 41 selected treatment sites, 26 sites were not included in the analysis as their CG estimates for the “after period” were zero. The actual and estimated crash counts during the “after period” of the treatment sites were 3.00 crashes and 7.14 crashes, respectively (excluding the outliers). The average safety effect of shoulder rumble strips was estimated to be a reduction of 74 percent in “most-severe” ROR crashes. The standard deviation of this estimate of average safety effect was 15 percent. This result was statistically significant at the 0.05 level. Using the 95^{th} percentile confidence interval, the results show that shoulder rumble strips reduced ROR severe crashes by 74 percent ± 30 percent. The lower limit of the estimated reduction in severe crashes as a result of shoulder rumble strips installation in two-lane rural highways is 44 percent. The upper limit of the crash reduction could be as high as 100 percent.

Table 10. Comparison-Group Analysis Results for Two-Lane Rural Highways (All ROR Crashes)

Segment	Length (miles)	Road Curvature Type	Count of Crashes During After Period	Expected Crashes During After Period Without Treatment	
			Actual Counts	CG Estimates	Standard Deviations
1	4.03	2	3	3.05	3.04
3	5.00	3	10	6.87	4.42
4	5.00	3	8	34.29	26.92
5	5.00	2	5	8.82	5.34
6	5.00	3	8	7.73	4.92
7	5.00	2	7	3.05	2.35
8	3.64	3	8	6.06	3.71
9	5.00	3	8	4.14	2.74
10	5.00	3	3	9.90	6.79
11	5.00	2	0	0.66	1.08
12	5.00	3	1	0.43	0.65
14	5.00	3	2	0.65	0.92
15	5.00	3	2	0.98	1.32
16	5.00	3	0	0.43	0.65
17	5.00	3	0	0.87	1.19
18	5.00	3	1	0.87	1.19
19	5.00	3	0	0.65	0.92
20	5.00	3	2	0.54	0.78
21	5.00	2	0	0.66	1.08
22	5.00	2	2	0.65	1.41
23	2.45	3	1	0.22	0.38
24	6.60	1	1	0.80	1.04
25	5.00	1	0	0.37	0.60
26	5.00	1	1	0.42	0.69
28	2.63	2	0	0.60	0.90
30	4.57	3	0	0.86	1.29
31	5.00	3	1	1.11	1.31
32	5.00	3	0	1.53	1.55
33	5.00	2	4	2.59	2.80
34	5.00	2	6	8.64	8.35
35	5.00	2	4	2.18	2.31
36	5.00	2	4	1.82	2.16
37	5.00	1	3	1.91	2.09
38	5.00	2	0	1.64	1.80
39	5.00	2	0	0.31	0.49
41	2.51	2	0	0.06	0.17
Total			95	116.35	

Table 11. Comparison-Group Analysis Results for Two-Lane Rural Highways (Severe ROR Crashes)

Segment	Length (miles)	Road Curvature Type	Count of Crashes During After Period	Expected Crashes During After Period Without Treatment	
			Actual Counts	CG Estimates	Standard Deviations
8	3.64	3	0	1.05	1.58
9	5.00	3	1	2.29	3.35
10	5.00	3	0	0.63	0.93
12	5.00	3	0	0.08	0.22
17	5.00	3	0	0.17	0.40
18	5.00	3	0	0.25	0.57
19	5.00	3	0	0.25	0.57
22	5.00	2	1	0.29	0.90
24	6.60	1	1	0.09	0.26
31	5.00	3	0	0.15	0.64
32	5.00	3	0	0.21	0.38
34	5.00	2	0	1.60	3.08
37	5.00	1	0	0.09	0.23
Total			3	7.14	

Table 12. Comparison-Group Analysis Results for Two-Lane Rural Highways (Truck ROR Crashes)

Segment	Length (miles)	Road Curvature Type	Count of Crashes During After Period	Expected Crashes During After Period Without Treatment	
			Actual Counts	CG Estimates	Standard Deviations
4	5.00	3	0	1.36	2.51
5	5.00	2	0	2.65	4.91
6	5.00	3	1	0.67	0.82
9	5.00	3	1	1.72	2.00
10	5.00	3	1	0.80	1.13
12	5.00	3	0	0.04	0.12
13	5.00	3	0	0.28	0.74
14	5.00	3	0	0.04	0.12
15	5.00	3	1	0.36	0.94
16	5.00	3	0	0.08	0.23
18	5.00	3	0	0.24	0.63
19	5.00	3	1	0.16	0.43
20	5.00	3	2	0.20	0.53
25	5.00	1	0	0.24	0.80
32	5.00	3	0	1.53	1.55
37	5.00	1	0	0.24	0.81
38	5.00	2	0	0.20	0.85
40	5.00	3	0	0.08	0.23
41	2.51	2	0	0.02	0.08
Total			7	10.90	

Four-Lane Rural Highway Comparison Group Analysis

CG analysis for four-lane rural highways was only conducted for ROR crashes as a whole. The analysis could not be performed for severe ROR crashes or truck crashes for two reasons. First, there were no severe ROR truck crashes at several of the treatment sites in the “before” or “after” period. Second, during the “before period” no crashes occurred at several treatment sites. For any of the cases mentioned, the expected “after period” crashes equals zero. Consequently, the index of effectiveness of the estimates cannot be determined.

The results of CG analysis for four-lane rural highways are presented in Table 13. The average safety effect of shoulder rumble strips showed a reduction of all ROR crashes by 60 percent. The standard deviation of the estimated average safety effect was 10 percent. This result was statistically significant at the 0.05 level. The 95th percentile confidence interval was a 60 percent ± 20 percent reduction in all ROR crashes. Accordingly, the lower limit of the estimated reduction in all ROR crashes (as a result of the installation of shoulder rumble strips in four-lane rural highways) was 40 percent and the upper limit of the crash reduction potential was 80 percent.

Table 13. Comparison-Group Analysis Results for Four-Lane Highways (All ROR Crashes)

Segment	Count of Crashes During After Period	Expected Crashes During After Period Without Treatment	
	Actual Counts	CG Estimates	Standard Deviations
1	4	1.14	1.45
2	2	10.40	7.59
3	2	4.00	3.39
4	4	38.40	17.82
5	8	24.00	11.76
6	6	4.86	3.86
7	12	11.43	7.40
8	5	17.14	10.68
9	2	2.47	2.78
10	2	2.62	2.50
11	2	0.58	0.84
Total	49	117.05	

Rural Freeway Comparison Group Analysis

Table 14 and Table 15 summarize the results of CG analysis for the selected test sites for all ROR crashes and severe ROR crashes, respectively. The unbiased estimate of safety effectiveness index and its variance was calculated for each case. It was estimated that the installation of rumble strips resulted in an average reduction of 14 percent for all ROR crashes and 63 percent for severe ROR crash. The corresponding standard deviation for these estimates was estimated respectively at 17 percent and 21 percent. Table 16 summarizes the results of the CG analysis for all ROR truck crashes. It was estimated that the installation of rumble strips resulted in a reduction of 44 percent for ROR truck crashes. The corresponding standard deviation of the estimates was 34 percent. All ROR crash results and truck ROR crash results were not statistically significant at the 0.05-level. However, severe crash results were statistically significant at the 0.05-level.

Table 14. Comparison-Group Analysis Results for Rural Freeways (All ROR Crashes)

Segment	Count of Crashes During After Period	Expected Crashes During After Period Without Treatment	
	Actual Counts	CG Estimates	Standard Deviations
1	9	7.65	3.96
2	5	6.21	3.35
3	5	2.37	2.30
4	6	3.95	3.40
5	0	4.74	3.95
6	0	0.79	1.10
7	3	4.74	3.95
8	3	4.81	2.94
9	4	3.21	2.17
10	7	3.74	2.43
11	7	6.95	3.95
12	9	6.41	4.00
13	5	8.29	4.96
14	8	11.06	6.48
15	9	13.39	7.69
16	4	3.90	3.10
Total	84	92.22	

Table 15. Comparison-Group Analysis Results for Rural Freeways (Severe ROR Crashes)

Segment	Count of Crashes During After Period	Expected Crashes During After Period Without Treatment	
	Actual Counts	CG Estimates	Standard Deviations
2	1	1.97	2.10
5	0	0.27	0.66
7	0	0.27	0.66
8	0	0.60	0.91
9	0	0.60	0.91
11	1	0.88	1.34
12	2	1.13	1.51
13	0	1.10	1.48
15	0	0.88	1.39
16	0	0.45	0.82
Total	4	8.15	

Table 16. Comparison-Group Analysis Results for Rural Freeways (Truck ROR Crashes)

Segment	Count of Crashes During After Period	Expected Crashes During After Period Without Treatment	
	Actual Counts	CG Estimates	Standard Deviations
1	2	0.40	0.80
2	1	1.60	2.71
3	0	0.27	0.66
9	0	1.85	2.85
11	1	0.62	1.13
12	2	0.53	0.91
13	0	0.35	0.75
15	0	1.09	2.01
16	0	0.11	0.55
Total	6	6.80	

Empirical Bayes Analysis

The EB methodology was used to estimate the safety benefit of shoulder rumble strips for two-lane rural highways and rural freeways. An SPF was developed using control sites data for both roadway types. The following section describes the development of an SPF for two-lane rural highways and rural freeways, followed by the results of the EB analysis.

Development of Safety Performance Functions

For the selected control group sites, an SPF was developed for all ROR crashes using the generalized linear modeling (GLM) technique. The developed SPF is assumed to follow the Negative Binomial Regression model. For two-lane rural highways, AADT, segment length, width of right paved shoulder, road curvature type, and yearly factors were used as independent variables in the developed SPF. The dependent variable in the SPF determines the expected number of crashes per year per segment of length of d-mile. Right paved shoulder width, road curvature type, and the yearly factor were introduced as class (dummy) variables. Right paved shoulder width and road curvature type variables incorporated their respective effect on the number of crashes. Yearly factors were introduced to consider various demographic changes that took place during the study period. Segment length was introduced as an offset variable, for which no regression parameter was estimated. This was based on the assumption that the number of crashes is proportional to the segment lengths. The basic equation of SPF used for two-lane rural highways is shown in Figure 7.

$$E\{\kappa_{i,y}\} = \alpha_y . r_j . psw_k . d . V^{\beta}$$

Figure 7. SPF Equation for Two-Lane Rural Highways

SAS was used to estimate the model parameters using the maximum likelihood as well as the dispersion parameter. The SAS code for two-lane highway control sites for all ROR crashes is given in Appendix C. Table 17 shows parameter estimates of the safety performance function for all ROR crashes.

Table 17. Negative Binomial Model Parameters (Two-Lane Rural Highways)

Parameter	Value	Estimate	Standard Error
Model Intercept		-7.714	1.086
Log (AADT)		0.766	0.137
Dispersion		0.111	0.073
year	2001	0.377	0.213
year	2002	0.306	0.216
year	2003	0.476	0.209
year	2004	0.381	0.212
year	2005	-0.060	0.232
year	2006	-0.114	0.234
year	2007	0.355	0.212
year	2008	-0.003	0.232
year	2009	0.000	0.000
Right Shoulder Width	1	0.534	0.228
Right Shoulder Width	2	0.069	0.239
Right Shoulder Width	3	0.363	0.222
Right Shoulder Width	4	0.256	0.210
Right Shoulder Width	5	-0.347	0.213
Right Shoulder Width	6	-0.120	0.311
Right Shoulder Width	7	0.000	0.000
Degree of Curvature	1	-0.484	0.217
Degree of Curvature	2	-0.136	0.126
Degree of Curvature	3	0.000	0.000

The Chi-Square test value for the selected independent variables and their corresponding P-values were also determined. The results of the statistical significance tests for the selected independent variables are shown in Table 18. The P-values for the selected independent variables were significant at the 0.05 level. All variables were kept in the model.

Table 18. Statistical Significance Test for the Independent Variables (All ROR Crashes)

Parameter	DF	Chi-Square	Pr >ChiSq
Model Intercept	1	50.42	<.0001
Log (AADT)	1	30.81	<.0001
year	8	18.23	0.0195
Right Shoulder Width	6	29.84	<.0001
Degree of Curvature	2	5.14	0.0766

The number of severe ROR crashes was small for most test and control sites. Therefore, several control sites were combined to ensure that the number of crashes at each site was enough to develop the SPF for severe ROR crashes. The combined control site data was used to develop the Negative Binomial regression model for the severe ROR crashes. Chi-square test values for the selected independent variables and their corresponding P-values were also determined. Statistical significance test results for the selected independent variables are shown in Table 19.

Table 19. Statistical Significance Test for the Independent Variables (Severe ROR Crashes)

Parameter	DF	Chi-Square	Pr >ChiSq
Model Intercept	1	3.40	0.0654
year	8	22.68	0.0038
Right Shoulder Width	4	5.56	0.2342
Degree of Curvature	2	1.95	0.378
Log (AADT)	1	0.00	0.9526

The P-value of the selected independent variables, except the yearly factor, showed that none of the selected variables were statistically significant for this crash type. Therefore, EB analysis could not be performed on the severe ROR crashes.

Diagnostic tests applicable for Generalized Linear Models were performed for the developed SPF of all ROR crashes. To identify the outliers of the independent variables which have a large effect on the outcome of the fitting regression model, the leverage of the regression model was calculated using the Hat-values. Hat-values, standardized residuals, and Cook's distance from the Negative Binomial regression for all ROR crashes are plotted in Figure 8. Vertical lines in this figure are drawn at the two times and three times the average Hat-value. Based on this plot, no observation was found with very large Hat-value to select a statistically significant outlier. Therefore, no significant outliers exist in the selected control sites.

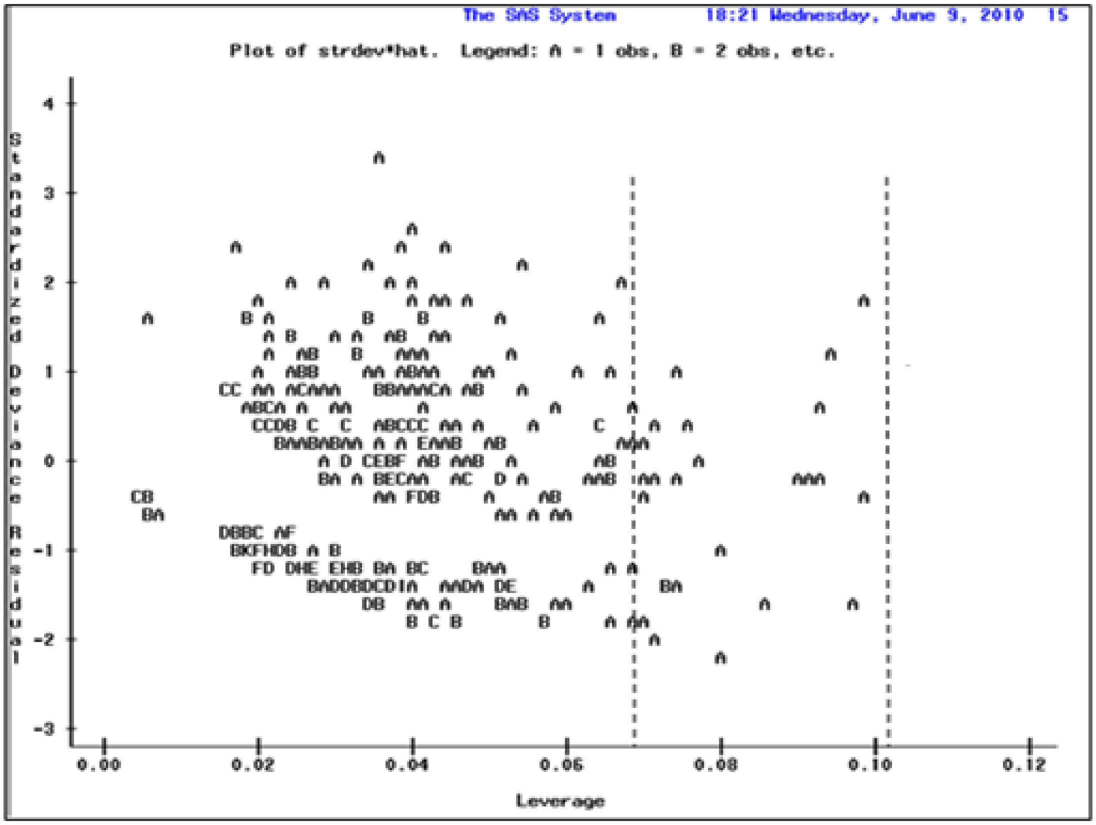

Figure 8. Diagnostic Test (All ROR crashes)

Standardized residual values of the model estimation were plotted against the predicted value using the model output. The plot is shown in Appendix D in Figure 39. The plots showed that the residuals were very close to zero for all predicted values. Standardized residual values for each independent variable were also plotted to examine whether the selected model fits the data. Plots for AADT, right paved shoulder width, and road curvature degree are also shown in Appendix D in Figures 40, 41, and 42, respectively. The plots also show that the residuals were very close to zero for all selected independent variables.

Using the developed SPF, the expected crash frequency for each test site was determined. The residual of the estimate was then calculated to select the sample outliers. These residuals are defined as the difference between the actual crash counts and the estimated number of crashes obtained from the SPF. The residuals versus the estimated number of crashes were plotted in Figure 9. From this figure, two test sections were found with a very high residual. These sections were identified from the selected 41 test sections and unselected for the rest of the analysis. EB estimation was performed using data from the remaining 39 test sites.

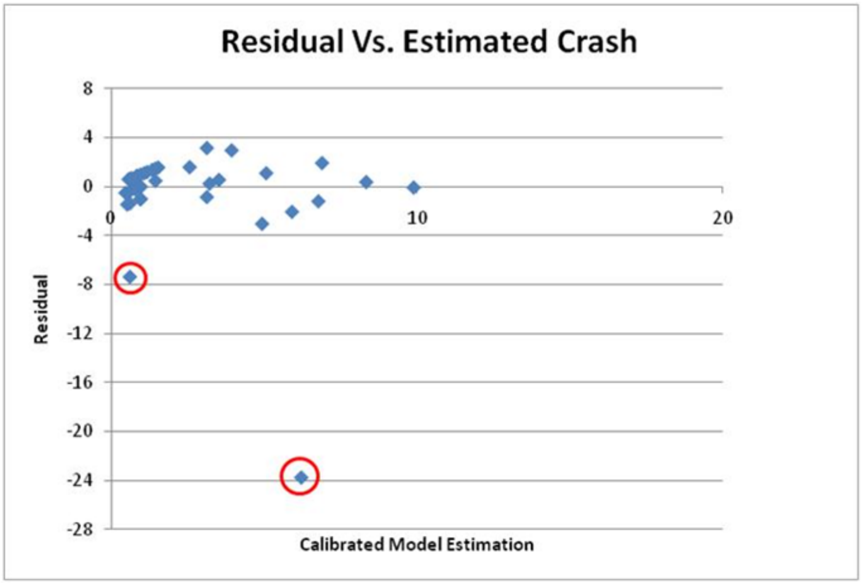

Figure 9. Residual Plot for Test Sites (All ROR Crashes)

For rural freeways, the SPF was developed using AADT, the segment length, and the yearly factor as the independent variables. Similar to two-lane rural highways, the dependent variable in the SPF is the number of crashes per year per d-mile of segment length. The yearly factor, however, was found statistically not significant for ROR crashes on rural freeways and was accordingly excluded from the SPF. The basic equation of the SPF for rural freeways is shown in Figure 10.

$$E\{\kappa_{i,y}\} = d.V^{\beta}$$

Figure 10. SPF Equation for Rural Freeways

The SAS code for freeway control sites for all ROR crashes and severe ROR crashes are given in Appendix C. Table 20 shows the parameter estimates and corresponding P-value for all types of ROR crashes and severe ROR crashes.

Table 20. Negative Binomial Model Parameters (Rural Freeways)

Parameter	All ROR Crashes			Severe ROR Crashes		
	Estimate	Standard Error	Pr >ChiSq	Estimate	Standard Error	Pr >ChiSq
Intercept	-5.871	0.642	<.001	-4.312	1.532	0.043
Log (AADT)	0.632	0.071	<.001	0.267	0.151	0.051
Dispersion	0.067	0.042		0.388	0.229	

The P-value for the AADT variable was statistically significant at the 0.05 level for all ROR crashes and for severe ROR crashes. The corresponding confidence level was considered satisfactory and the variable was kept in the model. Diagnostic tests applicable for Generalized Linear Models were performed for the developed SPFs. No significant outliers were found for the selected control sites. Diagnostic graph plots for rural freeways are shown in Appendix D in Figures 43 and 46.

Empirical Bayes Analysis for Two-Lane Rural Highways

Table 21 summarizes the results of the EB analysis for all ROR crashes on two-lane rural highways in Idaho. The unbiased estimate of the safety effectiveness index and its variance were calculated for each test site using the EB procedures outlined in Appendix A. It was estimated that the installation of shoulder rumble strips resulted in a 15 percent reduction for all ROR crashes. The corresponding standard deviation was estimated as 10 percent. The safety effect of shoulder rumble strips on highways with different road geometry types, varying paved right shoulder widths, and different AADT ranges are summarized in the following sections.

Treatment Evaluation in Context of Road Geometry Types

The actual and expected number of ROR crashes for different road curvature types and paved right shoulder widths are summarized in Table 22. For Road Curvature Type 1, all sections showed a reduction in ROR crashes in the "after periods." This was true for all paved right shoulder widths. Treatment sites with horizontal curves (Road Curvatures Type 2 and Type 3) showed higher reduction in ROR crashes for segments that have paved right shoulder width of 3 feet or more and lower reduction in the number of ROR crashes as the width of the paved right shoulder decreased, as shown in Table 22. The table shows one test section in Road Curvature Type 2 with two feet paved right shoulder width having a higher increase in ROR crash after the rumble strips installation. However, for this site, the standard deviation of the EB estimation is very high, and the site was selected as an outlier.

The results of EB before-and-after analysis for different road geometry types are summarized in Table 23. Installing rumble strips on two-lane rural highways resulted in reductions in ROR crashes for the following road sections (confidence levels are included):

- Road Curvature Type 1: 22 percent reduction, the statistical significance level for the estimate is 0.13.
- Road Curvature Type 2: 29 percent reduction, the statistical significance level for the estimate is 0.09.
- Road Curvature Type 3: 8 percent reduction, the statistical significance level for the estimate is 0.05.

The results indicate that shoulder rumble strips were most effective in reducing ROR crashes for roads with relatively moderate curvature and less effective in sections with sharp horizontal curves (Type 3).

Table 21. Empirical Bayes Analysis Results for Two-Lane Highway Treatment Sites (All ROR Crashes)

Segment	Count of Crashes During After Period	Expected Crashes During After Period Without Treatment	
	Actual Count	EB Estimates	Standard Deviation
1	1	3.64	1.32
3	10	9.48	2.16
4	8	10.70	2.20
5	5	6.87	2.62
6	8	8.16	1.80
7	7	5.00	1.35
8	8	6.29	1.43
9	8	7.57	1.65
10	3	5.13	1.18
11	0	0.93	0.52
12	1	0.75	0.33
14	2	1.10	0.59
15	2	0.94	0.46
16	0	0.68	0.39
17	0	0.89	0.45
18	1	1.25	0.63
19	0	1.07	0.59
20	2	0.99	0.57
21	0	0.91	0.52
22	2	0.59	0.35
23	1	0.46	0.30
24	1	1.21	1.10
25	0	1.16	1.08
26	1	0.71	0.84
27	0	0.47	0.37
28	0	0.96	0.56
29	1	0.56	0.39
30	0	1.03	0.59
31	1	2.15	1.07
32	0	3.27	1.02
33	4	2.50	0.85
34	6	4.97	1.58
35	4	3.14	1.34
36	4	3.39	1.52
37	3	2.87	1.69
38	0	2.69	1.24
39	0	1.15	0.64
40	0	0.94	0.60
41	0	0.51	0.31
Total	**94**	**107.08**	

Table 22. Empirical Bayes Analysis Results for Different Road Curvatures and Paved Right Shoulder Widths

Number of Sites	Road Curvature Type	Paved Right Shoulder Width	Length (mile)	Count of Crashes During After Period	Expected Crashes During After Period Without Treatment		% Change in Crashes	% Change in AADT
				Actual Count	EB Estimates	Standard Deviation		
2	1	4	10.00	3	4.03	1.46	34%	1%
2	1	5	11.60	2	1.91	0.80	11%	0%
4	2	<3	20.00	7	7.99	1.67	16%	7%
1	2	4	2.63	1	2.15	1.07	63%	2%
2	2	5	7.21	1	1.03	0.54	24%	11%
2	2	6	10.00	4	5.82	1.82	37%	1%
1	2	7	4.03	1	3.64	1.32	76%	7%
10	3	<3	46.09	35	34.87	3.64	1%	9%
7	3	<3	25.00	11	10.83	1.85	1%	7%
1	3	3	5.00	8	10.70	2.20	28%	7%
1	3	4	5.00	1	2.15	1.07	63%	2%
1	3	6	4.57	0	1.03	0.59	100%	3%

Table 23. Percent Reduction in ROR Crashes for Different Road Geometry Types

Number of Sites	Road Curvature Type	Length (mile)	Count of Crashes During After Period	Expected Crashes During After Period Without Treatment		% Change in Crashes	% Change in AADT
			Actual Count	EB Estimates	Standard Deviation		
4	1	21.60	5	5.94	1.66	22%	1%
14	2	56.37	22	30.22	4.21	29%	3%
23	3	100.66	65	70.32	5.22	8%	5%

Treatment Evaluation in Context of AADT

The percent reduction in ROR crashes under different AADT levels is tabulated in Table 24. Shoulder rumble strips were more effective in reducing ROR crashes on low-volume road sections (AADT less than 1,000) than in moderate- and high-volume road sections. Road sections with an average AADT less than 1,000, showed an estimated 33 percent reduction in ROR crashes after shoulder rumble strip installation. Road sections with AADT values of around 2,500, showed a marginal reduction in ROR crashes (3 percent) because of rumble strips installation. Road sections with AADT values that range from 3,500 to approximately 4,000 showed a 16 percent reduction in ROR crashes after shoulder rumble strip installation. Road sections with relatively high volumes (AADT values around 6,700) experienced a 24 percent reduction in ROR crashes after rumble strip installation. Although the estimates were not statistically significant at the 0.05-level, they were significant at the 0.10-level. The results give an idea about the benefits of shoulder rumble strips for different road traffic volumes.

Table 24. Percent Reduction in ROR Crashes Under Different AADT Levels

Number of Site	Length (mile)	AADT		Count of Crashes During After Period	Expected Crashes During After Period Without Treatment		% Reduction in Crashes
		Before	After	Actual Counts	EB Estimates	Standard Deviation	
15	69.96	736	739	12	17.70	2.24	33%
13	58.05	2542	2397	36	36.64	3.82	3%
7	36.60	3514	3936	36	42.23	5.08	16%
3	14.03	6718	6739	8	9.91	4.13	24%

Empirical Bayes Analysis for Rural Freeways

Table 25 and Table 26 summarize the results of the EB analysis for rural freeway treatment sites for all ROR crashes and for severe ROR crashes, respectively. The unbiased estimates of the safety effectiveness index and its variance were calculated for each case. It was estimated that the installation of shoulder rumble strips on rural freeways resulted in a reduction of 29 percent and 67 percent for all ROR crashes and severe crashes, respectively. The corresponding standard deviation was estimated at 9 percent and 14 percent. These estimates are statistically significant at the 95 percent confidence level. The reduction in truck ROR crashes as a result of shoulder rumble strip installation on rural freeways was estimated as 42 percent. Due to the limited number of truck crashes on both the test and control section, this estimate was not statistically significant at the 0.05 confidence level.

Table 25. Empirical Bayes Analysis Results for Rural Freeway Treatment Sites (All ROR Crashes)

Segment	Count of Crashes During After Period	Expected Crashes During After Period Without Treatment	
	Actual Counts	EB Estimates	Standard Deviation
1	9	10.8	2.9
2	5	9.7	2.6
3	5	4.6	1.2
4	6	5.4	1.4
5	0	5.4	1.4
6	0	4.1	1.1
7	3	6.9	1.8
8	3	7.3	1.9
9	4	6.6	1.8
10	7	6.9	1.8
11	7	9.2	2.4
12	9	9.5	2.5
13	5	8.1	2.1
14	8	9.5	2.5
15	9	10.3	2.7
16	4	4.0	1.1
Total	84	118.4	

Table 26. Empirical Bayes Analysis Results for Rural Freeway Treatment Sites (Severe ROR Crashes)

Segment	Count of Crashes During After Period	Expected Crashes During After Period Without Treatment	
	Actual Counts	EB Estimates	Standard Deviation
1	2	0.9	0.6
2	1	2.0	1.3
3	0	0.8	0.5
4	0	0.8	0.5
5	0	1.1	0.7
6	0	0.8	0.5
7	0	1.1	0.7
8	0	1.2	0.8
9	0	1.2	0.8
10	0	0.9	0.6
11	1	1.2	0.8
12	2	1.4	0.9
13	0	1.4	0.9
14	0	0.8	0.5
15	0	1.1	0.7
16	0	0.8	0.5
Total	**6**	**17.8**	

Naïve Analysis for Four-Lane Highways

For four-lane highways, the available data precluded the CG and EB analysis method for severe ROR crash and truck ROR crash. Therefore, a Naïve before-and-after study was conducted for these two cases to estimate the safety benefit of shoulder rumble strips for these two cases of four-lane rural highways.

The results of the Naive analysis for severe ROR crashes at the four-lane treatment sites are presented in Table 27. Using the Naïve method, severe ROR crashes were reduced by 45 percent. The standard deviation of this estimate of average safety effect was 21 percent. The results were statistically significant at the 0.05-level. The results of the Naive analysis for truck ROR crashes at the four-lane treatment sites are presented in Table 28. Truck ROR crashes were analyzed for 11 treatment sites and a 62 percent reduction was found after the installation of rumble strips. The standard deviation of the estimate was 23 percent. The results were statistically significant at the 0.05 level.

Table 27. Naïve Analysis Results for Rural Four-Lane Treatment Sites (Severe ROR Crashes)

Segment	Count of Crashes During After Period	Expected Crashes During After Period Without Treatment	
	Actual Counts	Naïve Estimate	Standard Deviation
1	1	0.14	0.38
2	0	0.67	0.82
3	0	0.00	0.00
4	1	3.00	1.73
5	1	3.00	1.73
6	0	0.60	0.77
7	1	0.60	0.77
8	1	3.00	1.73
9	0	0.00	0.00
10	1	0.67	0.82
11	1	0.00	0.00
Total	**7**	**11.68**	

Table 28. Naïve Analysis Results for Four-Lane Treatment Sites (Truck ROR Crashes)

Segment	Count of Crashes During After Period	Expected Crashes During After Period Without Treatment	
	Actual Counts	Naïve Estimate	Standard Deviation
1	0	0.00	0.00
2	0	1.67	1.29
3	0	0.33	0.58
4	0	3.00	1.73
5	1	0.00	0.00
6	1	0.00	0.00
7	1	1.20	1.10
8	0	0.60	0.77
9	0	0.00	0.00
10	0	0.00	0.00
11	0	0.00	0.00
Total	3	6.80	

Chapter 4
Conclusions and Recommendations

Conclusions

This study examined the effectiveness of shoulder rumble strips in reducing the number and severity of Idaho's ROR crashes for three different roadway types: two-lane rural highways, four-lane rural highways and rural freeways. Separate analysis was performed for all ROR crashes, severe ROR crashes, and ROR crashes involving trucks. The severe crash category included fatal crashes and Type A- serious injury crashes. The evaluation utilized two different evaluation methods: Comparison Groups (CG) before-and-after analysis and Empirical Bayes (EB) before-and-after analysis. For cases where the control section data was limited or not available, Naïve before-and-after analysis was used. Table 29 documents the findings from the analyses.

Table 29. Safety Effect of Shoulder Rumble Strips – Summary Results

Roadway Type	Crash Type	Comparison Group Method		Empirical Bayes Method		Naïve Method	
		Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
Two-Lane Highways	All ROR Crashes	23%*	7%	15%*	10%	-	-
	Severe ROR Crashes	74%*	15%	-	-	-	-
	Truck ROR Crashes	56%	32%	-	-	-	-
Four-Lane Highways	All ROR Crashes	60%*	10%	-	-	-	-
	Severe ROR Crashes	-	-	-	-	45%*	21%
	Truck ROR Crashes	-	-	-	-	62%*	23%
Rural Freeways	All ROR Crashes	14%	17%	29%*	9%	-	-
	Severe ROR Crashes	63%*	21%	67%*	14%	-	-
	Truck ROR Crashes	44%	34%	-	-	-	-

* Statistically Significant at the 0.05-Level

Overall Impact of Shoulder Rumble Strips for Two-Lane Rural Highways

- For two-lane rural highways, our analysis showed that there was a 23 percent reduction in ROR crashes using the CG method. The standard deviation was 7 percent and the estimate was statistically significant at the 0.05 level (95 percent confidence level). When using the EB analysis method, the results indicated installation of shoulder rumble strips resulted in 15 percent reduction in ROR crashes. In this analysis the standard deviation was 10 percent. The results were also statistically significant at the 0.05 level.

Impact of Shoulder Rumble Strips on Severe Crashes

- For two-lane rural highways, shoulder rumble strips reduced severe (fatal and serious injury) ROR crashes by 74 percent, with a standard deviation estimate of 15 percent. The estimated reduction in ROR truck crashes was 56 percent. However, this reduction in ROR truck crashes was not statistically significant because of its high standard deviation and due to the small number of truck crashes on the treatment and control sections.

Impact of Shoulder Rumble Strips by Road Curvature Type

- The effect of road geometry, defined here as degree of roadway curvature, on the effectiveness of shoulder rumble strips was considered in the analysis. Three different road curvature types were considered in the analysis:
    - Road Curvature Type 1 (relatively straight roadway segments).
    - Road Curvature Type 2 (horizontal curves with a design speed of 50 mph or more).
    - Road Curvature Type 3 (sharp horizontal curves with a design speed of 45 mph or lower).

- Shoulder rumble strips reduced all ROR crashes under the three road curvature types. Type 1 was reduced by 22 percent, Type 2 by 29 percent, and Type 3 by 8 percent. These results for Type 1 and Type 2 were not statistically significant at the 0.05 level. This evidence indicates shoulder rumble strips were less effective in reducing ROR crashes in Type 3 road curvatures. This could be attributed to the fact that drivers tend to be more alert driving in this type of roadway environment.

Impact of Shoulder Rumble Strips by Traffic Volume Level

- This study examined the percent reduction in ROR crashes under different AADT levels. Shoulder rumble strips were more effective in reducing ROR crashes in low-volume road sections (AADT less than 1,000) than in moderate- and/or high-volume road sections. Low-volume road sections showed an estimated 33 percent reduction in ROR crashes after the installation of shoulder rumble strips. Road sections with AADT values of around 2,500 showed a marginal reduction in ROR crashes (3 percent) as a result of shoulder rumble strips installation. Road sections with AADT values that ranged from 3,500 to approximately 4,000 showed a 16 percent reduction in ROR crashes with the installation of shoulder rumble strips. Road sections with relatively high volumes (AADT values around 6,700) experienced a 24 percent reduction in ROR crashes after the installation of shoulder rumble strips. Although the estimates were not statistically significant at the 0.05-level, the results give an idea about the benefits of shoulder rumble strips for different road traffic volume.

Impact of Shoulder Rumble Strips on Four-Lane Rural Highways

- The research showed that the safety effect of shoulder rumble strips installed on four-lane rural highways reduced ROR crashes by an average of 60 percent with a standard deviation of 10 percent. The estimated results were statistically significant at the 0.05 level. Using the Naïve before-and-after comparison, the average reduction resulting from the installation of rumble strips on four-lane rural highways in severe ROR crashes and truck ROR crashes was 45 percent and 62 percent, respectively, with a standard deviation of 21 percent and 23 percent. The results of the Naïve study were statistically significant at the 0.05-level, however, they may be subject to regression-to-the-mean bias.

Impact of Shoulder Rumble Strips on Rural Freeways

- For rural freeways, the EB method estimated that the installation of shoulder rumble strips resulted in a reduction of 29 percent and 67 percent for all ROR crashes and severe ROR crashes, respectively. The corresponding standard deviation was estimated respectively at 9 percent and 14 percent. These estimates were significant at the 0.05 level. The reduction in truck ROR crashes as a result of shoulder rumble strip installation in rural freeway was estimated at 42 percent. Due to the limited number of truck crashes on the test and control section, this estimate was not statistically significant at the 0.05 confidence level.

Recommendations

When conducting a benefit/cost analysis for shoulder rumble strips installation projects on rural Idaho highways, the crash reduction factors in Table 1 should be used. The sensitivity of these reduction factors to the geometric characteristics of the roadway segments should be factored into the analysis using the results documented in this report.

References

1. **Idaho Transportation Department**. *Strategic Highway Safety Plan*. Boise, ID: Idaho Transportation Department, Office of Highway Safety, 2006.
2. **U.S. Department of Transportation.** *Department of Transportation Strategic Plan 2003 – 2008*. Washington, D.C.: U.S. Department of Transportation, 2003. http://www.dot.gov/stratplan2008/strategic_plan.htm (Accessed October 2009).
3. **Federal Highway Administration (FHWA).** *Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU)*. Washington D.C.: Federal Highway Administration, Office of Legislation and Intergovernmental Affairs, 2005.
4. **Harkey, D. L., R. Srinivassan, C. Zegee, B. Persaud, C. Lyon, K. Eccles, F. Council, and H. McGee.** *Crash Reduction Factors for Traffic Engineering and Intelligent Transportation System (ITS) Improvements: State-of-Knowledge Report*. Washington, D.C.: NCHRP Research Results Digest 299, 2005.
5. **Bonneson, J., and D. Lord.** *Role and Application of Crash Modification Factors in the Highway Design Process.* College Station, TX: Texas Transportation Institute, 2005.
6. **Van Schalkwyk, I. and S. Washington.** *Cost Effective Safety Improvements on Two-Lane Rural State Roads in Washington State*. Olympia, WA: Washington State Department of Transportation, Report No. WA-RD 695.1, 2008.
7. **Idaho Transportation Department, Office of Highway Safety** (ITD- OHS). "WebCARS." http://apps.itd.idaho.gov/apps/webcars/ (Accessed March 2010).
8. **Idaho Transportation Department.** "Roadway Data Section." http://itd.idaho.gov/planning/roadwaydata/ (Accessed March 2010).
9. **Hauer, E.** *Observational Before–After Studies in Road Safety: Estimating the Effect of Highway and Traffic Engineering Measures on Road Safety*. London: Pergamon Publications, 1997.
10. **Hauer, E., D. W. Harwood, F. M. Council, and M. S. Griffith**. "Estimating Safety by the Empirical Bayes Method: A Tutorial." Transportation Research Record: Journal of the Research Board, No. 1784, (2002): 126–131.
11. **Torbic, D. J., J. M. Hutton, C. D. Bokenkroger, K. M. Bauer, D. W. Harwood, D. K. Gilmore, J. M. Dunn, J. J. Ronchetto, E. T. Donnell, H. J. Sommer, P. Garvey, B. Persaud, and C. Lyon.** *Guidance for the Design and Application of Shoulder and Centerline Rumble Strips*. Washington, D.C.: Transportation Research Board, NCHRP Report 641, 2009.
12. **Harwood, D. W., F. M. Council, E. Hauer, W. E. Hughes and A. Vogt.** *Prediction of Expected Safety Performance of Rural Two-Lane Highways*. McLean, VA: Federal Highway Administration, Report No. FHWA-RD-99-207, 2000.
13. **Sayed, T., P. DeLeur, and J. Pump.** *Impact of Rumble Strips on Collision Reduction on Highways in British Columbia: Comprehensive Before and After Safety Study*. Washington D.C.: Transportation Research Board, Annual Meeting 2010 Paper 10-0107, 2010.
14. **Patel, R. B., F. M. Council, and M. S. Griffith.** "Estimating Safety Benefits of Shoulder Rumble Strips on Two-Lane Rural Highways in Minnesota: Empirical Bayes Observational Before-and-After Study." *Transportation Research Record: Journal of the Transportation Research Board*, No 2019, (2007): 205–211.

15. **Persaud, B. N., R. A. Retting, and C. A. Lyon.** "Crash Reduction Following Installation of Centerline Rumble Strips on Rural Two-Lane Roads." *Crash Analysis & Prevention*, Vol. 36, No. 6, (Nov. 2004): 1073–1079.
16. **Srinivasan, R., J. Baek, and F. Council.** "Safety Evaluation of Transverse Rumble Strips on Approaches to Stop Controlled Intersections in Rural Areas." Washington D.C.: Transportation Research Board, Annual Meeting 2010 Paper No. 10-1141, 2010.
17. **Srinivasan, R., B. Persaud, K. A. Eccles, D. L. Carter, and J. Baek.** *Safety Evaluation of Improved Curve Delineation with Signing Enhancements*. Washington D.C.: Transportation Research Board Annual Meeting 2010 Paper No. 10-3568, 2010.
18. **Feldman, M., J. G. Manzi, and M. F. Mitman.** "An Empirical Bayesian evaluation of the Safety Effects of High-Visibility School (Yellow) Crosswalks in San Francisco." In *Transportation Research Board 89th Meeting*. CD-ROM. Transportation Research Board, Washington, D.C., 2010.
19. **Federal Highway Administration.** *Synthesis of Shoulder Rumble Strip Practices and Policies*. Washington D.C.: Federal Highway Administration, 2005. http://safety.fhwa.dot.gov/roadway_dept/rumble/synthesis/exec_summary.htm (Accessed July 2009).
20. **Griffith, M. S.** "Safety Evaluation of Rolled-In Continuous Shoulder Rumble Strips Installed on Freeways." *Transportation Research Record: Journal of the Transportation Research Board*, No. 1665, (1999): 28–34.
21. **Marvin, R. R., and D. J. Clark.** *An Evaluation of Shoulder Rumble Strips in Montana*. Helena MT: Montana Department of Transportation, 2003.
22. **Smith, E. B., and J. N. Ivan.** "Evaluation of Safety Benefits and Potential Crash Migration Due to Shoulder Rumble Strip Installation on Connecticut Freeways." *Transportation Research Record: Journal of the Transportation Research Board*, No. 1908 (2005): 104–113.
23. **Garder, P. E., and M. Davies.** "Safety Effect of Continuous Shoulder Rumble Strips on Rural Intersections in Maine." *Transportation Research Record: Journal of the Transportation Research Board,* No. 1953 (2006): 156–162

Appendix A.
Statistical Methods Used

Naïve Before-and-After Analysis

In Naïve before-and-after analysis, the crash counts for a location before and after a treatment are compared to assess the safety benefit attributed to a treatment. The crash data for the treatment sites are assumed to follow the Poisson distribution. In Naïve before-and-after analysis, the duration of the before period and the after period should be the same. If it is not the same, a ratio of duration (r_d) parameter needs to be incorporated in the analysis. Where:

$$r_d = \frac{\text{Duration of after period for entity i}}{\text{Duration of before period for entity i}}$$

Figure 11. Ratio of Duration Terms

If for the treatment group sites the actual crash counts for the "before period" is K and for the "after period" is L, then:

$$\kappa = r_d \times K,\ \lambda = L$$

Figure 12. Expected Number of Crashes

where:

κ	=	Estimate of the expected number of before crash counts for treatment group sites.
λ	=	Estimate of the expected number of after crash counts for treatment group sites.

The expected number of crashes (π) during the "after period" without the treatment can be predicted by using Figure 13.

$$\pi = \kappa$$

Figure 13. Expected Number of Crashes in "After Period" for the Treatment Site If There Had Not Been Any Treatment (Naïve Method)

The variances of the estimates are computed using Figure 14 and Figure 15.

$$\mathrm{VAR}\{\lambda\}=\mathrm{L}$$

Figure 14. Variance of Expected Crashes during the "After Period" with the Treatment

$$\mathrm{VAR}\{\pi\} = \pi$$

Figure 15. Variance of Expected Crashes During the "After Period" Without the Treatment

The change in the number of crashes at the treatment sites can be determined according to Figure 16**.**

$$\delta = \pi - \lambda$$

Figure 16. Change in Number of Crashes Due to Treatment

The overall index of effectiveness (θ) for the treatment is computed using Figure 17.

$$\theta = \frac{\sum \lambda}{\sum \pi}$$

Figure 17. Overall Index of Effectiveness for the Treatment

The unbiased estimate of the index of effectiveness (θ_u) is calculated using Figure 18.

$$\theta_u = \frac{\frac{\sum \lambda}{\sum \pi}}{1 + \frac{\sum \mathrm{VAR}\{\pi\}}{\sum \pi^2}}$$

Figure 18. Unbiased Estimate of the Index of Effectiveness

The percent change in number of crashes due to treatment is calculated using Figure 19.

$$\%\ \text{Change in Crash} = (1 - \theta_u) \times 100\%$$

Figure 19. Percent Change in Number of Crashes Due to Treatment

The variance of the index of effectiveness is computed using Figure 20.

$$\mathrm{VAR}\{\theta\} \simeq \theta_u^2 \times \frac{\left[\frac{\sum \mathrm{Var}\{\lambda\}}{\sum \lambda^2} + \frac{\sum \mathrm{VAR}\{\pi\}}{\sum \pi^2}\right]}{\left[1 + \frac{\sum \mathrm{VAR}\{\pi\}}{\sum \pi^2}\right]^2}$$

Figure 20. Variance of the Index of Effectiveness

If the treatment is effective then the percent change quantity is a positive value, which indicates the reduction in number of crashes due to treatment in place. On the other hand, negative value of percent change indicates increase in crash frequency after the treatment. The standard deviation of the index of effectiveness is calculated from its variance. The standard deviation is calculated to measure the variability of the treatment effect on different sites.

Comparison Group Method

The CG Method uses an untreated comparison site, or group of sites, that has similar road geographic and traffic volume characteristics as the treatment site. In the CG Method comparison site(s) crash data are used to estimate crashes that would have occurred at the treatment sites, during the "after period," if treatments were not in place. According to Hauer, CG Method is based on two assumptions: first, the causal factors change similarly from "before" to "after period" for both the treatment sites and comparison group sites.[9] Second, the changes in the causal factor affect safety of treatment site and comparison sites in a similar way.

Based on these two assumptions, two comparison ratio terms are introduced in the CG analysis. They are:

$$r_C = \frac{\nu}{\mu}$$

$$r_T = \frac{\pi}{\kappa}$$

where:

r_C	=	Ratio of the expected number of crashes for the comparison group sites.
r_T	=	Ratio of the expected crash counts for the treatment sites.
μ	=	Estimate of the expected number of before crash counts for comparison group sites.
ν	=	Estimate of the expected number of after crash counts for comparison group sites.
κ	=	Estimate of the expected number of before crash counts for treatment group sites.
λ	=	Estimate of the expected number of after crash counts for treatment group sites.

Figure 21. Comparison Ratios for CG Analysis

Crash data needs to be used for the same number of years for the treatment on comparison sites. When the years for the before-and-after periods vary, a ratio of duration term (r_d) needs to be incorporated in the analysis. Where:

$$r_d = \frac{\text{Duration of after period for entity i}}{\text{Duration of before period for entity i}}$$

Figure 22. Ratio of Duration Terms

If the actual crash counts for all before-and-after periods are M and N for the comparison group sites and K and L for the treatment group sites, respectively, then:

$$\mu = r_d \times M, \nu = N, \ \kappa = r_d \times K, \text{and } \lambda = L$$

Figure 23. Expected Number of Crashes

The expected number of crashes (π) during the “after period” without the treatment for the treatment sites can be predicted by using Figure 24.

$$\pi = r_T \times \kappa$$

Figure 24. Expected Number of Crashes (π) During the “After Period” Without the Treatment

Based on the two assumptions for CG Method:

$$r_C = r_T = \frac{\frac{\nu}{\mu}}{1 + \frac{1}{\mu}} \simeq \frac{\nu}{\mu}$$

Figure 25. Ratio of Expected Number of Crashes

Therefore, Figure 24 can be modified to Figure 26 to estimate the expected number of crashes (π) during the “after period”:

$$\pi = r_C \times \kappa$$

Figure 26. Expected Number of Crashes (π) During the “After Period” for the Treatment Site If There Had Not Been Any Treatment (CG Method)

The variances of the estimates are computed using Figure 27 and Figure 28.

$$\mathrm{VAR}\{\lambda\} = L$$

Figure 27. Variance of Expected Crashes During the “After Period” With the Treatment (CG Method)

$$\frac{\mathrm{VAR}\{r_T\}}{r_T^2} \simeq \frac{1}{M} + \frac{1}{N}$$

Figure 28. Variance of the Ratio of the Expected Crashes for the Treatment Sites

$$\mathrm{VAR}\{\pi\} \simeq \pi^2 \times \left[\frac{1}{K} + \frac{\mathrm{VAR}\{r_T\}}{r_T^2}\right]$$

Figure 29. Variance of Expected Crashes During the “After Period” Without the Treatment (CG Method)

The change in the number of crashes at the treatment sites can be determined according to Figure 16. The overall index of effectiveness (θ) is calculated by comparing the expected number of crashes in the "after period" without the treatment to the actual number of crashes in the "after period." The overall index of effectiveness (θ) for the treatment is computed using Figure 17. The unbiased estimate of the index of effectiveness (θ_u) is calculated using Figure 18. The percent change in number of crashes due to treatment is calculated using Figure 19. The variance of the index of effectiveness is computed using Figure 20.

If the treatment is effective, then the percent change quantity is a positive value. This indicates a reduction in number of crashes due to treatment in place. Conversely, a negative percent change value indicates an increase in crash frequency post-treatment. The standard deviation of the index of effectiveness is calculated from its variance. The standard deviation is calculated to measure the variability of the treatment effect on different sites. Safety estimation using CG Method depends on the selection of the comparison group. Although this method considers different causal factors that change with time, it has limitations in overcoming the regression-to-the-mean bias.

Empirical Bayes Method

The EB Method can overcome the limitation of the CG Method by accounting for the regression-to-the-mean effect. It also accounts for traffic volume changes and factors that change with time that affect crash occurrence. Such factors can be weather, crash reporting practices, and driving habits. The EB Method for estimating safety increases the precision of estimation and corrects for the regression-to-the-mean bias. This method is based on the recognition that crash counts are not the only measure of safety for an entity.

To estimate the expected number of crashes in the treatment site without treatment (π), two trends are considered with the EB Method:

- The crash trend at the treatment site prior to the treatment installation.
- The safety performance or crash trends at similar sites, referred to as control sites, that did not have any treatment during the analysis period.

A statistical model has been developed for modeling the safety performance function (SPF) at control sites. The SPF is a mathematical model that relates the dependent variable crash frequency of a road entity to independent variables, such as traffic volume and geometric characteristics of the entity. Literature shows that the Poisson and the Negative Binomial (NB) regression models have been extensively studied and developed for crash data analysis. However, the over-dispersion characteristics of crash data suggest that Poisson distribution is inadequate for crash data. NB distribution assumes the mean of Poisson distribution is gamma distributed. The NB regression model takes into account the over-dispersion parameter, and presently it is common to assume that the crash data comes from a negative binomial distribution.

In this study, a generalized linear modeling (GLM) approach has been used to develop SPF. The GENMOD procedure in the Statistical Analysis Software (SAS) allows the specification of a negative binomial distribution by fitting a generalized linear model to the data by maximum likelihood estimation of the parameters.

Safety performance or crash trends at control sites are taken into account in the SPF. The SPF used in this study for two-lane rural highway is shown in Figure 30. For rural freeways, a different SPF equation was considered. The road curviness and paved right shoulder widths show a larger variability within two-lane rural highways; there is a limited amount of variability within the rural freeways. The SPF used in this study for freeway is shown in Figure 31.

$$E\{\kappa_{i,y}\} = \alpha_y . r_j . psw_k . d . V^{\beta} \text{ (Two – Lane Rural Highways)}$$

Figure 30. SPF for Two-Lane Rural Highways

$$E\{\kappa_{i,y}\} = d . V^{\beta} \text{ (Rural Freeways)}$$

where:

$E\{\kappa_{i,y}\}$ = Estimate of crash frequency of the treatment site 'i' using safety performance function

α_y = Yearly factor model parameter that captures the influence of yearly changes except traffic volume

r_j = Road curvature type model parameter that captures the variability based on road curviness(i.e. j=1,2,3)

psw_k = Paved right shoulder width parameter for shoulder width 'k' feet that captures the variability based on paved right shoulder width

d = Length of the segment in miles

V = Annual Average Daily Traffic Volume

B = Model parameter that determines how crash frequency changes with traffic volume

Figure 31. SPF for Rural Freeways

The variance of the expected crash frequency is found using Figure 32.

$$\mathrm{Var}(\mathrm{E}\{\kappa_{\,\mathrm{i,y}}\}) = \frac{(\mathrm{E}\{\kappa\,\mathrm{i,y}\})^2}{\mathrm{b}}$$

where:

b = Over dispersion for negative binomial distribution

Figure 32. Variance of Expected Crashes Using SPF

In SAS software, the dispersion (ϕ) is found directly as an output with model parameters, and the relation between the dispersion and 'b' is shown in Figure 33.

$$\mathrm{b} = \frac{1}{\varphi}$$

where:

π = Expected number of crashes in the "after period" without the treatment

λ = Actual number of crashes reported in the "after period"

Figure 33. Relation Between Dispersion and Model Parameter 'b'

In the EB Method, estimate clues, from the historical crash counts of the treatment site and of the safety performance of the control sites, are taken into account using a parameter weight (ω). This weight determines the significance of two clues mentioned earlier. Parameter weight of the EB estimate is calculated using Figure 34. The EB estimate of crash frequency and its variance for the "before period" (i.e. before the treatment had taken place) is calculated using Figure 35 and Figure 36, respectively.

$$\omega_{\mathrm{i}} = \frac{1}{1 + \frac{\mathrm{Var}(\mathrm{E}\{\kappa_{\mathrm{i}}\})_{\mathrm{b}}}{(\mathrm{E}\{\kappa_{\mathrm{i}}\})_{\mathrm{b}}}}$$

Figure 34. Parameter Weight of EB Method

$$(\mathrm{EB_i})_{\mathrm{b}} = \omega_{\mathrm{i}}.\sum(\mathrm{E}\{\kappa_{\mathrm{i}}\})_{\mathrm{b}} + (1 - \omega_{\mathrm{i}}).\sum \mathrm{K_i}$$

Figure 35. EB Estimate of Crashes During the "Before Period"

$$\mathrm{Var}(\mathrm{EB_i})_\mathrm{b} = (1 - \omega_\mathrm{i}).(\mathrm{EB_i})_\mathrm{b}$$

where,

ω_i = Relative weight of Empirical Bayes Estimate and $0 \leq$ Weight $(\omega_i) \leq 1$

$(EB_i)_b$ = Empirical Bayes estimates of crash count for treatment site 'i' during the "before periods"

$Var(EBi)_b$= Variance of Empirical Bayes estimate for the "before period"

$E\{\kappa_i\}_b$ = Estimate of crash frequency of the treatment site 'i' using an SPF for the "before period"

$Var(E\{\kappa i\}_b)$= Variance of $E\{\kappa i\}_b$ for the treatment site 'i' during the "before period"

$\sum E\{\kappa i\}_b$ = Sum of estimate of crash frequency of the treatment site 'i' using an SPF for all "before periods"

$\sum K_i$ = Sum of the observed crash counts for entity 'i' during the "before periods"

Figure 36. Variance of EB Estimate of Crashes During the "Before Period"

A major assumption of the EB Methodology is that the safety performance model equation captures regularity on the time series for a specific entity. Using Figure 37, the expected number of crashes in the "after period" for the treatment site, if there had not been any treatment (π), is calculated. The variance of the estimate is calculated using Figure 38.

$$\pi = (\mathrm{EB_i})_\mathrm{a} = (\mathrm{EB_i})_\mathrm{b} * \frac{(\mathrm{E}\{\kappa_\mathrm{i}\})_\mathrm{a}}{(\mathrm{E}\{\kappa_\mathrm{i}\})_\mathrm{b}}$$

Figure 37. Expected Number of Crashes in the "After Period" for the Treatment Site If There Had Not Been Any Treatment (EB Method)

$$\mathrm{Var}(\mathrm{EB_i})_a = \mathrm{Var}(\mathrm{EB_i})_b * \frac{(\mathrm{E}\{\kappa_i\})_a{}^2}{(\mathrm{E}\{\kappa_i\})_b{}^2}$$

where:

π = EB estimate of expected crash frequency of the treated entity ‘i’ in the “after period” if there had been no treatment

$\mathrm{Var}(\mathrm{EB_i})_a$ = Variance of EB estimates of expected crash frequency of the treated entity ‘i’ in the “after period” if there had been no treatment

$(\mathrm{E}\{\kappa_i\})_a$= Estimate of crash frequency of the treatment site ‘i’ using an SPF for the “after period”

$(\mathrm{E}\{\kappa_i\})_b$= Estimate of crash frequency of the treatment site ‘i’ using an SPF for the “before period”

Figure 38. Variance of EB Estimate of Crashes During the “After Period”

The change in the number of crashes at the treatment sites can be determined according to Figure 16. The overall index of effectiveness (θ) is calculated by comparing the expected number of crashes in the “after period” without the treatment to the actual number of crashes in the “after period”. The overall index of effectiveness (θ) for the treatment is computed using Figure 17. The unbiased estimate of the index of effectiveness (θ_u) is calculated using Figure 18. The percent change in number of crashes due to treatment is calculated using Figure 19. The variance of the index of effectiveness is computed using Figure 20.

If the treatment is effective, then the percent change is a positive value, which indicates the reduction in number of crashes is due to treatment in place. Conversely, a negative value in the percent change indicates an increase in crash frequency post- treatment. The standard deviation of the index of effectiveness is calculated from its variance. The standard deviation is calculated to measure the variability of the treatment effect on different sites.

Appendix B
Control Sites Characteristics

Table 30. Two-Lane Highway Control Sites Details of All Passenger-Car ROR Crashes

Segment	Length (mile)	Road curvature type	Yearly Crash Per Segment									Yearly AADT Per Segment								
			2001	2002	2003	2004	2005	2006	2007	2008	2009	2001	2002	2003	2004	2005	2006	2007	2008	2009
1	5.00	3	1	4	1	1	3	1	2	1	1	1015	1000	1001	967	898	855	841	739	936
2	5.00	3	1	2	2	0	0	1	0	1	0	1015	1000	1001	967	898	855	841	739	936
3	5.00	2	0	0	1	1	0	1	1	0	1	677	667	668	645	599	570	561	493	624
4	5.00	3	2	0	1	0	1	0	1	0	1	677	667	668	645	599	570	561	493	624
5	5.00	3	0	1	0	2	1	0	2	0	0	677	667	668	645	599	570	561	493	624
6	5.00	3	0	0	2	1	1	2	2	1	0	677	667	668	645	599	570	561	493	624
7	0.96	2	0	1	0	0	0	0	0	0	0	677	667	668	645	599	570	561	493	624
8	2.87	1	0	0	1	0	1	1	2	2	2	3530	3640	3650	3897	3966	4170	4000	3793	4220
9	2.82	1	1	0	2	1	0	1	0	1	0	3530	3640	3650	3897	3966	4170	1600	3793	4220
10	4.98	2	0	0	0	0	1	1	0	0	0	2035	2002	2007	2143	2181	2293	2200	2086	2321
11	5.00	2	0	2	0	1	0	0	1	1	3	1480	1456	1460	1559	1587	1668	1600	1517	1688
12	5.00	2	0	2	1	1	0	1	1	0	1	1572	1547	1551	1656	1686	1772	1700	1612	1794
13	5.51	3	0	1	2	0	2	0	1	0	1	1757	1729	1734	1851	1884	1981	1900	1802	2005
14	4.63	1	3	1	1	2	2	2	1	1	1	5228	5145	5159	5508	5606	5894	5655	5361	5969
15	5.00	2	0	1	0	3	6	2	4	1	1	1829	1800	1808	1900	1931	1968	2039	1961	1955
16	5.00	2	0	0	2	0	0	2	0	2	2	1829	1800	1808	1900	1931	1968	2039	1961	1955
17	5.00	1	0	0	0	0	0	1	1	1	0	1829	1800	1808	1900	1931	1968	2039	1961	1955
18	5.00	2	4	1	0	1	2	0	2	0	0	1829	1800	1808	1900	1931	1968	2039	1961	1955
19	4.65	2	0	1	0	2	0	0	1	1	3	2243	2207	2217	2330	2368	2413	2500	2405	2397
20	4.12	2	3	0	1	2	0	0	1	0	0	4677	4541	4561	4793	4872	4965	5200	4794	4965
21	5.00	2	1	0	0	0	1	0	1	1	0	1432	1524	1547	1576	1651	1650	1651	1457	1513
22	5.00	2	0	0	0	1	0	0	0	0	0	1432	1524	1547	1576	1651	1650	1651	1457	1513
23	5.00	3	1	1	1	0	0	0	0	0	0	1432	1524	1547	1576	1651	1650	1651	1457	1513
24	5.00	3	0	1	1	0	0	2	0	0	0	1432	1524	1547	1576	1651	1650	1651	1457	1513
25	5.00	1	0	0	0	1	0	0	1	0	1	1432	1524	1547	1576	1651	1650	1651	1457	1513
26	5.00	2	1	0	1	0	2	1	2	1	2	5073	5397	5455	5377	5259	5433	5377	5089	4894
27	5.00	1	0	0	2	2	0	1	0	0	4	5073	5397	5455	5377	5259	5433	5377	5089	4894
28	5.00	1	1	0	1	1	0	0	1	0	0	3600	3740	3780	3726	3644	3765	3796	3525	3660
29	5.00	2	2	2	0	3	0	3	2	0	0	3600	3740	3780	3726	3644	3765	3796	3525	3660
30	5.00	1	3	2	3	1	2	0	4	0	1	5414	5676	5758	5905	5876	5991	6010	5590	5912

Table 30 (Cont.). Two-Lane Highway Control Sites Details of All Passenger-Car ROR Crashes

Segment	Length (mile)	Road curvature type	Yearly Crash Per Segment									Yearly AADT Per Segment								
			2001	2002	2003	2004	2005	2006	2007	2008	2009	2001	2002	2003	2004	2005	2006	2007	2008	2009
31	5.00	3	6	5	3	3	1	0	2	0	3	3175	3182	3349	3362	3437	3521	3617	3291	3446
32	5.00	2	0	3	1	2	0	0	1	0	1	3175	3182	3349	3362	3437	3521	3617	3291	3446
33	5.00	2	2	0	0	3	2	0	1	0	2	3175	3182	3349	3362	3437	3521	3617	3291	3446
34	5.00	2	1	1	1	1	0	0	2	2	0	1856	1974	2040	2072	2077	2145	2207	1961	2003
35	5.00	2	0	0	1	0	0	0	0	0	0	1856	1974	2040	2072	2077	2145	2207	1961	2003
36	5.00	3	0	0	0	0	1	0	2	3	0	1576	1645	1690	1761	1798	1866	1907	1643	1654
37	5.00	3	5	1	3	2	1	0	2	1	0	1576	1645	1690	1761	1798	1866	1907	1643	1654
38	5.00	2	2	1	1	3	1	1	1	1	0	1576	1645	1690	1761	1798	1866	1907	1643	1654
39	5.00	2	0	0	1	0	0	0	0	1	1	1576	1645	1690	1761	1798	1866	1907	1643	1654
40	5.00	3	2	2	5	4	2	1	0	1	1	1576	1645	1690	1761	1798	1866	1907	1643	1654
41	5.00	2	2	0	3	0	0	0	2	1	0	2193	2288	2334	2273	2213	2315	2335	2158	2249
42	5.00	2	1	1	1	2	0	1	1	1	0	2193	2288	2334	2273	2213	2315	2335	2158	2249
43	5.00	2	1	1	1	0	0	0	1	0	0	1879	1898	1967	1979	1942	2008	2038	1845	1931
44	5.00	3	0	1	5	1	1	0	1	1	0	1879	1898	1967	1979	1942	2008	2038	1845	1931
45	5.00	3	0	0	1	1	0	2	0	1	0	1879	1898	1967	1979	1942	2008	2038	1845	1931
46	4.09	3	2	0	2	2	0	0	0	1	0	1879	1898	1967	1979	1942	2008	2038	1845	1931
47	5.00	3	1	3	1	1	0	0	1	2	1	1879	1898	1967	1979	1942	2008	2038	1845	1931
48	5.00	2	2	3	1	2	0	1	2	0	1	1879	1898	1967	1979	1942	2008	2038	1845	1931
49	5.00	2	0	0	0	0	0	1	1	0	0	1879	1898	1967	1979	1942	2008	2038	1845	1931
50	5.00	1	1	1	1	1	0	2	1	1	0	2788	2908	2943	2969	2941	2960	2972	2790	2927
51	2.41	1	0	0	2	1	0	0	1	0	0	2788	2908	2943	2969	2941	2960	2972	2790	2927
52	5.00	2	3	2	3	3	2	4	2	3	5	2816	2883	2846	2824	2803	2735	2743	2848	3019
53	5.00	2	1	2	2	1	3	3	2	2	1	2598	2620	2688	2768	2683	2734	2763	2638	2830
54	5.00	2	0	1	2	2	0	0	2	2	0	2598	2620	2688	2768	2683	2734	2763	2638	2830
55	5.00	2	1	2	1	0	0	3	1	2	3	2598	2620	2688	2768	2683	2734	2763	2638	2830
56	5.00	2	4	3	3	1	1	0	1	2	1	2598	2620	2688	2768	2683	2734	2763	2638	2830
57	5.00	2	2	2	2	1	5	1	1	1	1	2598	2620	2688	2768	2683	2734	2763	2638	2830
58	5.00	3	1	0	0	1	0	0	1	1	0	2598	2620	2688	2768	2683	2734	2763	2638	2830

Table 31. Two-Lane Highway Control Sites Details of Passenger-Car Severe ROR Crashes

Segment	Length (mile)	Road curvature type	Yearly Crash Per Segment									Yearly AADT Per Segment								
			2001	2002	2003	2004	2005	2006	2007	2008	2009	2001	2002	2003	2004	2005	2006	2007	2008	2009
1	5.00	3	0	2	0	1	2	0	0	1	0	1015	1000	1001	967	898	855	841	739	936
2	5.00	3	1	1	1	0	0	0	0	0	0	1015	1000	1001	967	898	855	841	739	936
3	5.00	2	0	0	0	0	0	0	0	0	0	677	667	668	645	599	570	561	493	624
4	5.00	3	0	0	0	0	0	0	0	0	0	677	667	668	645	599	570	561	493	624
5	5.00	3	0	0	0	1	0	0	0	0	0	677	667	668	645	599	570	561	493	624
6	5.00	3	0	0	0	0	0	0	1	1	0	677	667	668	645	599	570	561	493	624
7	0.96	2	0	1	0	0	0	0	0	0	0	677	667	668	645	599	570	561	493	624
8	2.87	1	0	0	1	0	0	0	1	1	2	3530	3640	3650	3897	3966	4170	4000	3793	4220
9	2.82	1	0	0	0	0	0	0	0	0	0	3530	3640	3650	3897	3966	4170	1600	3793	4220
10	4.98	2	0	0	0	0	0	1	0	0	0	2035	2002	2007	2143	2181	2293	2200	2086	2321
11	5.00	2	0	0	0	0	0	0	1	1	3	1480	1456	1460	1559	1587	1668	1600	1517	1688
12	5.00	2	0	0	0	0	0	0	0	0	1	1572	1547	1551	1656	1686	1772	1700	1612	1794
13	5.51	3	0	0	0	0	0	0	0	0	1	1757	1729	1734	1851	1884	1981	1900	1802	2005
14	4.63	1	0	0	0	0	1	1	0	0	1	5228	5145	5159	5508	5606	5894	5655	5361	5969
15	5.00	2	0	0	1	0	0	0	0	0	1	1829	1800	1808	1900	1931	1968	2039	1961	1955
16	5.00	2	0	0	0	0	0	0	1	0	2	1829	1800	1808	1900	1931	1968	2039	1961	1955
17	5.00	1	1	1	0	0	1	0	0	0	0	1829	1800	1808	1900	1931	1968	2039	1961	1955
18	5.00	2	0	0	0	0	0	0	0	0	0	1829	1800	1808	1900	1931	1968	2039	1961	1955
19	4.65	2	0	0	0	0	0	0	0	0	3	2243	2207	2217	2330	2368	2413	2500	2405	2397
20	4.12	2	0	0	1	1	0	0	0	0	0	4677	4541	4561	4793	4872	4965	5200	4794	4965
21	5.00	2	0	0	0	0	0	0	1	0	0	1432	1524	1547	1576	1651	1650	1651	1457	1513
22	5.00	2	0	0	0	0	0	0	0	0	0	1432	1524	1547	1576	1651	1650	1651	1457	1513
23	5.00	3	0	0	0	0	0	0	0	0	0	1432	1524	1547	1576	1651	1650	1651	1457	1513
24	5.00	3	0	1	0	0	0	0	0	0	0	1432	1524	1547	1576	1651	1650	1651	1457	1513
25	5.00	1	0	0	0	1	0	0	0	0	0	1432	1524	1547	1576	1651	1650	1651	1457	1513
26	5.00	2	0	0	0	0	1	0	0	0	0	5073	5397	5455	5377	5259	5433	5377	5089	4894
27	5.00	1	0	0	0	0	0	0	0	0	0	5073	5397	5455	5377	5259	5433	5377	5089	4894
28	5.00	1	0	0	0	0	0	0	0	0	0	3600	3740	3780	3726	3644	3765	3796	3525	3660
29	5.00	2	1	1	0	3	0	1	0	0	0	3600	3740	3780	3726	3644	3765	3796	3525	3660
30	5.00	1	1	0	1	1	0	0	0	0	0	5414	5676	5758	5905	5876	5991	6010	5590	5912

Table 31 (Cont.) Two-Lane Highway Control Sites Details of Passenger-Car Severe ROR Crashes

Segment	Length (mile)	Road curvature type	Yearly Crash Per Segment									Yearly AADT Per Segment								
			2001	2002	2003	2004	2005	2006	2007	2008	2009	2001	2002	2003	2004	2005	2006	2007	2008	2009
31	5.00	3	1	0	0	0	0	0	0	0	0	3175	3182	3349	3362	3437	3521	3617	3291	3446
32	5.00	2	0	0	0	0	0	0	1	0	0	3175	3182	3349	3362	3437	3521	3617	3291	3446
33	5.00	2	0	0	0	1	0	0	0	0	0	3175	3182	3349	3362	3437	3521	3617	3291	3446
34	5.00	2	1	0	0	0	0	0	1	0	0	1856	1974	2040	2072	2077	2145	2207	1961	2003
35	5.00	2	0	0	1	0	0	0	0	0	0	1856	1974	2040	2072	2077	2145	2207	1961	2003
36	5.00	3	0	0	0	0	1	0	1	0	0	1576	1645	1690	1761	1798	1866	1907	1643	1654
37	5.00	3	0	0	2	0	0	0	1	0	0	1576	1645	1690	1761	1798	1866	1907	1643	1654
38	5.00	2	0	0	0	1	0	0	0	0	0	1576	1645	1690	1761	1798	1866	1907	1643	1654
39	5.00	2	0	0	0	0	0	0	0	0	0	1576	1645	1690	1761	1798	1866	1907	1643	1654
40	5.00	3	0	0	0	1	0	1	0	0	0	1576	1645	1690	1761	1798	1866	1907	1643	1654
41	5.00	2	0	0	1	0	0	0	1	0	0	2193	2288	2334	2273	2213	2315	2335	2158	2249
42	5.00	2	1	0	0	0	0	0	0	0	0	2193	2288	2334	2273	2213	2315	2335	2158	2249
43	5.00	2	0	1	0	0	0	0	0	0	0	1879	1898	1967	1979	1942	2008	2038	1845	1931
44	5.00	3	0	0	2	1	0	0	0	0	0	1879	1898	1967	1979	1942	2008	2038	1845	1931
45	5.00	3	0	0	0	0	0	1	0	0	0	1879	1898	1967	1979	1942	2008	2038	1845	1931
46	4.09	3	0	0	1	1	0	0	0	1	0	1879	1898	1967	1979	1942	2008	2038	1845	1931
47	5.00	3	0	0	0	0	0	0	0	0	0	1879	1898	1967	1979	1942	2008	2038	1845	1931
48	5.00	2	0	0	0	0	0	1	1	0	0	1879	1898	1967	1979	1942	2008	2038	1845	1931
49	5.00	2	0	0	0	0	0	0	0	0	0	1879	1898	1967	1979	1942	2008	2038	1845	1931
50	5.00	1	0	0	1	1	0	0	1	0	0	2788	2908	2943	2969	2941	2960	2972	2790	2927
51	2.41	1	0	0	1	1	0	0	0	0	0	2788	2908	2943	2969	2941	2960	2972	2790	2927
52	5.00	2	0	1	0	1	0	1	0	0	1	2816	2883	2846	2824	2803	2735	2743	2848	3019
53	5.00	2	1	0	0	0	0	0	0	0	1	2598	2620	2688	2768	2683	2734	2763	2638	2830
54	5.00	2	0	0	0	1	0	0	1	0	0	2598	2620	2688	2768	2683	2734	2763	2638	2830
55	5.00	2	0	1	0	0	0	0	0	0	1	2598	2620	2688	2768	2683	2734	2763	2638	2830
56	5.00	2	0	0	1	0	0	0	0	0	0	2598	2620	2688	2768	2683	2734	2763	2638	2830
57	5.00	2	0	1	1	0	0	0	0	0	0	2598	2620	2688	2768	2683	2734	2763	2638	2830
58	5.00	3	0	0	0	0	0	0	0	0	0	2598	2620	2688	2768	2683	2734	2763	2638	2830

Table 32. Two-Lane Highway Control Sites Details of All Truck ROR Crashes

Segment	Length (mile)	Road curvature type	Yearly Crash Per Segment									Yearly AADT Per Segment								
			2001	2002	2003	2004	2005	2006	2007	2008	2009	2001	2002	2003	2004	2005	2006	2007	2008	2009
1	5.00	3	0	1	0	0	0	0	1	0	0	1015	1000	1001	967	898	855	841	739	936
2	5.00	3	0	1	0	0	0	0	0	1	0	1015	1000	1001	967	898	855	841	739	936
3	5.00	2	0	0	0	0	0	0	0	0	0	677	667	668	645	599	570	561	493	624
4	5.00	3	1	0	0	0	0	0	0	0	0	677	667	668	645	599	570	561	493	624
5	5.00	3	0	0	0	0	0	0	0	0	0	677	667	668	645	599	570	561	493	624
6	5.00	3	3	0	1	2	1	0	1	0	0	677	667	668	645	599	570	561	493	624
7	0.96	2	0	0	0	0	0	0	0	0	0	677	667	668	645	599	570	561	493	624
8	2.87	1	0	0	0	0	0	0	0	0	0	3530	3640	3650	3897	3966	4170	4000	3793	4220
9	2.82	1	0	0	0	0	0	0	0	0	0	3530	3640	3650	3897	3966	4170	1600	3793	4220
10	4.98	2	0	0	0	0	0	0	0	0	0	2035	2002	2007	2143	2181	2293	2200	2086	2321
11	5.00	2	0	0	0	0	0	0	0	0	0	1480	1456	1460	1559	1587	1668	1600	1517	1688
12	5.00	2	0	0	0	0	0	0	0	0	0	1572	1547	1551	1656	1686	1772	1700	1612	1794
13	5.51	3	1	0	0	0	0	0	1	0	0	1757	1729	1734	1851	1884	1981	1900	1802	2005
14	4.63	1	0	0	0	0	0	0	0	0	0	5228	5145	5159	5508	5606	5894	5655	5361	5969
15	5.00	2	0	0	0	0	0	0	0	1	1	1829	1800	1808	1900	1931	1968	2039	1961	1955
16	5.00	2	0	0	0	1	0	0	0	0	0	1829	1800	1808	1900	1931	1968	2039	1961	1955
17	5.00	1	0	0	0	1	0	0	0	0	0	1829	1800	1808	1900	1931	1968	2039	1961	1955
18	5.00	2	0	0	0	0	0	0	0	0	0	1829	1800	1808	1900	1931	1968	2039	1961	1955
19	4.65	2	0	0	0	0	0	0	0	0	0	2243	2207	2217	2330	2368	2413	2500	2405	2397
20	4.12	2	0	0	0	0	0	0	0	0	0	4677	4541	4561	4793	4872	4965	5200	4794	4965
21	5.00	2	1	0	0	0	0	0	0	0	0	1432	1524	1547	1576	1651	1650	1651	1457	1513
22	5.00	2	1	1	0	0	0	0	0	0	0	1432	1524	1547	1576	1651	1650	1651	1457	1513
23	5.00	3	0	0	0	0	0	0	0	0	0	1432	1524	1547	1576	1651	1650	1651	1457	1513
24	5.00	3	0	0	0	0	0	0	0	0	0	1432	1524	1547	1576	1651	1650	1651	1457	1513
25	5.00	1	0	0	0	0	0	0	0	0	0	1432	1524	1547	1576	1651	1650	1651	1457	1513
26	5.00	2	0	0	0	0	0	0	0	2	0	5073	5397	5455	5377	5259	5433	5377	5089	4894
27	5.00	1	0	0	0	0	0	0	0	0	1	5073	5397	5455	5377	5259	5433	5377	5089	4894
28	5.00	1	0	0	0	0	0	0	0	0	0	3600	3740	3780	3726	3644	3765	3796	3525	3660
29	5.00	2	0	0	0	0	0	0	0	0	0	3600	3740	3780	3726	3644	3765	3796	3525	3660
30	5.00	1	0	1	0	0	0	0	1	0	0	5414	5676	5758	5905	5876	5991	6010	5590	5912

Table 32 (Cont.) Two-Lane Highway Control Sites Details of All Truck ROR Crashes

Segment	Length (mile)	Road curvature type	Yearly Crash Per Segment									Yearly AADT Per Segment								
			2001	2002	2003	2004	2005	2006	2007	2008	2009	2001	2002	2003	2004	2005	2006	2007	2008	2009
31	5.00	3	0	0	0	1	0	0	0	0	0	3175	3182	3349	3362	3437	3521	3617	3291	3446
32	5.00	2	0	0	0	0	1	0	1	0	1	3175	3182	3349	3362	3437	3521	3617	3291	3446
33	5.00	2	2	1	0	0	0	0	0	1	0	3175	3182	3349	3362	3437	3521	3617	3291	3446
34	5.00	2	0	0	0	0	0	0	0	0	0	1856	1974	2040	2072	2077	2145	2207	1961	2003
35	5.00	2	0	0	0	0	0	0	0	0	0	1856	1974	2040	2072	2077	2145	2207	1961	2003
36	5.00	3	1	0	0	0	1	0	0	0	0	1576	1645	1690	1761	1798	1866	1907	1643	1654
37	5.00	3	0	1	0	1	1	1	1	0	0	1576	1645	1690	1761	1798	1866	1907	1643	1654
38	5.00	2	0	0	0	1	1	1	1	0	0	1576	1645	1690	1761	1798	1866	1907	1643	1654
39	5.00	2	0	0	0	0	0	0	0	0	0	1576	1645	1690	1761	1798	1866	1907	1643	1654
40	5.00	3	1	2	0	0	1	1	0	0	0	1576	1645	1690	1761	1798	1866	1907	1643	1654
41	5.00	2	1	0	0	0	1	1	1	0	0	2193	2288	2334	2273	2213	2315	2335	2158	2249
42	5.00	2	0	1	0	0	0	0	0	0	0	2193	2288	2334	2273	2213	2315	2335	2158	2249
43	5.00	2	0	0	0	0	0	0	0	0	0	1879	1898	1967	1979	1942	2008	2038	1845	1931
44	5.00	3	1	0	0	0	1	0	0	0	0	1879	1898	1967	1979	1942	2008	2038	1845	1931
45	5.00	3	0	0	1	1	0	0	1	0	0	1879	1898	1967	1979	1942	2008	2038	1845	1931
46	4.09	3	0	0	1	0	0	1	0	0	0	1879	1898	1967	1979	1942	2008	2038	1845	1931
47	5.00	3	0	0	0	0	1	0	0	0	0	1879	1898	1967	1979	1942	2008	2038	1845	1931
48	5.00	2	0	0	0	1	0	0	0	0	0	1879	1898	1967	1979	1942	2008	2038	1845	1931
49	5.00	2	0	0	0	0	0	0	0	0	0	1879	1898	1967	1979	1942	2008	2038	1845	1931
50	5.00	1	0	0	0	0	0	0	2	0	0	2788	2908	2943	2969	2941	2960	2972	2790	2927
51	2.41	1	0	0	0	1	0	0	0	0	1	2788	2908	2943	2969	2941	2960	2972	2790	2927
52	5.00	2	0	0	0	0	0	0	0	0	0	2816	2883	2846	2824	2803	2735	2743	2848	3019
53	5.00	2	0	0	0	0	0	0	0	0	0	2598	2620	2688	2768	2683	2734	2763	2638	2830
54	5.00	2	0	0	0	0	0	0	0	0	0	2598	2620	2688	2768	2683	2734	2763	2638	2830
55	5.00	2	0	0	0	0	0	0	0	0	0	2598	2620	2688	2768	2683	2734	2763	2638	2830
56	5.00	2	1	0	0	0	0	0	0	0	1	2598	2620	2688	2768	2683	2734	2763	2638	2830
57	5.00	2	0	0	0	0	0	1	1	1	1	2598	2620	2688	2768	2683	2734	2763	2638	2830
58	5.00	3	0	0	0	0	0	0	0	0	0	2598	2620	2688	2768	2683	2734	2763	2638	2830

Table 33. Four-Lane Highway Control Sites Details of All Passenger-Car ROR Crashes

Segment	Length (mile)	Yearly Crash Per Segment									Yearly AADT Per Segment								
		2001	2002	2003	2004	2005	2006	2007	2008	2009	2001	2002	2003	2004	2005	2006	2007	2008	2009
1	0.64	1	2	0	0	0	2	1	1	0	10399	10677	10541	10460	10380	10294	10158	10042	10391
2	3.06	2	0	0	0	1	1	0	0	0	10399	10677	10541	10460	10380	10294	10158	10042	10391
3	6.53	5	3	2	4	4	3	3	3	4	6020	6220	6289	6252	6150	6178	6078	5946	6243
4	5.00	2	4	3	2	2	1	1	2	5	6020	6220	6289	6252	6150	6178	6078	5946	6243
5	5.00	1	2	3	0	1	0	2	2	0	6020	6220	6289	6252	6150	6178	6078	5946	6243
6	5.00	0	3	3	2	2	2	4	3	3	30815	29798	30809	32823	34293	32992	30847	29405	29680

Table 34. Four-Lane Highway Control Sites Details of Passenger-Car Severe ROR Crashes

Segment	Length (mile)	rash Per Segment									Yearly AADT Per Segment								
		2001	2002	2003	2004	2005	2006	2007	2008	2009	2001	2002	2003	2004	2005	2006	2007	2008	2009
1	0.64	0	0	0	0	0	0	0	0	0	10399	10677	10541	10460	10380	10294	10158	10042	10391
2	3.06	0	0	0	0	0	0	0	0	0	10399	10677	10541	10460	10380	10294	10158	10042	10391
3	6.53	0	1	0	0	0	1	0	2	0	6020	6220	6289	6252	6150	6178	6078	5946	6243
4	5.00	0	1	1	0	1	0	0	0	1	6020	6220	6289	6252	6150	6178	6078	5946	6243
5	5.00	0	0	0	0	0	0	0	0	0	6020	6220	6289	6252	6150	6178	6078	5946	6243
6	5.00	0	0	1	0	0	0	0	0	0	30815	29798	30809	32823	34293	32992	30847	29405	29680

Table 35. Four-Lane Highway Control Sites Details of All Truck ROR Crashes

Segment	Length (mile)	Yearly Crash Per Segment									Yearly AADT Per Segment								
		2001	2002	2003	2004	2005	2006	2007	2008	2009	2001	2002	2003	2004	2005	2006	2007	2008	2009
1	0.64	0	0	0	0	0	0	0	0	0	10399	10677	10541	10460	10380	10294	10158	10042	10391
2	3.06	0	0	0	0	0	0	0	0	0	10399	10677	10541	10460	10380	10294	10158	10042	10391
3	6.53	0	0	0	0	0	0	0	1	0	6020	6220	6289	6252	6150	6178	6078	5946	6243
4	5.00	0	0	1	0	0	0	0	0	0	6020	6220	6289	6252	6150	6178	6078	5946	6243
5	5.00	0	0	0	0	0	0	0	0	0	6020	6220	6289	6252	6150	6178	6078	5946	6243
6	5.00	0	0	0	0	0	0	0	0	0	30815	29798	30809	32823	34293	32992	30847	29405	29680

Table 36. Freeway Control Sites Details of All Passenger-Car ROR Crashes

Segment	Length (mile)	Yearly Crash Counts per Segment						Yearly AADT per Segment					
		2004	2005	2006	2007	2008	2009	2004	2005	2006	2007	2008	2009
1	5.00	0	3	2	0	1	1	8836	8858	9017	9244	8770	9391
2	5.00	1	4	0	0	1	4	8836	8858	9017	9244	8770	9391
3	2.40	1	2	0	1	1	1	8836	8858	9017	9244	8770	9391
4	1.00	1	0	0	1	0	0	7964	7914	8109	8330	7902	8423
5	3.38	5	5	9	8	7	7	36828	28475	42132	42505	40239	40967
6	5.00	8	9	9	9	11	4	36828	28475	42132	42505	40239	40967
7	5.00	11	13	9	19	12	6	76829	77538	78789	78597	72107	69008
8	3.69	18	16	9	9	7	5	76829	77538	78789	78597	72107	69008
9	4.19	8	14	7	6	8	8	60239	60795	61776	61625	56537	54107
10	3.95	2	7	7	2	1	6	21008	20606	21340	22093	19666	20658
11	5.00	2	3	5	8	2	2	20841	20422	21150	22077	19575	19944
12	5.00	6	7	5	9	4	4	20841	20422	21150	22077	19575	19944
13	5.00	9	4	6	4	5	3	13335	13608	14204	14334	13376	13800
14	5.00	4	5	6	10	5	7	13335	13608	14204	14334	13376	13800
15	5.00	6	11	8	8	8	7	13335	13608	14204	14334	13376	13800
16	5.00	12	9	12	5	7	9	13335	13608	14204	14334	13376	13800
18	1.09	0	2	0	0	0	1	13335	13608	14204	14334	13376	13800
19	3.87	9	10	7	7	8	5	35141	35816	37531	37159	34196	36278
20	0.90	2	2	0	0	0	3	11724	10892	11406	11396	10489	10976
21	1.56	2	0	0	2	0	0	11724	10892	11406	11396	10489	10976
22	3.22	3	4	1	5	2	5	9774	9080	9505	9500	8741	9150
23	1.07	0	1	1	0	2	1	7199	7231	7356	7500	6901	7149
24	0.59	0	0	0	1	0	0	6364	6392	6503	6657	6101	6320

Table 37. Freeway Control Sites Details of Passenger–Car Injury Type A and Fatal ROR Crashes

Segment	Length (mile)	Yearly Crash Counts per Segment						Yearly AADT per Segment					
		2004	2005	2006	2007	2008	2009	2004	2005	2006	2007	2008	2009
1	5.00	0	1	0	0	0	0	8836	8858	9017	9244	8770	9391
2	5.00	0	1	0	0	1	0	8836	8858	9017	9244	8770	9391
3	2.40	0	0	0	0	0	0	8836	8858	9017	9244	8770	9391
4	1.00	0	0	0	0	0	0	7964	7914	8109	8330	7902	8423
5	3.38	1	0	2	0	1	1	36828	28475	42132	42505	40239	40967
6	5.00	2	2	0	0	2	0	36828	28475	42132	42505	40239	40967
7	5.00	1	0	3	3	2	0	76829	77538	78789	78597	72107	69008
8	3.69	2	2	0	1	0	0	76829	77538	78789	78597	72107	69008
9	4.19	1	2	0	2	3	0	60239	60795	61776	61625	56537	54107
10	3.95	0	0	1	1	0	0	21008	20606	21340	22093	19666	20658
11	5.00	0	0	2	2	2	0	20841	20422	21150	22077	19575	19944
12	5.00	1	1	2	2	2	2	20841	20422	21150	22077	19575	19944
13	5.00	0	2	2	1	4	0	13335	13608	14204	14334	13376	13800
14	5.00	0	0	0	4	1	4	13335	13608	14204	14334	13376	13800
15	5.00	1	2	3	1	1	6	13335	13608	14204	14334	13376	13800
16	5.00	5	3	4	1	2	2	13335	13608	14204	14334	13376	13800
18	1.09	0	0	0	0	0	0	13335	13608	14204	14334	13376	13800
19	3.87	1	0	1	1	0	1	35141	35816	37531	37159	34196	36278
20	0.90	0	0	0	0	0	0	11724	10892	11406	11396	10489	10976
21	1.56	1	0	0	0	0	0	11724	10892	11406	11396	10489	10976
22	3.22	0	0	0	2	0	1	9774	9080	9505	9500	8741	9150
23	1.07	0	0	0	0	0	0	7199	7231	7356	7500	6901	7149
24	0.59	0	0	0	0	0	0	6364	6392	6503	6657	6101	6320

Table 38. Freeway Control Sites Details of All Truck ROR Crashes

Segment	Length (mile)	Yearly Crash Counts per Segment						Yearly AADT per Segment					
		2004	2005	2006	2007	2008	2009	2004	2005	2006	2007	2008	2009
1	5.00	0	1	0	0	0	0	8836	8858	9017	9244	8770	9391
2	5.00	0	0	0	0	0	0	8836	8858	9017	9244	8770	9391
3	2.40	0	1	0	0	0	0	8836	8858	9017	9244	8770	9391
4	1.00	0	0	0	0	0	0	7964	7914	8109	8330	7902	8423
5	3.38	0	0	0	0	0	1	36828	28475	42132	42505	40239	40967
6	5.00	3	0	0	1	0	1	36828	28475	42132	42505	40239	40967
7	5.00	0	0	1	1	0	0	76829	77538	78789	78597	72107	69008
8	3.69	0	0	0	0	0	0	76829	77538	78789	78597	72107	69008
9	4.19	0	2	0	0	2	1	60239	60795	61776	61625	56537	54107
10	3.95	0	0	1	0	0	0	21008	20606	21340	22093	19666	20658
11	5.00	1	0	0	0	0	0	20841	20422	21150	22077	19575	19944
12	5.00	0	0	0	1	0	0	20841	20422	21150	22077	19575	19944
13	5.00	1	0	0	2	0	2	13335	13608	14204	14334	13376	13800
14	5.00	1	0	1	2	0	0	13335	13608	14204	14334	13376	13800
15	5.00	0	0	0	1	2	0	13335	13608	14204	14334	13376	13800
16	5.00	1	0	1	3	3	0	13335	13608	14204	14334	13376	13800
18	1.09	0	0	0	0	0	0	13335	13608	14204	14334	13376	13800
19	3.87	0	0	1	0	1	0	35141	35816	37531	37159	34196	36278
20	0.90	0	0	0	0	0	0	11724	10892	11406	11396	10489	10976
21	1.56	0	1	0	0	0	0	11724	10892	11406	11396	10489	10976
22	3.22	0	0	0	0	1	0	9774	9080	9505	9500	8741	9150
23	1.07	0	0	0	0	0	1	7199	7231	7356	7500	6901	7149
24	0.59	0	0	0	1	0	0	6364	6392	6503	6657	6101	6320

Appendix C
SAS Code Files

SAS Code 1: Two-Lane Highway All ROR Crash

```
data TwoLaneHW ;
 infile 'U:\2 Lane HW\2001-2010_allcrash.csv' delimiter=',' firstobs = 2;
 input segment year length rshoulderw rdegree aadt crashes ;
 loglength=log(length);
 logaadt=log(aadt);
 rshoulder = rshoulderw ;

 if rshoulderw le 1 then rshoulder = 1 ;
 if rshoulderw ge 7 then rshoulder = 7 ;
 run ;

proc print ; run ;

proc freq data = TwoLaneHW ; run ;

proc genmod data= TwoLaneHW;
class year rshoulder rdegree;
model crashes=year rshoulder rdegree logaadt/ offset=loglength
   dist=negbin link=log type3 ;

 output out = TwoLaneHW  p = pred resdev = rdev  stdresdev = strdev resraw = rawres
         leverage = hat cooksd = cook ;
 run ;
 proc plot data = TwoLaneHW vpercent = 85 ;
  plot strdev*pred strdev*hat strdev*logaadt strdev*rshoulder strdev*rdegree ;
  run ;
run ;
```

SAS Code 2: Freeway All ROR Crash

```
data Interstates;

 infile 'U:\Interstates\2004-2010_allcrash.csv' delimiter=','firstobs = 2;
 input segment length aadt crashes ;
 loglength=log(length);
 logaadt=log(aadt);
 run ;

proc print ; run ;

proc genmod data= Interstates;
model crashes= logaadt/ offset=loglength
   dist=negbin link=log type3 ;

 output out = Interstates  p = pred resdev = rdev  stdresdev = strdev resraw = rawres
         leverage = hat cooksd = cook ;
 run ;
 proc plot data = Interstates vpercent = 85 ;
  plot strdev*pred strdev*hat strdev*logaadt;
  run ;
run ;
```

Appendix D
Standardized Residual Plots

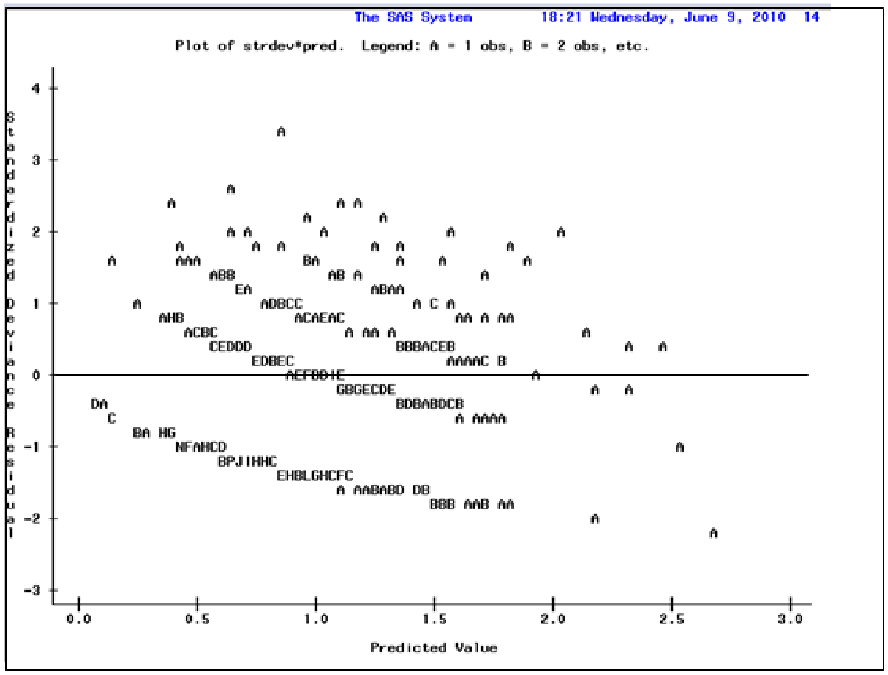

Figure 39. Standardized Residual Plot for Predicted Value

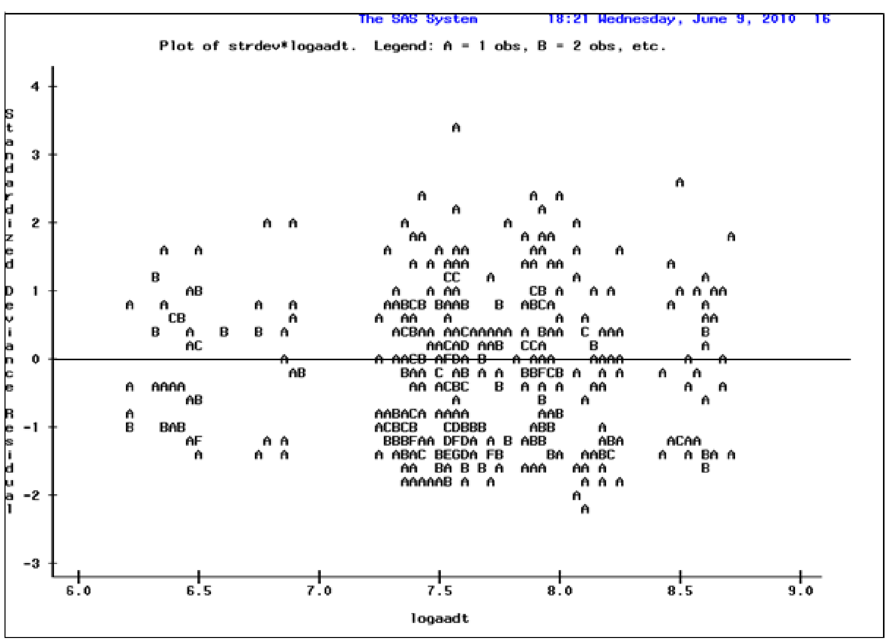

Figure 40. Standardized Residual Plot for AADT

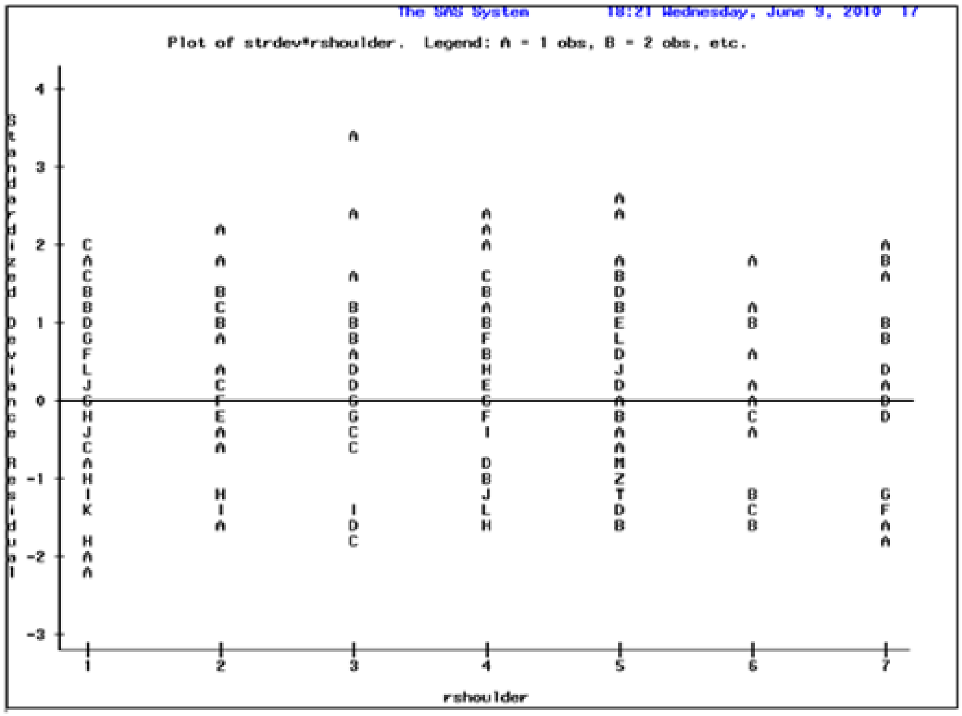

Figure 41. Standardized Residual Plot for Paved Right Shoulder Width

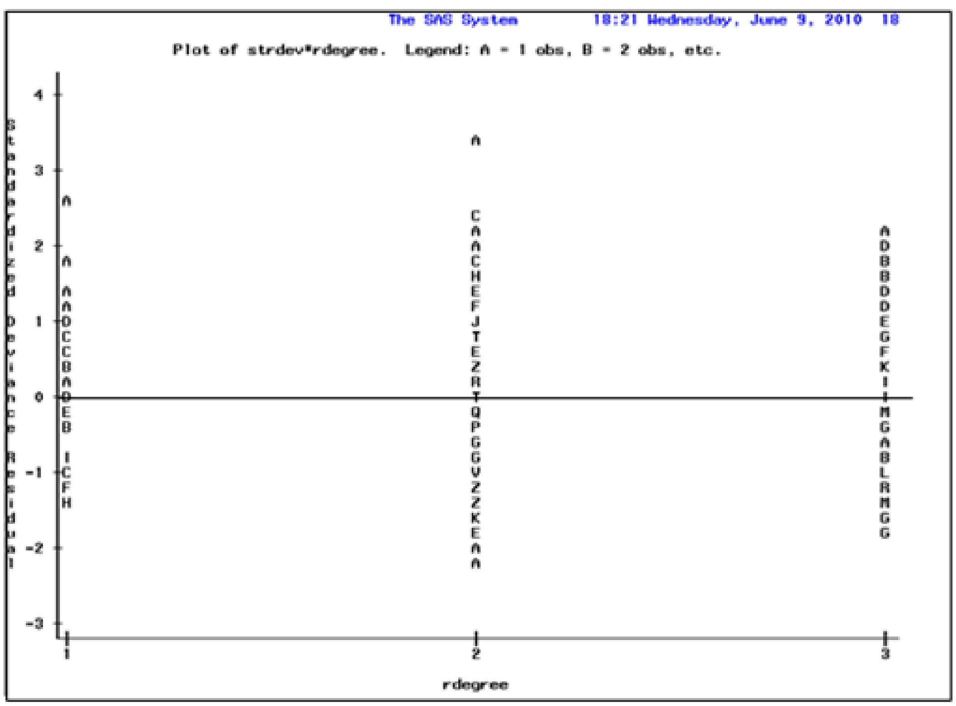

Figure 42. Standardized Residual Plot for Road

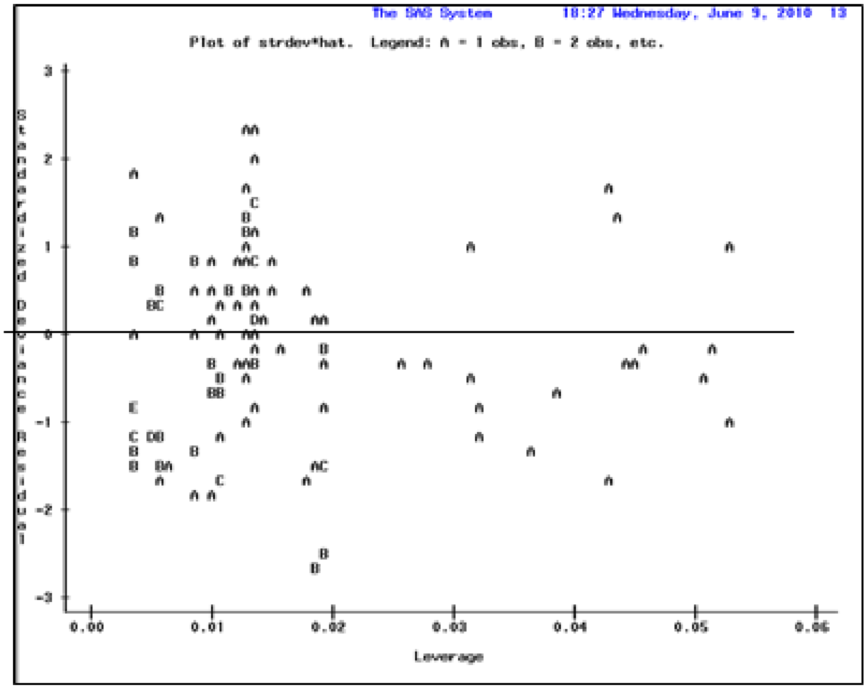

Figure 43. Diagnostic Test (Freeway All ROR Crashes)

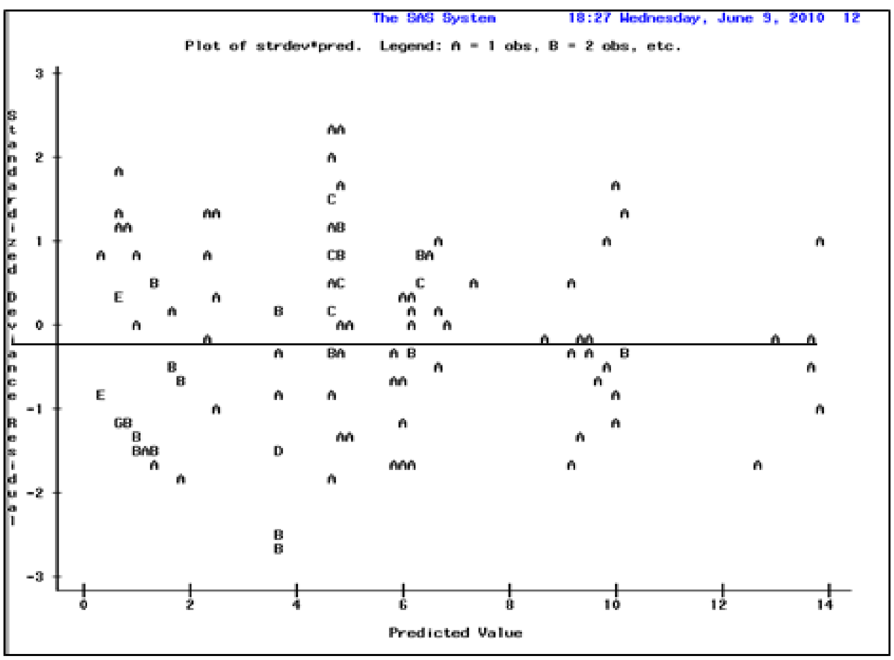

Figure 44. Standardized Residual Plot for Predicted Value (Freeway All ROR Crashes)

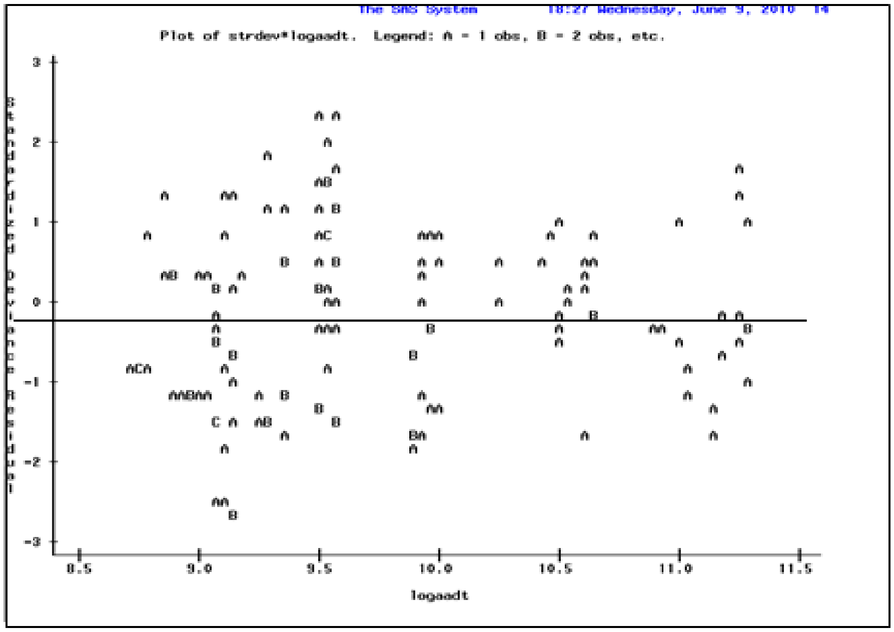

Figure 45. Standardized Residual Plot for AADT (Freeway All ROR Crashes)

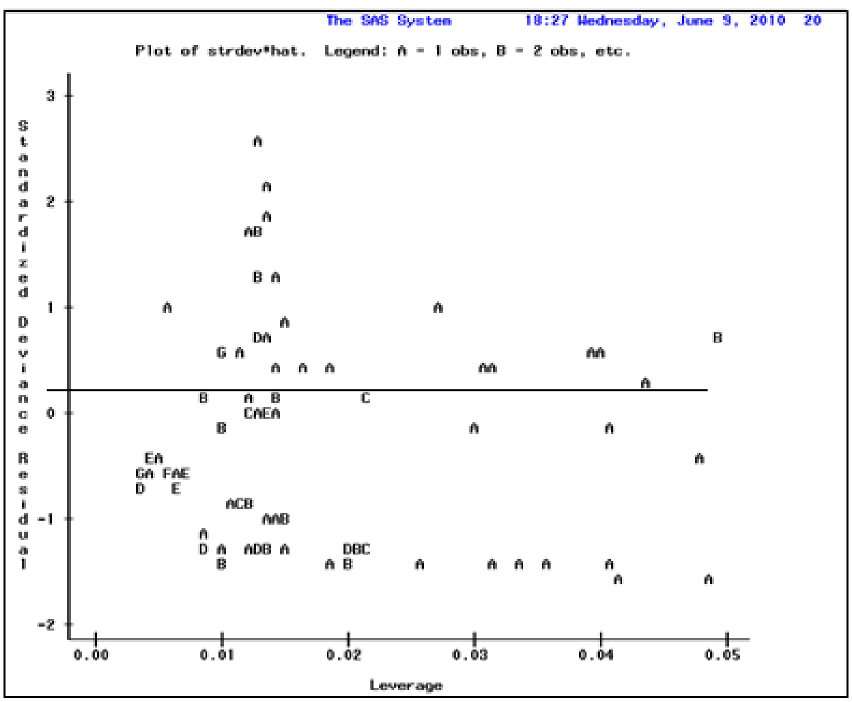

Figure 46. Diagnostic Test (Freeway Severe ROR Crashes)

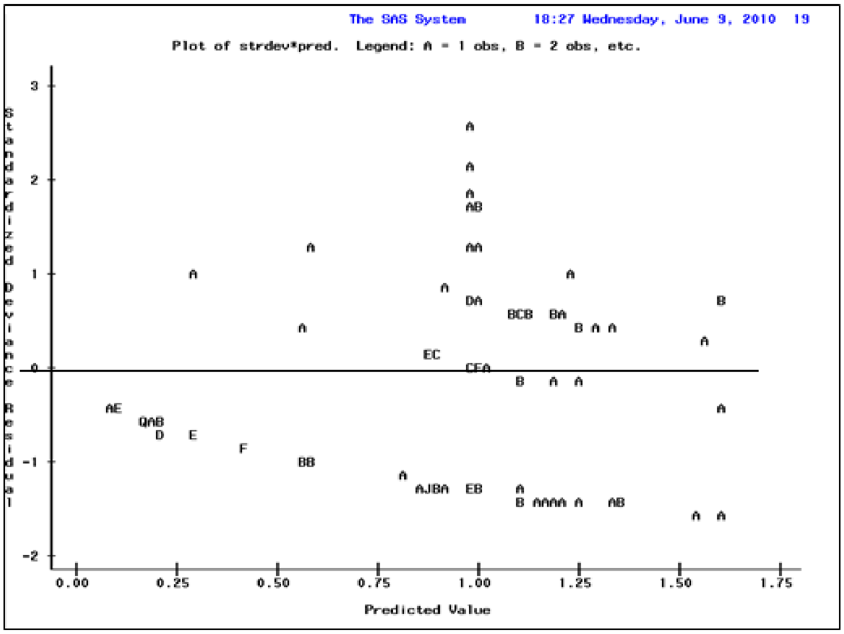

Figure 47. Standardized Residual Plot for Predicted Value (Freeway Severe ROR Crashes)

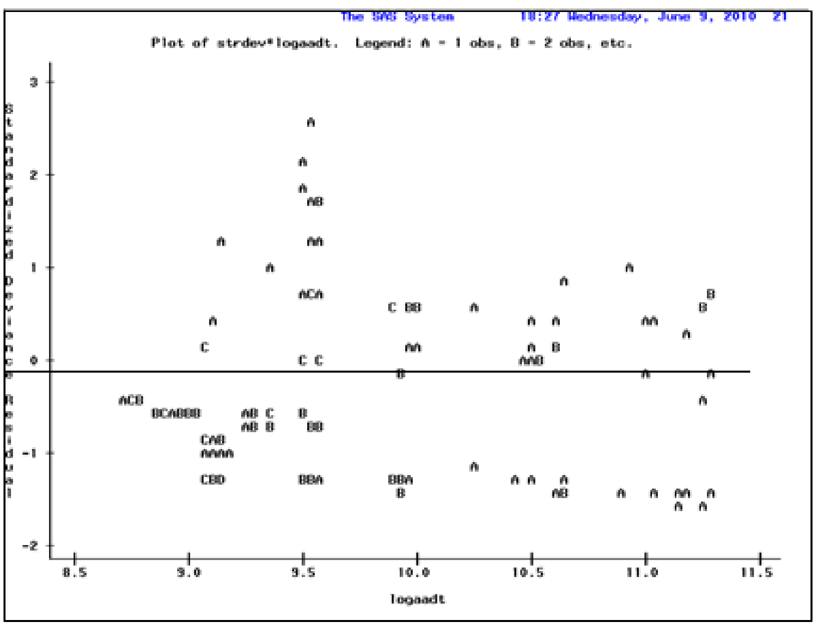

Figure 48. Standardized Residual Plot for AADT (Freeway Severe ROR Crashes)