NDOT Research Report

Report No: RDT07-001

Evaluating the Effectiveness of Continuous Shoulder Rumble Strips in Reducing "Ran-off-roadway" Single-vehicle Crashes

March 2007

Prepared by Research Division
Nevada Department of Transportation
1263 South Stewart Street
Carson City, Nevada 89712

NEVADA DOT

TECHNICAL REPORT DOCUMENTATION PAGE

Report No. RDT07-001		2. Government Accession No.	3. Recipient s Catalog No.
4. Title and Subtitle Evaluating the Effectiveness of Continuous Shoulder Rumble Strips in Reducing “Ran-off-roadway” Single-Vehicle Crashes		5. Report Date: March 2007 6. Performing Organization Code	
7. Author(s) Dr. Shashi Nambisan, Dr. Vinay Vanapalli, Dr. Mukund Dangeti, and Dr. Srinivas S. Pulugurtha		8. Performing Organization Report No.	
9. Performing Organization Name and Address Transportation Research Center University of Nevada, Las Vegas 4505 South Maryland Parkway, Box 454007 Las Vegas, NV 89154-4007 Department of Civil and Environmental Engineering University of North Carolina at Charlotte 9201 University City Boulevard Charlotte, NC 28223-001		10. Work Unit No. 11. Contract or Grant No. P092-05-803	
12. Sponsoring Agency Name and Address Nevada Department of Transportation 1263 South Stewart Carson City, Nevada 89712		13. Type or Report and Period Covered 14. Sponsoring Agency Code NDOT	
15. Supplementary Notes			

16. Abstract

The research efforts presented in this report, prepared for the Nevada Department of Transportation, summarizes the evaluation of the effectiveness of continuous shoulder rumble strip treatment to reduce single-vehicle ran-off-roadway crashes in Nevada. The roadways studied included Interstate freeways, US routes, and state routes (SR) totaling 306 individual segments for a total of 1,303 centerline miles of roadways. Data for the period from 1995 to 2003 were used for the analyses. Key data considered in the analyses included the locations and dates of installation of continuous shoulder rumble strips, crash data, posted speed limits, and average daily traffic volumes. Crash records in Nevada for this period include over 33,000 ran-off-roadway single-vehicle crashes; of those 772 were fatal and 11,976 involved injuries. The crash data was determined for periods before and after the installation of the continuous shoulder rumble strips. Analyses of the data showed that overall the treatment has been effective in reducing the number of crashes and the corresponding crash rates. Linear regression models were developed to relate the crash rates during the “before” period to those during the “after” period. These models indicated that for any given crash rate, the predicted “after” crash rate was lower. The models suggested a reduction in the crash rates with higher values of average daily traffic, wider shoulders, and higher speeds. Roadways with posted speed limits greater than 65 miles/hour (105 kilometers/hour) showed significant improvements after the installation of rumble strips based on crash rates and crash density. An analysis, based on Ezra Hauer’s method for evaluation of safety, indicated that the installation of continuous shoulder rumble strips resulted in a significant reduction in the expected number of crashes on a vast majority of the roadways studied. Regression models developed indicated that the installations of rumble strips typically resulted in a reduction in the crash frequency, rate, or density. A comparison of the mean crash rates for roadways treated with rumble strips using Cox’s method of comparing Poisson means further validated the finding that treatments were effective in reducing the crash rates on all roadways with the exception of one. In summary, the installation of continuous shoulder rumble strips on roadways in Nevada has resulted in improved safety for single-vehicle ran-off-roadway crashes. The outcomes of this research will assist transportation safety managers in Nevada and nationwide to better understand the effectiveness of continuous shoulder rumble strips in reducing ran-off-roadway single-vehicle crashes and identifying opportunities for applications of these rumble strips.

17. Key Words Continuous shoulder rumble stips, Crash frequency, Crash rate, Crash density, Ran-off-roadway crashes, Before-after analyses		18. Distribution Statement Unrestricted. This document is available through the National Technical Information Service, Springfield, VA 21161	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. Of Pages 146	22. Price

TECHNICAL REPORT DOCUMENTATION PAGE

Report No. RDT07-001	2. Government Accession No.	3. Recipient s Catalog No.

4. Title & Subtitle:
Evaluating the Effectiveness of Continuous Shoulder Rumble Strips in Reducing “Ran-off-roadway” Single-vehicle Crashes

5. Report Date
March 2007

6. Performing Organization Code

7. Author(s)
Dr. Shashi Nambisan, Dr. Vinay Vanapalli, Dr. Mukund Dangeti, and Dr. Srinivas S. Pulugurtha

8. Performing Organization Report No.

9. Performing Organization Name and Address
Transportation Research Center
University of Nevada, Las Vegas
4505 South Maryland Parkway, Box 454007
Las Vegas, NV 89154-4007

Department of Civil and Environmental Engineering
University of North Carolina at Charlotte
9201 University City Boulevard
Charlotte, NC 28223-001

10. Work Unit No.

11. Contract or Grant No. P092-05-803

12. Sponsoring Agency Name and Address
Nevada Department of Transportation
1263 South Stewart
Carson City, Nevada 89712

13. Type or Report and Period Covered

14. Sponsoring Agency Code NDOT

15. Supplementary Notes

16. Abstract
The research efforts presented in this report, prepared for the Nevada Department of Transportation, summarizes the evaluation of the effectiveness of continuous shoulder rumble strip treatment to reduce single-vehicle ran-off-roadway crashes in Nevada. The roadways studied included Interstate freeways, US routes, and state routes (SR) totaling 306 individual segments for a total of 1,303 centerline miles of roadways. Data for the period from 1995 to 2003 were used for the analyses. Key data considered in the analyses included the locations and dates of installation of continuous shoulder rumble strips, crash data, posted speed limits, and average daily traffic volumes. Crash records in Nevada for this period include over 33,000 ran-off-roadway single-vehicle crashes; of those 772 were fatal and 11,976 involved injuries. The crash data was determined for periods before and after the installation of the continuous shoulder rumble strips. Analyses of the data showed that overall the treatment has been effective in reducing the number of crashes and the corresponding crash rates. Linear regression models were developed to relate the crash rates during the “before” period to those during the “after” period. These models indicated that for any given crash rate, the predicted “after” crash rate was lower. The models suggested a reduction in the crash rates with higher values of average daily traffic, wider shoulders, and higher speeds. Roadways with posted speed limits greater than 65 miles/hour (105 kilometers/hour) showed significant improvements after the installation of rumble strips based on crash rates and crash density. An analysis, based on Ezra Hauer’s method for evaluation of safety, indicated that the installation of continuous shoulder rumble strips resulted in a significant reduction in the expected number of crashes on a vast majority of the roadways studied. Regression models developed indicated that the installations of rumble strips typically resulted in a reduction in the crash frequency, rate, or density. A comparison of the mean crash rates for roadways treated with rumble strips using Cox’s method of comparing Poisson means further validated the finding that treatments were effective in reducing the crash rates on all roadways with the exception of one. In summary, the installation of continuous shoulder rumble strips on roadways in Nevada has resulted in improved safety for single-vehicle ran-off-roadway crashes. The outcomes of this research will assist transportation safety managers in Nevada and nationwide to better understand the effectiveness of continuous shoulder rumble strips in reducing ran-off-roadway single-vehicle crashes and identifying opportunities for applications of these rumble strips.

17. Key Words
Continuous shoulder rumble stips, Crash frequency, Crash rate, Crash density, Ran-off-roadway crashes, Before-after analyses

18. Distribution Statement
Unrestricted. This document is available through the National Technical Information Service, Springfield, VA 21161

19. Security Classif. (of this report)	19. Security Classif. (of this page)	21. No. Of Pages	22. Price
Unclassified	Unclassified	146	

EXECUTIVE SUMMARY

Single-vehicle ran-off-roadway crashes are of significant concern in Nevada. The research efforts presented in this report, prepared for the Nevada Department of Transportation, summarizes the evaluation of the effectiveness of continuous shoulder rumble strip treatment to reduce such crashes in Nevada. The efforts evaluated crash records involving single-vehicle ran-off-roadway crashes in Nevada on which rumble strips had been installed and were used to evaluate the effectiveness of treatment. The roadways studied included Interstate freeways, US routes, and state routes (SR) totaling 306 individual segments corresponding to a total of 1,303 centerline miles of roadways. Data for the period from 1995 to 2003 were used for the analyses. Key data considered in the analyses included the locations and dates of installation of continuous shoulder rumble strips on roadway segments, crash data, posted speed limits, and average daily traffic volumes. Crash records in Nevada for this period include over 33,000 ran-off-roadway single-vehicle crashes; of those 772 were fatal crashes and 11,976 were injury crashes. The number and rates of single-vehicle ran-off-roadway crashes were determined for periods before and after the installation of the continuous shoulder rumble strips.

Analyses of the data showed that overall the treatment has been effective in reducing single-vehicle ran-off-roadway crashes and the corresponding crash rates. Sixty-eight percent of the segments showed improvements based on crash rates and these segments accounted for 83 percent of the centerline miles of the roadways. Likewise 11 percent of the segments (4 percent of centerline miles) showed no change in crash rates, and 21 percent of the segments (14 percent of the centerline miles) showed worse crash rates. The results based on crash densities were similar: 66 percent of the segments (81 percent of centerline miles) showed improvement, 12 percent of the segments (4 percent of centerline miles) showed no change and 23 percent of the segments (15 percent of centerline miles) experienced higher rates after the installation of the rumble strips. Statistical analyses of the data affirm these findings.

Linear regression models were developed to relate the crash rates during the “before” period to those during the “after” period. These models indicated that for any given crash rate, the predicted “after” crash rate was lower. Though not clearly established, the models developed suggest a reduction in the crash rates with higher values of average daily traffic, wider shoulders, and higher speeds. Roadways with posted speed limits greater than 65 miles/hour (105 kilometers/hour) showed significant improvements after the installation of rumble strips based on crash rates and crash density. As the posted speed limit increases, the crash rates decrease. In general, crash rates decline as the shoulder widths increase; however, no significant relationships between shoulder widths or average daily traffic on single-vehicle ran-off-roadway crashes were discernible from the analyses.

An analysis, based on Ezra Hauer’s method for evaluation of safety, indicated that the installation of continuous shoulder rumble strips resulted in a significant reduction in the expected number of crashes on a vast majority of the roadways studied. Regression models developed indicated that the installations of rumble strips typically resulted in a reduction in the crash frequency, rate, or density on a segment. A comparison of the mean crash rates for roadways treated with rumble strips using Cox’s method of comparing Poisson means further validated the finding that treatments were effective in reducing the crash rates on all roadways with the exception of one, highway SR-160.

In summary, the installation of continuous shoulder rumble strips on roadways in Nevada has resulted in improved safety in terms of single-vehicle ran-off-roadway crash frequencies, rates, and densities. The outcomes of this research will assist transportation safety managers in Nevada and nationwide to better understand the effectiveness of continuous shoulder rumble strips in reducing ran-off-roadway single-vehicle crashes and identifying opportunities for applications of these rumble strips.

TABLE OF CONTENTS

LIST OF TABLES

Appendices:

LIST OF FIGURES

ACKNOWLEDGEMENTS

The project team and the University of Nevada, Las Vegas (UNLV) Transportation Research Center are grateful to the Nevada Department of Transportation (NDOT) for affording us the opportunity to work on the project. Working on the continuous shoulder rumble strips project has been a challenging, exciting, and rewarding experience for the project team. The final outcomes of the project benefited significantly from the help provided by several individuals. Briefly mentioning their names does not completely express our gratitude towards them. The project team would like to express our deepest appreciation to Reed Gibby, Project Manager at NDOT for his help and guidance through the entire project duration. We thank members of the Technical Research Panel: Kelly Anrig (NDOT), Sharon Hansen (FHWA), Melanie Mucha (FHWA), and Scott Thorson (NDOT) for their guidance, support and efforts in reviewing the research project's progress. Also, the project team would like to thank Roma Clewell (NDOT), Tie He (NDOT), and Bryan McCurdy (NDOT) for their role in the successful completion of this project. Further, we extend our appreciation and thanks to Dr. Ashok Singh (UNLV) for his input, guidance, and efforts on statistical analysis of the data. We also appreciate the help provided by the staff of NDOT Contract Records Office for providing us access to the road and geometric relation information. Last but not least; we would like to thank the students and staff at the University of Nevada, Las Vegas Transportation Research Center for all their help and support in completing this project.

1.0 INTRODUCTION

Driving is a task that requires complete attention from the drivers. Fatigue, boredom, and other human and psychological factors contribute to a lack of attention by drivers. Environmental conditions (e.g., the landscape around the roadway), roadway design characteristics, traffic conditions, and length (duration) of the drive are factors that affect driver fatigue and boredom. These factors often result in drivers running off the roadway leading to single-vehicle crashes. Statistics showed that a significant proportion of the single-vehicle crashes were fatal (Taylor and Meczkowski, 2003). Experiments in the states of Alaska, Illinois, Kentucky, Utah, and in other countries have shown that the provision of rumble strips on the paved shoulder area gives an effective warning to the drivers who were about to run off the road (Transportation Research News, 1988). Thus, providing shoulder rumble strips has the potential of saving lives.

In 2002, single-vehicle ran-off-roadway crashes accounted for more than 120 fatalities and 2,400 injuries in the State of Nevada (FHWA Official Website: Facts, Statistics and Data, Safety Section, 2002). The fatalities accounted for more than 30 percent of total fatalities statewide. Likewise, the injury related crashes accounted for more than 15 percent of the total injury crashes statewide. The United States began in the mid-1980s to install and deploy rumble strip treatment as a way to address ran-off-roadway crashes (Chaudoin and Nelson 1985, Ligon et al., 1985). The Nevada Department of Transportation (NDOT) installed continuous shoulder rumble strips along Interstate freeways and highways in urban and rural areas of Nevada to alert the drivers and reduce ran-off-roadway single-vehicle crashes. There was a need to evaluate the effectiveness of these rumble strips in reducing these ran-off-roadway single-vehicle crashes.

The types of rumble strips and the design specifications, such as shoulder widths, are some factors that might affect the effectiveness of continuous shoulder rumble strips in enhancing safety. The major goal of this research project was to develop a methodology and evaluate the effectiveness of different types of rumble strips in reducing ran-off-roadway single-vehicle crashes in Nevada. The following tasks were used for the research effort.

1) Literature Review
2) Develop Methodology
3) Data Collection
4) Test Locations Identification
5) Descriptive Analyses of Single-vehicle Crashes at Test Locations
6) Statistical Analysis

2.0 REVIEW OF LITERATURE

2.1 Overview

This section discusses the findings discovered from the literature review. Rumble strips are intended to alert drivers that they are drifting off the roadway so corrective action might be taken. Research has been done on the different types of rumble strips including design specifications to evaluate their effectiveness. Studies of the adverse effects of the rumble strips report that emphasis was on what bicyclists may face and the noise surrounding neighborhoods might have on increasing roadway tire noise. A summary of different types of continuous shoulder rumble strips, research on effectiveness of rumble strips and their design specifications, adverse effects of shoulder rumble strips, bicyclists reaction, and noise impacts were presented and discussed in detail below.

2.2 Types of Continuous Shoulder Rumble Strips

The different types of continuous shoulder rumble strips that have been previously or are currently being used in the United States include the following: Milled Rumble Strips, Rolled Rumble Strips, Raised Rumble Strips, and Formed Rumble Strips. These types of continuous shoulder rumble strips differ in their method of installation, size, shape, spacing, noise, and vibration they produce (Hickey, 1997). Milled rumble strips (Figure 1) are wider than rolled rumble strips and can be installed on a new or existing pavement and on both flexible and rigid pavements. The milled rumble strips produce greater tire noise and vibration on the pavement structure than rolled or formed rumble strips and, therefore, have little or no integrity on pavement structure. Rolled rumble strips (Figure 2) are installed by pressing a “depression” on freshly placed hot asphalt pavements or on fresh, uncured Portland cement concrete pavements. Raised rumble strips (Figure 3) are pavement markers that adhere to new or existing pavements. The markers are often reflective to define traffic lanes at night and in poor weather. As the rumble strips extend above the pavement, raised rumble strips are usually restricted to warmer climates that do not require snow removal. Formed rumble strips are normally installed on Portland Cement Concrete pavements, but have not been used much during the last decade. In general the installation cost of shoulder rumble strips has reduced significantly and is low as compared to the costs that are saved by the decline in crashes.

Figure 1: Milled Rumble Strips
(Source: http://people.umass.edu/vetri/ThesisProposal.pdf; Accessed November 2004)

Figure 2: Rolled Rumble Strips

(Source: http://people.umass.edu/vetri/ThesisProposal.pdf; Accessed November 2004)

Figure 3: Raised Rumble Strips

(Source: http://www.davidsonplastics.net/whatsnew_arch2.htm; Accessed November 2004)

2.3 Effectiveness of Continuous Shoulder Rumble Strips

Numerous research studies have been performed on shoulder rumble strips since their conception in the mid-1950s. This literature review focused on work performed since 1975. Caltrans, the California Transportation Department, in 1975 added grooved rumble strips to the outside shoulders of a 24-mile section of I-15 next to the Nevada State line. Preliminary results were favorable, and this success led to the installation of shoulder rumble strips in the late 1970s as part of overlaying an additional 130 miles of I-15 and 5 miles of I-40 east of Needles, California. The use of shoulder rumble strips was outlined in the 18th Edition of Caltrans' Traffic Manual under Special Pavement Treatments (Chaudoin and Nelson, 1985).

A chi-squared analyses performed by Ligon on the before-after crash data for rural freeways and expressways with shoulder rumble strips revealed a 19.8 percent decrease in crashes at test sites with shoulder rumble strips as compared to a 9.3 percent increase in crashes at control sites. Their analyses based on crash rates did not show statistically significant differences for the following variables on roadways with textured treatment: 1) high average daily traffic versus low average daily traffic sites, 2) day versus night reduction in accidents, 3) wide versus narrow shoulder textured treatments, and 4) discontinuous versus continuous shoulder textured treatments. One of the main recommendations of the study was to place the textured treatments as close to the edge line as possible on shoulders of the Interstate roadways during the resurfacing (Ligon et al., 1985).

A before-after analysis of 1990-1992 crash data on a Utah road network showed that freeways without shoulder rumble strips experienced a higher rate of ran-off-the-road crashes (33.4 percent) compared to those with shoulder rumble strips (26.9 percent). The study also stated that highway segments with continuous asphalt shoulder rumble strips located near the travel lane experienced lower crash rates than highway segments with Portland cement concrete shoulder rumble strips that were discontinuous (skip pattern) and offset from the travel lane (Cheng et al., 1993).

Sonic Nap Alert Pattern, an innovative type of shoulder rumble strips, was installed in Pennsylvania to decrease the number of crashes caused by drowsy drivers. An evaluation by Wood showed that after installation of Sonic Nap Alert Pattern, drift-off-road accidents decreased by 65 percent (Wood, 1994). In 1997 Hickey conducted a follow up study to Wood's 1994 observations in which he added traffic exposure to compare crash volume, crashes/vehicle-distance-traveled, and made adjustments to account for a decline in all crashes during the study years. Hickey's study also corrected the initially reported crash reduction rate from 70 to 65 percent. The study was carried out on 53 segments accounting for 348 miles along roadways and reported a decline of 2.3 crashes/MVMT (Hickey, 1997).

In 1997, Morgan and McAuliffe conducted a study of the current practice on effectiveness of shoulder rumble strips. The study's objectives were 1) to solicit information on policies and standards of as many agencies as might respond, 2) to summarize the information collected, and 3) to recommend changes as needed for the Department's policy and specifications. It was concluded that milled rumble strips were the most preferred type of rumble strip. The study recommended that factors such as comfort of bicyclist and noise complaints from the neighborhood should be considered while designing rumble strips in future (Morgan and McAuliffe, 1997).

Perrillo evaluated the effectiveness of continuous shoulder rumble strips for the Federal Highway Administration (Perrillo, 1998). Many issues regarding the installation and placement of rumble strips were discussed and the experiences in New York region detailed. It was observed that treatment placed on roadway shoulders reduced the number of crashes, injuries, and fatalities on roadways in New York State by nearly 70 percent. Cost-benefit analyses were conducted and it was concluded that the cost of installing continuous shoulder rumble strips was very low

($0.49/linear meter) when compared to savings due to prevention of crashes. Data collected by the New York State Department of Transportation and the New York State Thruway Authority were utilized by Perrillo to perform a before-after analysis. The results of the analysis for both agencies revealed at least a 65 percent reduction in ran-off-roadway crashes on rural Interstates and parkways due to milled shoulder rumble strips.

Griffith extracted data from California and Illinois and estimated the safety effects of continuous rolled shoulder rumble strips on freeways. To perform this study, treatment and downstream freeway sections were initially analyzed for all fatigue / drowsy crashes. It was not possible to identify all fatigue / drowsy crashes in this dataset; therefore, an alternative analysis was performed using alcohol / drug-impaired drivers as a substitute for fatigued drivers. The results from this analysis estimated that rumble strips reduced single-vehicle ran-off-roadway crashes on average by 18.3 percent on all freeways, with no regard to urban / rural classification, and 21.1 percent on rural freeways (Griffith, 1999).

A Marvin & Associates study in 2003 for the Montana Department of Transportation on 393 Interstate miles indicated a 14 percent reduction on crash rates and 23.5 percent reduction on severity rates on the Interstates. The study estimated the benefit-cost ratio for the construction of rumble strips on Interstates to be 19.5. A shoulder rumble strip driver survey was also conducted as part of the study, which indicated that 95 percent of the drivers were aware of the concept of rumble strips and most of them liked the benefits that rumble strips provide (Marvin & Associates, 2003).

Annino attempted to measure the safety benefits achieved from rumble strips along roadways in Connecticut. Safety benefits were considered to be a factor in the reduction in single-vehicle, fixed object, ran-off-the-roadway crashes. The results indicated that the number of rumble strip related single-vehicle, fixed object, ran-off-the-road crashes decreased as did the number of "asleep" and “injury / fatal” crashes. The study incorporated a methodology that used comparative sections to predict the "what if" scenario of the number of crashes that would have occurred if rumble strips had not been installed. The statistical analysis calculated an Index of Effectiveness based on crash data for the rumble strip and comparison sections. The Index of Effectiveness showed a decrease in “rumble strip related” crashes for the collected accident data. This study used the Comparison Group methodology to predict rumble strip crashes, without reference to causal factors, such as, driver behavior, crash reporting, and traffic counts. The study concludes with guidance to researchers about causal factors, such as traffic that can be incorporated into future rumble strip studies (Annino, 2003).

2.4 Design Features

Design features of shoulder rumble strips could play a key role in alerting drivers and reducing ran-off-roadway single-vehicle crashes. A few researchers have focused on this aspect and are discussed next.

Chen performed an analysis of milled, rolled, and formed shoulder rumble strips at 112 locations on two Interstate highways in Virginia. A portion of the report was devoted to a theoretical analysis of tire drop, which was used to help determine rumble strip effectiveness. The analysis showed that tire drop could be up to 50 times greater for milled rumble strips than rolled rumble strips at 65 miles/hour (105 kilometers/hour). Chen concluded that milled rumble strips were more effective than rolled rumble strips since they produced 12.5 times more vibration stimulus and 3.35 times more auditory stimulus. Finally, a survey conducted by Chen found that an increasing number of jurisdictions believe rolled rumble strips have very little effect on truck drivers (Chen, 1994).

A study was performed by the California Department of Transportation (Bucko et. Al., Caltrans, 2001) of various shoulder rumble strip designs and five prototypes of incised or pressed rumble strip configurations. Six test vehicles, ranging from a compact automobile to large commercial vehicles were used to collect auditory and vibration data while traversing the various shoulder rumble strips. Two test drivers were asked to subjectively rate characteristics of the various test patterns based on the drivers' perspective. Fifty-five bicyclists of various skill levels and ages volunteered to evaluate the shoulder rumble strip designs. The recommendation of the study was to replace the existing rolled rumble strip design with a milled rumble strips design that was 1 foot (300 millimeters) in transverse width and 5/16 ± 1/16 inches (8 ± 1.5 millimeters) in depth on shoulders that were at least 5 feet (1.5 meters) wide. For shoulders less than this width, the installation of raised / inverted profile thermoplastic was recommended.

The Pennsylvania Department of Transportation researched milled rumble strip patterns that were found to be safe and effective for bicyclists and motorists on non-freeway roads (Elefteriadou, 2000). After an assessment of the Pennsylvania Department of Transportation rumble strip patterns, 25 alternatives were developed and evaluated. Then a simulation model was developed and validated. Researchers focused on determining optimum groove width and spacing between grooves. The simulation model favored potential configurations with narrow grooves, 4 to 5 inches (102 to 127 millimeters) in width.

A study was conducted on the effectiveness of rumble strips in the State of Missouri. The study recommended that the rumble strips only be used on rural roadways and on urban highways in cases where the ran-off-roadway crash history exceeds the acceptable values (Spring, 2003). The study suggested that the rumble strips were more effective when speed limits exceed 45 miles/hour (72 kilometers/hour); the uninterrupted length of the highway rumble strip installations should be more than 1/30 of the design speed; and for non-freeways, the shoulder width should be more than 2 feet (610 millimeters) wide to install rumble strips. Spring also suggested several modifications in rumble strip dimensions such as milled-in shoulder rumble strips with 5 inch (127 millimeter) grooves, 7/16 inches (11 millimeters) deep, on 12 inches (305 millimeters) spacing, and for all freeways continuous strips that are 16 inches (406 millimeters) wide and 6 inches (152 millimeters) offset from the shy line.

In 2005 a study by Hirasawa examined centerline rumble strips of various specifications to determine the sound and vibration generated for each rumble strip specification. These strips were also investigated by driving vehicles on a test track to determine whether the rumble strips posed a danger to 2-wheel vehicles running on the strips and to survey the subjective danger felt by drivers of 2-and 4-wheel vehicles running on the strips. The optimal size was determined to be a longitudinal width of 150 millimeters (6 inch), transverse width of 1 foot 2 inches (350 millimeters), and depth of ½ inch (12 millimeters). A noise level of 80 decibels was produced inside the vehicle, which was of sufficient volume to warrant a warning. The study concluded that the installation of centerline rumble strips showed a 55.2 percent reduction in head-on collisions. The study also stated that the installation of centerline rumble strips was very cost-effective considering its low installation cost (Hirasawa et al., 2005).

2.5 Adverse Effects of Continuous Shoulder Rumble Strips

Along with the advantages, the use of shoulder rumble strips has some adverse effects on the road users (FHWA Online Library: Rumble Strips, 2006). They were:

1. Roadways introduced with shoulder rumble strips will have a reduction in effective shoulder widths for the road user.
2. Shoulder rumble strips can cause discomfort to bicyclists who ride over them and can cause loss of control of the bicycle, which is a serious safety issue (Perrillo, 1998). Although bicyclists usually travel on the shoulder outside of the rumble strip, they occasionally need to cross it; for example, to make a left turn or avoid debris.
3. For safety reasons, cyclists need to maintain a straight line, as well as, a substantial shy distance from the rumble strips. Hence, shoulder rumble strips may force bicyclists to use a travel lane resulting in a hazardous situation.

4. Vehicles often cause annoyance to nearby neighborhoods because of the tire noise produced when vehicles travel on shoulder rumble strips (Perrillo, 1998). This was the most import of the considerations.

2.6 Bicyclist Reaction

Bicycles are generally not a concern on freeways, Interstates, and parkways, as most states prohibit bicycles on such facilities. However, bicycle use is significant on rural highways and scenic routes. Thus, recent research efforts addressed the design aspects of shoulder rumble strips considering bicyclist comfort.

The placements of continuous shoulder rumble strips (either near the edge of the shoulder or near the edge line) could affect bicyclist safety and comfort. Forty-six percent of the 126 survey participants in a study preferred shoulder rumble strips placement near the edge line, whereas 35 percent preferred shoulder rumble strips placement near the edge of shoulder (Cheng et al., 1993).

Khan and Bacchus presented economic and safety benefits to bicyclists derived from highway shoulder use. The authors commented that the addition of shoulder rumble strips improved the benefit-cost ratios considerably because the benefits were much higher than the costs. The study highlighted the importance of shoulder width for the cyclists by estimating the lateral force on bicycles by heavy vehicles. The data from the study suggested that 7 feet (2 meters) of separation between bicyclist and motor vehicles was required for motor vehicles traveling at speeds of 65 miles/hour (105 kilometers/hour). The width from the edge of the travel way to the outside of the rumble strips was up to 3 feet (910 millimeters). The remaining width provided an area that was comfortable and safe for a bicyclist (Khan and Bacchus, 1995).

To evaluate the discomfort for cyclists, 28 bicyclists (5 basic, 17 skilled, and 6 experienced) were tested in an Arizona field study by riding over various skipped shoulder rumble strip sections to determine acceptable skip patterns (Moeur, 2000). Skips of 12 feet (3.7 meters) in a ground-in shoulder rumble strip pattern were discovered to permit bicyclists to cross "higher speed" streets at

23-28 miles/hour (37-45 kilometers/hour). Either 40 or 60 feet (12 or 18 meters) spacing for the skip pattern were determined acceptable.

Cyclist discomfort factors were also addressed in a Pennsylvania Transportation Institute study (Elefteriadou et al., 2000). The objective of the study was to develop new shoulder rumble strip configurations that decreased the level of vibration experienced by bicyclists while providing an adequate amount of stimulus to alert inattentive or drowsy drivers. Twenty-five intermediate and advanced bicyclists tested six configurations. The researchers recommended the adoption of two new bicycle-tolerable rumble patterns, one for non-freeway facilities operating near 55 miles/hour (88 kilometers/hour) and the other for those operating at 45 miles/hour (72 kilometers/hour).

Various types of shoulder rumble strips in Colorado were compared and recommendations were made based upon input from 29 bicyclists (Outcalt, 2001). Vibrations and auditory data were collected for four different types of vehicles: a 1994 station wagon, a 1999 full sized pickup truck, a 2000 minivan, and an unloaded tandem axle dump truck. While data were collected on milled and rolled asphalt concrete shoulder rumble strips and milled Portland cement concrete shoulder rumble strips, no recommendations were made concerning Portland cement concrete shoulder rumble strips. Of the ten styles tested, those that provided the most noticeable vibration and auditory stimuli to the vehicles were rated worst by the bicyclists. The milled shoulder rumble strips with a depth of 3/8 ± 1.8 inches (4 ± 46 millimeters) on 12 inch (305 millimeter) centers in a skip pattern of 48 feet (14.6 meters) of shoulder rumble strips followed by 12 feet (3.7 meters) of gap was recommended.

The Gary Spring's study in the State of Missouri suggested that no roadway with considerable bicyclist traffic should be installed with rumble strips if the shoulder width was less than 4 feet - 5 feet (1.2 – 1.5 meters) in case of guard rail sections. In cases where the shoulder width was less than 4 feet (1.2 meters) and wider than 2 feet (610 millimeters), Spring suggested a decision must be made whether crash history or cyclist usage should be given priority on the facility (Spring, 2003).

2.7 Noise Considerations

The vibrations and tire noise produced to alert drivers are the desired result from continuous shoulder rumble strips; however, high levels of noise can be a significant nuisance for nearby residential and business neighborhoods. Residents living in close proximity to roadways equipped with continuous shoulder rumble strips may get annoyed with the noises produced by the rumble strips when a vehicle travels over them. Ideally, the desired effect of a vehicle passing over continuous shoulder rumble strips should have enough noise to be heard inside any type of vehicle with a strong vibration serving as the main indicator for drivers. Higgins and Barbel studied, in Illinois, the vibration and tire noise produced by shoulder rumble strips and determined that outside noise did not vary considerably with different types and configurations of shoulder rumble strips (Higgins and Barbel, 1984). It was determined that shoulder rumble strips produced a low frequency noise that increased the ambient decibel (dB) level an additional 7 dB over noise levels produced by traffic on normal pavement. In general the frequencies measured were commonly varying between 50 and 160 hertz.

A study was conducted in 2002 to evaluate the effect of rumble strip configuration on sound level readings and vibration levels (Walton and Meyer, 2002). This study examined the effects that changes to rumble strip configurations have on the levels of noise and vibration produced. Noise and vibration data were collected and analyzed to compare three rumble strip cross-sections and 12 different layouts with respect to their ability to produce audible and tactile stimuli. These data analyzed the relationships between various configuration parameters and the level of noise and vibration generated. The results of the study indicated that the vibration detected in passenger vehicles was not the same as that from heavy vehicles.

2.8 Statistical Analyses

Griffith used two of the statistical methods suggested by Ezra Hauer namely, evaluation with yoked comparisons and the comparison group methods (Griffin 1999, Hauer 1997). Empirical Bayes method was considered as a third method of analysis but was not used since there was no bias in the selection of treatment sites. This was because the treatment sites were not selected due to high crash histories. When using the Illinois data for the first analysis method, there was a reduction of 18.3 percent observed after the treatment of the roadway rumble strips. The second analysis method used urban and rural roadways separately. Since the urban test groups did not meet the required comparability parameters, the analysis was performed only for the rural roadways where the experience of relevant crashes declined by 21.1 percent after treatment.

Cheng analyzed the effectiveness of rumble strips on Utah roads using the comparison group method (Cheng et el., 2000). The crash volume rates for the two comparison groups were observed to be 33.4 and 26.9 percent higher than those on the treated group. Statistical t-tests were conducted to verify the significant level of difference. But the F-tests conducted precluded use of t-tests to verify the significant level of difference in accident rates.

A study evaluated the effectiveness of rumble strips and driver behavior analysis (Noyce and Elango, 2004). A simulation study was conducted in which the participating drivers of three age groups were asked to drive a driving simulator with different scenarios. The results from this experiment were used to conduct a comparison group analysis. The analysis concluded that although there was no significant improvement in safety when the crash rates were compared, the severity reduced significantly after the installation of rumble strips. The study further concluded that 53 percent of drivers overcorrected when they ran off the road and onto the rumble strips and observed that the reaction time of the drivers was longer initially, but decreased with experience. When the driver recovery time was compared for shoulder rumble strips and centerline rumble strips, it was observed that the drivers took 250 milliseconds longer to recover from shoulders when compared to the centerline rumble strips.

2.9 Summary

Table 1 summarizes the literature review on effectiveness of shoulder rumble strips, bicyclist reaction, and noise considerations. In general, studies showed that freeways without shoulder rumble strips experienced a higher rate of ran-off-roadway single-vehicle crashes. Experiments on various types of rumble strips in use concluded that milled rumble strips were more effective than rolled rumble strips since they were found to produce 12.5 times more vibration stimulus and 3.35 times more auditory stimulus. It was determined 12 feet (3.7 meter) skips in grinded-in shoulder rumble strips pattern would adequately permit bicyclists to cross at high bicycle speeds 23-28 miles/hour (37-45 kilometers/hour). However, literature search did not document any studies citing the correlation between shoulder widths and the effectiveness of shoulder rumble strips.

Table 1: Summary of Literature Review on Shoulder Rumble Strips

S. No	Author/ Organization	Location	Title	Type of Shoulder Rumble Strips (SRS)	Year	Researched on/ Significant Result/conclusion
1	Chaudoin and Nelson	I-15, I-40 in California		Grooved SRS	1975	Success on initial 23.5 miles led to installation of rumble strips on another 130 miles on I-15
2	Higgins and Barbel	Illinois	Rumble strip noise-TRB	SRS	1984	Shoulder rumble strips produces low frequency noise 7dB more than that on normal pavement
3	Ligon et al	Rural Freeways, Expressways	Effects of shoulder texture treatments on safety, FHWA		1985	Decrease of 19.8% in accidents by providing rumble strips
4	FHWA		RSR Alert Drivers – Save Lives	SRS	1988	FHWA Ran-off-roadway Data
5	Cheng	Utah	Safety of Rumble Strips installed on Highways	SRS	1993	Evaluated rumble strip skip patterns and their placement
6	Wood	Pennsylvania	Shoulder rumble strips-A method to alert drifting drivers	Sonic Nap Alert Pattern (SNAP)	1994	Decrease of 65% in drift-off-road accidents
7	Chen	Interstate highways in Virginia	A study of effectiveness of various shoulder rumble strips on highway safety	Milled, Rolled & Formed SRS	1994	Tire drop analysis for various types of SRS done Concluded that rolled rumble strips have little effect on trucks
8	Khan and Bacchus		Economic feasibility and related issues of highway shoulder rumble strips	SRS	1995	Safety benefits to cyclists
9	Hauer		Before-After Studies in Road Safety	SRS	1997	Reduction of 65% in crashes after installing SRS
10	Hickey Jr	Pennsylvania	Shoulder rumble strip effectiveness, Drift-off road accident reductions on the Pennsylvania turnpike	SRS	1997	Reduction of 65% in crashes after installing SRS
11	Morgan and McAuliffe		Effectiveness of Shoulder Rumble Strips A Survey of Current Practice	Milled SRS	1997	Conclusion that milled rumble strips were the most preferred
12	Perrillo	New York	The effectiveness and use of Continuous Shoulder Rumble Strips, FHWA	SRS	1998	Cost of Rumble Strips evaluated at $0.49 per linear meter Reduction of 65% in crashes
13	Griffith	California, Illinois	Safety evaluation of Continuous Shoulder Rumble Strips installed on freeways	Rolled SRS	1999	Tests performed on alcohol/drug-impaired drivers, 18.3% crash reduction on Urban freeways, 21.1% crash reduction of rural freeways

S. No	Author/ Organization	Location	Title	Type of Shoulder Rumble Strips (SRS)	Year	Researched on/ Significant Result/conclusion
14	Cheng	Utah	Safety of Rumble Strips installed on Highways	SRS	2000	Evaluated crash volume rates using the Comparison Group Method
15	Moeur	Arizona		SRS	2000	Evaluation of discomfort levels to cyclists due to the presence of SRS
16	Ekefteriadou et al	Pennsylvania	Bicycle tolerable shoulder rumble strips, PENNDOT		2000	Bicycle tolerable rumble strips were recommended
17	Bucko and Khorashadi	California	Evaluation of milled-in rumble strips, rolled-in rumble strips and propriety application	All types	2001	Evaluation of designs for all types of SRS
18	Wood	Pennsylvania		Milled SRS	2001	A rumble Strip simulation model was developed and evaluated
19	Outcalt	Colorado	Bicycle-Friendly Rumble Strips	Milled asphalt, concrete SRS and Rolled	2001	Cyclist comfort levels evaluated
20	Walton and Meyer	Kansas	The effect of Rumble strip configuration on Sound and Vibration levels	SRS	2002	Sound and vibration level testing
21	Annino	Connecticut	Rumble strips in Connecticut - A before/after analysis of safety benefits	SRS	2003	Safety benefits of rumble strips evaluated
22	Marvin and Associates	Montana	Benefit Cost Ratio of SRS	SRS	2003	Benefit cost ratio of shoulder rumble strips at 19.5.
23	Spring	Missouri	Rumble Strips in Missouri	SRS	2003	Design features suggested Bicyclist comfort discussed
24	Taylor and Meczkowski		Safer Roads	SRS	2003	Driving Factors of Ran-off-roadway Accidents/Fatalities
25	Noyce and Elango	Massachusetts	Safety evaluation of centerline rumble strips: A crash and driver behavior analysis	SRS and centerline rumble strips	2004	Driver recovery times, crash rates, severity levels evaluated
26	Hirasawa et al	Hokkaido, Japan	Optimal Centerline Rumble Strips	CRS	2005	Sound and vibration generated from rumble strips
27	FHWA		Rumble Strip Effects on Road Users	SRS	2006	Adverse effects on road users

3.0 METHODOLOGY

This section presents the processes used to evaluate the effectiveness of continuous shoulder rumble strips. It includes sub-sections on data collection, identification of test locations, and the analyses. The evaluation of the effectiveness of rumble strips was based on addressing the following questions:

1. What types of continuous shoulder rumble strips are used?
2. What measures or variables can be used to evaluate the effectiveness of continuous shoulder rumble strips?
3. What types of analyses are needed?
4. What sources of information will the analyses require?
   a. When and where were continuous shoulder rumble strips installed on roadways in Nevada?
   b. What were the characteristics of the roadway sections with treatment?
      i. Roadway characteristics
      ii. Traffic characteristics
      iii. Crash characteristics
5. Were the observed changes in safety performance on roadways with treatment significant?

Discussions on these questions are presented in the remainder of this section.

3.1 Data Identification, Collection, and Analyses

The data required to support the analyses consisted of information pertaining to crashes, roadway design, and operational characteristics. Data elements of interest in this regard included the following:

- o Road Network Data (for locations with continuous shoulder rumble strips)
  - Functional Classification of Roadway

        - Identification of Roadway Segments
    - Data About Continuous Shoulder Rumble Strips
        - Date and Location of Continuous Shoulder Rumble Strip Installation
        - Type of Continuous Shoulder Rumble Strips
        - Shoulder Width
    - Single-vehicle Ran-off-roadway Crash Data
    - Traffic Data for Locations with Continuous Shoulder Rumble Strips
        - Average Daily Traffic (ADT)
        - Posted Speed Limit

3.1.1 Road Network Data

The NDOT maintains 5,400 centerline miles of highways in the state of Nevada. At the commencement of this study more than 1,455 centerline miles in both directions and on divided roadways had been treated with continuous shoulder rumble strips from 1998 to 2004. Key characteristics pertaining to the roadway network, such as the functional classification and the beginning-ending of each roadway section were needed to perform the before-after analyses.

The road network with continuous shoulder rumble strips treatment was created as a layer using Geographic Information System software. Figure 4 details various roadways (routes) and length of roadways with continuous shoulder rumble strips along with the year in which the continuous shoulder rumble strip treatment was installed.

Figure 4: Nevada Road Network Identifying Sections with Continuous Shoulder Rumble Strip Treatment

3.1.1.1 Functional Classification of Roadway

For purposes of performing the analyses in this study, the roadway sections with continuous shoulder rumble strips were divided into smaller segments. The sections with treatment were located on different functional classes or types of roadways such as Interstate freeways, US routes, and state routes.

3.1.1.2 Identification of Roadway Segments

The types of functional roadways were further divided into segments. The segments had varying characteristics such as the installation dates for continuous shoulder rumble strips, posted speed limits, traffic volumes, section lengths, and shoulder widths. A stretch of road between two significant locations (e.g., access or egress points) was defined as one exclusive segment. Care was taken to keep the segments relatively homogeneous based on factors such as average daily traffic and shoulder width. A total of 370 individual segments were identified. The details regarding the number of segments identified on each roadway, based on the year of rumble strip installation are shown in Table 2.

Year	*1998 1999*	*1999*	*1999 2000*	*2000*	*2000 2001*	*2001*	*2001 2002*	*2002*	*2002 2003*	*2003*	*2003 2004*	*2004*	***Total***
I-15N	0	32	0	0	0	0	0	0	2	0	0	0	**34**
I-15S	0	29	0	3	0	0	0	0	3	0	0	0	**35**
I-80E	13	34	1	0	27	0	0	3	13	0	10	2	**103**
I-80W	15	30	1	0	28	0	0	1	13	0	9	2	**99**
US-95	0	46	0	0	0	0	0	0	2	0	0	0	**48**
US-95A	0	1	0	0	0	0	1	0	0	0	0	0	**2**
US-93	0	5	3	0	0	0	0	0	0	1	0	0	**9**
US-93A	0	1	0	0	0	0	0	0	0	0	0	0	**1**
US-50	0	11	1	0	0	0	0	0	0	0	0	0	**12**
US-6	0	1	3	0	0	0	0	0	0	0	0	0	**4**
US-395	0	5	0	0	0	0	0	0	0	0	6	1	**12**
SR-766	0	0	3	0	0	0	0	0	0	0	0	0	**3**
SR-160	1	1	0	0	0	0	0	0	0	0	0	0	**2**
SR-163	0	1	0	0	0	0	0	0	0	0	0	0	**1**
SR-221	0	0	1	0	0	0	0	0	0	0	0	0	**1**
SR-227	0	0	0	1	0	0	0	0	0	0	0	0	**1**
SR-228	0	0	0	1	0	0	0	0	0	0	0	0	**1**
SR-318	0	1	0	0	0	0	0	0	0	0	0	0	**1**
SR-604	0	1	0	0	0	0	0	0	0	0	0	0	**1**
Total	**29**	**199**	**13**	**5**	**55**	**0**	**1**	**4**	**33**	**1**	**25**	**5**	**370**

Table 2: Length and Year of Continuous Shoulder Rumble Strip Installation for Individual Roadways (in centerline miles)

Identification numbers were assigned to each of the roadway segments with continuous shoulder rumble strips. A 4-digit numbering system was designed to uniquely identify individual segments. A typical 4-digit segment number started with 1, which indicated that the direction of travel on the segment was North. Similarly segment numbers starting with 2, 3 and 4 represented direction of travel as South, East, and West respectively. The remaining three digits of the number represented the serial number of the road sections.

3.1.2 Data about Continuous Shoulder Rumble Strips

Key data pertaining to the road segments with treatment were obtained from NDOT. These included the following: the date of continuous shoulder rumble strip installation, traffic volumes, crash data, posted speed limits, shoulder width, and section lengths.

3.1.2.1 Date and Location of Continuous Shoulder Rumble Strip Installation

The Nevada Department of Transportation began installing continuous shoulder rumble strips on Interstate routes, major US routes, and major state routes in Nevada from 1998 to 2004. Most of the 1,455 miles of rumble strip installation were done during the year 1999 with 1,017 centerline miles of roadway treated with rumble strips during the year.

As previously described, it was necessary to account for the continuous shoulder rumble strip installation period in the before-after analyses. Since the rumble strips were installed on short road sections based on individual installation construction contracts, the start and end dates of each contract could be considered in determining the "construction" period for the installation of continuous shoulder rumble strips. The commencement and completion dates of the installation contracts were used to demarcate three time periods as follows:

- "Before" Period
- "Construction" Period
- "After" Period

The period, from the first date of the year 1995 to the "Notice-to-Proceed" date for construction, was defined as the "before" period. The period between the "Notice-to-Proceed" date and the "End Date" of contract was defined as the "construction" period. The "after" period was defined as the time period from the "End Date" of construction to the last day of the year 2003.

The before-after analysis required data for periods prior to and following the construction of continuous shoulder rumble strips on each segment to be evaluated. Among the 370 roadway segments identified for evaluation, 64 segments had their installations done in the year 2003 or 2004. Thus, they did not have any "after" condition data. The remaining 306 roadway segments had at least one year of crash data for each of the before-after conditions with respect to the treatment. These segments, which account for 1,303 centerline miles of roadway, were considered for evaluation and analyses in this study. The segments range in length from less than one mile to several miles depending on roadway characteristics. The Geographic Information System layer was modified to identify segments based on the dates of installation of the rumble strips.

Of the roadways considered for analyses, 49 centerline miles of roadway had continuous shoulder rumble strips installed in the year 1998-1999, 1,017 miles of roadway had continuous shoulder rumble strips installed in the year 1999, and 115 miles of roadway had continuous shoulder rumble strips installed in 200-2002. Most of the 1,455 miles of rumble strip installations were done during the year 1999. Table 3 presented the spatial extent of this network of rumble strips as shown in Figure 5 that details various roadways (routes) and lengths of roadways with continuous shoulder rumble strips along with the year in which the treatment was installed.

Table 3: Segments on Roadways Continuous Shoulder Rumble Strips Treated Based on Year of Installation

Year	***1998 1999***	***1999***	***1999 2000***	***2000***	***2000 2001***	***2001***	***2001 2002***	***2002***	***2002 2003***	***2003***	***2003 2004***	***2004***	***Total***
I-15N	0.00	89.46	0.00	0.00	0.00	0.00	0.00	0.00	4.71	0.00	0.00	0.00	**94.17**
I-15S	0.00	88.68	0.00	3.05	0.00	0.00	0.00	0.00	5.56	0.00	0.00	0.00	**97.29**
I-80E	15.85	111.80	3.87	0.00	55.95	0.00	0.00	1.48	30.29	0.00	16.64	5.51	**241.39**
I-80W	16.92	96.21	3.89	0.00	58.90	0.00	0.00	0.90	30.25	0.00	20.16	5.59	**232.82**
US-95	0.00	341.50	0.00	0.00	0.00	0.00	0.00	0.00	12.26	0.00	0.00	0.00	**353.76**
US-95A	0.00	21.78	0.00	0.00	0.00	0.00	19.32	0.00	0.00	0.00	0.00	0.00	**41.10**
US-93	0.00	78.31	50.24	0.00	0.00	0.00	0.00	0.00	0.00	9.09	0.00	0.00	**137.64**
US-93A	0.00	14.26	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**14.26**
US-50	0.00	93.48	4.93	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**98.41**
US-6	0.00	23.50	12.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**35.50**
US-395	0.00	12.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.15	8.61	**24.43**
SR-766	0.00	0.00	11.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**11.60**
SR-160	16.18	5.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**21.52**
SR-163	0.00	19.36	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**19.36**
SR-221	0.00	0.00	0.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**0.34**
SR-227	0.00	0.00	0.00	5.53	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**5.53**
SR-228	0.00	0.00	0.00	4.73	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**4.73**
SR-318	0.00	5.47	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**5.47**
SR-604	0.00	15.69	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	**15.69**
Total	**48.95**	**1,017.51**	**86.87**	**13.31**	**114.85**	**0.00**	**19.32**	**2.38**	**83.07**	**9.09**	**39.95**	**19.71**	**1,455.01**

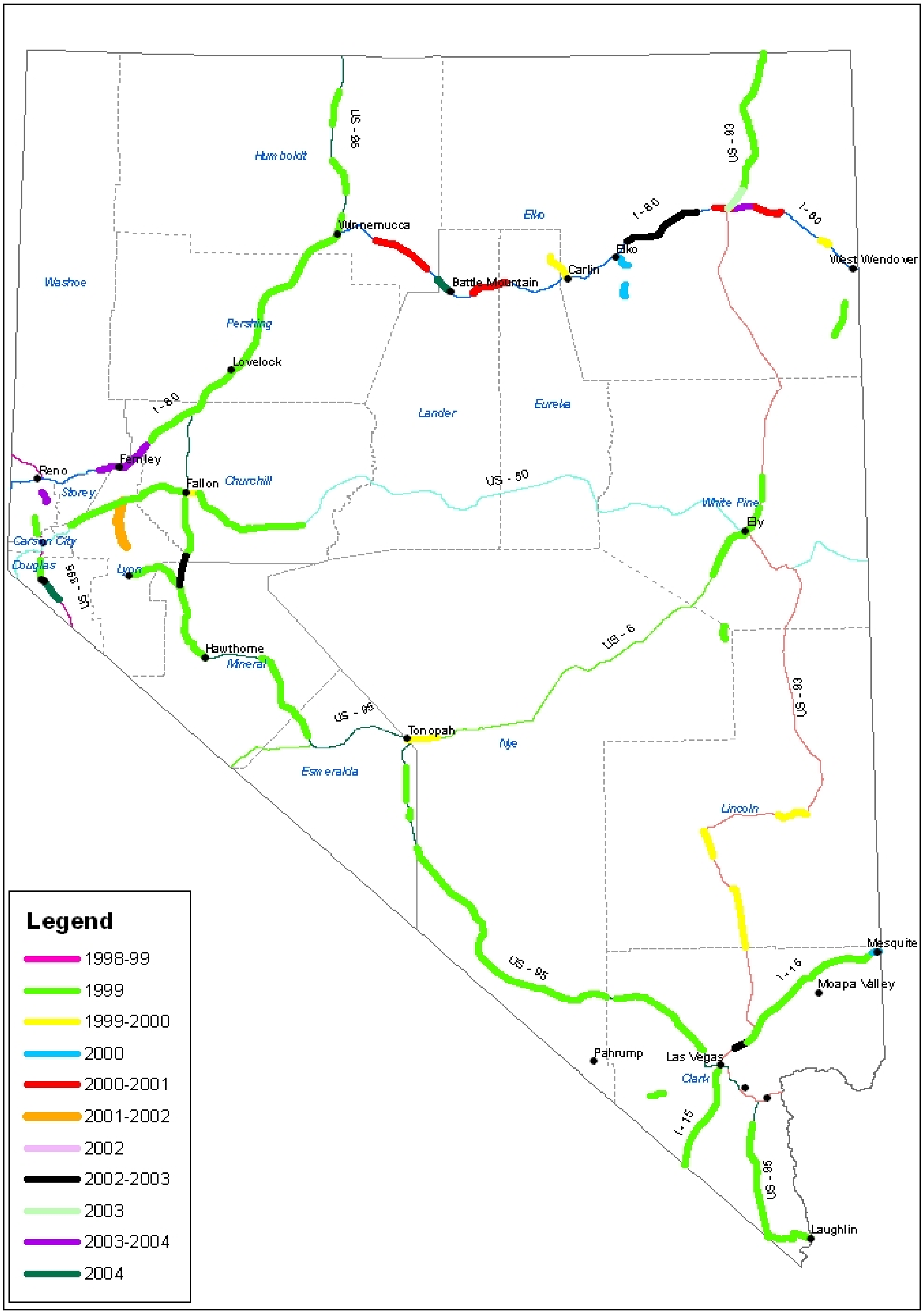

Figure 5: Roadway Sections in Nevada with the Year of Continuous Shoulder Rumble Strip Installation

3.1.2.2 Type of Continuous Shoulder Rumble Strips

Although four types of rumble strips are used in practice around the nation, NDOT has selected the milled rumble strips for use in Nevada because they produce higher levels of noise and vibration than other rumble strips. The noise and vibration produced by milled rumble strips are caused by a "tire drop" of 0.51 inches (13 millimeters) compared with 0.29 inches (0.75 millimeters) for the other types of rumble strips. Milled rumble strips have an additional advantage in that there was minimal effect on the integrity of the pavement structure.

The histories from other states have shown that milled rumble strips are more effective than the other types in technical and economical aspects; were preferred over raised rumble strips because of the obvious problems with snow and garbage removal; and were more effective in producing high levels of noise and vibration than formed and rolled rumble strips.

Experiments on various types of rumble strips in use concluded that milled rumble strips was more effective than rolled rumble strips since they were found to produce 12.5 times more vibration stimulus and 3.35 times more auditory stimulus. It was determined 3.7 meters (12 feet) skips in grinded-in shoulder rumble strips pattern would adequately permit bicyclists to cross at high bicycle speeds of 23-28 miles/hour (37-45 kilometers/hour).

3.1.2.3 Shoulder Width

Rumble strips served to alert drivers that they were drifting away from the marked travel lanes. The location of the rumble strip on the shoulder and the width of the shoulder affected the time and space available for a driver to take corrective action when alerted by the vehicle's tires crossing the rumble strips.

Rumble strips are placed in the same location on Nevada roadways, but the shoulder widths vary. It was expected that wider shoulder widths would provide more time and space for drivers to recover from drifting onto the shoulders, so linear regression models were developed to better evaluate the relationship between crash rates and shoulder widths.

3.1.3 Crash Data for Single-vehicle Ran-off-roadway Incidents

In order to study the effectiveness of continuous shoulder rumble strip treatment, it was necessary to compile and evaluate data related to single-vehicle ran-off-roadway crashes that occurred on the road segments of interest for time periods "before and after" the installation of rumble strips. Such crash data for the roadway network in Nevada for the years from 1995 to 2003 were obtained from NDOT. During the 9-year period under consideration, this amounted to a total of 33,117 single-vehicle ran-off-roadway crashes, for an average of 3,680 crashes/year. Of the 33,117 crashes 2.3 percent (772) resulted in one or more fatalities and 35.7 percent (11,812) of the crashes involved human injuries. The remaining 62 percent (20,532) of the crashes involved property damage. The 4,173 single-vehicle crashes reported in the year 1998 was the highest number of crashes in any year during the analysis period; the 2,817 crashes for 2003 was the lowest number of crashes.

The 33,117 crashes were geographically located with reference to the road network using a Geographic Information System program. Buffers were generated around each study segment in the system's environment generated to help identify crashes on each roadway segment. The Geographic Information System covering the 9-years of data for single-vehicle ran-of-roadway crashes was overlaid with the buffers. Capabilities afforded in the system's environment such as "clipping" were used to identify the crashes associated with roadway segments installed with continuous shoulder rumble strip treatment from those crashes not on these segments. Then, a "join" operation was performed in the Geographic Information System environment to determine the number of crashes that occurred on each study segment. This process facilitated identifying the crashes that occurred only on the roadway segments of interest i.e., those with continuous shoulder rumble strips. A total of 7,313 single-vehicle ran-off-roadway crashes were identified on the 1,455 mile road network with treatment. Most of these crashes caused either injury to the occupants or damaged property; however, there were 301 fatal crashes that resulted in 344 deaths. The crash data were summarized on a yearly basis in Table 4. As previously mentioned the crashes, which occurred during the construction period of the continuous shoulder rumble strip treatment, were not considered in the analysis. A total of 572 crashes occurred during the construction period.

Table 4: Year-wise Summary of Single-vehicle Ran-off-roadway Crashes on the 1,455 mile Road Network with Continuous Shoulder Rumble Strip Treatment

Year	No. of Ran-off-roadway Crashes	No. of Injury Crashes	No. of Fatal Crashes	No. of Fatalities
1995	793	356	32	37
1996	979	445	44	45
1997	854	364	36	39
1998	1033	437	38	42
1999	885	412	36	40
2000	725	296	33	50
2001	743	297	27	29
2002	742	319	30	33
2003	559	278	25	29
Total	**7,313**	**3,204**	**301**	**344**

3.1.4 Traffic Data for Locations with Continuous Shoulder Rumble Strips

NDOT Contract Records Office provided traffic data for the locations of continuous shoulder rumble strip installation for the 9-years of study. The data included posted speed limits, traffic volumes, and shoulder width. An example of the rumble strips database developed is presented in Table 5.

Table 5: **Illustration of the Database Developed for the Continuous Shoulder Rumble Strip Analyses**

Route Name	Segment Code	Contract Number	Contract Start Date	Contract End Date	Shoulder Width	Segment Length in Miles	ADT 1995	MVMT 1995	Construction Period	# Crashes 1995	Speed	Cumulative Begin Mile	Cumulative End Mile	"before"' period of Analysis in Year	"after"' Period of Analysis in Years
IR15N	1032	2920	1/4/1999	3/1/1999	10	0.140	29090	1.488	56	0	70	0.000	0.140	4.011	4.836
IR15N	1031	2920	1/4/1999	3/1/1999	10	0.577	32740	6.901	56	0	70	0.140	0.718	4.011	4.836
IR15S	2025	2920	1/4/1999	3/1/1999	10	0.542	13975	2.765	56	0	75	57.880	58.420	4.011	4.836
IR15S	2024	2920	1/4/1999	3/1/1999	10	5.708	13975	29.110	56	3	75	58.420	64.130	4.011	4.836
IR80E	3088	2919	1/4/1999	10/15/1999	10	0.536	6795	1.330	284	0	75	64.770	65.300	4.011	4.211
IR80E	3087	2919	1/4/1999	10/15/1999	10	13.350	6795	33.110	284	10	75	65.300	78.650	4.011	4.211
IR80W	4077	2919	1/4/1999	10/15/1999	10	0.652	6715	1.597	284	0	75	106.300	106.900	4.011	4.211
IR80W	4076	2919	1/4/1999	10/15/1999	10	0.839	6715	2.056	284	0	75	106.900	107.700	4.011	4.211
SR604	1152	2967	6/21/1999	10/7/1999	4	15.690	4545	26.030	108	42	0	13.070	28.760	4.471	4.233
US395N	1146	2976	7/12/1999	11/12/1999	10	0.436	10365	1.648	123	3	65	43.980	44.410	4.529	4.134
US50	1155	2942	4/12/1999	9/15/1999	10	0.180	6760	0.444	156	0	55	345.400	345.600	4.279	4.293
US6	1122	2942	4/12/1999	9/15/1999	10	23.500	1170	10.040	156	2	70	218.800	242.300	4.279	4.293
US93N	1124	2942	4/12/1999	9/15/1999	10	7.629	1050	2.924	156	3	55	318.700	326.300	4.279	4.293
US95N	1047	2936	4/5/1999	6/3/1999	8	0.698	8350	2.128	59	0	65	91.470	92.160	4.260	4.578
US95N	1049	2936	4/5/1999	6/3/1999	8	0.518	8350	1.578	59	0	70	98.940	99.450	4.260	4.578

Note: Average Daily Traffic (ADT), Million Vehicle Miles of Travel (MVMT), and Number of Crashes were shown only for one year of the available 9-year data.

3.1.4.1 Average Daily Traffic Sections

The volume of traffic on each roadway segment was a factor for consideration in evaluating the effectiveness of rumble strip treatment. Traffic volumes were used to determine measures of exposure in computing crash rates. For example, a roadway with a lower traffic volume would have a higher crash rate than a roadway section of the same length, which has a higher traffic volume but the same number of crashes. NDOT has 93 automatic traffic recorders at various sites on its roadway network. These recorders provide annual average daily traffic (AADT) counts at the respective sites. Additionally traffic counts were conducted annually at several thousand other sites. Annual reports listed AADT for these sites, identified as stations, over a 10-year period. These data were published and posted on the NDOT website. Traffic volume data was extracted from the NDOT website as needed for this analysis. These data were to calculate the million vehicle miles of travel (MVMT) for each roadway segment treated with shoulder rumble strips. This vehicular travel and the number of crashes were used to determine crash rates along roadway sections. The 9-year ADT or AADT for the segments used in this study were shown in Figure 6.

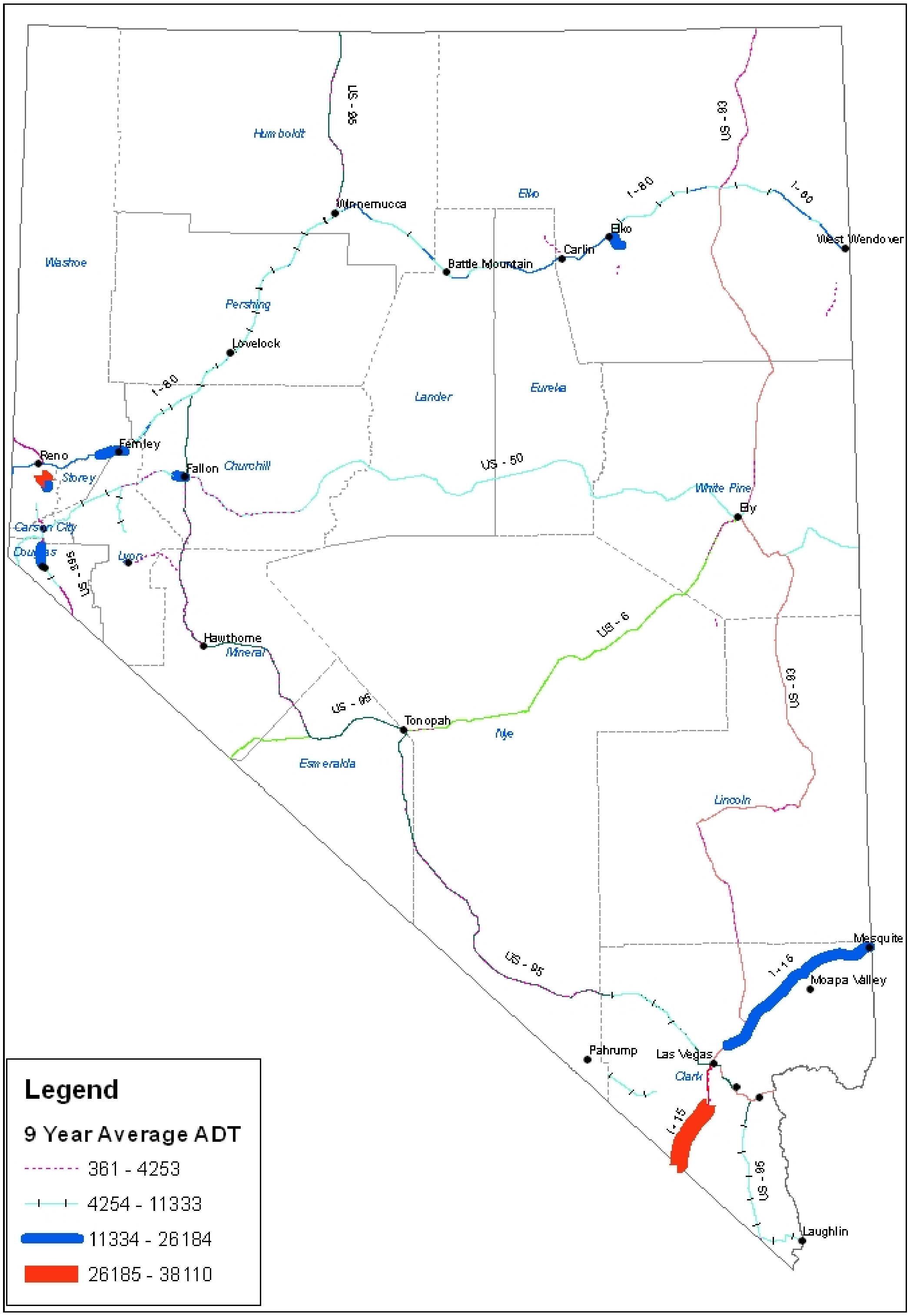

Figure 6: 9-Year Average Daily Traffic (ADT) on the Continuous Shoulder Rumble Strip Sections

3.1.4.2 Posted Speed Limit

Speed could be a major contributor to the occurrence of crashes. Drivers who were inattentive were more likely to be in single-vehicle ran-off-roadway crashes at high speeds of travel than at low speeds. Conversely, the chances of a driver recovering from drifting away on the roadway were better at lower speeds than at higher speeds. This was because the distance traveled during the reaction and response time was lower in the case of the lower speed. Since the actual speeds at which a vehicle that was involved in a single-vehicle ran-off-roadway crash traveled was not easily accessible, the posted speed limits were used as surrogate indicators of vehicle speeds on a roadway segment. In order to determine the effectiveness of rumble strip treatment, the impact of speed relationship was evaluated using the posted speed limit on roadway segments as an indicator of operating speeds.

3.2 Evaluating Safety

The single-vehicle ran-off roadway crashes are, where the vehicle departed the roadway and in which only one vehicle was involved. A key factor for this kind of crash was the driver losing focus / attention or falling asleep / drowsy. The primary purpose of the installation of continuous shoulder rumble strips is to prevent or reduce the probability of such single-vehicle crashes by alerting the drivers who begin to drift off the roadway through the application of rumble strips. A combination of vibration and tire noise is produced when the drifting vehicle's wheels pass over the rumble strips. A before and after comparison strategy was used to determine the effectiveness of treatment.

Based on the literature review, two approaches were adopted to evaluate the effectiveness of continuous shoulder rumble strips in Nevada: descriptive analysis and statistical analysis. These analyses began with the identification of individual roadway sections. The individual sections served as the basic units for the analyses. Data pertaining to the individual sections of a roadway were aggregated to evaluate the roadway. Likewise, data for the roadways will be aggregated for the composite analyses.

The individual segments accounted for different types of rumble strips so as to compare the advantage of one type over the other. To study the correlation between various geometric characteristics and safety, the test segments included locations with different design specifications. Thus, data pertaining to the type of continuous shoulder rumble strips and design features for each test location needed to be collected. To study the statistical significance, a sufficient number of test segments were selected for each combination. The analyses were based on single-vehicle ran-off-the-road crashes in Nevada recorded by law enforcement agencies. It is recognized that not all crashes are recorded, especially minor ones. Consequently, a basic assumption is made that the unreported crashes will not adversely affect the analyses. A crash database was developed to identify the crashes of interest, their characteristics, including their location on the road network. This involved the identification of single-vehicle ran-off-roadway crashes for each selected roadway section. The before-after analyses involved comparisons of the number of crashes and the corresponding crash rates that were recorded on individual sections with before and after treatment. In order to compare the crash rates various influencing factors such as the average daily traffic, length of the section, and the vehicle miles of travel where crash rates were computed for each roadway section using the vehicle miles traveled on that particular section. These crashes were segregated for the before-after conditions based on the construction dates for the installation of continuous shoulder rumble strips.

Traffic conditions were not normal during the construction period due to a number of factors. These included the presence of construction equipment and personnel that result in "not normal" operating conditions. For example, the observed speeds would be less as compared to the normally observed speeds; the number of lanes on which traffic was allowed during the construction period may be less than what it was under "normal" conditions. Hence it would not be appropriate to consider crashes that occurred during the continuous shoulder rumble strips construction period. Appropriate corrections were applied to the other factors, which were used in computing the crash rates.

3.3 Computation of Safety Indicators

A comparison of the number of crashes during the period "before" treatment and after installation was a good indicator of the effectiveness of continuous shoulder rumble strips. To account for a variety of factors, which might have a bearing on the increase or reduction of the number of crashes; the analyses were carried out based on three indicators of safety for each segment, namely:

- Crash Frequency in Crashes/Year
- Crash Rate in Crashes/Million Vehicle Miles of Travel (MVMT)
- Crash Density in Crashes/Mile/Year

The quantification of these safety indicators is presented next.

3.3.1 Computation of Crash Frequency

The simplest of the aforementioned safety indicators was the crash frequency. The frequency was computed by dividing the total number of crashes recorded on each segment during the "before-after" period by their respective duration expressed in years. It was computed using the following equations:

$$\textit{Crashes/Year}_{\text{before}} = \sum C_{ij\,\text{before}} / P_{i\,\text{before}}$$
$$\textit{Crashes/Year}_{\text{after}} = \sum C_{ij\,\text{after}} / P_{i\,\text{after}}$$

Where

$C_{ij\,\text{before}}$ = Total number of crashes recorded on segment *i* in year *j* during the "before" period
$C_{ij\,\text{after}}$ = Total number of crashes recorded on segment *i* in year *j* during the "after" period
$P_{i\,\text{before}}$ = duration of the "before" period of segment *i* in years
$P_{i\,\text{after}}$ = duration of the "after" period of segment *i* in years

The computation of single-vehicle ran-off-roadway crash frequency was illustrated using an example in Appendix 1. The aggregation of individual segments led to sections, and likewise roadways, that were made up of sections. In order to compute the single-vehicle ran-off-roadway crash frequency on each section of roadway or facility, the total number of crashes on the facility and the average “before-after” periods were computed. The total number of crashes on each facility was obtained by the simple addition of the number of crashes on each constituent segment. Since different roadway segments have different construction periods, it was implied that the “before-after” periods were also different for many of these roadway segments. In order to compute the crash rate in terms of crash frequency, a weighted average of the “before-after” periods was computed separately as described next:

Average “before” period (P_{before}) = $\sum L_i * P_{i\,before} / \sum L_i$

Where

L_i is the length of each segment
P_i is the “before” period of each segment

A similar computation was used to obtain the average “after” period (P_a). The crashes/year for each facility was computed as follows:

$\text{Crashes/Year}_{before} = \Sigma_i \Sigma_j C_{ij\,before} / P_{before}$
$\text{Crashes/Year}_{after} = \Sigma_i \Sigma_j C_{ij\,after} / P_{after}$

3.3.2 Computation of Crash Rate

The safety indicator in terms of crash rate was the ratio of the number of crashes/million vehicle miles of travel (MVMT) on a segment. The MVMT on a segment was estimated as a function of the average daily traffic volume on the segment and the segment’s length. The following equation was used to estimate MVMT on a segment:

$MVMT_{ij} = ADT_{ij} * 365 * L_j / 1{,}000{,}000$

Where

$MVMT_{ij}$ is the MVMT of segment *i* during year *j*
ADT_{ij} is the ADT of segment *i* during year *j*
L_i is the length of segment *i (in miles)*

If year *j* was the roadway section that was treated with rumble strips, then a *modified MVMT* was computed using the non-construction days during that year. The *modified MVMT* was given by:

$$\textit{Modified } MVMT_{ij} = ADT_{ij} * \textit{(non-construction period in days)} * L_j / 1{,}000{,}000$$

The modified MVMT was computed separately using data for the "before-after" periods and using the "before-after" non-construction days during the year of construction. The crash rate on the segment during the "before-after" periods was then computed using the following equation:

$$\text{Crash Rate}_{before} = \Sigma_j \# C_{j\ before} \ / \ \Sigma MVMT_j$$
$$\text{Crash Rate}_{after} = \Sigma_j \# C_{j\ after} \ / \ \Sigma MVMT_j$$

Where

C_j is the number of crashes during year *j*

Similarly the crash rates for each facility were computed as per the following equation:

$$\text{Crash Rate}_{before} = \Sigma_i \Sigma_j \# C_{ij\ before} \ / \ \Sigma_i \Sigma_j\ MVMT_{ij}$$
$$\text{Crash Rate}_{after} = \Sigma_i \Sigma_j \# C_{ij\ after} \ / \ \Sigma_i \Sigma_j\ MVMT_{ij}$$

Where

C_{ij} is the number of crashes on segment *i* during year *j*
$MVMT_{ij}$ is the MVMT of segment *i* during year *j*

The effect of the type of roadway also needs to be evaluated in determining the effectiveness of the continuous shoulder rumble strip treatment. The total number of crashes before and after the installation of rumble strips was to be aggregated to summarize the effect of the type of roadway on these single-vehicle crashes. The crash rate was computed for each roadway's functional class as a single unit to analyze the crash trend on each type of roadway class exclusively.

3.3.3 Computation of Crash Density

The safety indicator in terms of crash density was computed as the crashes/year divided by the length of each segment. To compute the crash rates in terms of crashes/mile/year for each facility as a single unit the following expression was used:

$$\text{Crashes/Mile/Year}_{before} = \Sigma_i \Sigma_j C_{ij\ before} / (\sum L_i * P_{i\ before})$$

Where

C_{ij} = Number of crashes of segment *i* in year j
L_i = Length of Segment *i*
$P_{i\ before}$ = "before" period of analysis of segment i

3.4 Statistical Analyses

The statistical analyses to estimate the effectiveness of treatment comprised of comparing crash data before and after the treatment of the roadway with continuous shoulder rumble strips. The effect of the treatment was estimated by comparing the prediction of what safety "would have been" to the estimate of what safety "was" prior to the deployment of the treatment. Some of Ezra Hauer's approaches are widely used in the field of transportation safety to evaluate the effectiveness of treatments applied to roadway facilities (Hauer, 1997). Hauer assumed that the crash frequencies over the years followed a Poisson's distribution. Similarly Cox assumed that the crash frequencies followed a Poisson's distribution and suggested a method to compare the Poisson's means to study the variation in the situation before and after any treatment (Cox, 1953). Hauer also suggested different methods to evaluate the effectiveness of any treatment on the facility. The conventional methods basically comprised methods comparing various averages of the indicators and the pair-wise comparison method. Different averages of the number of crashes before-after an improvement can also be compared to see if the treatment of the roadway with continuous shoulder rumble strips has any effect in reducing the crash rates.

3.4.1 Ezra Hauer's Comparison Group Method

In Hauer's observational before-after methods, the predicted crash frequencies were compared to the estimated "after" crash rates to determine the effectiveness of the treatment. The *"Predicted"* value was the expected value of what "would have been" the safety of the entity in the "after" period had treatment not been deployed. These predicted values of indicators were compared with the estimated or actual values of the same indicators after the treatment "was" deployed along the roadway. The *"Estimated"* value was the "actual or computed" value of the indicator in the period after the deployment of the treatment. Once the prediction was made for the "after" period, a comparison was made as to what safety "was" in the period after the treatment was deployed. The following notation was used for the analyses:

> π – Expected number of crashes of a specific entity in the "after" period if the treatment was not done
> λ - Actual number of crashes of a specific entity in the "after" period following the treatment

The effect of treatment on the entity was judged by comparing π and λ. The following coefficients were estimated to facilitate the comparison:

> δ= π-λ, the reduction in the "after" period of the expected number of target accidents
> θ= λ/π,the ratio of what safety was with treatment to what it would have been without the treatment – 'the index of effectiveness'

When the index of effectiveness was less than one then the treatment was effective and if it was more than one then the treatment was not effective.

One of the main tasks of any before-after study, was to predict the value that the variable of interest had if the facility had not been treated. There were several methods currently in practice, though no method could predict exactly what the value would have been if the facility had not been treated. The accuracy of the prediction was improved to account for the influence of a variety of casual factors that change with time by applying a comparison group device.

The central idea of using a comparison group method was:

(1) To identify a group of entities or segments that remained untreated and that were similar to the treated entities or segments, and

(2) To compare the two identified groups.

These untreated entities (segments) were called the "Comparison Group". The treated entities were called the "Treatment Group". It was hoped that in the comparison group method, the change in the number of crashes of the comparison group during "before-after" periods, was indicative of how the number of crashes for the treatment group would have changed. It was assumed that the other factors that affect the change in number of crashes have changed in the same manner for the entire study period on both comparison and treatment groups.

Once the comparison group was identified, the number of crashes for the comparison group during the ”before-after” periods were used to compute the “Comparison Ratio.” The “Comparison Ratio” (r_c) was defined as the ratio of expected number of crashes during the “after” period to the expected number of crashes during the “before” period for the comparison group.

$$r_c = N / M$$

Where

N is expected # crashes “after” the Comparison Group
M is expected # crashes “before” the Comparison Group

The above expression gives a biased r_c value. To obtain an unbiased r_c value, the value obtained from the above expression was to be divided by (1+1/M). Hence, the unbiased r_c value was defined as follows:

$$r_c = (N/M) / (1+1/M)$$

Hauer defines ‘expected value’ as a value obtained from a large number of trials. In this research the ‘expected values’ were the true accident counts observed on site. The expected number of crashes for the treatment group was then computed, as it was hoped that the ratio would be the same for the treatment group had the treatment not been done to the treatment group. Hence, the expected number of crashes for the treatment group was determined as follows:

$$\pi = (\text{\# Crashes on Treatment Group ‘before’}) \bullet r_c$$

But the actual number of crashes was given by (λ). The index of effectiveness was then computed using actual λ and predicted π number of crashes in the “after” period. As mentioned earlier, a segment with an index of effectiveness of less than one indicated improvement in the condition, i.e. and implied that the number of crashes would have been higher than the observed number of crashes if the roadway were not treated with continuous shoulder rumble strips. A sample calculation was illustrated for a roadway segment on I-80 eastbound. Details of this sample calculation are included in Appendix 2.

The data and methods presented in this section were used to evaluate the effectiveness of the continuous shoulder rumble strip treatment. These analyses were presented in the next chapter.

Another method used in the statistical analysis of evaluating the effectiveness of rumble strips was comparing the Poisson's means of the crash rates before and after the rumble strip treatment. A hypothesis test was performed to define the hypothesis that the Poisson means of the crash rates were equal during the "before-after" periods.

3.4.2 Comparison of Poisson's Means

If the events, such as accidents or stoppages of machine, occur randomly in time at a true rate "λ", the number of events in a fixed time "t" follows a Poisson distribution of mean λt (Cox, 1953). If two populations were sampled with rates of occurrence of λ_1, λ_2 and in times t_1 (before), t_2 (after), observe n_1, n_2 events then the expression $[t_1 (n_2 + 1/2) \lambda_1] / [t_2 (n_1 + 1/2) \lambda_2]$ was distributed approximately as F with ($2n_1$+1, $2n_2$+1) degrees of freedom. Thus, the hypothesis could be tested that $\lambda_1 = \lambda_2$ by comparing $F = [t_1 (n_2 + 1/2) \lambda_1] / [t_2 (n_1 + 1/2) \lambda_2]$ with the F tables with ($2n_1$+1, $2n_2$+1) degrees of freedom. Also (100-2α) percent confidence intervals for λ_1/λ_2 could be obtained from $[t_2 (n_2 + 1/2)] / [t_1 (n_1 + 1/2)](FL) < \lambda_1/\lambda_2 < [t_2 (n_2 + 1/2)] / [t_1 (n_1 + 1/2)](FU)$.

FL and FU were the lower and upper α percent points of F with ($2n_1$+1, $2n_2$+1) degrees of freedom. If the ratio of the means (i.e., λ_1 / λ_2) was greater than 1.0, then there was a statistically significant improvement in the statistic from the "before" period to the "after" period.

Example calculations for Comparison of Poisson's Means were presented in Appendix 2. For the example considered, the ratio of the Poisson's means of the number of crashes before and after the installation of rumble strips was greater than one, the reduction in the number of crashes on this section of roadway was statistically significant. The data and methods presented in this section were used to evaluate the effectiveness of the continuous shoulder rumble strip treatment.

4.0 ANALYSIS OF SINGLE-VEHICLE RAN-OFF-ROADWAY CRASHES

The effectiveness of the continuous shoulder rumble strips in reducing single vehicle ran-off-roadway crashes was evaluated based on a before-after analysis. It involved a comparison of the number of crashes and the crash rates on individual segments or roadways, as well as, sections and roadways / routes at the aggregate level with continuous shoulder rumble strips before and after the treatment installation. The average daily traffic and the length of the segment accounted for the exposure. A database developed on the basis of the variables identified in the preceding section was used for the analyses. The single-vehicle ran-off-roadway crashes were identified for each selected test segment. These crashes were segregated for the before-after conditions based on the date of installation of continuous shoulder rumble strips. Crash rates were computed for each roadway segment. The analyses were performed based on the computed various crash rates including descriptive analyses and statistical analyses.

4.1 Descriptive Analysis

The analyses of single-vehicle ran-off-road crashes for roadway segments with continuous shoulder rumble strips involved integrating crash data and their attributes with the road network data and their characteristics. As described previously, a layer, consisting of only the rumble strip roadway segments in Nevada, was developed using a Geographic Information System based on the road network maintained by the NDOT. Using the system, data pertaining to single-vehicle crashes were linked to the street network to identify crashes on each roadway segment. The crashes were linked to the individual roadway sections defined based on their roadway characteristics. This combined layer in the Geographical Information System environment was used to develop the crash database for the 306 roadway segments identified for evaluation. An example illustrating the results of this process showing the number of ran-off-roadway crashes each year during the study period for some roadway segments is presented in Table 6. This database was then used to support the descriptive and statistical analyses.

Table 6: Crash Data Records of some Randomly Selected Roadway Sections in Nevada

Route Name	Segment Code	1995	1996	1997	1998	1999	2000	2001	2002	2003
IR15N	1032	0	0	1	1	0	0	1	0	0
IR15N	1031	0	1	1	1	0	0	3	0	0
IR15S	2025	0	0	1	3	1	0	0	1	0
IR15S	2024	3	11	6	9	3	7	5	5	4
IR80E	3088	0	0	1	0	0	0	3	1	0
IR80E	3087	10	7	10	9	1	3	11	5	2
IR80W	4077	0	0	0	0	0	0	0	0	0
IR80W	4076	0	2	1	0	0	0	0	0	0
SR604	1152	42	29	36	54	31	30	36	41	20
US395N	1146	3	2	1	1	1	0	2	0	0
US50	1155	0	0	0	0	0	0	0	0	0
US6	1122	2	7	6	15	2	8	8	8	6
US93N	1124	3	1	1	6	1	2	2	2	2
US95N	1047	0	1	0	1	0	1	1	0	0
US95N	1049	0	1	0	0	0	0	0	0	0

As mentioned before, the single-vehicle ran-off-roadway crashes for all the study segments were evaluated for the periods before and after the installation of the shoulder rumble strips. The date of installation of rumble strips was used to identify the “before-after” thresholds. The construction period was defined as “the period between the date when the Notice-to-Proceed was issued to the contractor and the date when the installation was completed”. As previously discussed, in performing the before-after analyses, the crashes that occurred during the construction period were not considered.

The analyses were carried out computing three types of crash data, namely:

- Crash Frequency
- Crash Rate
- Crash Density

The crash frequencies computed on different roadways show a wide range of values. Interstate facilities typically were observed to have lower crash frequencies. A 15.7-mile long segment on SR-604 had a mean annual frequency of 41.2 crashes during the “before” period, which was the highest frequency. The segment registered a 22.5 percent reduction after the continuous shoulder rumble strip treatment. The mean crash frequency decreased from approximately 2.7 crashes during the "before" period to 1.9 crashes after treatment for an overall 30 percent reduction.

The highest crash rate was observed to be 5.25 crashes/MVMT during the "before" period. This crash rate was observed on a 0.27-mile long segment on US 95. The crash rate on this segment of US 95 decreased to a crash rate of 0.72 after treatment. The lowest crash rate was observed to be zero. This was observed on many segments where no crashes were recorded during the "before-after" period. The mean crash rate was computed to be 0.33 for the "before" period, and this was reduced to a crash rate of 0.19 for the "after" period. This amounted to a 42 percent reduction in crashes.

The highest crash density during the "before" period was recorded on a short section of I-15 N; however, this segment was very short and only had a length of 0.09 miles. The crash density during the "after" period became zero for this segment, as there were no crashes recorded during the period. The mean number of crash density reduced from 0.76 crashes/mile/year during the "before" period to 0.49 crashes/mile/year after the rumble strip deployment for a total crash density reduction of 35 percent. The basic statistics of the various safety indicators (crash rates) analyzed in this study were presented in Table 7.

Table 7: **Summary Basic Statistics of Safety Indicators for the Study Segments**

	Minimum		Mean		Maximum		Standard Deviation	
	Before	After	Before	After	Before	After	Before	After
Crash Frequency (/year)	0.000	0.000	2.695	1.884	41.150	31.890	4.655	3.595
Crash Rate (/mvmt)	0.000	0.000	0.325	0.188	5.246	1.576	0.426	0.235
Crash Density (/mile/year)	0.000	0.000	0.759	0.488	5.602	2.948	0.789	0.561

To facilitate a visual comparison of the change in crash rates due to the continuous shoulder rumble strip treatment, maps were prepared depicting the crash rates in individual segments before and after the installation of rumble strips. Examples of these are presented in Figures 7 to 10 which show the crashes for the “before-after” periods. Note that there are two figures each for the “before-after” periods. The difference between the two figures for each period was the direction travel for the I-15 and I-80 segments. The crash data for each figure were divided into three ranges namely *Minimum+ Standard Deviation*, *Minimum+2*Standard Deviation,* and the remaining crash rates were the 3rd group.

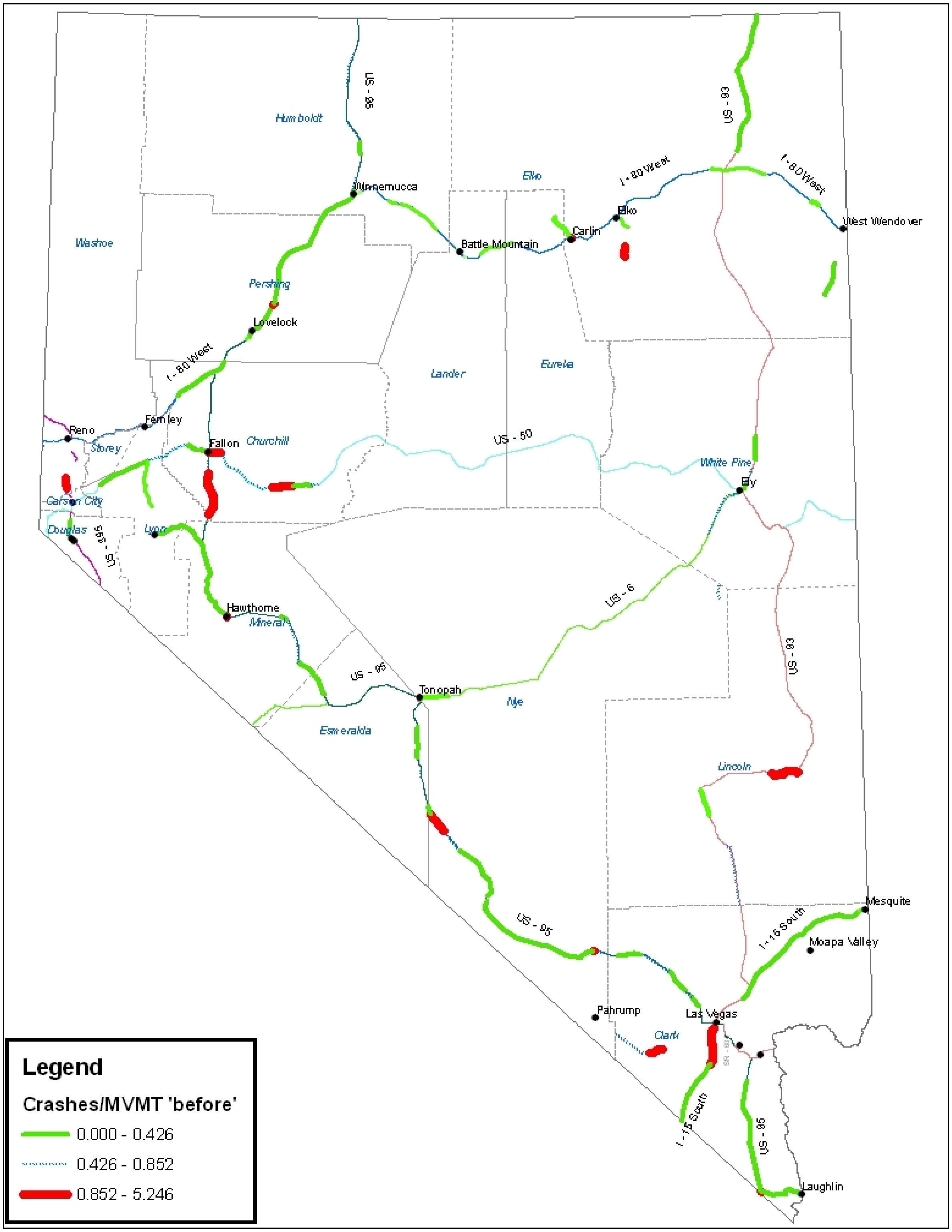

Figure 7: Crash Rates before Continuous Shoulder Rumble Strip Treatment (I–80 W, I–15 S)

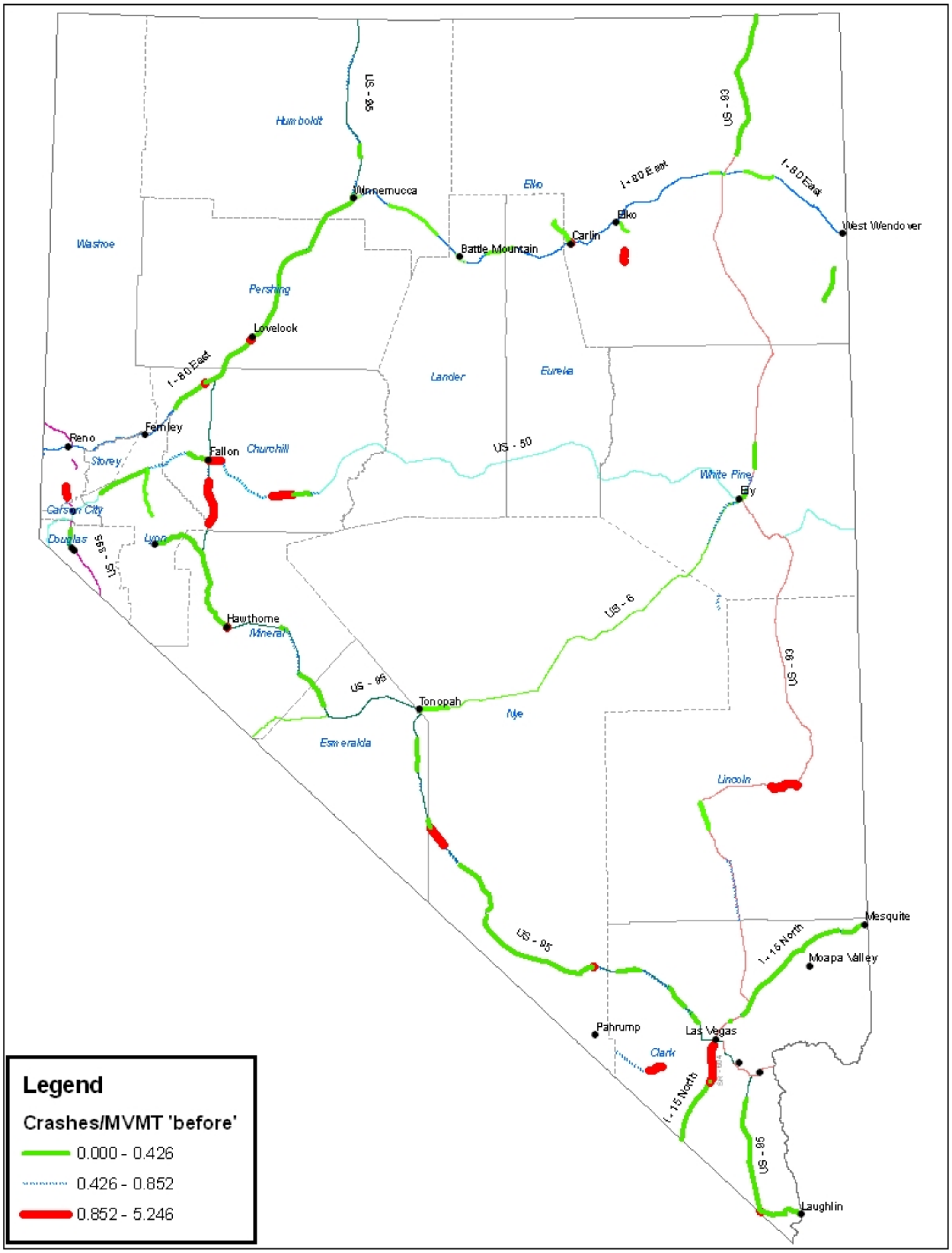

Figure 8: Crash Rates before Continuous Shoulder Rumble Strip treatment (I–80 E, I–15 N)

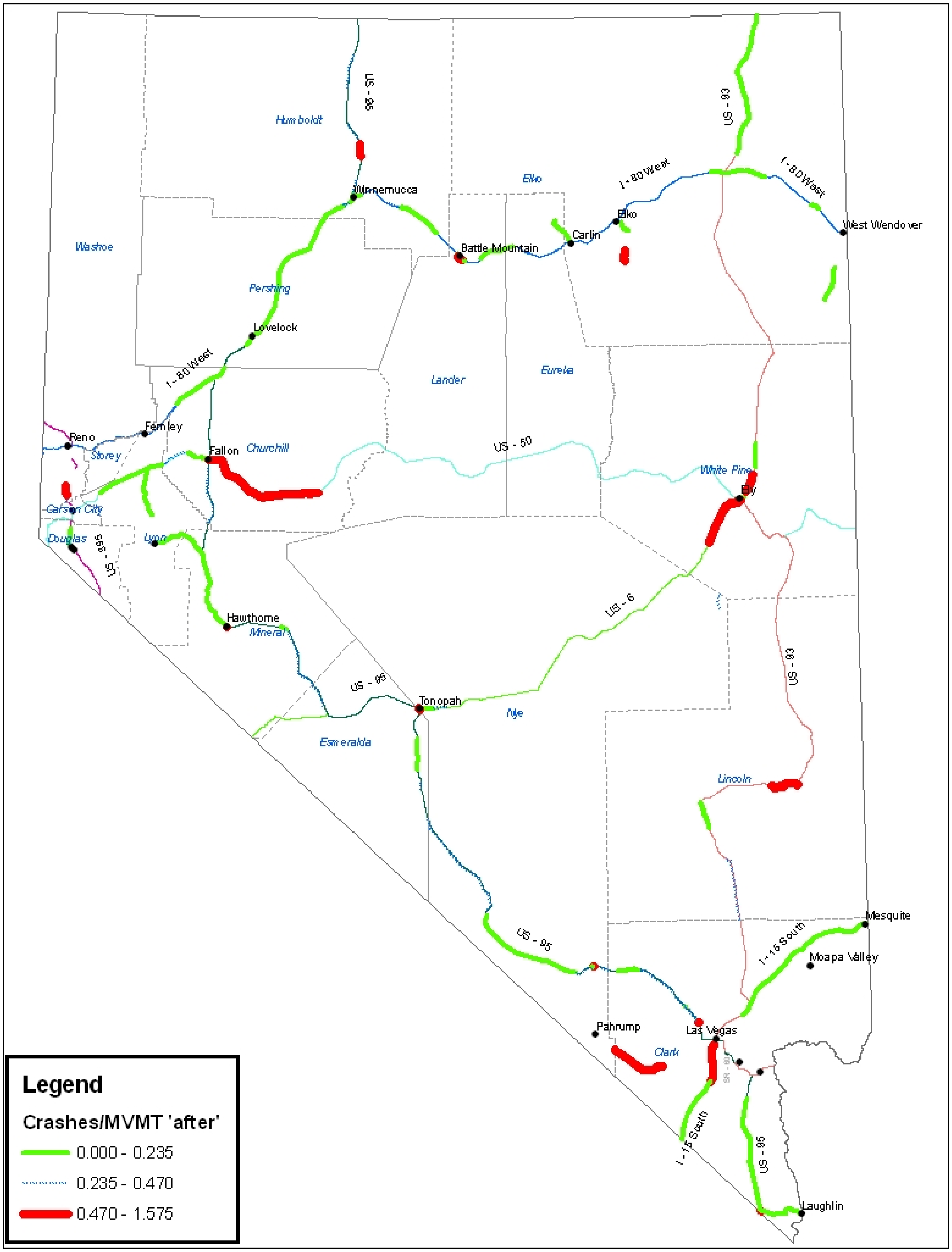

Figure 9: Crash Rates after Continuous Shoulder Rumble Strip Treatment (I–80 W, I–15 S)

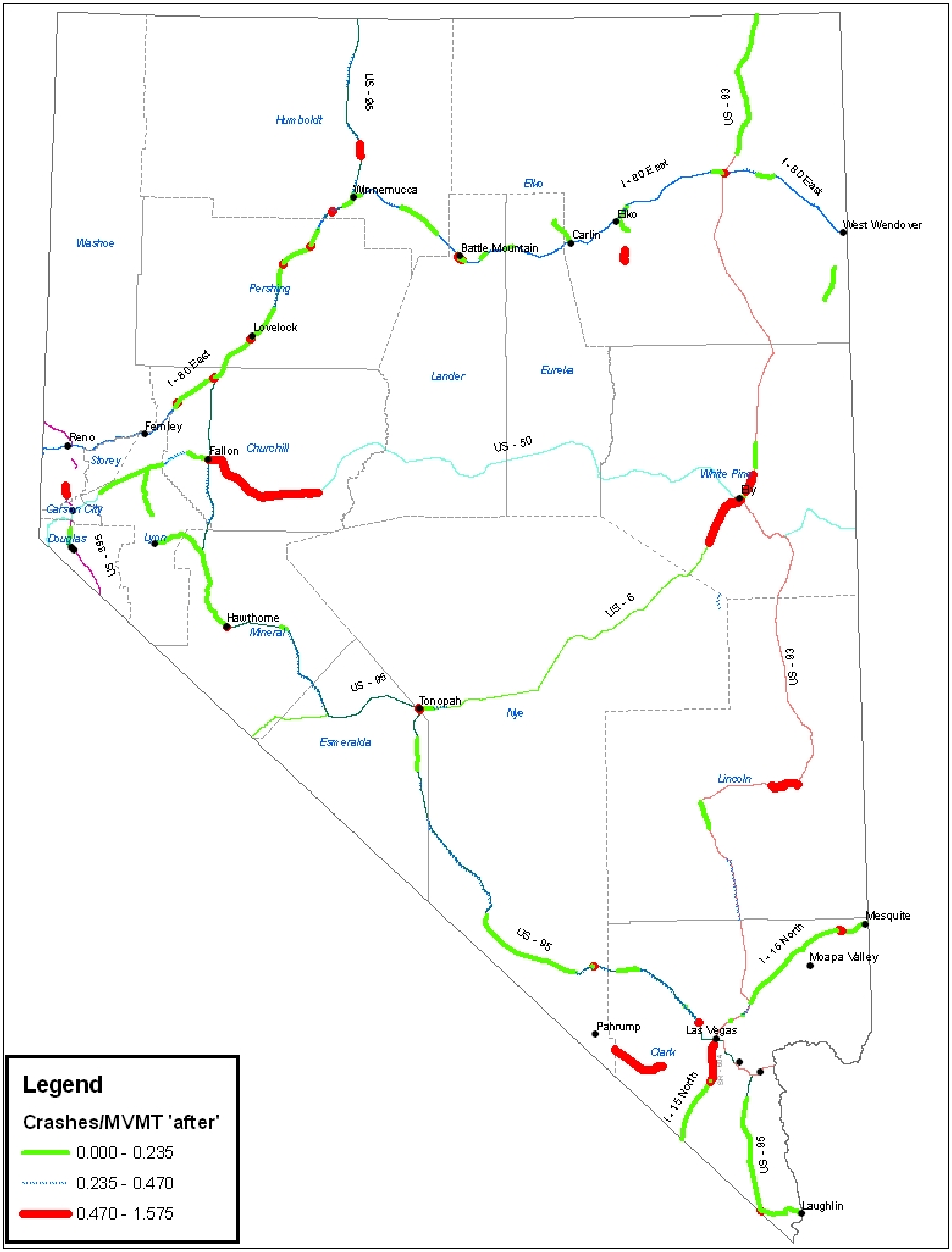

Figure 10: Crash Rates after Continuous Shoulder Rumble Strip Treatment (I–80 E, I–15 N)

4.1.1 Crash Frequency

The first type of analysis was performed by computing the crash frequency in terms of crashes/year during the "before-after" periods. The number of crashes on each segment was divided by the "before-after" period in years to get the crash frequency. Once the crash frequency was computed the percent change in crash rates was computed to determine if the safety condition on the roadway had improved or deteriorated after the continuous shoulder rumble strip treatment.

4.1.1.1 Crash Frequency for Individual Segments

A summary of the analysis of the crash frequency based on individual segments was presented in Table 8.

Table 8: Summary of the Analysis of Crash Frequency

Number of Segments						
Total	**Improved**	**%**	**No Change**	**%**	**Deteriorated**	**%**
306	201	65.69	36	11.76	69	22.55
Centerline Miles						
1303.185	1051.488	80.69	55.650	4.27	196.047	15.04

When the crash frequency of each of the 306 segments was compared, it was observed that 66 percent of the segments showed a decline in the number of annual crashes. These segments accounted for 81 percent of the total centerline miles of roadway. Likewise, 12 percent of the segments (4 percent of centerline miles) showed no change in frequency and 23 percent of the segments (15 percent of centerline miles) showed deterioration in the crash frequency. The results suggested that, overall the rumble strip treatment was effective in reducing the number of single vehicle ran-off roadway crashes.

4.1.1.2 Crash Frequency for each Facility

Although major proportions of the individual segments showed improvement after treatment, it remained to be seen if there was improvement on the individual facilities as a whole. The analysis showed that most of the facilities improved in the single-vehicle ran-off-roadway crash trend after treatment.

The two major Interstate facilities in Nevada, I-15 and I-80, recorded 23 percent and 36 percent reductions respectively in crash frequencies. The two major US routes, US–95 and US–93, also showed reductions in the crash frequencies registering 32 percent and 38 percent reductions respectively. The results of these analyses are shown in Table 9.

Table 9: **Summary of Before-after Analysis Based on Crash Frequency**

Facility	#Segments	CL Miles	SV ROR Crashes/Year		
			Before	After	% Change
I-15N	32	89.459	110.95	91.41	17.61
I-15S	32	91.732	93.12	65.33	29.84
I-15	64	181.191	203.97	156.86	23.09
I-80E	78	188.959	114.87	77.97	32.12
I-80W	75	176.834	96.25	55.50	42.34
I-80	153	365.793	211.09	133.65	36.68
US-95	48	382.596	179.53	122.05	32.02
US-93	9	142.807	50.11	30.75	38.64
US-50	12	98.414	48.59	35.64	26.65
US-6	4	35.507	8.77	8.79	-0.17
US-395	5	12.672	30.91	19.83	35.84
SR-766	3	11.595	2.02	0.00	100.00
SR-160	2	21.516	36.41	54.10	-48.58
SR-163	1	19.36	0.00	0.00	0.00
SR-221	1	0.337	0.00	0.00	0.00
SR-227	1	5.504	6.16	3.05	50.57
SR-228	1	4.732	0.74	0.61	17.83
SR-318	1	5.471	1.17	0.70	40.19
SR-604	1	15.69	41.15	31.89	22.49
Total	**306**	**1303.2**	**810.56**	**604.44**	**25.43**
Roadway Class	**#Segments**	**CL Miles**	**SV ROR Crashes/Year**		
			Before	**After**	**% Change**
Interstates	217	547	409.29	310.15	24.22
US Routes	78	672	371.43	214.67	42.21
SR without SR-160	9	62.684	51.86	37.18	28.30
State Routes	11	84.2	86.26	79.04	8.38

Although not very high, it was observed that US-6 experienced a slight increase in the crash frequency, and SR-160 showed a significant increase in the crash frequency. The segments along SR-160 included in the evaluation have experienced significant changes in operating conditions, including increased travel demand during the study period. Thus, the results for SR-160 need to be either discounted or considered with the stated qualification. Overall, when the effectiveness of the continuous shoulder rumble strip treatment, based on individual facilities, was considered all state routes except SR-160 showed improvement after treatment.

4.1.1.3 Crash Frequency for each Roadway Functional Class

The results of the analyses for crash frequency based on roadway functional class (namely Interstates, US routes and the state routes) are shown in Table 9. The results showed that the Interstates experienced a 24 percent reduction in the single-vehicle ran-off-roadway crashes after rumble strip treatment and the US Routes recorded a 42 percent decline in the annual crashes. The state routes witnessed a considerable percent reduction of 28 percent when SR-160 was not considered based on the aforementioned rationale, in computing percent reduction in crash frequencies. The percent reduction was only 8 percent when SR-160 was included in the percent change calculation.

A summary of the crash rates before and after installation of rumble strips with their corresponding percent changes is presented in Figures 11 to 13. Figure 11 showed results for roadways with crash frequencies ranging between 0 and 250 crashes/year, while Figure 12 provided the results for facilities whose frequencies vary between 0 and 60 crashes/year. Results of the analyses for each roadway functional class are shown in Figure 13.

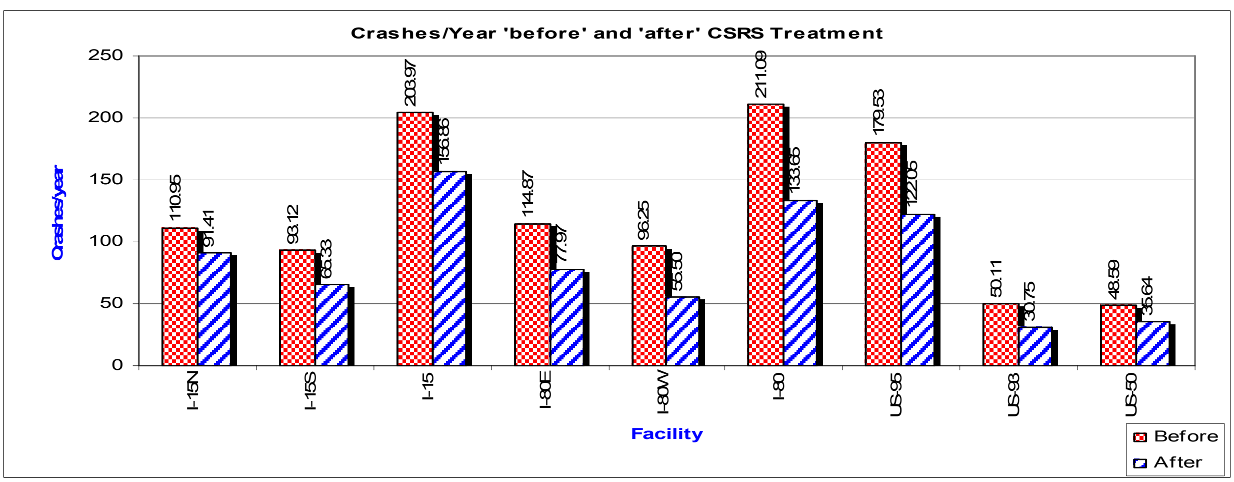

Figure 11: Single-vehicle Ran-off-roadway Frequency Before-After Continuous Shoulder Rumble Strip Treatment with 0 to 250 crashes/year

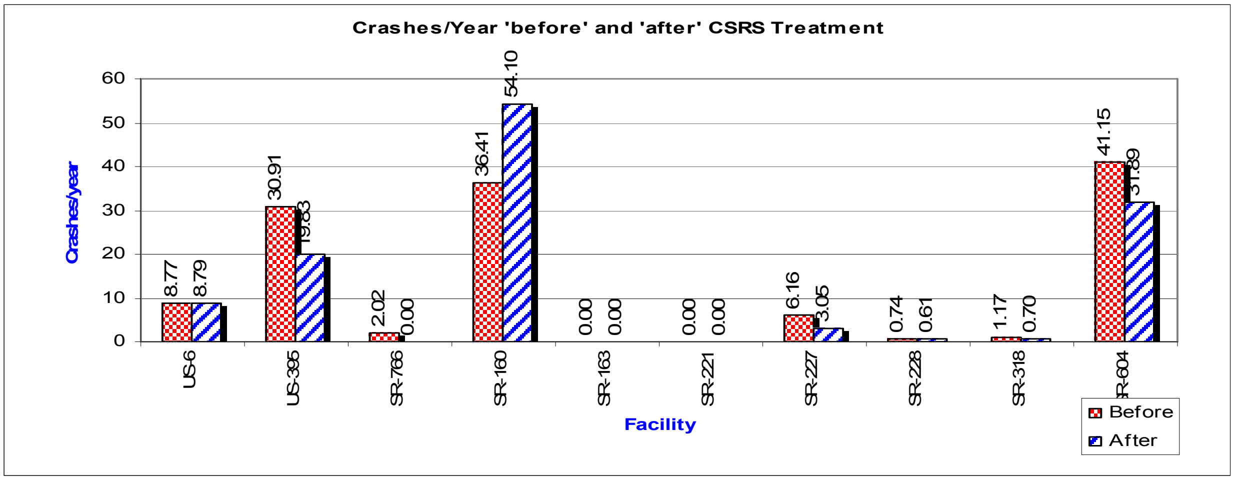

Figure 12: Single-vehicle Ran-off-roadway Frequency Before-After Continuous Shoulder Rumble Strip Treatment with 0 to 60 crashes/year

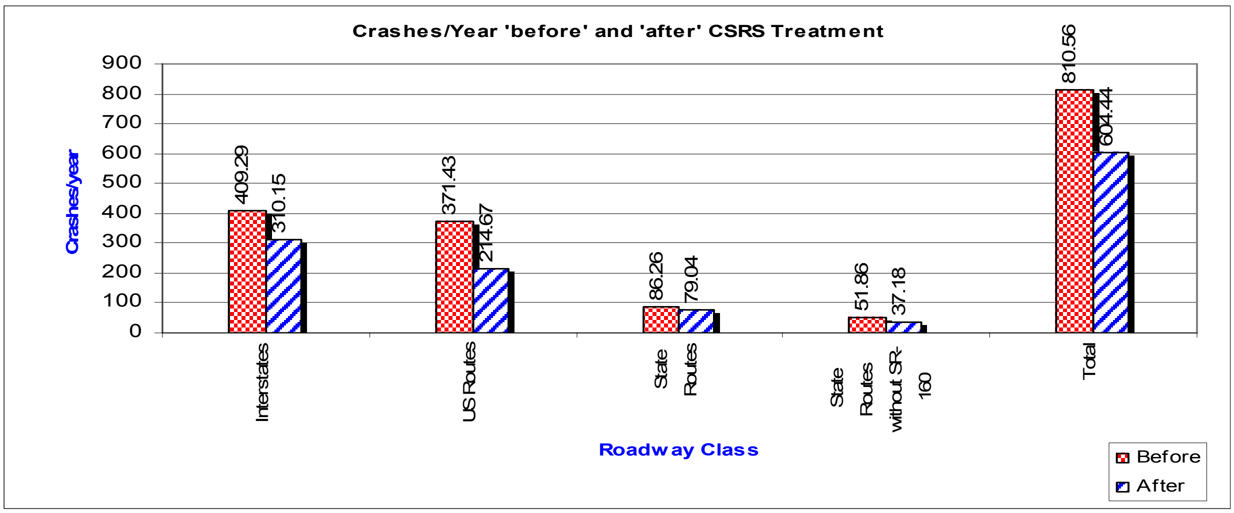

Figure 13: Single-vehicle Ran-off-roadway Frequency Before-After Continuous Shoulder Rumble Strips Treatment for each Roadway Functional Class

Though it was clearly evident that the frequency of occurrence of single-vehicle ran-off-roadway crashes on each facility or each roadway class has reduced after treatment, not every mile of the roadway saw a decline in the crash frequency even with the presence of rumble strips. The results of the analysis based on the total centerline miles of roadway segments are shown in Table 10.

Table 10: Summary of Analysis Based on Centerline Miles considering Crash Frequency

Facility	Total	Improved	%	No Change	%	Worsen	%
I-15N	89.459	59.978	67.05	0.641	0.717	28.840	32.24
I-15S	91.732	82.103	89.50	3.667	4.00	5.961	6.50
I-15	181.191	142.081	78.42	4.309	2.38	34.801	19.21
I-80E	188.959	132.809	70.28	12.254	6.48	43.897	23.23
I-80W	176.834	148.752	84.12	11.279	6.38	16.803	9.50
I-80	365.793	281.56	76.97	23.53	6.43	60.70	16.59
US-95	382.596	321.013	83.90	1.502	0.39	60.081	15.70
US-93	142.807	130.223	91.19	0.034	0.02	12.550	8.79
US-50	98.414	76.666	77.90	0.180	0.18	21.569	21.92
US-6	35.507	34.496	97.15	0.000	0.00	1.011	2.85
US-395	12.672	12.672	100.00	0.000	0.00	0.000	0.00
SR-766	11.595	5.199	44.84	6.396	55.16	0.000	0.00
SR-160	21.516	16.180	75.20	0.000	0.00	5.336	24.80
SR-163	19.36	0.000	0.00	19.360	100.00	0.000	0.00
SR-221	0.337	0.000	0.00	0.337	100.00	0.000	0.00
SR-227	5.504	5.504	100.00	0.000	0.00	0.000	0.00
SR-228	4.732	4.732	100.00	0.000	0.00	0.000	0.00
SR-318	5.471	5.471	100.00	0.000	0.00	0.000	0.00
SR-604	15.69	15.690	100.00	0.000	0.00	0.000	0.00
Total	***1303.185***	***1051.488***	***80.69***	***55.650***	***4.27***	***196.047***	***15.04***

Observations from Table 10 showed that over 142 of the 181 centerline miles of I-15 (78 percent) after rumble strip treatment saw a decline in the number of single-vehicle ran-off-roadway crashes. Similarly on I-80, 281 miles of the 366 centerline miles recorded a decline in the number of single-vehicle ran-off-roadway crashes after rumble strip treatment. On US-95, 320 miles of the 380 centerline miles (80 percent) evaluated showed improvement. Likewise, on US-93, 91 percent of the 143 centerline miles studied showed a decline in the number of single-vehicle ran-off-roadway annual crashes after installation of rumble strips. Overall, of the 1,303 miles of roadways with treatment, 1,051 miles (82 percent) experienced a reduced number of single-vehicle ran-off-roadway crash frequency. This clearly showed that the continuous shoulder rumble strip treatment was effective.

4.1.2 Crash Rate

An evaluation, based solely on the number of crashes, did not accurately reflect important attributes that change with time and sometimes might have been key contributors to the rise/decline in the crash rates. The average daily traffic was one such factor, which had a bearing on the crash rates. To take average daily traffic into account, the factor of million vehicle miles traveled (MVMT) was computed using the average daily traffic and the length of each segment. The crash rate was computed and compared for before-after conditions. The results of the analyses disaggregated by each facility are shown in Table 11.

Table 11: Influence of Continuous Shoulder Rumble Strips on Crash Rates

Crashes/MVMT														
Facility	Number of Segments							Centerline Miles						
	Total	Improved	%	No Change	%	Worsen	%	Total	Improved	%	No Change	%	Worsen	%
I-15N	32	23	71.88	2	6.25	7	21.875	89.459	84.987	95.00	0.641	0.717	3.831	4.283
I-15S	32	20	62.50	5	15.63	7	21.88	91.732	82.103	89.50	3.667	4.00	5.961	6.50
I-15	64	43	67.19	7	10.94	14	21.88	181.191	167.090	92.22	4.309	2.38	9.793	5.40
I-80E	78	45	57.69	9	11.54	24	30.77	188.959	132.809	70.28	6.896	3.65	49.255	26.07
I-80W	75	52	69.33	10	13.33	13	17.33	176.834	150.957	85.37	11.279	6.38	14.597	8.25
I-80	153	97	63.40	19	12.42	37	24.18	365.793	283.77	77.58	18.18	4.97	63.85	17.46
US-95	48	38	79.17	4	8.33	6	12.50	382.596	342.793	89.60	1.502	0.39	38.301	10.01
US-93	9	7	77.78	1	11.11	1	11.11	142.807	130.223	91.19	0.034	0.02	12.550	8.79
US-50	12	7	58.33	1	8.33	4	33.33	98.414	52.244	53.09	0.180	0.18	45.990	46.73
US-6	4	3	75.00	0	0.00	1	25.00	35.507	34.496	97.15	0.000	0.00	1.011	2.85
US-395	5	5	100.00	0	0.00	0	0.00	12.672	12.672	100.00	0.000	0.00	0.000	0.00
SR-766	3	2	66.67	1	33.33	0	0.00	11.595	5.199	44.84	6.396	55.16	0.000	0.00
SR-160	2	1	50.00	0	0.00	1	50.00	21.516	16.180	75.20	0.000	0.00	5.336	24.80
SR-163	1	0	0.00	1	100.00	0	0.00	19.36	0.000	0.00	19.360	100.00	0.000	0.00
SR-221	1	0	0.00	1	100.00	0	0.00	0.337	0.000	0.00	0.337	100.00	0.000	0.00
SR-227	1	1	100.00	0	0.00	0	0.00	5.504	5.504	100.00	0.000	0.00	0.000	0.00
SR-228	1	1	100.00	0	0.00	0	0.00	4.732	4.732	100.00	0.000	0.00	0.000	0.00
SR-318	1	1	100.00	0	0.00	0	0.00	5.471	5.471	100.00	0.000	0.00	0.000	0.00
SR-604	1	1	100.00	0	0.00	0	0.00	15.69	15.690	100.00	0.000	0.00	0.000	0.00
Total	***306***	***207***	***67.65***	***35***	***11.44***	***64***	***20.92***	***1303.18***	***1076.061***	***82.57***	***50.292***	***3.86***	***176.833***	***13.57***

4.1.2.1 Crash Rate for Individual Segments

The results presented in Table 11 showed that, overall 207 of the 306 segments (67.7 percent) showed a reduction in crash rates. These segments accounted for 1,076 centerline miles (82.6 percent) of the roadways studied. Likewise, 35 segments (11.4 percent) showed no change in the crash rates. These segments accounted for 3.9 percent of the centerline miles of the roadways studied. Furthermore, 64 segments (20.9 percent) experienced increased crash rates after the continuous shoulder rumble strip treatment. They constituted 13.6 percent of the centerline miles studied. A detailed breakdown of the results for individual facilities was included in Table 11 and illustrated in Figures 14 to 17. Figures 14 and 15 show the results based on the number of segments for each facility. Similarly Figures 16 and 17 show results based on centerline miles for each facility.

On I-15 the single-vehicle ran-off-roadway crash rates decreased on 167 of the 181 treated centerline miles (92 percent). Only 5 percent of the roadway lengths on I-15 accounting for 9.7 miles experienced a rise in the crash rate after treatment. Similarly, more than 77 percent of the treated 365 centerline miles on I-80 saw a decline in the crash rates after treatment. On US-95, more than 342 centerline miles (90 percent) of the 382 miles treated had lower crash rates after the rumble strip treatment. On US-93, over 130 miles (91percent) of the treated 142 centerline miles showed improvements in crash rates after treatment and only 12.6 miles (8.2 percent) of the roadways experienced an increase in the crash rates after treatment. Overall, 83 percent of the treated roadways accounted for more than 1,076 miles of the treated 1,303 miles experienced lower single vehicle crashes after the rumble strip treatment when compared to the same stretches of roadways during the period before the treatment. These results clearly indicate that the continuous shoulder rumble strips have been effective in reducing the rate of single-vehicle ran-off-roadway crashes.

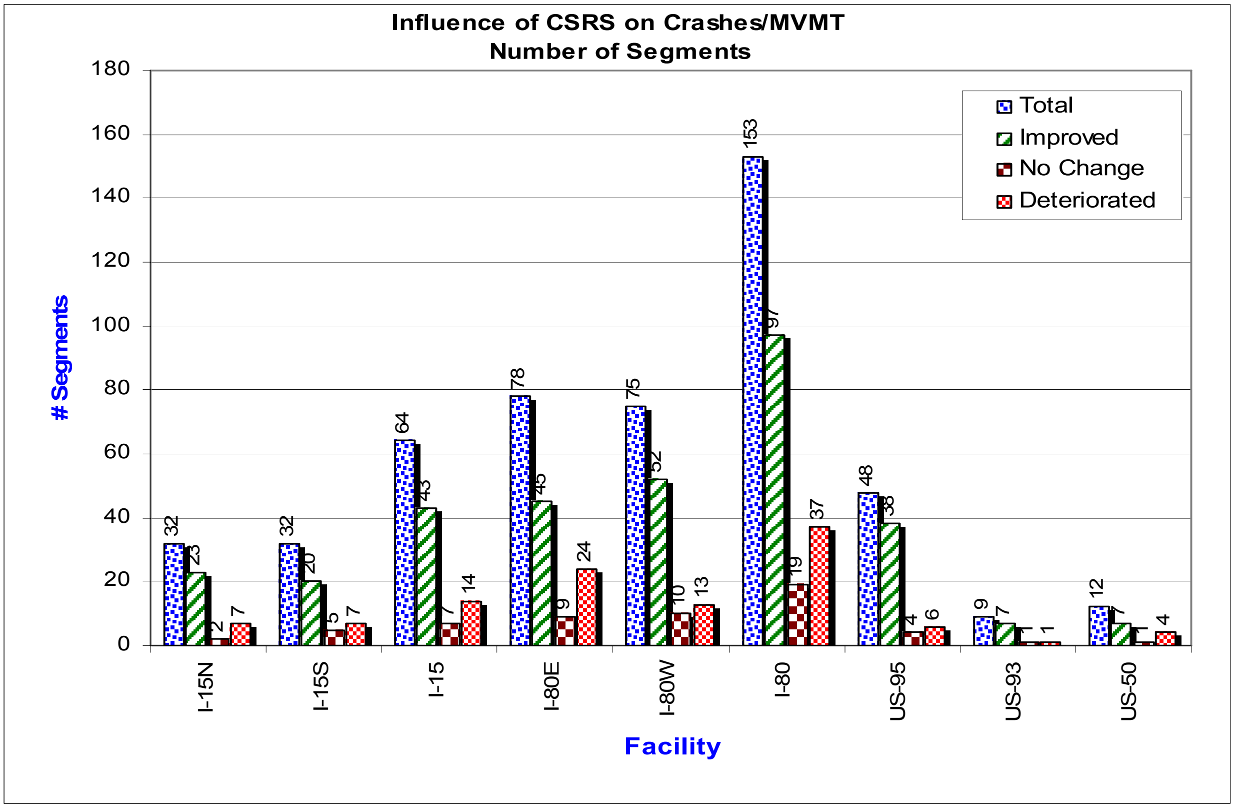

Figure 14: Influence of Continuous Shoulder Rumble Strips in Reducing Crash Rates (# segments)

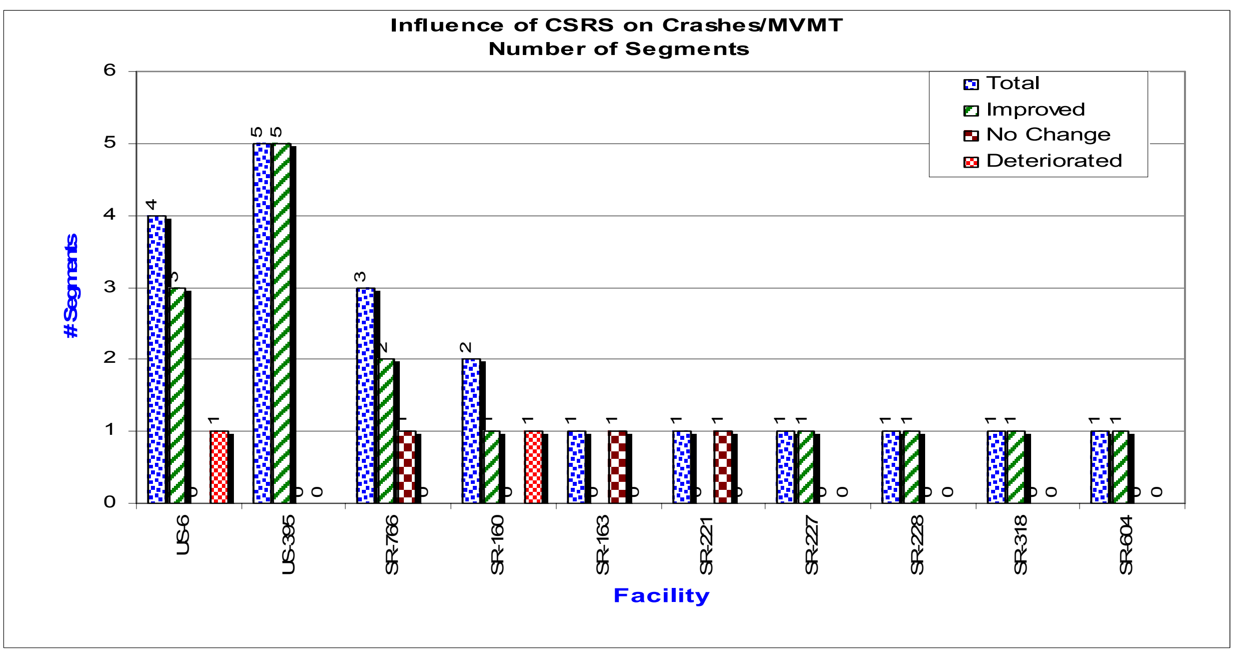

Figure 15: Influence of Continuous Shoulder Rumble Strips in Reducing Crash Rates (# segments)

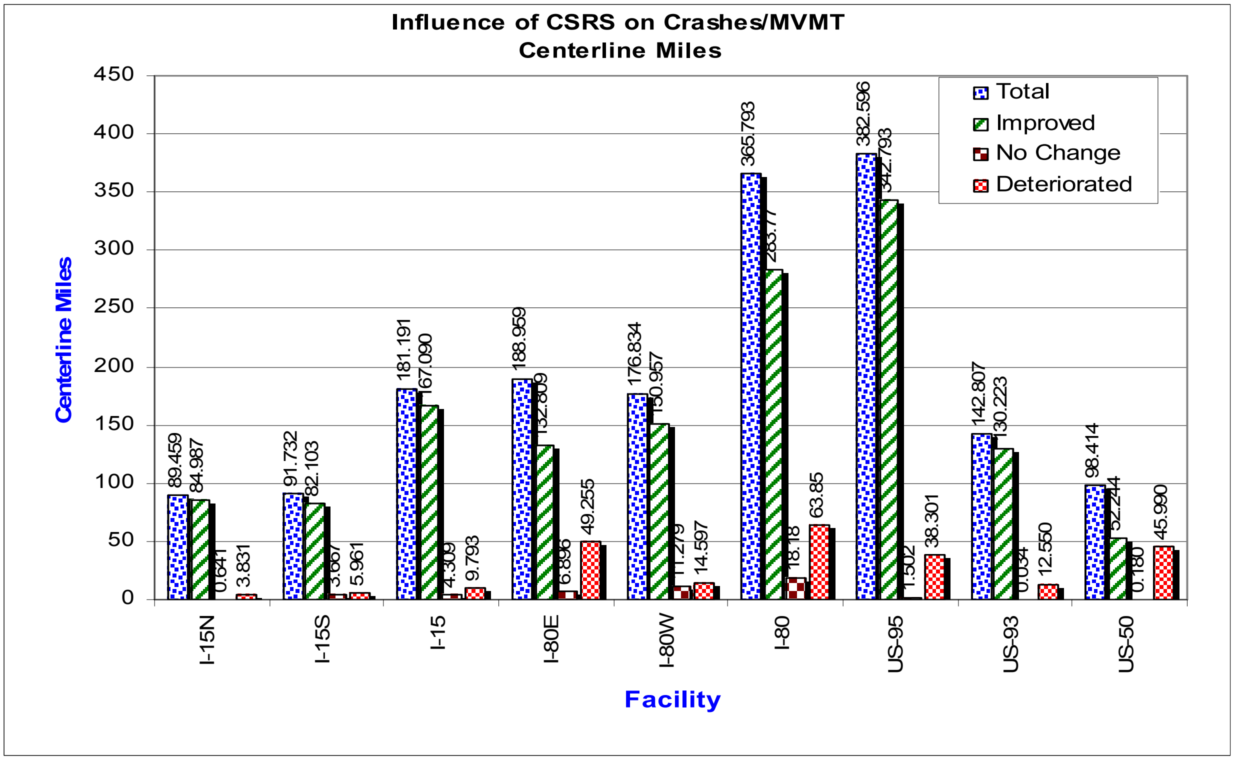

Figure 16: Influence of Continuous Shoulder Rumble Strips in Reducing Crash Rates (centerline miles)

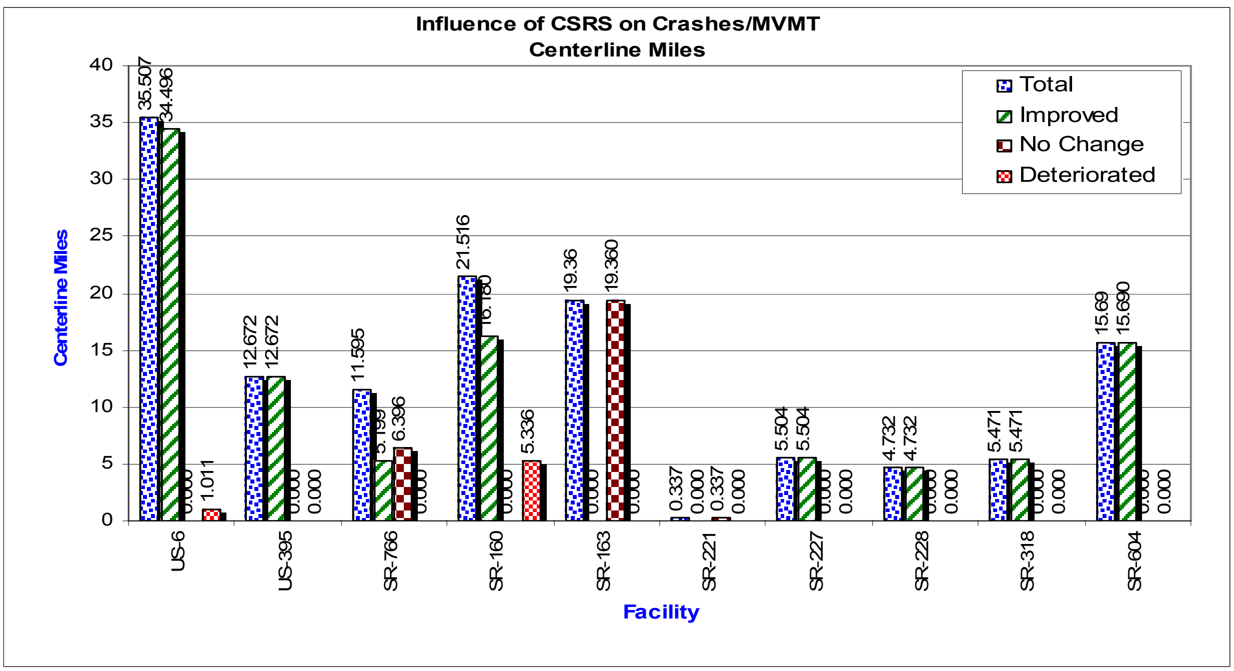

Figure 17: Influence of Continuous Shoulder Rumble Strips in Reducing Crash Rates (centerline miles)

4.1.2.2 Crash Rate for each Facility

The crash rates of each facility used the annual number of single-vehicle crashes and annual average daily traffic on each segment, and the segment length based on the methodology described earlier. The crash rates for the individual facilities over the study period are shown in Table 12 and illustrated in Figure 18. Note that Table 12 and Figure 18 only show crash rates over time, and they do not show the date when the continuous shoulder rumble strip treatment was applied. The fact that the treatment took place at different times for different study segments made it difficult to clearly show the impact of the treatment on crash rates used in Table 12 and Figure 18. The results of the before-after analyses of each facility are shown in Table 13:

Table 12: Crash Rates during the 9-Year Period on Different Roadway Facilities

Year	I - 15	I - 80	US - 395	US - 50	US - 93	US - 95
1995	0.125	0.204	0.377	0.431	0.305	0.384
1996	0.159	0.265	0.442	0.488	0.416	0.406
1997	0.155	0.172	0.379	0.387	0.276	0.340
1998	0.189	0.249	0.356	0.365	0.369	0.390
1999	0.115	0.064	0.372	0.214	0.255	0.346
2000	0.093	0.119	0.193	0.376	0.218	0.252
2001	0.088	0.214	0.339	0.328	0.143	0.194
2002	0.108	0.166	0.263	0.255	0.207	0.238
2003	0.093	0.074	0.082	0.147	0.178	0.232

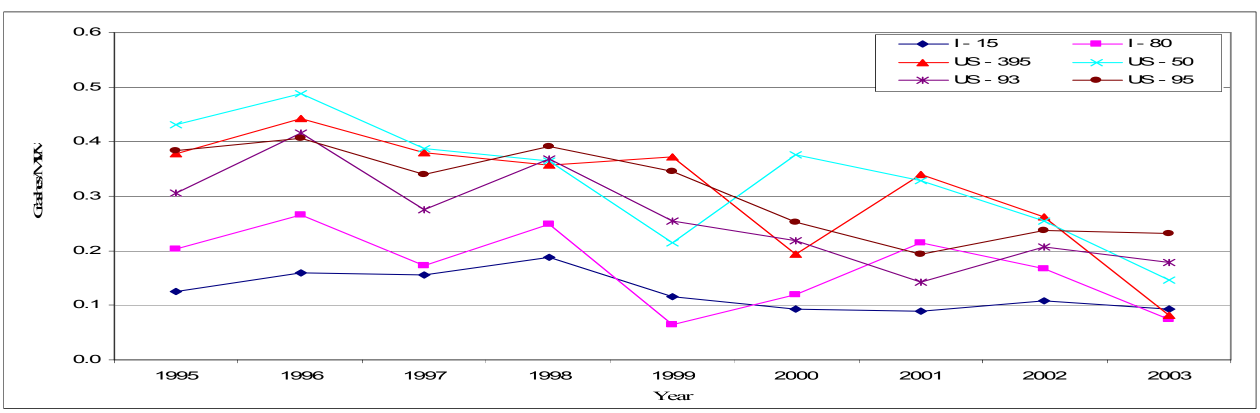

Figure 18: Crash Rate Trends with Time (Continuous Shoulder Rumble Strips Treatment 1999)

Table 13: Summary of Before-after Analysis Based on Crash Frequency

Facility	#Segments	CL Miles	SV ROR Crashes/MVMT		
			Before	After	% Change
I-15N	32	89.459	0.169	0.115	31.953
I-15S	32	91.732	0.140	0.081	42.143
I-15	64	181.191	0.155	0.098	36.745
I-80E	78	188.959	0.252	0.159	36.905
I-80W	75	176.834	0.228	0.121	46.930
I-80	153	365.793	0.241	0.141	41.512
US-95	48	382.596	0.362	0.228	37.017
US-93	9	142.807	0.379	0.218	42.480
US-50	12	98.414	0.435	0.297	31.724
US-6	4	35.507	0.600	0.542	9.667
US-395	5	12.672	0.392	0.215	45.153
SR-766	3	11.595	0.175	0.000	100.000
SR-160	2	21.516	0.848	0.683	19.458
SR-227	1	5.504	0.237	0.119	49.789
SR-228	1	4.732	1.227	0.947	22.820
SR-318	1	5.471	0.688	0.349	49.273
SR-604	1	15.690	1.611	1.576	2.173
Total	**306**	**1303.2**	**0.262**	**0.158**	**39.695**
Roadway Class	**#Segments**	**CL Miles**	**Crashes/MVMT**		
			Before	**After**	**% Change**
Interstates	217	547.000	0.191	0.111	41.885
US Routes	78	672.000	0.382	0.240	37.173
State Routes	11	84.200	0.571	0.491	14.011
State Routes without SR-160	9	62.684	0.477	0.369	22.590
Total	**306**	**1303.2**	**0.262**	**0.158**	**39.695**

From Table 13, it was observed that the single-vehicle ran-off-roadway crash rate on I-15 changed from 0.16 crashes/MVMT prior to treatment to 0.10 crashes/MVMT following treatment. This represented a 37 percent reduction in the crash rate. Likewise, the crash rate on I-80 decreased from 0.24 crashes/MVMT before treatment to a crash rate of 0.14 crashes/MVMT after the rumble strip application for a 41 percent decrease. US-95 crash rate changed from 0.36 crashes/MVMT prior to treatment to a crash rate of 0.23 crashes/MVMT after application of rumble strips for a 37 percent reduction. The other facilities in the State of Nevada experienced a reduction in crash rates as well. As a whole, the road network in Nevada treated with rumble strips had a crash rate of 0.26 crashes/MVMT before treatment, which was reduced to 0.16

crashes/MVMT after installation of rumble strips for a 40 percent reduction in the crash rate. It was also noted that the Interstate facilities have lower crash rates when compared to the US routes and the state routes because the Interstates have high design standards. The changes in crash rates for each of the facilities studied are shown in Figures 19 and 20. These figures clearly show pictorially that the continuous shoulder rumble strip treatment helped reduce the crash rate on each of the facilities.

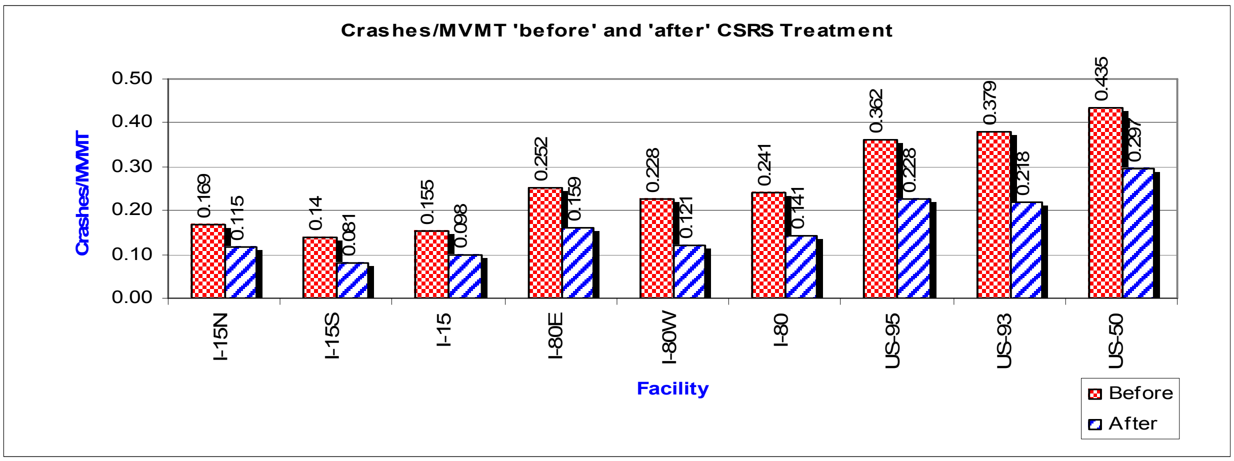

Figure 19: Single-vehicle Ran-off-roadway Crash Rates Before-After on each Facility

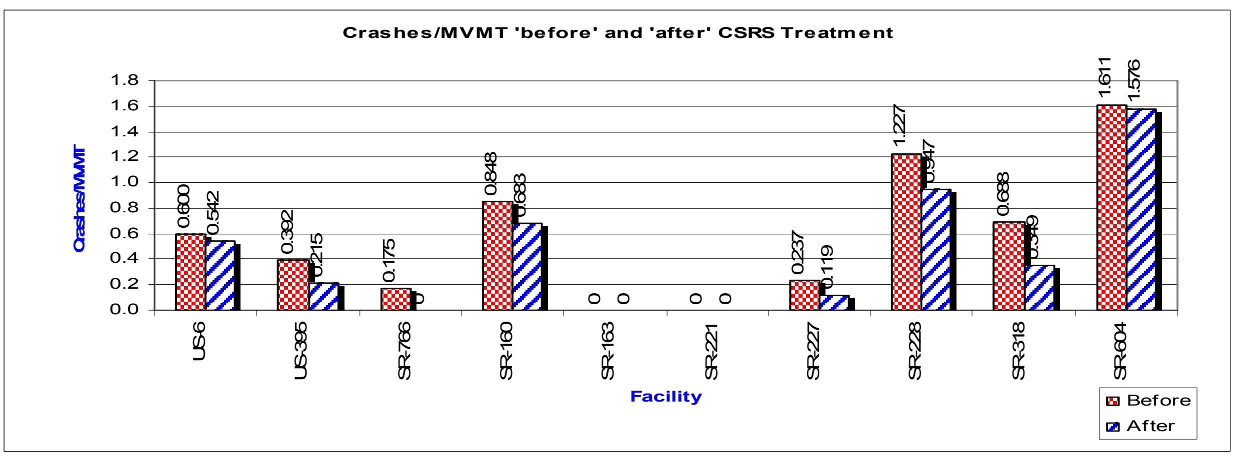

Figure 20: Single-vehicle Ran-off-roadway Crash Rates Before-After on each Facility

4.1.2.3 Crash Rate for each Roadway Functional Class

Results of the analyses of crash rates based on roadway class are shown in Table 15. The 547 miles of Interstate roadways treated with rumble strips experienced a crash rate of 0.19 crashes/MVMT prior to treatment. This rate decreased to a crash rate of 0.11 after rumble strip installation for a 42 percent reduction. The 672 miles of US routes installed with rumble strips saw their average crash rate drop from 0.38 crashes/MVMT during the “before” period to 0.24 crashes/MVMT during the “after” period. This was a 37 percent reduction in the crash rate. The crash rates for state routes changed from 0.57 crashes/MVMT to 0.49 crashes/MVMT, a 14 percent reduction after treatment. However, if SR-160 was not considered, state routes showed a 22 percent reduction in the crash rate after the deployment of rumble strips. These results were summarized graphically in Figure 21. The percent change in crash rates for the individual sections evaluated are shown in Figures 22 and 23. These figures clearly showed that a vast majority of the segments experienced reduced crash rates following the installation of shoulder rumble strips.

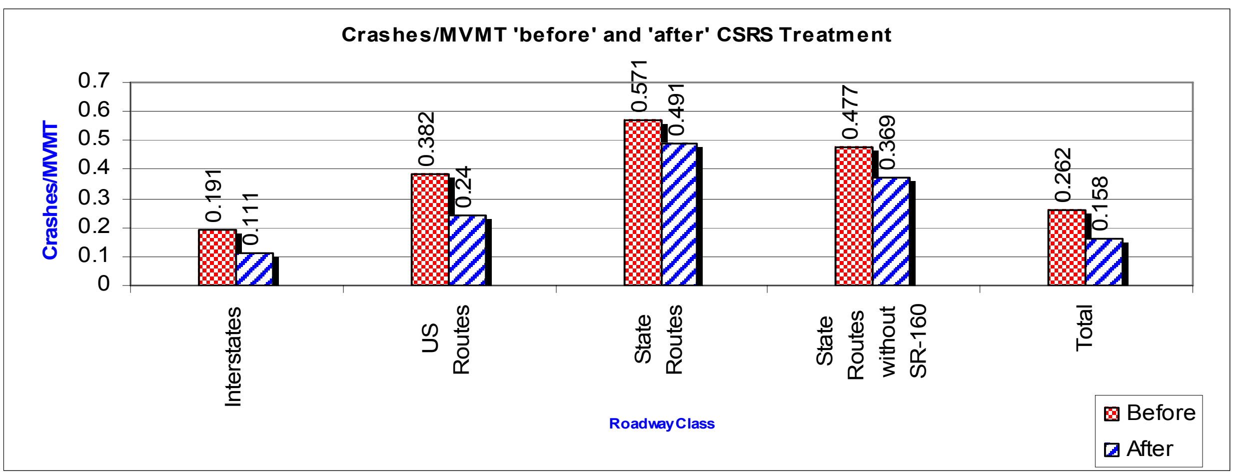

Figure 21: Single-vehicle Ran-off-roadway Crash Rates Before-After on each Roadway Class

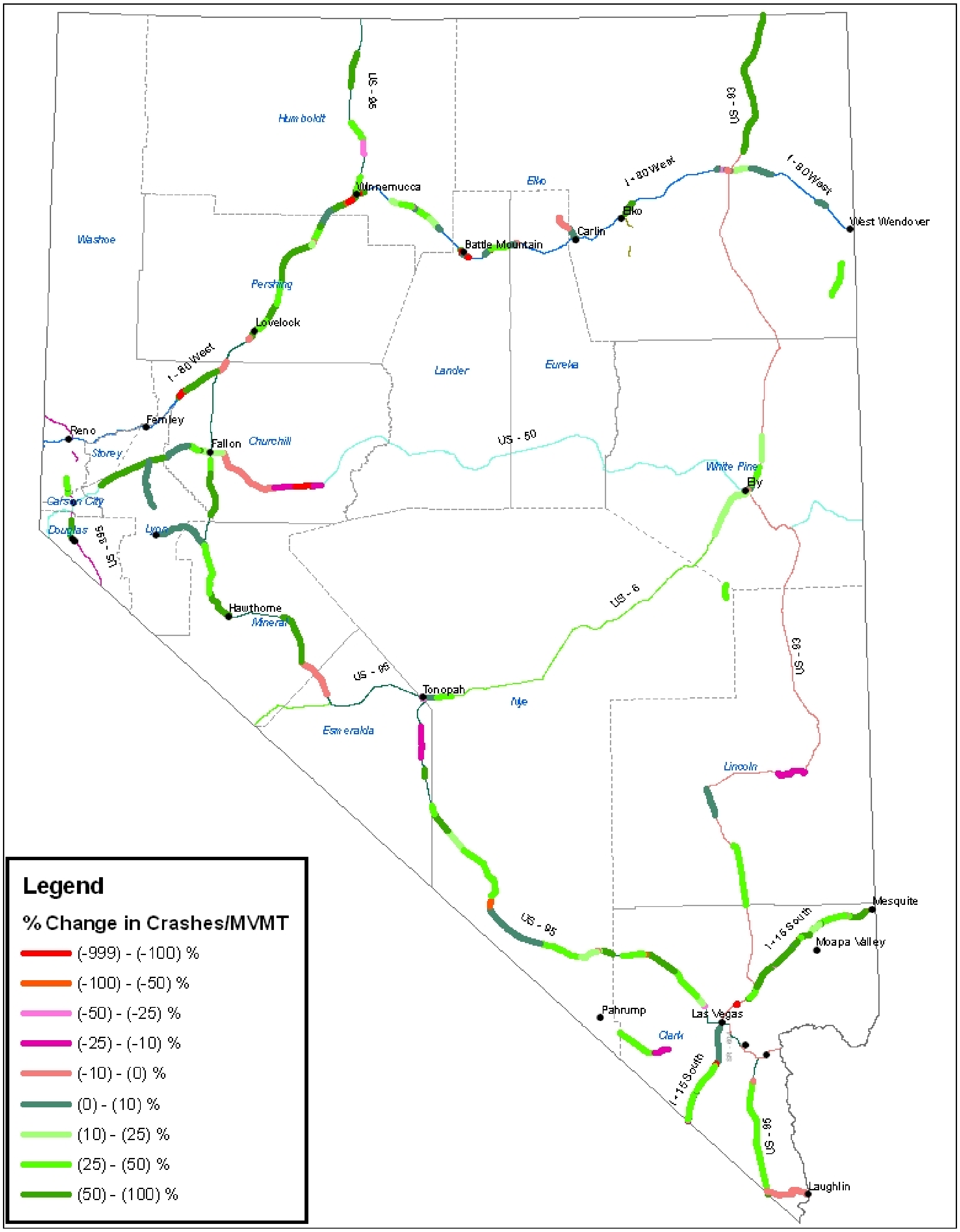

Figure 22: Percent Change in Crash Rates (I–80 W, I–15 S)

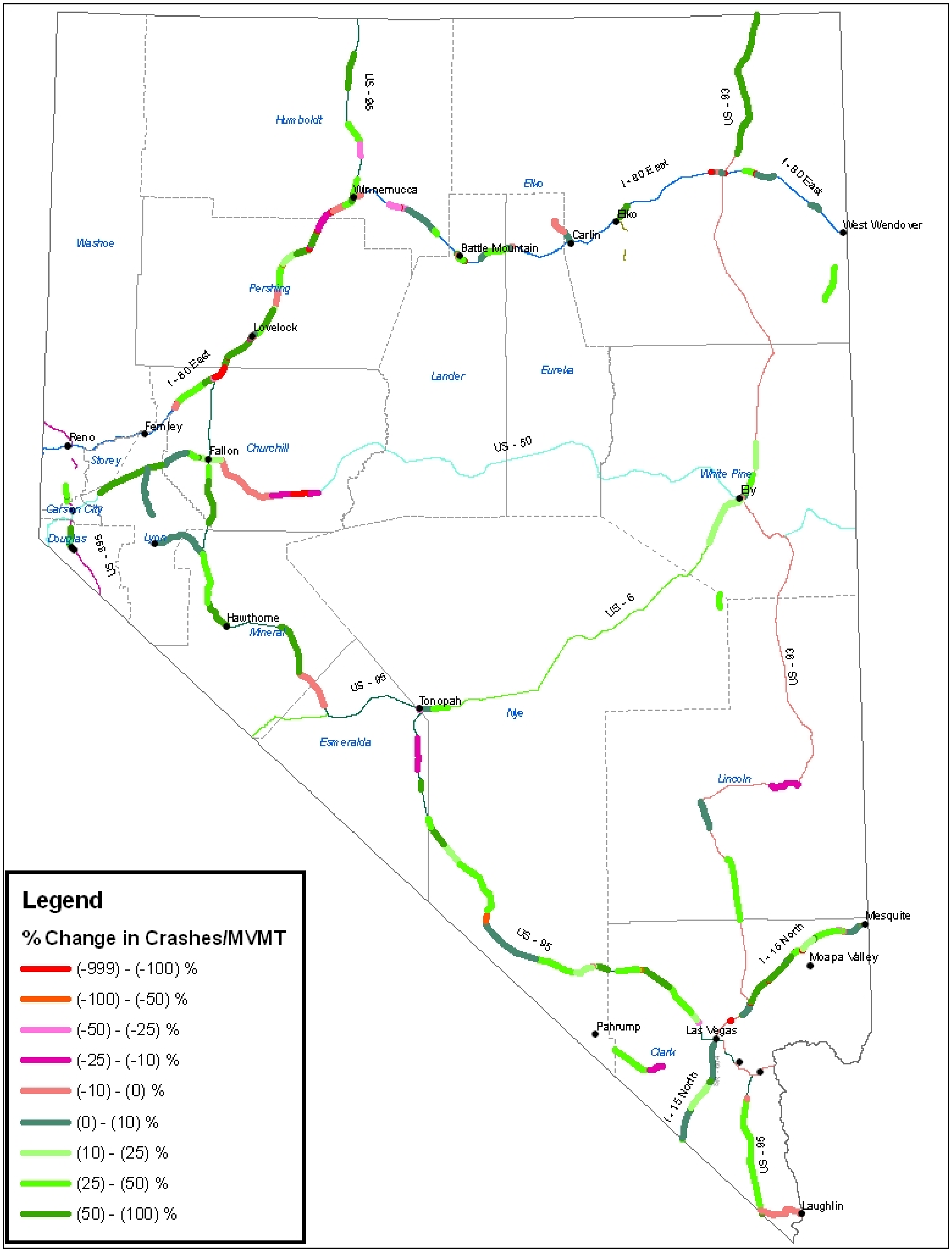

Figure 23: Percent Change in Crash Rates (I–80 E, I–15 N)

4.1.2.4 Crash Rate vs Speed

Speed could be a major contributor to the occurrence of crashes. Drivers who were inattentive were more likely to be in single-vehicle ran-off-roadway crashes at high speeds of travel than at low speeds. Conversely, the chances of a driver recovering from drifting away from the roadway were better at lower speeds than at higher speeds. This was because the distance traveled during the reaction and response time was lower in the case of the lower speed. Since the actual speeds at which a vehicle that was involved in a single-vehicle ran-off-roadway crash traveled was not easily accessible. The impact of speed relationship was evaluated using the posted speed limit on roadway segments as a surrogate indicator of operating speeds.

Six posted speed limits were in existence during the study period on the road network in Nevada. These speeds ranged between 45 miles/hour (72 kilometers/hour) and 75 miles/hour (120 kilometers/hour). They were based on the road functional class and on the area. Interstates typically have speed limits of 75 miles/hour (120 kilometers/hour) or 70 miles/hour (113 kilometers/hour), except for segments within urban areas, which had lower posted speed limits. The entire length of I-80 considered for the analysis had 75 miles/hour (120 kilometers/hour) as the posted speed limit.

Crash frequencies and crash rates were computed for both the “before-after” periods for various speed limits to determine the percent change in crash rates. A summary of the crash frequency / rate computations and their respective percent changes for different posted speed limits were shown in Tables 14 and 15. It was observed from these tables that the percent change in crash rates appeared to be better at lower speed limits as compared to the higher speed limits. However, the fact that data for segments with posted speed limits less than or equal to 60 miles/hour (98 kilometers/hour) were limited needed to be taken into account when drawing conclusions. The results for segments with posted speed limits of 70 miles/hour (113 kilometers/hour) or 75 miles/hour (120 kilometers/hour) were far more conclusive because their sample sizes were reasonably large.

Table 14: Single-vehicle Ran-off-roadway Crash Frequency for Before-After Conditions for Various Speed Limits

Crashes/Mile					
Speed	**# Segments**	**CL Miles**	**Crashes/Mile 'Before'**	**Crashes/Mile 'After'**	**% Change**
45	2	0.830	2.500	0.250	90.000
55	5	23.295	8.500	5.250	38.235
60	5	17.435	9.500	2.667	71.931
65	24	176.457	142.730	122.918	13.881
70	68	590.680	358.706	238.018	33.646
75	202	494.488	328.187	226.124	31.099

Table 15: **Single-vehicle Ran-off-roadway Crash Rate for Before-After Conditions for Various Speed Limits**

Crashes/MVMT					
Speed	**# Segments**	**CL Miles**	**Crashes/MVMT 'Before'**	**Crashes/MVMT 'After'**	**% Change**
45	2	0.830	2.609	0.237	90.925
55	5	23.295	0.360	0.202	43.882
60	5	17.435	0.232	0.079	66.017
65	24	176.457	0.367	0.269	26.896
70	68	590.680	0.306	0.173	43.322
75	202	494.488	0.215	0.121	43.597

4.1.2.5 Combined Effect of Factors on Crash Rate

As discussed in the previous sections, factors such as speed, average daily traffic, shoulder widths, and length of the segments had a bearing on the crash rates. After analyses, the effect of each of these factors individually and the combined effect of one or more of these factors on the crash rates, needed to be investigated. Once again, simple linear regression models were used for this purpose. Two groups of models were developed: one based on crash frequencies and the other based on crash rates.

Crash Frequency (crashes/year)$_{after}$ = f (Speed, ADT $_{after}$, Shoulder Width, Length)

The regression equation is:

Crashes/year $_{after}$ = 12.2 - 0.184 Speed + 0.108 ADT $_{after}$ + 0.0460 Shoulder Width + 0.333 Length

Predictor	Coef	SE Coef	T	P
Constant	12.239	1.740	7.03	0.000
Speed	-0.18369	0.02629	-6.99	0.000
ADT $_{after}$	0.10758	0.01792	6.01	0.000
Shoulder Width	0.04599	0.08344	0.55	0.582
Length	0.33338	0.02399	13.90	0.000

R-Sq = 51.7%   R-Sq(adj) = 51.0%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	4	2037.04	509.26	80.51	0.000
Residual Error	301	1904.06	6.33		
Total	305	3941.10			

The model with an adjusted R^2 value of 51 percent was reasonably good. The standard errors and the corresponding T-statistics for the coefficients indicated that the coefficients were very significant except for shoulder width. The F-statistic for the model as a whole indicated a high level of statistical significance. The model indicated that as the posted speed limit increased, the crash rates decreased. This reflected the fact that the posted speed limits on Interstates were high and the crash rates on Interstates were observed to be low. The model showed that crash rates increased with average daily traffic and the length of the segment.

Crash Frequency (crashes/year)$_{after}$ = f (ADT $_{after}$, Shoulder Width, Length)

The regression equation is:

Crashes/year $_{after}$ = 1.11 + 0.119 ADT $_{after}$ - 0.212 Shoulder Width + 0.363 Length

Predictor	Coef	SE Coef	T	P
Constant	1.1108	0.7546	1.47	0.142
ADT $_{after}$	0.11943	0.01920	6.22	0.000
Shoulder Width	-0.21172	0.08056	-2.63	0.009
Length	0.36266	0.02542	14.26	0.000

R-Sq = 43.9%   R-Sq(adj) = 43.3%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	3	1728.18	576.06	78.62	0.000
Residual Error	302	2212.92	7.33		
Total	305	3941.10			

The model had a lower adjusted R^2 value of 43.3 percent. The standard errors and the corresponding T-statistics for the coefficients indicated that the coefficients were significant, including shoulder widths. The F-statistic for the model as a whole indicated a high level of statistical significance. The model indicated that crash rates increased with average daily traffic and the length of the segment, and decreased with an increase in shoulder widths.

Crash Rate (crashes/MVMT)$_{after}$ = f (ADT $_{after}$, Length, Shoulder Width, Speed)

The regression equation is:

Crashes/ MVMT $_{after}$ = 1.20 - 0.00535 ADT $_{after}$ + 0.00174 Length - 0.0109 Shoulder Width - 0.0120 Speed

Predictor	Coef	SE Coef	T	P
Constant	1.1971	0.1453	8.24	0.000
ADT $_{after}$	-0.005353	0.001496	-3.58	0.000
Length	0.001736	0.002003	0.87	0.387
Shoulder Width	-0.010945	0.006966	-1.57	0.117
Speed	-0.011973	0.002195	-5.46	0.000

R-Sq = 21.1%   R-Sq(adj) = 20.0%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	4	3.54283	0.88571	20.09	0.000
Residual Error	301	13.27087	0.04409		
Total	305	16.81370			

The model had a low adjusted R^2 value of 20.0 percent. The standard errors and the corresponding T-statistics for the coefficients for average daily traffic and speed were very significant, while those for length and shoulder widths were not as significant. The F-statistic for the model as a whole indicated a very high level of statistical significance. The model indicated a reduction in the crash rate with an increase in average daily traffic or speed. This was attributed to the safety conditions on “higher” class / type facilities such as the Interstates. This model also showed that roadway segments with wider shoulders had lower crash rates, and that crash rates increased with an increase in segment length (although this relationship was not as statistically significant).

Crash Rate $(crashes/MVMT)_{after} = f(ADT_{after}, Length, Speed)$

The regression equation is:

$Crashes/MVMT_{after} = 1.21 - 0.00601\ ADT_{after} + 0.00189\ Length - 0.0135\ Speed$

Predictor	Coef	SE Coef	T	P
Constant	1.2126	0.1453	8.35	0.000
ADT_{after}	-0.006014	0.001439	-4.18	0.000
Length	0.001895	0.002005	0.94	0.345
Speed	-0.013496	0.001973	-6.84	0.000

R-Sq = 20.4%   R-Sq(adj) = 19.6%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	3	3.4340	1.1447	25.84	0.000
Residual Error	302	13.3797	0.0443		
Total	305	16.8137			

The model had a low adjusted R^2 value of 19.6 percent. The standard errors and the corresponding T-statistics for the coefficients for average daily traffic and speed were very significant, while those for length were far less significant. The F-statistic for the model as a whole indicated a very high level of statistical significance. The model indicated a reduction in the crash rate with the increase in average daily traffic and speed, which can be attributed to the conditions on Interstates. This model also showed that longer roadway segments had higher crash rates (although this was not statistically very significant).

Crash Rate $(crashes/MVMT)_{after} = f(ADT_{after}, Shoulder\ Width, Speed)$

The regression equation is:

$Crashes/MVMT_{after} = 1.23 - 0.00554\ ADT_{after} - 0.0112\ Shoulder\ Width - 0.0123\ Speed$

Predictor	Coef	SE Coef	T	P
Constant	1.2331	0.1392	8.86	0.000
ADT_{after}	-0.005540	0.001479	-3.75	0.000
Shoulder Width	-0.011248	0.006955	-1.62	0.107
Speed	-0.012305	0.002160	-5.70	0.000

R-Sq = 20.9%   R-Sq(adj) = 20.1%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	3	3.5097	1.1699	26.56	0.000
Residual Error	302	13.3040	0.0441		
Total	305	16.8137			

Although the models presented had low R^2 values, it suggested that the crash rates were lower when the roadways with rumble strips had wider shoulder, higher average daily traffic values, and higher posted speed limits.

4.1.2.6 Crash Rate Variation with Shoulder Width

The purpose of rumble strips was to alert drivers that they were drifting away from the marked travel lanes. The location of the rumble strip on the shoulder and the width of the shoulder affected the time and space available for a driver to take corrective action when alerted by the vehicle's tires crossing the rumble strips. Thus, it was expected that wider shoulder widths would provide more time and space for the driver to recover from the situation.

The placement of the rumble strips was consistent on shoulders along roadways in Nevada. So there was no variation in the location of the rumble strips on the shoulder. Typical shoulder widths on the roadways in Nevada with treatment ranged from 4 feet to 10 feet (1.2 meters to 3 meters). Very few segments had shoulder widths of 6 feet or 8 feet (1.8 meters or 2.4 meters). Twenty-eight segments had shoulder widths of 4 feet (1.2 meters), and 251 segments had shoulder widths of 10 feet (3 meters). The relationship between before-after crash rates as a function of shoulder widths was shown in Figures 24, 25 and 26. The figures do not suggest any definitive patterns. Thus, linear regression models were developed to better evaluate potential relationships between crash rates and shoulder widths.

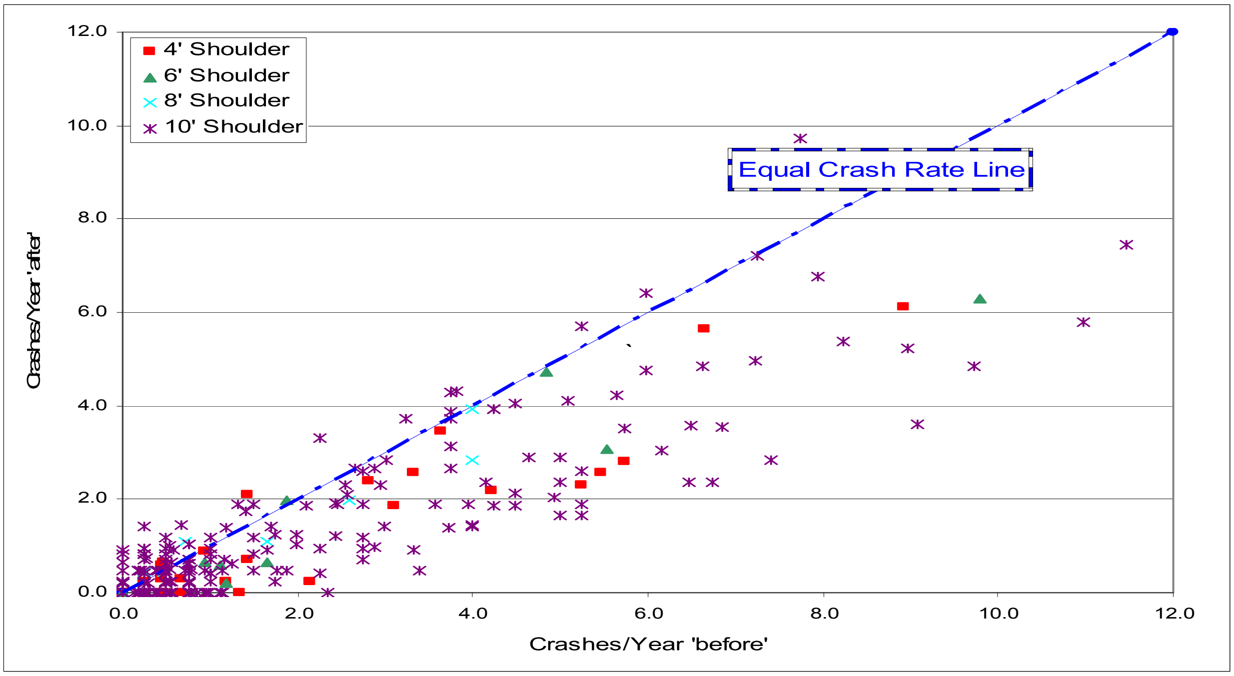

Figure 24: Crash Frequency Before-After Continuous Shoulder Rumble Strip Treatment for Various Shoulder Widths

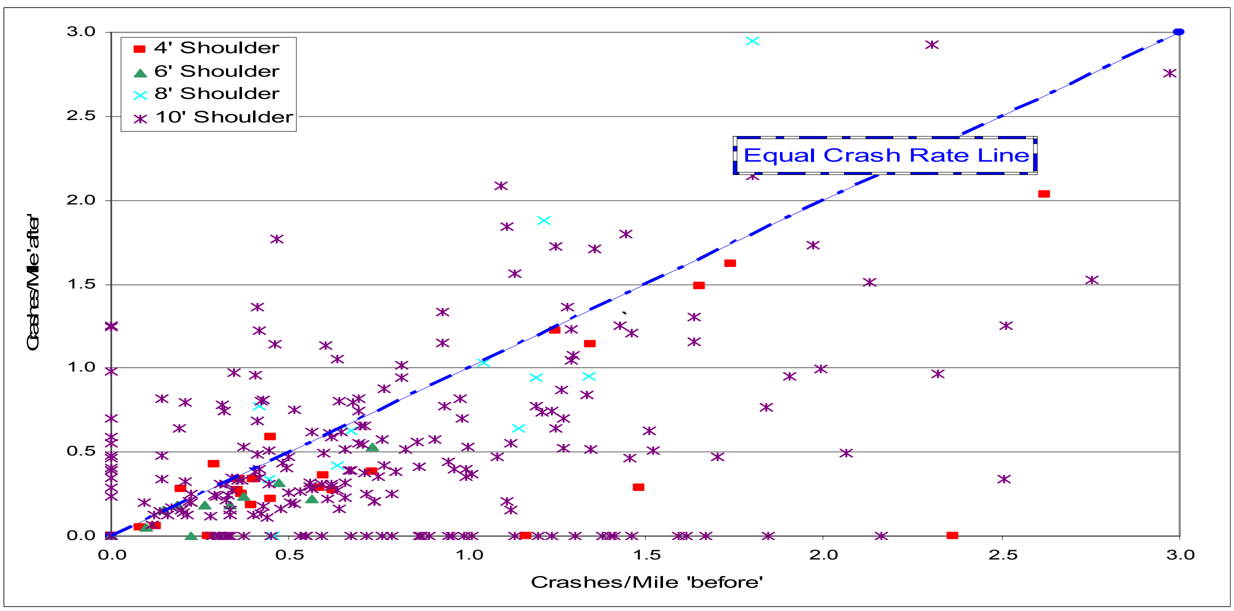

Figure 25: Crash Rate Before-After Continuous Shoulder Rumble Strip Treatment for Various Shoulder Widths

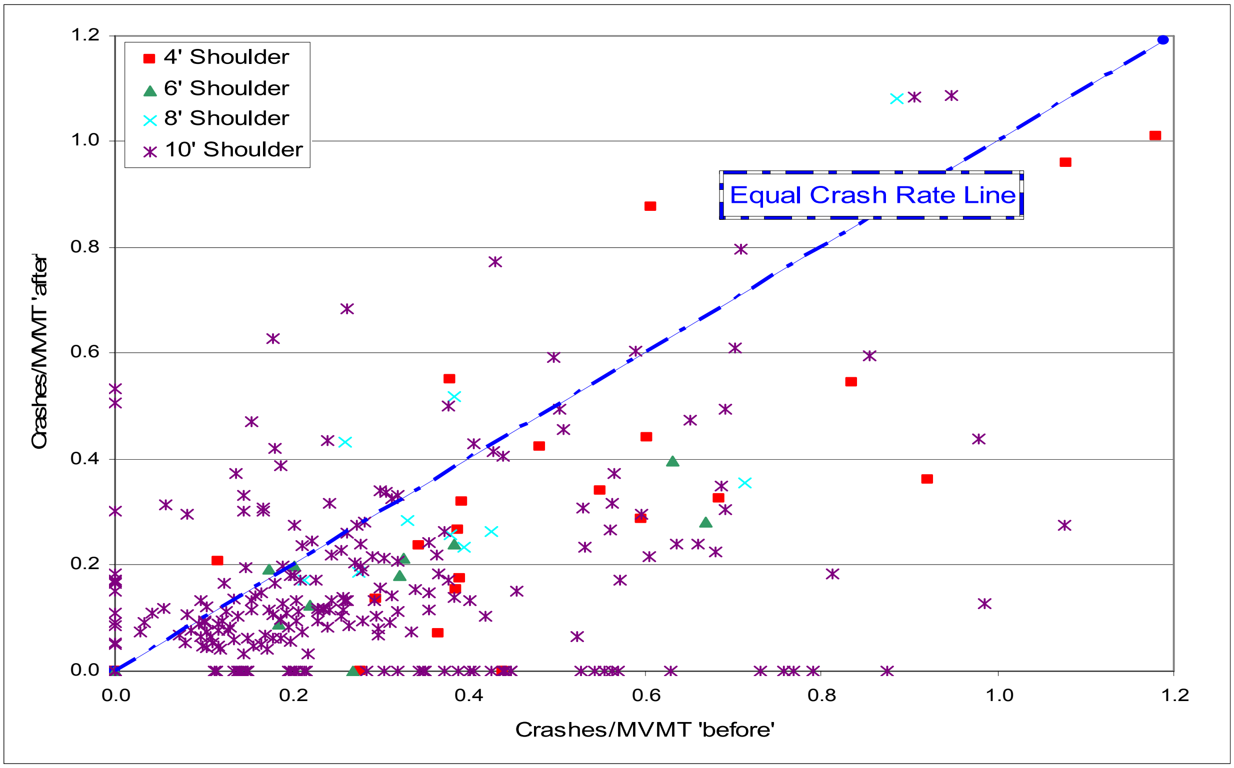

Figure 26: Crash Density Before-After Continuous Shoulder Rumble Strip Treatment for Various Shoulder Widths

The regression models that attempted to relate crash rates to shoulder widths on an aggregated level did not result in any meaningful results. Therefore, individual models were developed for various shoulder widths. These are presented next. Linear regression equations were developed for before-after crash rates for 4 feet to 10 feet (1.2 meters to 3 meters) shoulder widths. The number of segments for the other shoulder widths was too small to be considered so a model was not developed. Regression models were developed for the "after" crash rates as a function of the "before" crash rates for each shoulder width. The following were the equations and the corresponding statistics for the crash rates for the two shoulder widths.

Shoulder Width 4 feet (28 Segments)

Crash Frequency (crashes/mile) $_{after\ 4\ feet\ shoulder}$ *= 0.160 + 0.343 Crashes/Mile* $_{before\ 4\ feet\ shoulder}$

Predictor	Coef	SE Coef	T	P
Constant	0.1604	0.1226	1.31	0.202
Crashes/Mile B	0.3428	0.1033	3.32	0.003

R-Sq = 29.7%   R-Sq(adj) = 27.0%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	2.3579	2.3579	11.01	0.003
Residual Error	26	5.5694	0.2142		
Total	27	7.9273			

Crash Rate (crashes/MVMT) $_{after\ 4\ feet\ shoulder}$ *= 0.198 + 0.273 Crashes/MVMT* $_{before\ 4\ feet\ shoulder}$

Predictor	Coef	SE Coef	T	P
Constant	0.1979	0.1031	1.92	0.066
Crashes/MVMT B	0.2733	0.1106	2.47	0.020

R-Sq = 19.0%   R-Sq(adj) = 15.9%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	0.8349	0.8349	6.10	0.020
Residual Error	26	3.5556	0.1368		
Total	27	4.3905			

Shoulder Width 10 feet (251 Segments)

Crash Frequency (crashes/mile) $_{after\ 10\ feet\ shoulder}$ *= 0.218 + 0.359 Crashes/Mile* $_{before\ 10\ feet\ shoulder}$

Predictor	Coef	SE Coef	T	P
Constant	0.21786	0.04258	5.12	0.000
Crashes/Mile B	0.35944	0.03935	9.13	0.000

R-Sq = 25.1%   R-Sq(adj) = 24.8%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	19.265	19.265	83.42	0.000
Residual Error	249	57.501	0.231		
Total	250	76.766			

Crash Rate (crashes/MVMT)$_{after\ 10\ feet\ shoulder}$ = 0.0603 + 0.366 Crashes/MVMT $_{before\ 10\ feet\ shoulder}$

Predictor	Coef	SE Coef	T	P
Constant	0.06028	0.01579	3.82	0.000
Crashes/MVMT B	0.36587	0.04479	8.17	0.000

R-Sq = 21.1%   R-Sq(adj) = 20.8%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	1.8386	1.8386	66.73	0.000
Residual Error	249	6.8605	0.0276		
Total	250	8.6991			

The four models presented showed that the “after” crash rate was less than the “before” crash rate regardless of the shoulder width. The adjusted R^2 for the density models were 27.0 percent and 24.8 percent respectively for the 4 feet to 10 feet (1.2 meters to 3 meters), while the adjusted R^2 for the models were 15.8 percent and 20.8 percent respectively. These R^2 values were low. The standard errors and the corresponding T-statistics for the coefficients in each model indicated that the coefficients were very significant, as were the F-statistics for the models. If the models were considered on roadways with 10 feet (3 meters) wide shoulders, then for a given value of the “before” crash density (typically around 0.2), was lower than the “after” crash density.

The variations of crash rates, as a function of shoulder widths, were examined; the crash rates versus shoulder widths were plotted. These were shown in Figures 27, 28, and 29. Figure 27 shows a decline in the crash rate as the shoulder widths increase. It indicated that wider shoulders are better with and without continuous shoulder rumble strip treatment. Figure 28 shows that the treatment placed on 4 foot (1.2 meter) shoulders will probably yield more benefits in reducing the crash rate than 10 foot (3 meter) shoulders and the crash frequency for the 4 foot (1.2 meter) shoulders is lower than the 10 foot (3 meter) shoulders. Similar conclusions can be observed from Figure 29. Generally highways with 10 foot (3 meter) shoulders have greater speed limits and much higher traffic volumes, and thereby have higher crash frequencies, but the density is about the same for each shoulder width. Highways with higher speed limits and higher volumes of traffic have more chances for ran-off-roadway crashes. Therefore similar crash densities on Figure 29 were not surprising.

The figures also showed the best-fit linear regression relationships – these appear as "trend" lines. From the trend lines of the crash rates before and after continuous shoulder rumble strip treatment, it was clearly evident that the crash rate trend in the "after" period was lower irrespective of the shoulder width. Further, the slope of the trend lines of the crash rates of both the periods indicated a reduction in the crash rate with increased shoulder widths. The variation of crash rates in terms of frequencies with shoulder widths suggested a decline in crash rates with the increase in shoulder widths. However the trend lines for densities vary very little with shoulder widths.

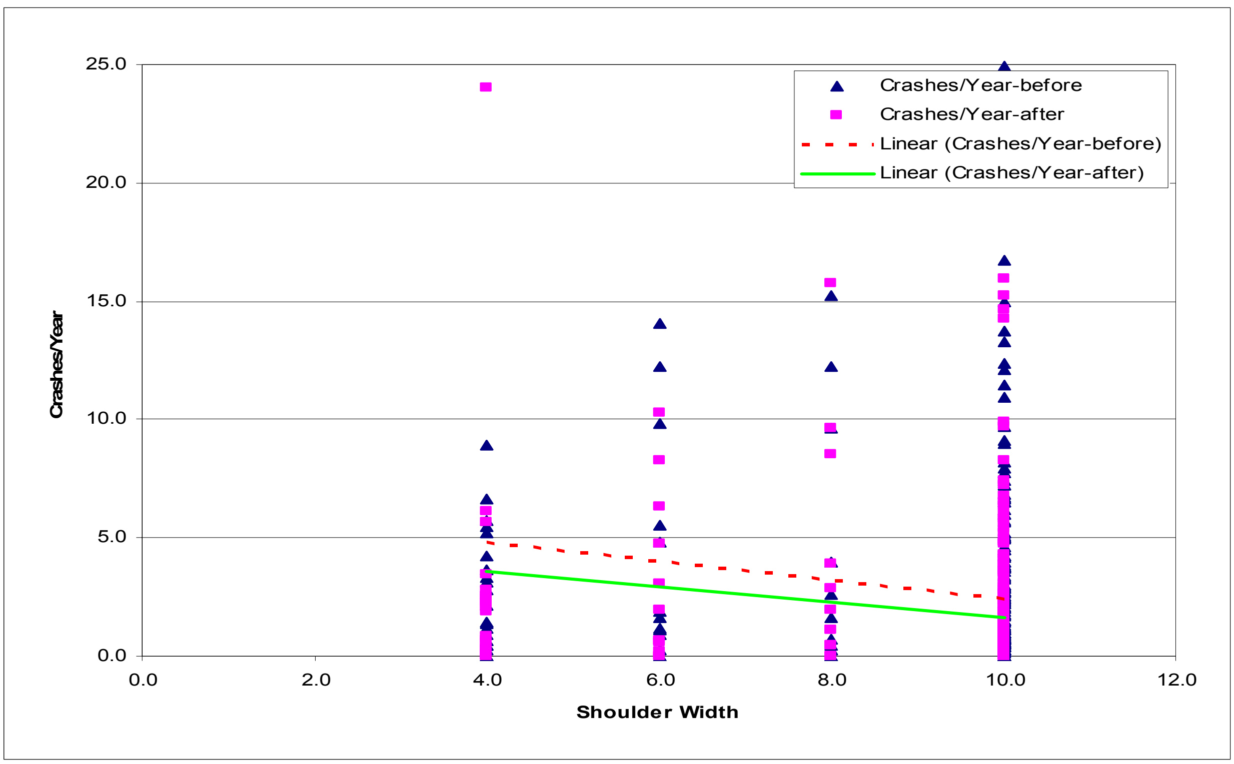

Figure 27: Variation of Crash Frequency with Shoulder Width

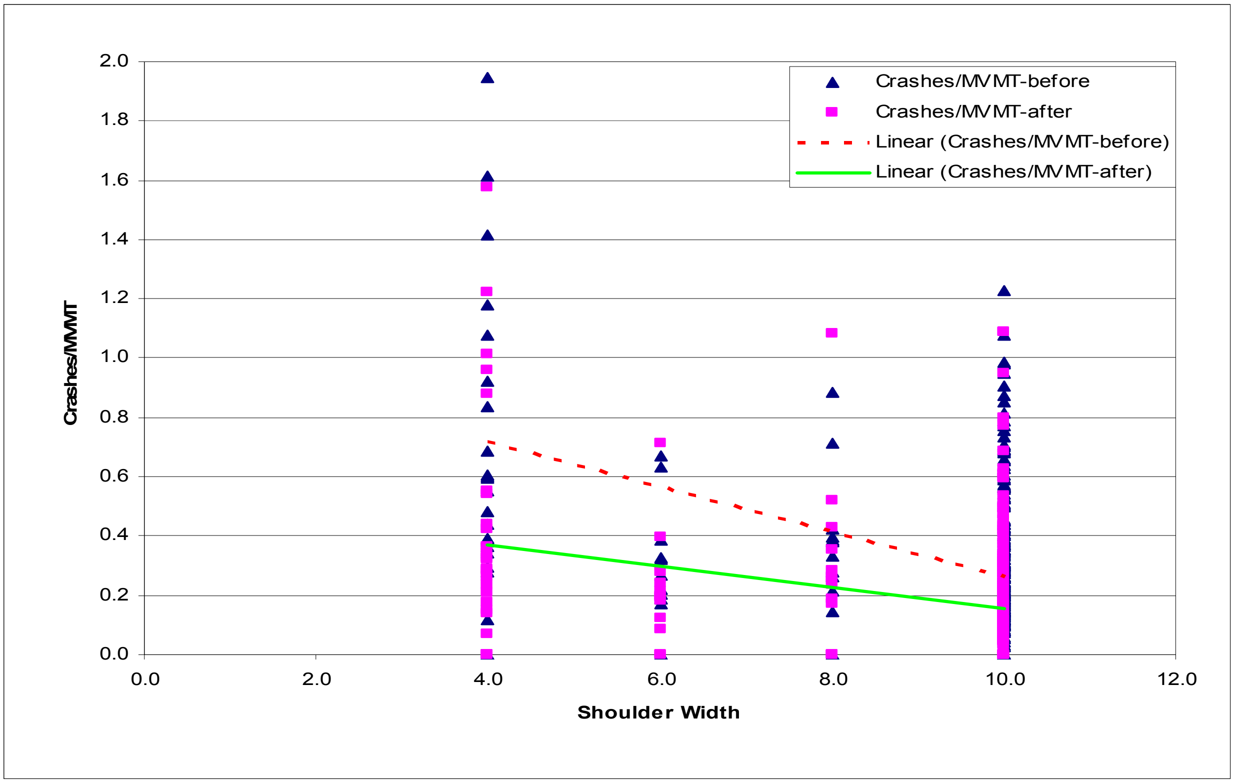

Figure 28: Variation of Crash Rate with Shoulder Width

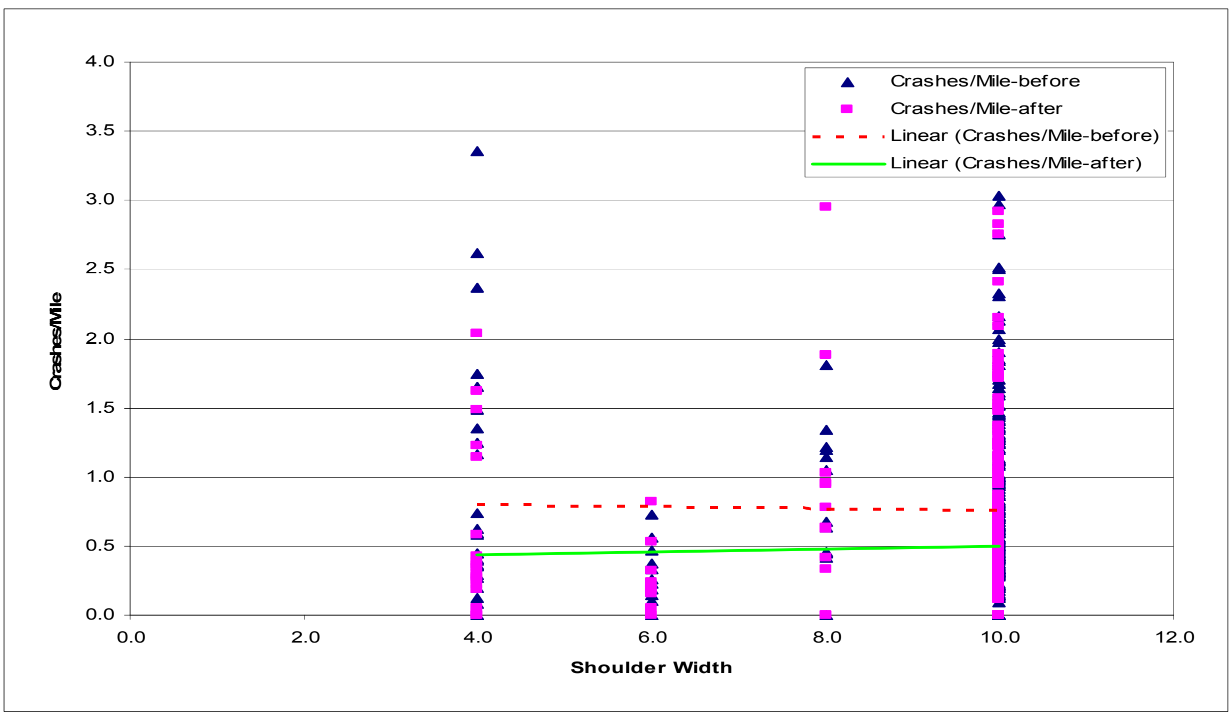

Figure 29: Variation of Crash Density with Shoulder Width

4.1.4 *Factors Affecting Crash Rate*

Factors such as average daily traffic, speed, and shoulder width may affect vehicle ran-off-road crash rates. For example, wider shoulders may offer drivers more time and space to recover when alerted by the tires going over the rumble strips while the vehicle was drifting off the roadway. The relationship of crash rates with these factors was discussed next.

4.1.3.7 Relationship between "Before-After" Periods of Crash Rates

In order to evaluate the effectiveness of the continuous shoulder rumble strip treatment, the crash rates after installation can be compared to those prior to the installation. The safety indicators previously identified for crash frequency, rate, and density were used for this purpose.

A graphical representation of the crash rate in the "after" period as a function of the crash rate in the "before" period helped with the qualitative evaluation of their relationship. If the crash rates in the "after" period were the same as those in the "before" period, then the scatter plot showed points along a straight line that had a slope of 1.0 "equal crash rate" line. In other words, any point on the scatter plot that lay on the "equal crash rate" line represented a roadway segment that experienced no change in crash rate after the rumble strips were installed. Any point that lay below the "equal-crash rate" line represented a roadway segment, which had a decrease in crash rates following the installation. Conversely, a point that lay above this line represented a roadway segment, which had an increase in crash rate following the rumble strip installation. The scatter plots for crash frequency, rate, and density are shown in Figures 37, 38, and 39 respectively.

The figures clearly showed that a vast majority of the points lay below the "equal crash line" indicating that on the whole, the continuous shoulder rumble strip treatment resulted in a decrease of the crash rate on individual segments. This qualitative assessment was validated using quantitative analysis methods. One approach developed simple linear regression models with the crash rate for the "after" period as a function of the crash rate for the "before" period. These models are presented next.

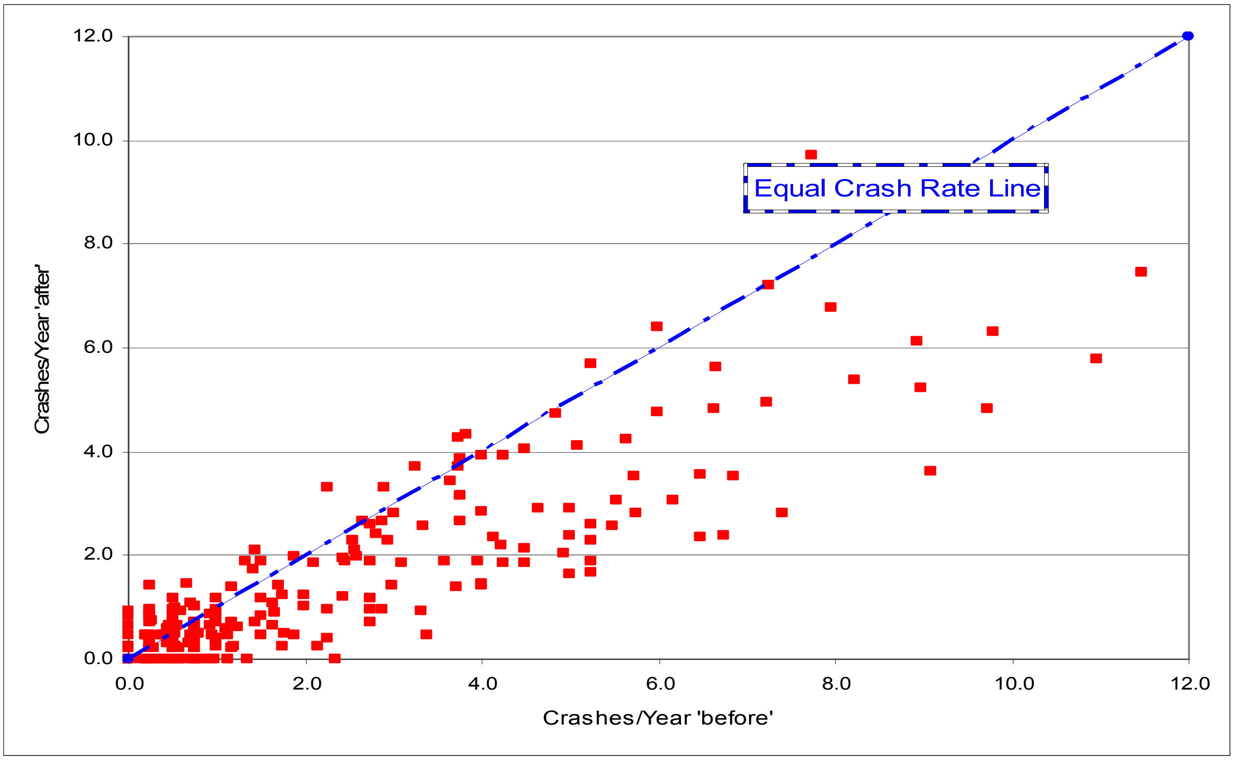

Figure 30: Crash Frequency Before-After the Continuous Shoulder Rumble Strip Treatment

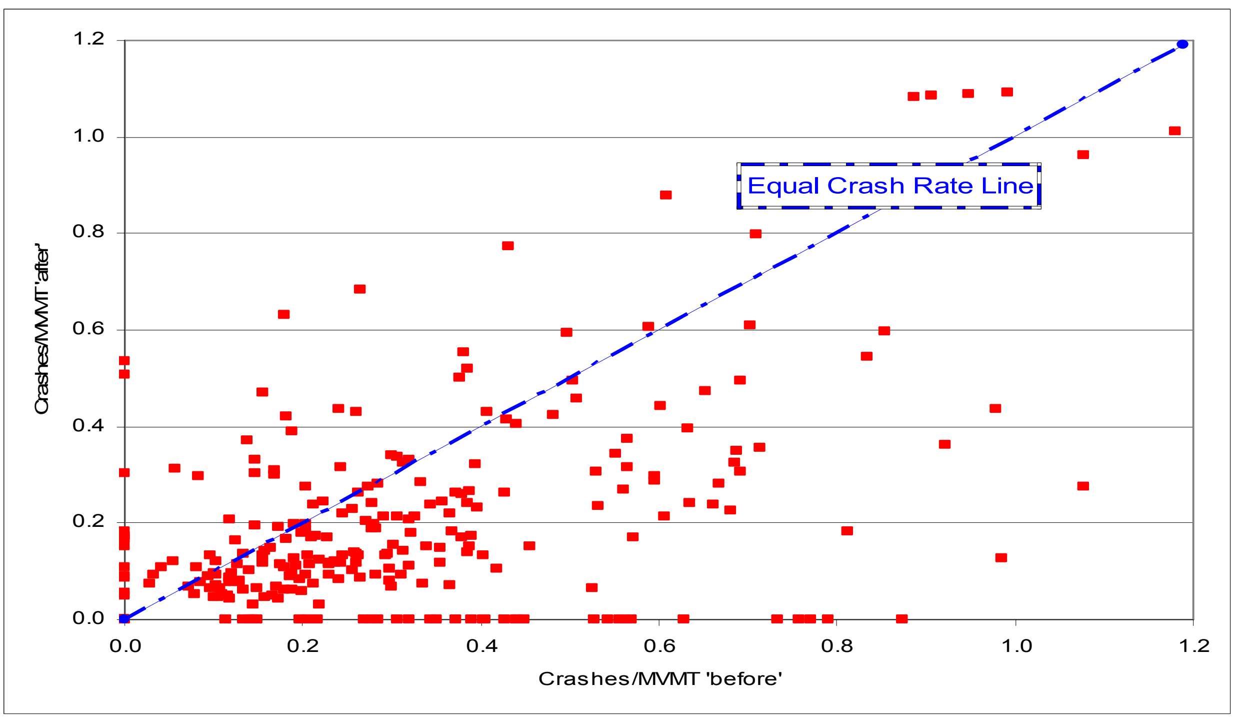

Figure 31: Crash Rate Before-After the Continuous Shoulder Rumble Strip Treatment

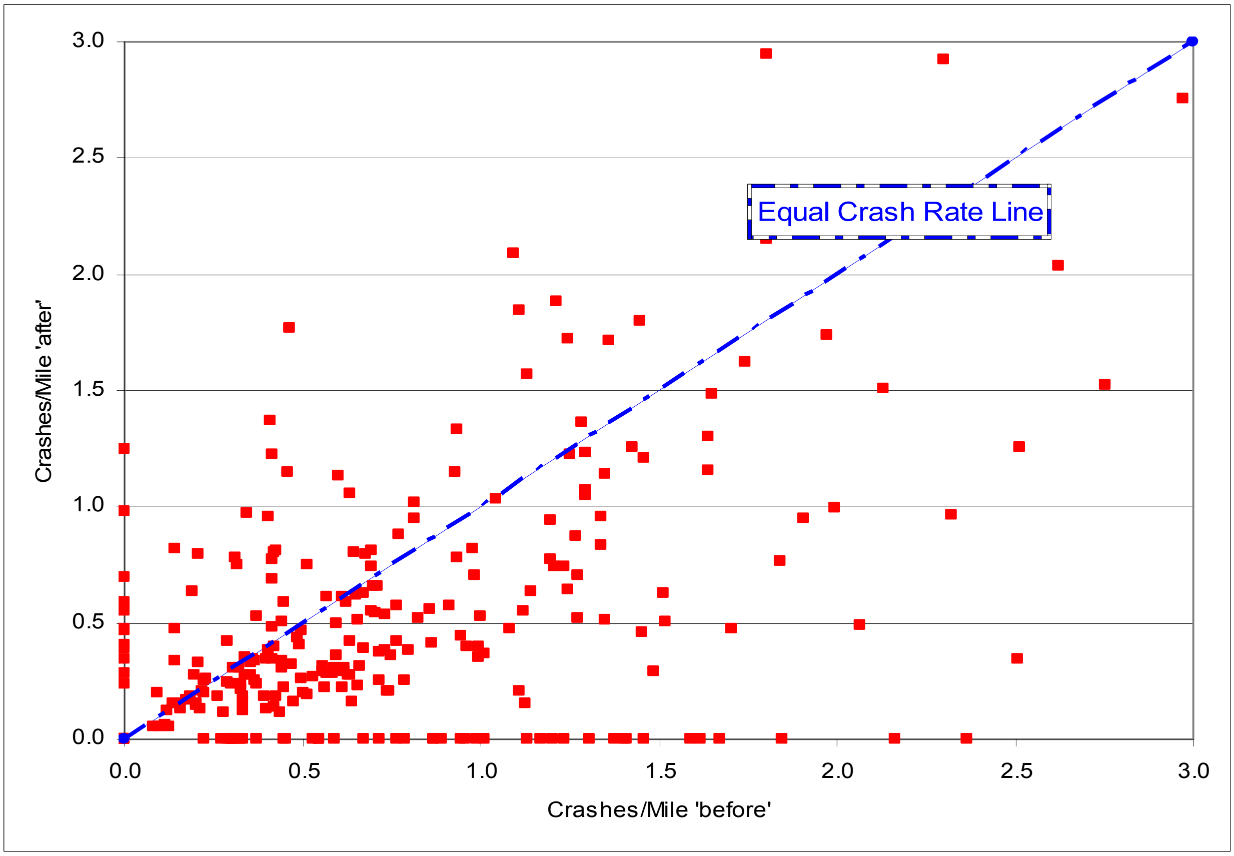

Figure 32: Crash Density Before-After the Continuous Shoulder Rumble Strip Treatment

Crash Frequency (crashes/year)$_{after}$ = - 0.0906 + 0.733 Crashes/year $_{before}$

Predictor	Coef	Std Error	T-stat	P-value
Constant	-0.09056	0.07508	-1.21	0.229
Crashes/year B	0.73274	0.01397	52.44	0.000

R-Sq = 90.0%   R-Sq(adj) = 90.0%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	3548.7	3548.7	2749.44	0.000
Residual Error	304	392.4	1.3		
Total	305	3941.1			

Crash Rate (crashes/MVMT)$_{after}$ = 0.102 + 0.266 Crashes/MVMT $_{before}$

Predictor	Coef	Std Error	T-stat	P-value
Constant	0.10191	0.01481	6.88	0.000
Crashes/MVMT B	0.26605	0.02767	9.62	0.000

R-Sq = 23.3%   R-Sq(adj) = 23.1%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	3.9209	3.9209	92.45	0.000
Residual Error	304	12.8928	0.0424		
Total	305	16.8137			

Crash Density (crashes/mile)$_{after}$ = 0.214 + 0.362 Crashes/Mile $_{before}$

Predictor	Coef	Std Error	T-stat	P-value
Constant	0.21373	0.03841	5.56	0.000
Crashes/mile B	0.36154	0.03513	10.29	0.000

R-Sq = 25.8%   R-Sq(adj) = 25.6%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	24.794	24.794	105.94	0.000
Residual Error	304	71.148	0.234		
Total	305	95.942			

The three models presented showed that the crash rate during the "after" period was less than the crash rate during the "before" period. This quantitatively validated the findings from the qualitative analyses shown in Figures 31 to 33. The adjusted R^2 for the crashes/year frequency model was approximately 90 percent, while those for the crashes/mile/year density model, and crashes/MVMT crash rate model were 25.6 percent and 23.1 percent respectively. The latter R^2 values were low. Each of the three models had values of less than 1.0 for both the intercept and the coefficient for the crash rate for the "before" period. The standard errors for the coefficients in each model indicated that the coefficients were very significant, as were the F-statistics for the models.

4.1.3 Crash Density

Computing and comparing just the crash rate, did not accurately reflect the changes in safety due to factors related to measures of exposure. If a roadway segment of short length experienced a high number of crashes then the crash density of the roadway would be high. On the other hand, if a longer roadway segment had the same number of crashes then the crash density would be less. Hence, to address such scenarios, crash density was computed for each segment by computing the density segments where relatively high crash concentrations or densities were identified. Once the densities were computed for the "before-after" periods, these densities were compared to evaluate the effectiveness of rumble strips in reducing the ran-off-roadway crashes. The results of these analyses, based on individual segments, facility type, and roadway class are presented in Table 16, and discussed next.

Table 16: Influence of Continuous Shoulder Rumble Strips on Single-vehicle Ran-off-roadway Densities

Facility	Crashes/Mile												
	Number of Segments							Centerline Miles					
	Total	Improved	%	No Change	%	Worsen	%	Total	Improved	%	No Change	%	Worsen	%
I-15N	32	19	59.38	2	6.25	11	34.375	89.459	59.978	67.05	0.641	0.717	28.840	32.24
I-15S	32	20	62.50	5	15.63	7	21.88	91.732	82.103	89.50	3.667	4.00	5.961	6.50
I-15	64	39	60.94	7	10.94	18	28.13	181.191	142.081	78.42	4.309	2.38	34.801	19.21
I-80E	78	45	57.69	10	12.82	23	29.49	188.959	132.809	70.28	12.254	6.48	43.897	23.23
I-80W	75	50	66.67	10	13.33	15	20.00	176.834	148.752	84.12	11.279	6.38	16.803	9.50
I-80	153	95	62.09	20	13.07	38	24.84	365.793	281.56	76.97	23.53	6.43	60.70	16.59
US-95	48	37	77.08	4	8.33	7	14.58	382.596	321.013	83.90	1.502	0.39	60.081	15.70
US-93	9	7	77.78	1	11.11	1	11.11	142.807	130.223	91.19	0.034	0.02	12.550	8.79
US-50	12	8	66.67	1	8.33	3	25.00	98.414	76.666	77.90	0.180	0.18	21.569	21.92
US-6	4	3	75.00	0	0.00	1	25.00	35.507	34.496	97.15	0.000	0.00	1.011	2.85
US-395	5	5	100.00	0	0.00	0	0.00	12.672	12.672	100.00	0.000	0.00	0.000	0.00
SR-766	3	2	66.67	1	33.33	0	0.00	11.595	5.199	44.84	6.396	55.16	0.000	0.00
SR-160	2	1	50.00	0	0.00	1	50.00	21.516	16.180	75.20	0.000	0.00	5.336	24.80
SR-163	1	0	0.00	1	100.00	0	0.00	19.36	0.000	0.00	19.360	100.00	0.000	0.00
SR-221	1	0	0.00	1	100.00	0	0.00	0.337	0.000	0.00	0.337	100.00	0.000	0.00
SR-227	1	1	100.00	0	0.00	0	0.00	5.504	5.504	100.00	0.000	0.00	0.000	0.00
SR-228	1	1	100.00	0	0.00	0	0.00	4.732	4.732	100.00	0.000	0.00	0.000	0.00
SR-318	1	1	100.00	0	0.00	0	0.00	5.471	5.471	100.00	0.000	0.00	0.000	0.00
SR-604	1	1	100.00	0	0.00	0	0.00	15.69	15.690	100.00	0.000	0.00	0.000	0.00
Total	***306***	***201***	***65.69***	***36***	***11.76***	***69***	***22.55***	***1303.185***	***1051.488***	***80.69***	***55.650***	***4.27***	***196.047***	***15.04***

4.1.3.1 Crash Density for Individual Segments

The results presented in Table 16 show that, overall 201 of the 306 segments (65.7 percent) studied showed a reduction in crash density, which equate to improvements in safety. These segments accounted for 1,051 centerline miles (80.7 percent) of the roadways studied. Likewise, 36 segments (11.8 percent) showed no change in crash density. These segments accounted for 4.3 percent of the centerline miles of the roadways studied. Further, 69 segments (22.6 percent) experienced increased crash density after treatment. The segments constituted 15 percent of the centerline miles studied. A detailed breakdown of the results for individual facilities is included in Table 16, and illustrated in Figures 30 to 33. Figures 30 and 31 show results based on the number of segments for each facility. Similarly Figures 32 and 33 show results based on centerline miles for each facility.

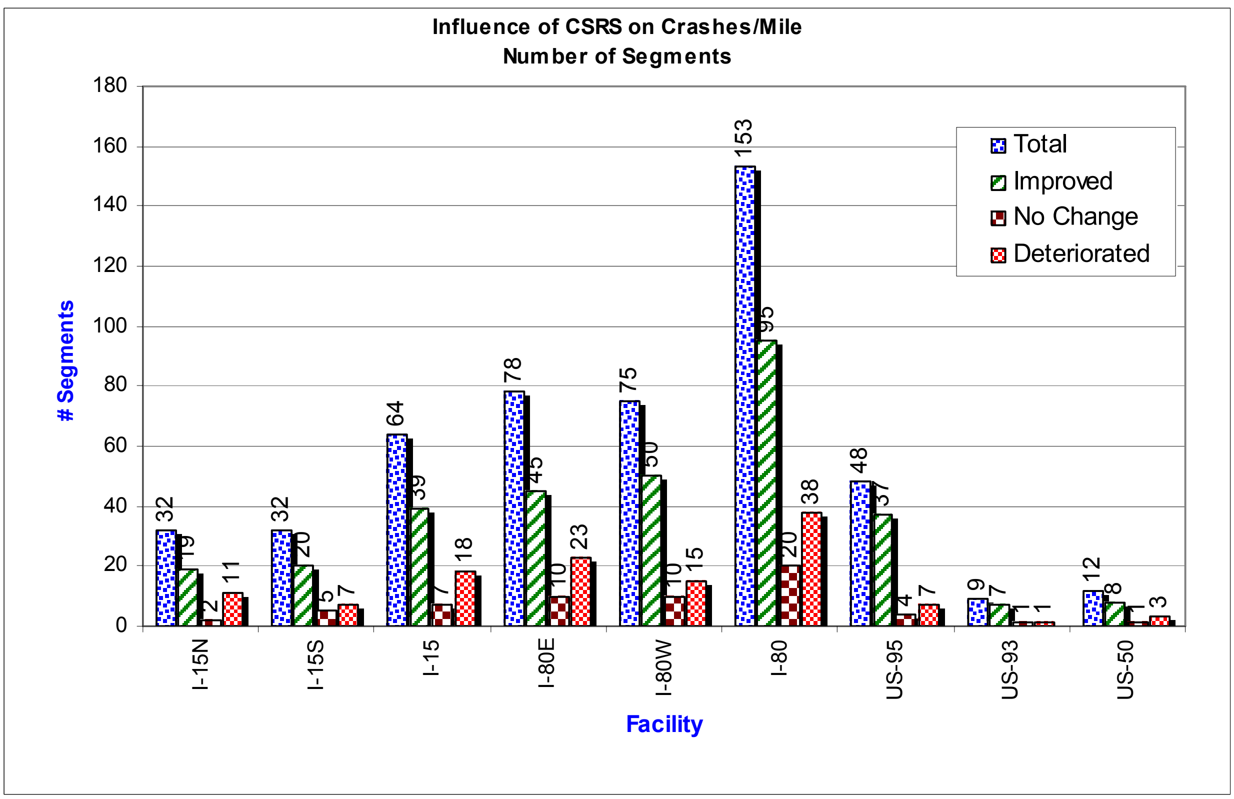

Figure 33: Influence of Continuous Shoulder Rumble Strips on Crash Density (#segments)

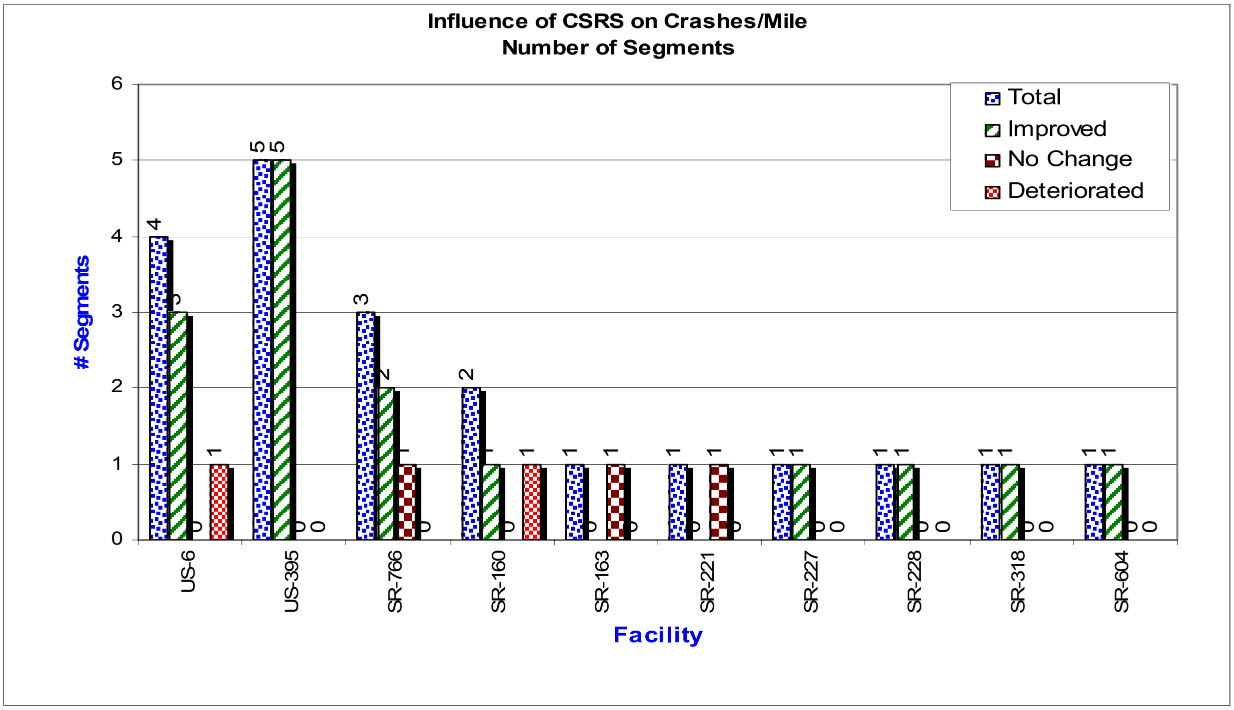

Figure 34: Influence of Continuous Shoulder Rumble Strips on Crash Density (#segments)

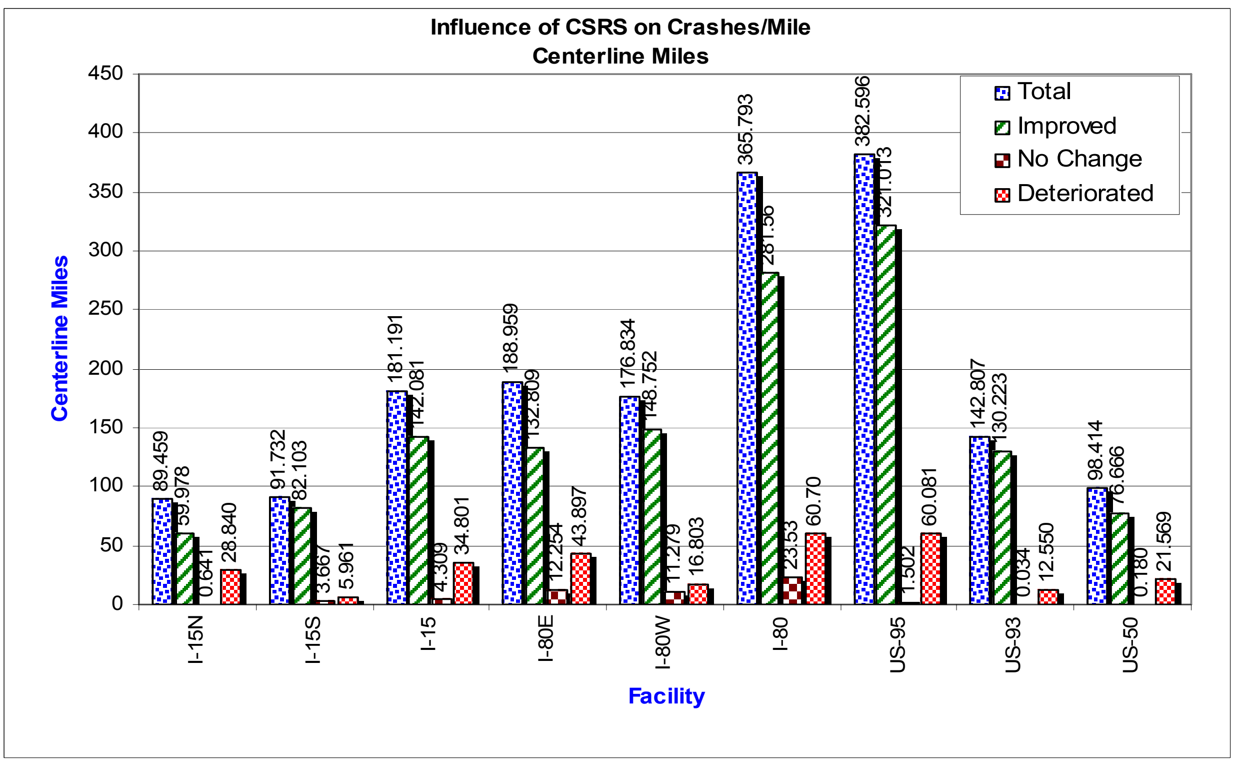

Figure 35: Influence of Continuous Shoulder Rumble Strips on Crash Density (centerline miles)

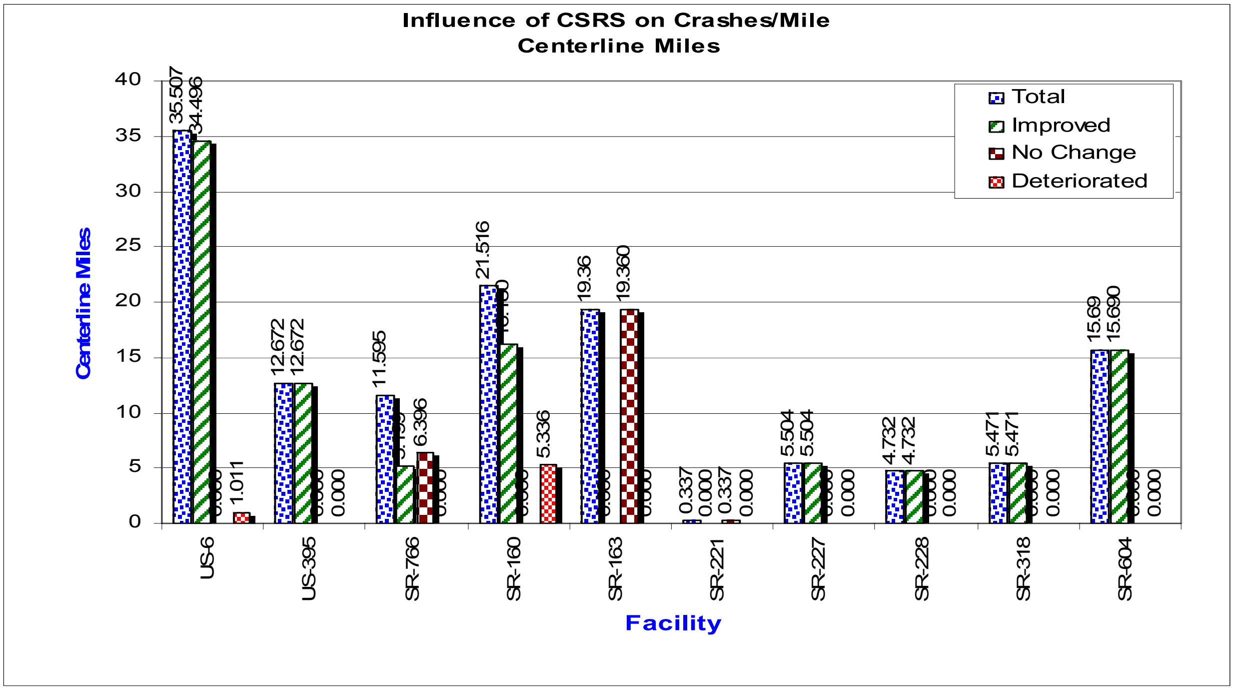

Figure 36: Influence of Continuous Shoulder Rumble Strips on Crash Density (centerline miles)

4.1.3.2 Crash Density for each Facility

The results of the analyses of each facility are shown in Table 17. These results indicated that the rumble strips were effective in reducing the crash density at the facility level. Table 17 also shows that there were at least 1.126 crashes/mile/year of roadway on I-15 prior to installation of rumble strips.

Table 17: Single-vehicle Ran-off-roadway Crash Density Before-After Continuous Shoulder Rumble Strips Treatment on Each Facility

Facility	#Segments	CL Miles	Crashes/Mile/Year		
			Before	After	% Change
I-15N	32	89.459	1.240	1.022	17.61
I-15S	32	91.732	1.015	0.712	29.84
I-15	64	181.191	1.126	0.866	23.09
I-80E	78	188.959	0.608	0.413	32.12
I-80W	75	176.834	0.544	0.314	42.34
I-80	153	365.793	0.577	0.365	36.68
US-95	48	382.596	0.469	0.319	32.02
US-93	9	142.807	0.351	0.215	38.64
US-50	12	98.414	0.494	0.362	26.65
US-6	4	35.507	0.247	0.247	-0.17
US-395	5	12.672	2.440	1.565	35.84
SR-766	3	11.595	0.174	0.000	100.00
SR-160	2	21.516	1.692	2.514	-48.58
SR-163	1	19.36	0.000	0.000	0.00
SR-221	1	0.337	0.000	0.000	0.00
SR-227	1	5.504	1.120	0.554	50.57
SR-228	1	4.732	0.157	0.129	17.83
SR-318	1	5.471	0.214	0.128	40.19
SR-604	1	15.69	2.623	2.033	22.49
Total	**306**	**1303.2**	**0.622**	**0.464**	**25.43**
Roadway Class	**#Segments**	**CL Miles**	**Crashes/Mile/Year**		
			Before	**After**	**% Change**
Interstates	217	547	0.748	0.567	24.22
US Routes	78	672	0.553	0.319	42.21
State Routes	11	84.2	1.024	0.939	8.38
State Routes without SR-160	9	1281.684	0.827	0.593	28.30
Total	**306**	**1303.2**	**0.622**	**0.464**	**25.43**

After the continuous shoulder rumble strip treatment, the number of single-vehicle ran-off-roadway crashes on these 181.191 centerline miles of roadway, considering both directions of travel independently, declined to a crash density of 0.87. This reduction of crash density was due to the improvement seen on 142 of the 181 treated miles. The crash density on the 366 treated miles of roadway on I-80 decreased from a crash density of 0.58 to 0.37 after treatment. On US–95 there was a crash density of 0.36 before the rumble strip treatment, which reduced to a crash density of 0.23 after installation. Overall, the 1,303 continuous shoulder rumble strip treated miles had a crash density of 0.62 before treatment and the crash density was reduced to 0.46 after installation. This equated to 25.4 percent improvement of single-vehicle ran-off-roadway crashes.

4.1.3.3 Crash Density for each Roadway Functional Class

Table 17 includes results of analysis based on a comparison of annual crash densities for each roadway class. The results showed that the Interstate highways treated with continuous shoulder rumble strips had 0.75 crashes/mile/year before treatment. This crash density decreased to 0.57 crashes/mile/year after the installation of rumble strips. This amounted to a 24.2 percent improvement. Similarly the US routes saw a 42 percent reduction in the crash density with the deployment of rumble strips that reduced the crash density from 0.55 crashes/mile/year to 0.32 crashes/mile/year. In spite of the high crash rate on SR-160, the state routes overall registered an 8 percent reduction in crash density after the rumble strip treatment. The reduction however, was 28 percent when SR-160 was not included in the analysis. The percent of change in crash density based on individual segments evaluated are presented in Figures 34 and 35. The figures clearly show that a majority of the segments, as well as centerline miles of roadways with treatment, showed improvements in crash density following the installation of continuous shoulder rumble strip treatment.

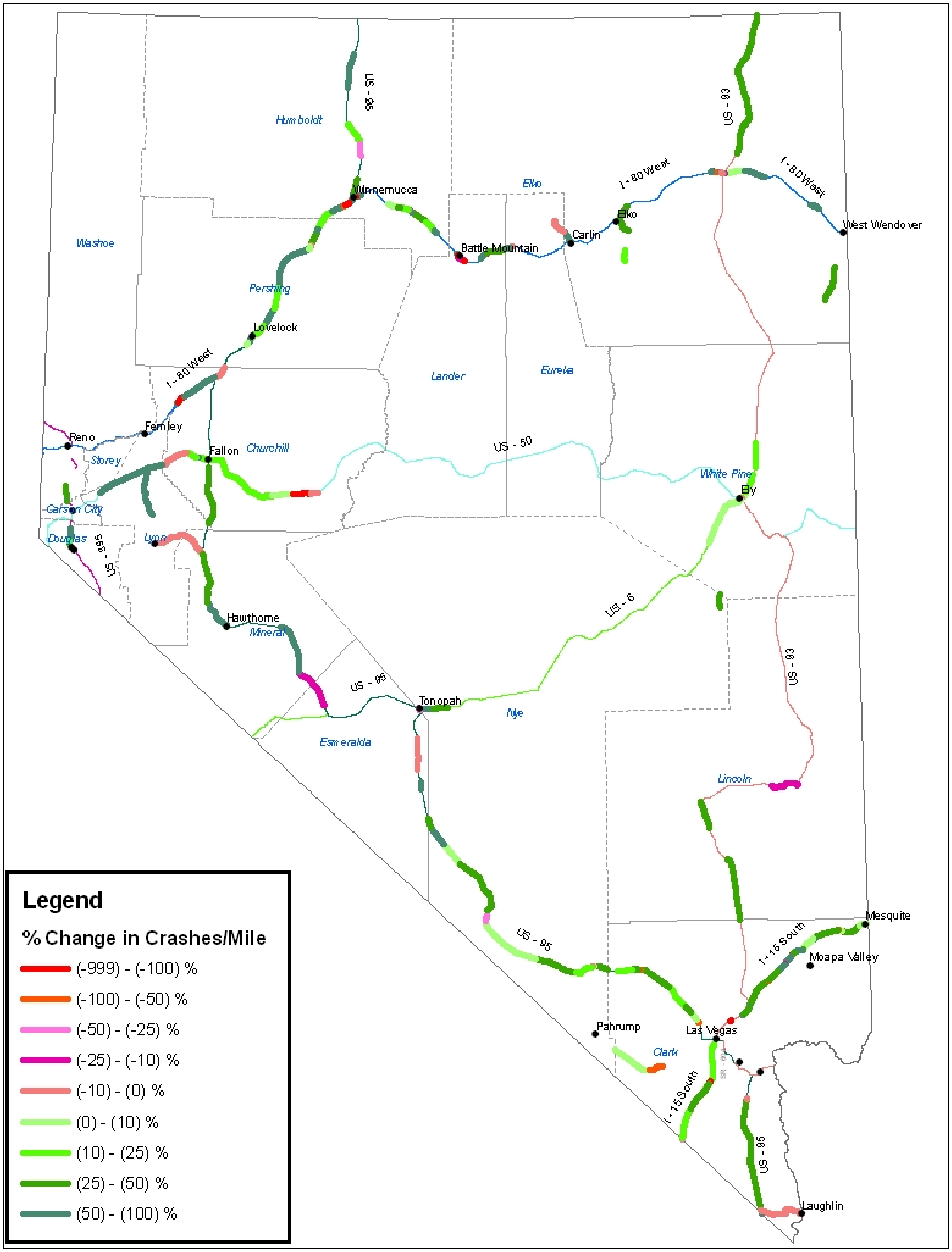

Figure 37: Percent Change in Crash Density (I–80 W, I–15 S)

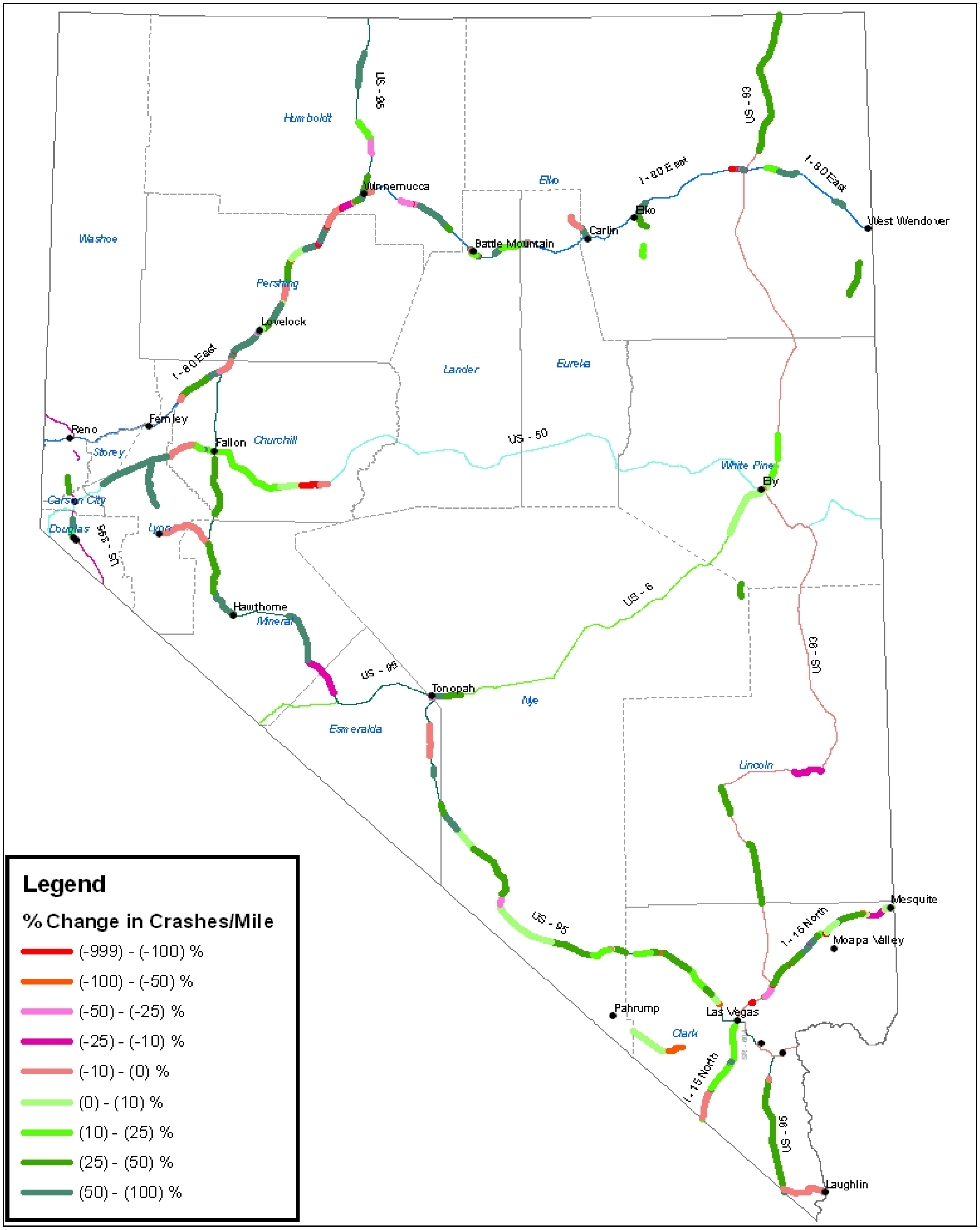

Figure 38: Percent Change in Crash Density (I–80 E, I–15 N)

4.1.3.4 Crash Density vs Average Daily Traffic (ADT)

While million vehicle miles of travel was a measure of exposure in quantifying single-vehicle ran-off-roadway crash rates, the average daily traffic (ADT) on a roadway segment was another measure of exposure. In this case, the density was modeled as a function of ADT. The average daily traffic values, for study segments, ranged from a few hundred to over 40,000 vehicles/day. The highest values of the ADT were observed on I-15 on segments south of the Las Vegas metropolitan area where some segments had a 9-year average ADT of 38,110 vehicles/day and a high of 43,000 vehicles/day in 2003. The average values for I-15 north of the Las Vegas metropolitan area vary typically between 11,000 and 26,000 vehicles/day. The ADT values on I-80 range between 4,790 and 11,300, with most parts of I-80 between Fernley and Winnemucca recording ADTs at the higher value of this range. Segments on US-95 south of the Las Vegas metropolitan area typically had ADTs in the order of 6,000 vehicles/day, with portions south of Junction SR-163 having ADTs of about 2,000 vehicles/day. The remaining sections of US-95 had ADTs ranging between 600 and 2,980, except for the portion between Yerington and Hawthorne and on segments north of the Las Vegas metropolitan area, where the ADT ranged from 3,000 to 4,800 vehicles/day. It was observed that SR-228 had the lowest traffic levels with a 9-year average ADT value of 360 vehicles/day.

The relationship between density and average daily traffic for the "before-after" conditions are shown graphically in Figure 36. In this figure, single-vehicle ran-off-roadway densities were plotted as a function of average daily traffic on the roadway segments.

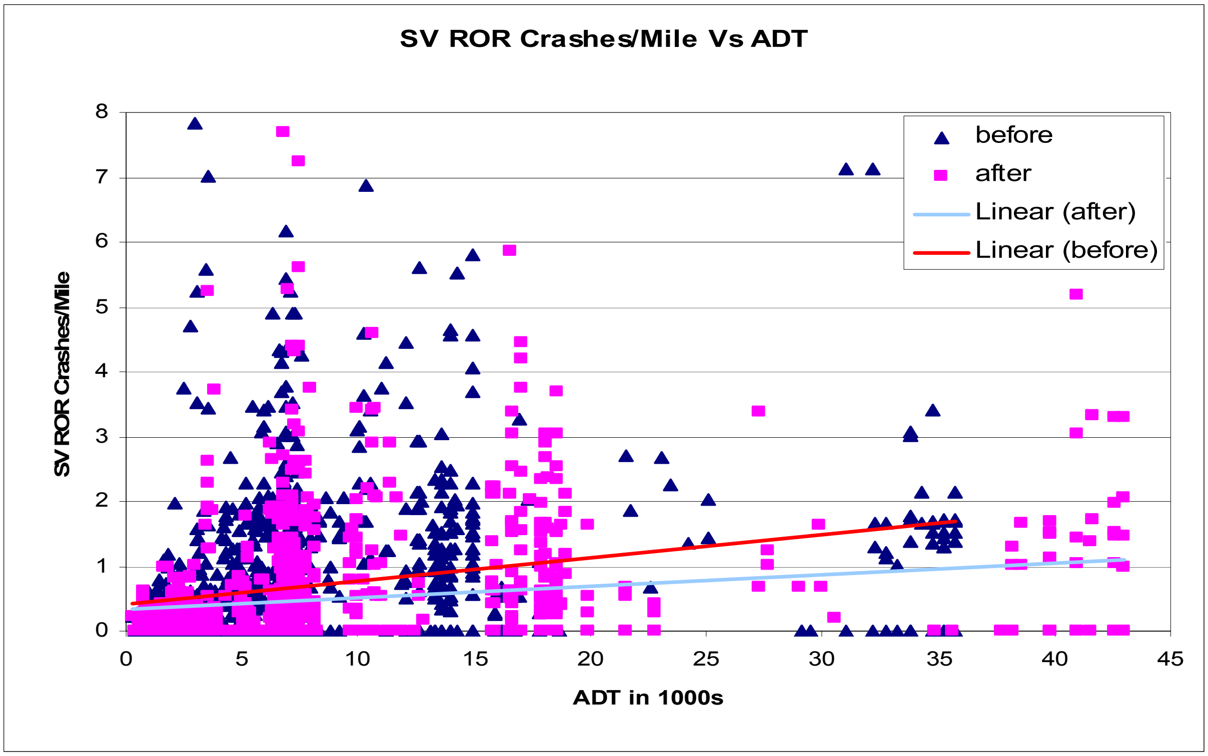

Figure 39: Variation of Single-vehicle Ran-off-roadway (SV ROR) Crash Density with Average Daily Traffic

At first glance the figure did not indicate any well-defined pattern, but a closer look at the figure suggested a possible increase in crash density as the average daily traffic increased. Simple linear regression models were developed to attempt to quantify this apparent relationship. The models developed for the "before-after" periods are shown in the form of the following equations.

Crashes/Mile $_{before}$ = f (ADT $_{before}$)

Density (crashes/mile) $_{before}$ = 0.421 + 0.0395 ADT $_{before}$ Where ADT is in 1,000s

Predictor	Coef	SE Coef	T	P
Constant	0.42147	0.06680	6.31	0.000
ADT B	0.039473	0.006049	6.53	0.000

R-Sq = 12.3%   R-Sq(adj) = 12.0%

Analysis of Variance

S Source	DF	SS	MS	F	P

Regression	1	23.306	23.306	42.58	0.000
Residual Error	304	166.380	0.547		
Total	305	189.686			

Density (crashes/mile) $_{after}$ = f (ADT $_{after}$

Crashes/Mile $_{after}$ = 0.267 + 0.0226 ADT $_{after}$ Where ADT is in 1000s

Predictor	Coef	SE Coef	T	P
Constant	0.26740	0.04599	5.81	0.000
ADT A	0.022562	0.003548	6.36	0.000

R-Sq = 11.7%   R-Sq(adj) = 11.4%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	11.264	11.264	40.44	0.000
Residual Error	304	84.679	0.279		
Total	305	95.942			

Each of the linear regression models had a coefficient of determination (R^2 values) of 12 percent. This means that the average daily traffic was a poor explanatory variable for density. However, note that the intercept and the coefficient of average daily traffic were lower for the model for the “after” period when compared to those for the “before” period. The lower coefficient for ADT in the model for the “after” period indicated that that the density as a function of ADT was lower for the “after” period when compared to the “before” period.

4.2 Statistical Analysis and Results

The analyses presented thus far consisted of subjective analyses and simple regression models. These analyses indicated that the shoulder rumble strip treatment had been effective in reducing single-vehicle ran-off-road crash rates on roadways in Nevada. To further ascertain if such improvements in safety were indeed significant, additional statistical analyses were necessary. Such statistical analyses were presented in this section.

Safety treatment on a roadway facility was evaluated to see its effect in improving the safety of the facility. The effect of the treatment was estimated by comparing the prediction of what safety “would have been” to the estimate of what safety “was” prior to the deployment of the treatment. The statistical analysis used to determine the effectiveness of continuous shoulder rumble strips treatment comprises of comparing various averages and means of the crash rates before and after the treatment of the roadway with continuous shoulder rumble strips. This was based on Hauer's "observational before-after studies in road safety" method.

Hauer suggested different conventional methods to evaluate the effectiveness of any treatment on the facility. The conventional methods comprised of comparing various averages of the indicators with the pair-wise comparison methods. The averages of the number of crashes before-after could be compared to see if the treatment of the roadway shoulders with rumble strips had any effect in reducing the crash rates.

4.2.1 Ezra Hauer's Comparison Group Method

In Hauer's observational of his before-after methods, predicted crash frequencies were compared to the estimated "after" crash frequencies to determine the effectiveness of the treatment. The *"Predicted"* value was the expected value of what would be the safety indicator of the roadway segment during the "after" period had the treatment not been deployed. These predicted values of safety indicators were compared with the estimated or actual values of the same indicators after the treatment was deployed along the roadway. The *"Estimated"* was the actual or computed value of the indicator in the period "after" the deployment of the treatment. Once the prediction was made for the "after" period, a comparison was made as to what safety was in the "after" period after the treatment was deployed.

4.2.1.1 Comparison Groups

The central idea of a 'comparison group' was to identify a group of entities (segments), which remain untreated and that were similar to the treated segments. The expectation was that the change in crash rates of the comparison group from the "before" to the "after" condition was indicative of how the crash rates on the treatment group would change. Hence to perform a "Comparison Group Study" each roadway segment in the study would have a comparison segment group so as to compare its crash rates with the comparison group. Since a substantial length of the facilities considered for research were treated with continuous shoulder rumble strips, finding appropriate comparison groups for all the roadway segments treated with rumble strips was not possible. Hence, for each facility considerably long roadway sections of comparison groups were selected. The crashes on these roadway sections had been extracted for all the 9-years of study in order to perform the comparison group study.

4.2.1.2 Comparison Group for I-15

Though comparison groups for all the facilities were available with the aforementioned caveat, no suitable comparison groups were available for I-15 because a major proportion of I-15 passing through the state of Nevada was already treated with shoulder rumble strips. Only the sections that were in the metropolitan Las Vegas area had no continuous shoulder rumble strips treatment. In order to obtain the comparison group, and subsequently the comparison ratio, the number of crashes occurring during the four years prior to the shoulder rumble strip installation (i.e., 1995 to 1998) for the entire stretch of I-15 was considered. The comparison ratio (r_c) was calculated using the initial 2 years as the "before" period and the next two years as the "after" period. The r_c for this case was obtained using the following expression:

$$r_{c\,(I\text{-}15)} = (X/Y) / (1+1/Y)$$

where

X = # Crashes during year 1997 & 1998, and
Y = # Crashes during year 1995 & 1996

However to compute the index of effectiveness for the entire length of I-15, considering it as a single entity treated with continuous shoulder rumble strips in the year 1999, a group of roadway segments, which had not been treated with rumble strips, were chosen. The details of the comparison group selected for analysis of I-15 were presented next.

4.2.1.3 Interstates

The state of Nevada has two major Interstate routes (I-15 and I-80); I-15 was the most important means of road transport to and from Southern Nevada. It served as the only road, which leads heavy traffic from Southern California to the important tourist attraction of Las Vegas. Almost the entire stretch of 124 miles along I-15 in the state of Nevada was treated with continuous shoulder rumble strips. This was done during the year 1999. Only the section of I-15 in the Las Vegas metropolitan area was not subjected to treatment. A significant length of the 410 mile long stretch of I-80, which was the other Interstate in the state of Nevada that had also been treated with continuous shoulder rumble strips. I-80 was observed to have a high frequency and rate of ran-off-roadway single-vehicle crashes. Both Interstates experienced significant improvement in the ran-off-roadway crash pattern after installation of rumble strips.

Details of the comparison groups used for the analysis were provided in Table 18. The first column identifies the roadway facility, and the next column shows the length of the facility (in Centerline miles). The next set of columns provided the number of single-vehicle ran-off-roadway crashes in the years from 1995 to 2003. The columns titled “Crashes before” and “Crashes after” provided data based on the actual construction dates for the continuous shoulder rumble strips treatment. The last column, titled “r_c”, shows the computed comparison ratio as defined previously. The last row in Table 18 showed the cumulative data for the entire roadway network analyzed. The results of the analyses using the comparison group data for individual roadways and the entire roadway network studied are presented in Table 19.

Table 19 presents the number of crashes recorded on the comparison group and on the facilities, which were treated with rumble strips along with the computed comparison ratios for each facility. The table presents the index of effectiveness value and the reduction threshold values of the number of crashes on each facility, which were very good indicators of the significance of the improvement on each roadway. From table 19 it can be clearly observed that each of the roadway facilities, except SR-160, had the index of effectiveness value of less than one indicating that the rumble strips were effective in reducing the ran-off-roadway crashes. In most of the cases the effectiveness of the continuous shoulder rumble strips was significant, as the actual number of crashes recorded after treatment was lower as compared to the "significant reduction threshold value" indicated in the table. On facilities where the actual number of "after" crashes was lower than the "highly significant threshold value," the improvement can be termed as highly significant. Further observation of Figure 40 showed that facilities I-80, US-95, and US-93 were examples where the improvement in safety after the continuous shoulder rumble strips treatment was highly significant.

Table 18: **Details of the Comparison Groups used for the Comparison Group Analysis**

	Total		Comparison Group		Treatment Group						Improved			
Facility	**# Segments**	**CL Miles**	**Before**	**After**	**Before**	**After**	**Comparison Ratio**	**Index of Effectiveness**	**Significant Reduction Threshold**	**Highly Significant Reduction Threshold**	**# Segments**	**%**	**CL Miles**	**%**
I - 15	61	178.140	101	89	819	617	0.873	0.863	635.7	596.2	30	48.39	102.57	57.58
I - 80	64	208.006	95	90	473	318	0.938	0.717	376.6	343.2	34	53.13	143.18	68.84
US - 95	47	363.276	31	33	688	458	1.031	0.646	644.5	612.0	37	78.72	311.27	85.68
US - 93	6	92.567	73	64	146	83	0.865	0.657	106.9	97.1	4	66.67	89.82	97.03
US - 50	11	93.482	16	13	175	126	0.765	0.942	113.800	103.800	3	27.27	28.46	30.44
US - 395	5	12.670	7	7	121	80	0.875	0.756	88.820	80.300	5	100.00	12.67	100.00
US - 6	1	23.500	41	61	30	30	1.452	0.689	36.320	32.700	1	100.00	23.50	100.00
SR - 160	1	5.336	40	38	38	65	0.927	1.842	24.890	19.720	0	0.00	0.00	0.00
SR - 318	1	5.471	21	39	3	3	1.773	0.564	3.904	3.197	1	100.00	5.47	100.00
SR - 604	1	15.690	12	14	161	127	1.077	0.732	153.000	142.800	1	100.00	15.69	100.00
Total	198	998.138	437	448	2654	1907	1.023	0.702	2712.6	2360.0	116	58.29	732.63	73.40

Table 19: Results of Comparison Group Analysis of the Sections Continuous Shoulder Rumble Strips Treated in 1999

	Length in Miles	1995	1996	1997	1998	1999	2000	2001	2002	2003	Crashes Before	Crashes After	r_c
CG1_I80E	10.020	6	10	8	6	8	11	10	9	2	30	32	1.032
CG2_I80W	10.060	7	16	12	6	11	8	11	10	8	41	37	0.881
CG3_I80E	6.150	3	5	3	4	4	5	2	3	1	15	11	0.688
CG4_I80W	6.060	0	5	1	3	5	1	3	4	2	9	10	1.000
CG_I80	*32.290*	*16*	*36*	*24*	*19*	*28*	*25*	*26*	*26*	*13*	*95*	*90*	*0.938*
CG5_I15N	1.827	1	2	2	2	2	0	0	1	3	7	4	0.500
CG6_I15S	1.970	3	1	2	2	0	1	4	2	4	8	11	1.222
CG7_I15N	5.350	15	21	16	12	12	13	6	10	12	64	41	0.631
CG8_I15S	5.430	7	8	3	4	7	4	9	12	8	22	33	1.435
CG_I15	*14.577*	*26*	*32*	*23*	*20*	*21*	*18*	*19*	*25*	*27*	*101*	*89*	*0.873*
CG9_US93	45.500	15	20	17	21	22	12	21	20	11	73	64	0.865
CG10_US95	30.830	2	3	16	10	7	8	12	8	5	31	33	1.031
CG11_US6	32.729	6	12	11	12	14	12	29	10	10	41	61	1.452
CG12_US395	2.111	2	1	4	0	0	1	3	2	1	7	7	0.875
CG13_US50	20.970	2	7	1	6	3	2	4	5	2	16	13	0.765
CG14_SR160	27.350	5	9	10	16	16	13	7	10	8	40	38	0.927
CG15_SR318	48.500	6	4	5	6	15	12	10	10	7	21	39	1.773
CG16_SR604	7.478	1	5	2	4	3	4	4	4	2	12	14	1.077
Total	**262**	**123**	**197**	**160**	**153**	**178**	**150**	**180**	**171**	**126**	**437**	**448**	**1.023**

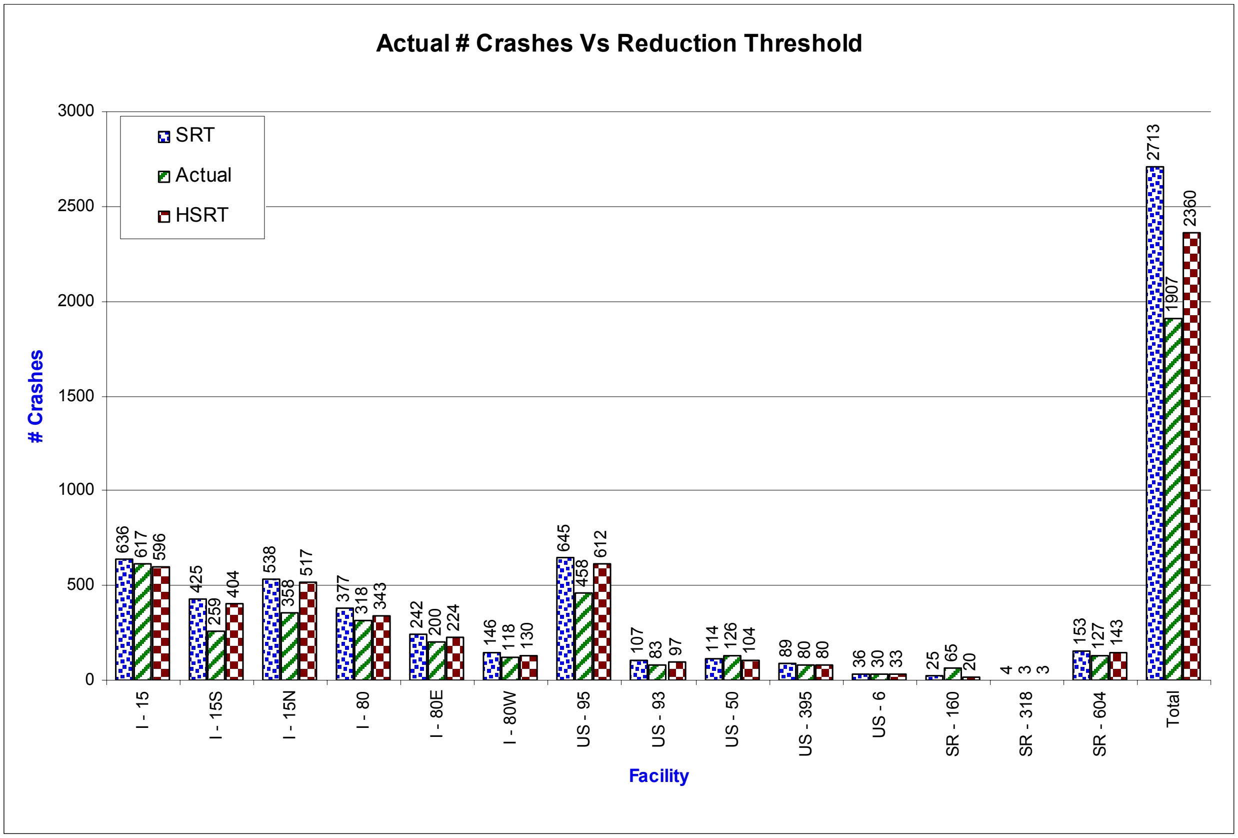

Figure 40: Threshold Values of Crashes on Each Facility by Comparison Group Method

4.2.1.3.1. Interstate-15

In 1999, a length of 178.14 centerline miles (61 segments) of I-15 (both northbound and southbound sections) was treated with continuous shoulder rumble strips. These 61 segments experienced 819 single-vehicle ran-off-roadway crashes in the four years "before" period from year 1995 to 1998 and 617 crashes were recorded during the four year "after" period from year 2000 to 2003. The comparison group roadway sections for I-15 were 14.577 miles in length. Details of this comparison group were presented in Table 20. Data for the comparison groups were used to compute the "index of effectiveness" for segments of I-15, which have rumble strip treatment. The comparison groups had experienced 101 single-vehicle ran-off-roadway crashes in the four years "before" and 89 crashes in the four years "after" period.

Table 20: Details of Comparison Group Used to Evaluate the Continuous Shoulder Rumble Strips Effectiveness on I-15

Comparison Group	Length in miles	Number of crashes during each year									Number of Crashes 'before'	Number of Crashes 'after'
		1995	1996	1997	1998	1999	2000	2001	2002	2003		
CG5_I15N	1.827	1	2	2	2	2	0	0	1	3	7	4
CG6_I15S	1.970	3	1	2	2	0	1	4	2	4	8	11
CG7_I15N	5.350	15	21	16	12	12	13	6	10	12	64	41
CG8_I15S	5.430	7	8	3	4	7	4	9	12	8	22	33
Total	**14.577**	**26**	**32**	**23**	**20**	**21**	**18**	**19**	**25**	**27**	**101**	**89**

The unbiased comparison ratio (r_c) of the comparison group was 0.87 = [(89 / 101) / {1+ (1/101)}]. According to the premise of the Comparison Group Method the same r_c should hold good for the treatment group. Hence, if the continuous shoulder rumble strips treatment was not done for the treatment group, then the treatment group, which had 819 crashes in the "before" period, should have experienced at least 714 = (0.87 * 819) crashes in the "after" period. The index of effectiveness for this 178 mile section of I-15 was 0.86 = (617 / 714), which was less than 1.0, indicating an apparent reduction in the ran-off-roadway single-vehicle crashes after treatment of these roadway sections. The significant reduction threshold of 635.7 (> actual number of crashes 617) as presented in Table 18 also indicated that the I-15 experienced statistically significant improvement after the treatment with continuous shoulder rumble strips. A summary of the computations for the analysis was presented in Table 21.

Table 21: Results of Comparison Group Analysis for I-15 section Continuous Shoulder Rumble Strips Treated in 1999

	Length in miles	Number of crashes during each year								# Crashes 'before'	# Crashes 'after'	r_c
		Before				After						
		1995	1996	1997	1998	2000	2001	2002	2003			
Treatment Group	178.14	159	200	204	256	141	141	181	154	819	617	0.873
Comparison Group	14.577	26	32	23	20	18	19	25	27	101	89	0.873

Of the 61 segments on I-15 (178 miles in length) that had rumble strip treatment, a total of 30 segments accounted for 102 centerlines miles with an index of effectiveness of less than one. A summary of computations for the analysis was presented in Table 22.

Table 22: Results of the Comparison Group Analysis for I-15 Continuous Shoulder Rumble Strips Treated in 1999

Total		**Improvement (Index of effectiveness < 1)**		**% Improved**	
Segments	Centerline Miles	Segments	Centerline Miles	Segments	Centerline Miles
61	178	30	102	49	57

<u>4.2.1.3.1.1 Interstate-15 South</u>

As mentioned earlier, there was not enough length on I-15 without treatment; hence, the comparison ratio for analyzing I-15 south bound was computed using the crash data from the first four years of the study period. Using the r_c value of 1.25 = [(208 / 166) / {1+ (1/166)}], where 166 was the number of crashes during 1995 and 1996, and 208 was the number of crashes during 1997 and 1998; it was found that 82.63 miles of the total 88.7 mile treated segments on I-15 south had an index of effectiveness of less than one, indicating marked improvement in the single vehicle crash scenario after the continuous shoulder rumble strip treatment. Twenty roadway segments out of 29 total south bound segments that showed improvement had at least one crash in the "before" period.

Table 23: Results of Comparison Group Analysis for I-15 Continuous Shoulder Rumble Strips Treated in 1999

Total		Comparison Group		Treatment Group		Comparison Ratio	Index of Effectiveness	Significant Reduction Threshold	Highly Significant Reduction Threshold
# Segments	CL Miles	Before	After	Before	After				
29	88.678	166	208	374	259	1.246	0.556	424.7	404.1

Table 24: Results of Comparison Group Analysis of I-15S Using Four Years Crash Data Comparison Ratio

Total		Improvement (Index of effectiveness < 1)		% Improved	
Segments	Centerline Miles	Segments	Centerline Miles	Segments	Centerline Miles
29	88.7	20	82.63	69	93

4.2.1.3.1.2 Interstate-15 North

Similar analysis for the north bound I-15 shows that 80.6 miles of roadway showed improvement after the treatment on 89.5 miles of roadway, with an index of effectiveness of less than one. The 24 roadway segments out of 32 total northbound segments that showed improvement had at least one crash in the "before" period. The comparison ratio (r_c) for the analysis was computed to be 1.3 = [(252 / 193) / {1+ (1/193)}], where 193 was the number of crashes during 1995 and 1996, and 252 was the number of crashes during 1997 and 1998.

Using the crash data for the first four years of the study period, an analysis was carried out considering the entire I-15 North as a single unit. The index of effectiveness was found to be 0.62 (<1), indicating a significant reduction in the crash rates. The actual number of crashes recorded, 358, was much lower when compared to the significant reduction threshold 537.6, and highly significant reduction threshold value 517.4 presented in Table 25 that indicated that the facility experienced highly significant improvement with the continuous shoulder rumble strip treatment.

Table 25: Comparison Group Analysis Results of I-15 North Using 4-Years Comparison Group

Total		Comparison Group		Treatment Group		Comparison Ratio	Index of Effectiveness	Significant Reduction Threshold	Highly Significant Reduction Threshold
# Segments	CL Miles	Before	After	Before	After				
31	89.459	193	252	445	358	1.299	0.619	537.6	517.4

4.2.1.3.2 Interstate-80

A major portion of the 410 centerline miles of I-80 in the State of Nevada was treated with continuous shoulders rumble strips. In 1999, about 111 miles of the east bound I-80 and 96 miles of west bound I-80 were treated with rumble strips. In order to test the sections treated, the sections of I-80, which were not treated were considered as the comparison group.

Table 26: Details of Comparison Group Used to Evaluate the Continuous Shoulder Rumble Strips Effectiveness on I-80

Comparison Group	Length in miles	Number of crashes during each year									Number of Crashes 'before'	Number of Crashes 'after'
		1995	1996	1997	1998	1999	2000	2001	2002	2003		
CG1_I80E	10.020	6	10	8	6	8	11	10	9	2	30	32
CG2_I80W	10.060	7	16	12	6	11	8	11	10	8	41	37
CG3_I80E	6.150	3	5	3	4	4	5	2	3	1	15	11
CG4_I80W	6.060	0	5	1	3	5	1	3	4	2	9	10
Total	**32.290**	**16**	**36**	**24**	**19**	**28**	**25**	**26**	**26**	**13**	**95**	**90**

The cumulative comparison group, which included all the four individual groups, was used to analyze all sections of I-80 installed with rumble strips including east bound and west bound sections. The Comparison Ratio (r_c) of the comparison group was computed to be 0.94 = [(90 / 95) / {1+ (1/95)}]. The east bound and west bound roadways of I-80 experienced 473 crashes in four years from 1995 to 1998. As per the principle of the Comparison Group Method, the treatment group would have the same comparison ratio. Therefore, the four years after treatment would record at least 443 = (0.94 * 473) crashes if the road section had not been treated with continuous shoulder rumble strips.

Table 27: Results of Comparison Group Analysis for I-80 Section Continuous Shoulder Rumble Strips Treated in 1999

		Number of crashes during each year										
		before				after						
	Length in miles	1995	1996	1997	1998	2000	2001	2002	2003	# Crashes 'before'	# Crashes 'after'	r_c
Treatment Group	208.00	104	140	91	138	63	116	94	45	473	318	0.938
Comparison Group	32.29	16	36	24	19	25	26	26	13	95	90	0.938

But in reality, this section of I-80 saw 318 crashes in the four-year period from 2000 to 2003. The index of effectiveness was computed to be 0.72 = (318 / 443), which indicated a striking improvement after the treatment of I-80 with continuous shoulder rumble strips. As presented in Table 28, the significant reduction threshold value of 376.6 and the highly significant reduction threshold value of 343.2 also reaffirmed the improvement to be highly significant as the actual recorded number of crashes was only 318, which was lower than both the significant reduction threshold value and the highly significant reduction threshold value.

Table 28: Results of the Comparison Group Analysis for I-80 Continuous Shoulder Rumble Strips Treated in 1999

Total		Comparison Group		Treatment Group					
# Segments	CL Miles	Before	After	Before	After	Comparison Ratio	Index of Effectiveness	Significant Reduction Threshold	Highly Significant Reduction Threshold
64	208	95	90	473	318	0.938	0.717	376.6	343.2

The results of the analysis for the sections along I-80 with treatment are presented in Table 29. As can be seen in Table 29, the analysis indicated that the index of effectiveness was less than one for 143 miles of the total 208 continuous shoulder rumble strip treated miles (34 of the total 64 segments).

Table 29: Results of the Comparison Group Analysis for I-80 Continuous Shoulder Rumble Strips Treated in 1999

Total		Improvement (Index of effectiveness < 1)		% Improved	
Segments	Centerline Miles	Segments	Centerline Miles	Segments	Centerline Miles
64	208	34	143	53	69

4.2.1.3.2.1 Interstate-80 East

Each direction of this section of I-80 was analyzed separately. The 111 miles of roadway had 270 crashes from year 1995 to 1998. A 10 mile long section of I-80 not treated with rumble strips was used as the comparison group for analyzing eastbound I-80 treated with rumble strips in 1999. The treated sections of the roadway witnessed a total of 270 crashes from the year 1995 to 1998. Based on the comparison group method, with a comparison ratio of 1.03 = [(32 / 30) / {1+ (1/30)}] these sections together would have 278 = (1.03 * 270) crashes in the four year "after" period. In reality, 200 crashes were recorded on this 111 mile section of roadway. The index of effectiveness for this section was computed to be 0.72 = (200 / 278), which indicated a substantial improvement in the safety performance based on single-vehicle ran-off-roadway crashes. This data is shown in Table 30.

Table 30: Results of Comparison Group Analysis for I-80 East Section Continuous Shoulder Rumble Strips Treated in 1999

	Length in miles	Number of crashes during each year								# Crashes 'before'	# Crashes 'after'	r_c
		before				after						
		1995	1996	1997	1998	2000	2001	2002	2003			
Treatment Group	111.8	67	76	46	81	44	72	56	28	270	200	1.032
Comparison Group	10.02	6	10	8	6	11	10	9	2	30	32	1.032

The actual number of crashes 318 recorded after the roadways were installed with rumble strips were much lower when compared to the significant threshold of 376.6 and highly significant threshold of 343.2 values. These are shown in Table 31. This indicated that the safety improvement was highly significant after the continuous shoulder rumble strips treatment.

Table 31: Results of Comparison Group Analysis for I-80 East Section Continuous Shoulder Rumble Strips Treated in 1999

Total		Comparison Group		Treatment Group		Comparison Ratio	Index of Effectiveness	Significant Reduction Threshold	Highly Significant Reduction Threshold
# Segments	CL Miles	Before	After	Before	After				
64	208	30	32	270	200	0.938	0.718	376.6	343.2

An analysis of individual segments showed in Table 32 that 75 miles of the 111 mile section improved with an index of effectiveness of less than one for each of the 18 segments showing improvement. The 18 roadway segments out of 34 total east bound segments, which showed improvement had at least one crash in the "before" period.

Table 32: Results of Comparison Group Analysis for I-80 East Section Continuous Shoulder Rumble Strips Treated in 1999

Total		Improvement (Index of effectiveness < 1)		% Improved	
Segments	Centerline Miles	Segments	Centerline Miles	Segments	Centerline Miles
34	111	18	75	53	68

4.2.1.3.2.2 Interstate-80 West

The 96 mile westbound I-80 section treated with continuous shoulder rumble strips in 1999 recorded 203 crashes from year 1995 to 1998. A 10 mile long comparison group was used to evaluate the effectiveness of this section. This comparison section experienced 41 crashes in the four year "before" period and 37 crashes in the four year "after" period. The comparison ratio (r_c) of the comparison group was 0.88 = [(37 / 41) / {1+ (1/41)}]. Using the comparison ratio computations, it showed that if the rumble strips were not present on the treatment group, there would have been at least 178 = (0.88 * 203) crashes in the following four years. But the actual number of crashes that were recorded on this section of I-80 from the year 2000 to 2003 was 118. This equates to an index of effectiveness of 0.66 = (118 / 178) indicating a significant improvement in the single-vehicle crash trend. These data are presented in Table 33.

Table 33: Results of Comparison Group Analysis for I-80 West Section Continuous Shoulder Rumble Strips Treated in 1999

		Number of crashes during each year										
		before				after						
	Length in miles	1995	1996	1997	1998	2000	2001	2002	2003	# Crashes 'before'	# Crashes 'after'	r_c
Treatment Group	96.207	37	64	45	57	19	44	38	17	203	118	0.881
Comparison Group	10.06	7	16	12	6	8	11	10	8	41	37	0.881

Further, the improvement was stated as highly significant, since the actual number of crashes recorded during the four years after the continuous shoulder rumble strips treatment was lower than the significant reduction threshold values 146 and 129.6, which are shown in Table 34.

Table 34: Results of Comparison Group Analysis for I-80 West Section of Continuous Shoulder Rumble Strips Treated in 1999

Total		Comparison Group		Treatment Group		Comparison Ratio	Index of Effectiveness	Significant Reduction Threshold	Highly Significant Reduction Threshold
# Segments	CL Miles	Before	After	Before	After				
30	96	41	37	203	118	0.831	0.660	146	129.6

The results of the analysis of individual segments of I-80 west proved that the installation of continuous shoulder rumble strips was effective based on the single vehicle crash rate being reduced in 19 of the total 30 segments. In other words, 71 centerline miles of treatment of a total of 96 miles experienced a decline in the crash rates after installation. The results of the analysis were summarized in Table 35.

Table 35: Results of Comparison Group Analysis for I-80 West Section of Continuous Shoulder Rumble Strips Treated in 1999

Total		**Improvement (Index of effectiveness < 1)**		**% Improved**	
Segments	Centerline Miles	Segments	Centerline Miles	Segments	Centerline Miles
30	96	19	71	63	74

4.2.1.4 US Routes

Some US routes traversed the State of Nevada. These included US-93, US-95, US-50, US-6, and US-395. The Nevada Department of Transportation started treating these US routes with continuous shoulder rumble strips. The crash patterns before and after the rumble strip treatment were analyzed using the comparison group method and the results for each facility were discussed next.

4.2.4.1 US-95

US-95 was one of the important north-south connectors starting at the Mexican border in Arizona and ending at the Canadian border in the State of Idaho. It was one of the major US routes in the State of Nevada with a length of 665 miles within Nevada. More than 353 miles of the route in Nevada was treated with continuous shoulder rumble strips. This was in addition to stretches of US-95 that overlap with Interstate-80. The US-95 sections, which were treated with rumble strips in the year 1999, were analyzed along with a 21 mile long section of US-95A. In total, the 363 mile section has recorded 688 crashes in four years from 1995 to 1998. A US-95 untreated section, approximately 31 miles long, was used as the comparison group so as to perform the Comparison Group Analysis. This comparison section experienced 31 crashes during 1995-1999 and 33 crashes during the four year period from 2000 to 2003. The comparison ratio for the comparison group was 1.03 = [(33 / 31) / {1+ (1/31)}]. If the same ratio held good for the treatment group, then the treatment group would have recorded more than 709 = (1.03 * 688) crashes if the roadway sections were not treated with rumble strips. But in reality, during the four year "after" period, the sections experienced only 458 crashes in total. This indicated the effectiveness of the continuous shoulder rumble strips in reducing ran-off-roadway single-vehicle crash rates was reaffirmed with an index of effectiveness value 0.65 = (458 / 709).

Table 36: Results of Comparison Group Analysis for US-95 Sections of Continuous Shoulder Rumble Strips Treated in 1999

		Number of crashes during each year										
		before				after						
	Length in miles	1995	1996	1997	1998	2000	2001	2002	2003	# Crashes 'before'	# Crashes 'after'	r_c
Treatment Group	363.28	175	176	157	180	122	96	121	119	688	458	1.031
Comparison Group	30.83	2	3	16	10	8	12	8	5	31	33	1.031

Other markers, such as the significant reduction threshold of 644 and the highly significant reduction threshold of 612, indicated that the improvement was highly significant as the actual number of crashes recorded after treatment was much lower than the threshold values as shown in Table 36.

Table 37: Results of Comparison Group Analysis for US-95 Sections Continuous Shoulder Rumble Strips Treated in 1999

Total		Comparison Group		Treatment Group					
# Segments	CL Miles	Before	After	Before	After	Comparison Ratio	Index of Effectiveness	Significant Reduction Threshold	Highly Significant Reduction Threshold
47	363	31	33	688	458	1.031	0.646	644	612

An analysis of the 47 individual sections of the 363 miles of roadway, as shown in Tables 37 and 38 demonstrate a marked improvement in the single vehicle crash pattern with 37 segments of the total 47 segments (311 miles of the total 363 miles) having an index of effectiveness value of less than one. These 37 improved sections had at least one crash recorded during the four year "before" analysis period.

Table 38: Results of Comparison Group Analysis for US-95 Sections Continuous Shoulder Rumble Strips Treated in 1999

Total		**Improvement (Index of effectiveness < 1)**		**% Improved**	
Segments	Centerline Miles	Segments	Centerline Miles	Segments	Centerline Miles
47	363	37	311	79	86

4.2.4.2 US-93

US-93 in Nevada was about 521 miles in length, of which 151 miles had been treated with continuous shoulder rumble strips. This included a 14 mile long stretch of US-93 alternate route. The 92 mile roadway section treated with rumble strips in 1999, had 146 crashes in the four year "before" period. A 45 mile long untreated section of roadway was used as the comparison group. The comparison group had 73 and 64 crashes during the "before" and "after" four year periods respectively, which resulted in a comparison ratio (r_c) of 0.87 = [(64 / 73) / {1+ (1/73)}]. The treated section of US-93 experienced 146 crashes during the "before" period. The assumption of the comparison group method was that the treatment group should also have the same comparison ratio if it were not treated with rumble strips. In this case, the treatment group would have had at least 126 = (146 * 0.87) single vehicle crashes recorded during the four year period from 2000 to 2003. But, after the treatment of the roadway section with rumble strips in the year 1999, the number of crashes recorded was only 83, which indicated the rumble strips were effective in reducing the crash rates. The index of effectiveness for this section of US-93 was 0.657 = (83 / 126). These results were summarized in Table 39.

Table 39: Results of Comparison Group Analysis for US-93 Sections Continuous Shoulder Rumble Strips Treated in 1999

		Number of crashes during each year										
		before				after						
	Length in miles	1995	1996	1997	1998	2000	2001	2002	2003	# Crashes 'before'	# Crashes 'after'	r_c
Treatment Group	92.57	32	43	30	41	24	16	23	20	146	83	0.865
Comparison Group	45.50	15	20	17	21	12	21	20	11	73	64	0.865

The reduction in the crash rate could be termed as highly significant when the number of crashes recorded actually on the field was compared with the significant reduction threshold value of 106.9 and the highly significant reduction threshold value of 97.1. The actual number of crashes recorded after the continuous shoulder rumble strip treatment, 83, was much lower as compared to the threshold values. The results of the analysis performed are presented in Table 40.

Table 40: Results of Comparison Group Analysis for US-93 Sections Continuous Shoulder Rumble Strips Treated in 1999

Total		Comparison Group		Treatment Group					
# Segments	CL Miles	Before	After	Before	After	Comparison Ratio	Index of Effectiveness	Significant Reduction Threshold	Highly Significant Reduction Threshold
6	92	73	64	146	83	0.865	0.657	106.9	97.14

An evaluation of the individual segments showed that 4 of the total 6 (89.82 miles of 92.57 miles) of roadway segments had an index of effectiveness of less than one, indicating that the roadway segments experienced improvement in their crash rates after the installation of rumble strips. All these four segments had at least one crash recorded during the four year "before" period of analysis. This is shown in Table 41.

Table 41: Results of Comparison Group Analysis for US-93 Sections Continuous Shoulder Rumble Strips Treated in 1999

Total		**Improvement (Index of effectiveness < 1)**		**% Improved**	
Segments	Centerline Miles	Segments	Centerline Miles	Segments	Centerline Miles
6	92	4	89.82	67	97

4.2.4.3 US-50

The 3,073 mile US 50 route, which is also called "the loneliest road in America", runs across the width of Nevada in an east-west direction. A considerable length of the route within the state had been treated with continuous shoulder rumble strips. In the year 1999, more than 93 miles of this section was treated with rumble strips. There were 175 single-vehicle crashes during the "before" four year period of the analysis. A 20.97 mile long comparison group, which experienced 16 crashes during the same period, was used for the comparison group.

With 13 crashes recorded in the "after" period, the comparison group had a comparison ratio of (r_c) of 0.77 = [(13 / 16) / {1+ (1/16)}]. Based on the premise of the Comparison Group Method, the treatment group would have had at least 133 = (0.765 * 175) crashes during the four years from the year 2000 to 2003, if the roadway were not treated with rumble strips. After the 93 miles of roadway was treated with rumble strips, a total of 126 crashes were recorded in the four years "after" period indicating a definite effect in the application of rumble strips in reducing the crash rate and providing an index of effectiveness value of 0.99 = (126 / 133). The results of the analyses are shown in Table 42.

Table 42: Results of Comparison Group Analysis for US-50 Sections Continuous Shoulder Rumble Strips Treated in 1999

		Number of crashes during each year										
		before				after						
	Length in miles	1995	1996	1997	1998	2000	2001	2002	2003	# Crashes 'before'	# Crashes 'after'	r_c
Treatment Group	20.97	42	49	42	42	43	36	30	17	175	126	0.765
Comparison Group	93.48	2	7	1	6	2	4	5	2	16	13	0.765

The fact that the significant and highly significant reduction threshold values of 113.8, 103.8 respectively were lower as compared to the actual number of crashes, 126, recorded after the continuous shoulder rumble strip treatment indicated that the improvement was not significant. Table 43 provides a summary of this analysis.

Table 43: Results of Comparison Group Analysis for US-50 Sections Continuous Shoulder Rumble Strips Treated in 1999

Total		**Comparison Group**		**Treatment Group**					
# Segments	**CL Miles**	**Before**	**After**	**Before**	**After**	**Comparison Ratio**	**Index of Effectiveness**	**Significant Reduction Threshold**	**Highly Significant Reduction Threshold**
11	93	16	13	175	126	0.765	0.992	113.8	103.8

An analysis of individual roadway segments indicated that only 3 out of 11 (28 miles of the total 93 miles) showed improvement. Due to the low r_c value, a large number of segments had an index of effectiveness of more than one. The results of the Comparison Group Method analysis of US-50 are presented in Table 44.

Table 44: Results of Comparison Group Analysis for US-50 Sections Continuous Shoulder Rumble Strip treated in 1999

Total		Improvement (Index of effectiveness < 1)		% Improved	
Segments	Centerline Miles	Segments	Centerline Miles	Segments	Centerline Miles
11	93	3	28	27	30

4.2.4.4 US-395

US-395 was a route in the North-Western quadrant in Nevada. It serves the transportation needs of Carson City and the City of Reno. Approximately 12 miles of the highway was treated with continuous shoulder rumble strips. The roadway sections with rumble strips recorded 120 crashes in the four year “before” period. A roadway section that did not have the treatment, which was 2.111 miles long, was taken as the comparison group. This section had seven crashes recorded each during the four year period “before-after” the continuous shoulder rumble strips treatment. The comparison ratio of the comparison group was calculated to be 0.88 = [(7 / 7) / {1+ (1/7)}]. This denoted that if the rumble strip installation was not applied on the treatment group, there would be a minimum of 105 = (0.88 * 121) single-vehicle crashes during the four year period from 2000 to 2003 on the treatment group. But, after treatment, the segments with continuous shoulder rumble strips had only 80 crashes. This translated into an overall index of effectiveness value of 0.76 = (80 / 105). The results of this analysis are presented in Table 45.

Table 45: Results of Comparison Group Analysis for US-395 Sections Continuous Shoulder Rumble Strips Treated in 1999

	Length in miles	Number of crashes during each year								# Crashes 'before'	# Crashes 'after'	r_c
		before				after						
		1995	1996	1997	1998	2000	2001	2002	2003			
Treatment Group	12.67	28	34	30	29	17	30	25	8	121	80	0.875
Comparison Group	2.11	2	1	4	0	1	3	2	1	7	7	0.875

The significant and highly significant reduction threshold values of 88.82 and 80.3 respectively indicated that the rumble strips were effectively reducing the single vehicle crash rates and their improvement can be termed as significant. The results of this analysis are shown in Table 46.

Table 46: Results of Comparison Group Analysis for US-395 Sections Continuous Shoulder Rumble Strips Treated in 1999

Total		Comparison Group		Treatment Group		Comparison Ratio	Index of Effectiveness	Significant Reduction Threshold	Highly Significant Reduction Threshold
# Segments	CL Miles	Before	After	Before	After				
5	12.67	7	7	121	80	0.875	0.756	88.82	80.3

An analysis of the individual segments showed that the treatment was effective in reducing the single-vehicle crashes with all five segments having an index of effectiveness value that was less than one.

4.2.4.5 US-6

Over 305 miles of the 3,205 mile long US-6 highway was within the state of Nevada. Out of the 305 miles, a 23.5 mile long section of the roadway was treated with continuous shoulder rumble strips in the year 1999. This 23.5 mile long section had 30 crashes during the four year “before” period. As a comparison group, a 32-mile long section was considered. This comparison group had experienced 41 crashes during the “before” period and 61 crashes during the “after” period. The comparison ratio (r_c) of the section was 1.452 = [(61 / 41) / {1+ (1/41)}]. According to the comparison group method, the treatment group would have at least 43 = (30 * 1.452) crashes during the four year “after” period if it were not treated with continuous shoulder rumble strips. In reality, the treatment group recorded only 30 crashes during the “after” period. Though the section has not seen any decline in the number of crashes during the “after” period as compared to the “before” period, it can be stated that the section has shown improvement as per the Comparison Group Method with an index of effectiveness value of less than one, 0.69 = (30 / 43). The results of this analysis are shown in Table 47.

Table 47: Results of Comparison Group Analysis for US-6 Sections Continuous Shoulder Rumble Strips Treated in 1999

		Number of crashes during each year										
		before				after						
	Length in miles	1995	1996	1997	1998	2000	2001	2002	2003	# Crashes 'before'	# Crashes 'after'	r_c
Treatment Group	23.5	2	7	6	15	8	8	8	6	30	30	1.452
Comparison Group	32.729	6	12	11	12	12	29	10	10	41	61	1.452

Though the number of crashes had not reduced, it did not increase either. The significant and highly significant reduction threshold values of 36.2 and 32.7 respectively were higher compared to the actual number of crashes (30) recorded. This signifies that the improvement was highly significant as per Comparison Group Method. Only one segment of 23.5 miles length had the continuous shoulder rumble strips treatment in 1999, and it showed improvement compared to the single-vehicle ran-off-roadway crashes on the untreated US-6 roadway segments. These results are shown in Table 48.

Table 48: Results of Comparison Group Analysis for US-6 Sections Continuous Shoulder Rumble Strips Treated in 1999

Total		Comparison Group		Treatment Group					
# Segments	CL Miles	Before	After	Before	After	Comparison Ratio	Index of Effectiveness	Significant Reduction Threshold	Highly Significant Reduction Threshold
1	23.5	41	61	30	30	1.452	0.69	36.2	32.7

4.2.5 State Routes

State routes 160, 318, and 604 were three state routes in Nevada that had continuous shoulder rumble strip treatment during the study period. A portion of SR-160 that was 5.336 miles in length, 5.471 miles of SR-318, and 15.69 miles of SR-604 had treatment applied in the year

1999. To evaluate the effectiveness of rumble strips in reducing the ran-off-roadway crashes comparison groups were identified from the untreated portions of the state routes.

For SR-160 (also known as Blue Diamond highway), a 27.35 mile long untreated section was considered as the comparison group. The four year "before" period had 40 crashes recorded and the four year "after" period had 38 crashes recorded resulting in an r_c value of 0.93. The treatment group experienced 38 crashes during the four year "before" period. With a comparison ratio of 0.93, the treatment group should record around 35 crashes during the four year "after" period. But in reality this route recorded 65 crashes with 1.85 as the index of effectiveness. An index of effectiveness value of greater than one indicated that the highway has seen deterioration in the single-vehicle crash scenario. As previously indicated, the conditions on SR-160 warrant special consideration and it merits exclusion in the overall analysis.

The treated portion of SR-318 was analyzed by comparing the section to a 48.5 mile long untreated section. The comparison section had a comparison ratio (r_c) of 1.77 with 21 crashes in the "before" period and 39 crashes in the "after" period. The 5.5 mile treatment group experienced three crashes during the four year "before" period and it should have experienced at least 5 = (1.77 * 3) crashes if the section of roadway was not treated with rumble strips. But it was observed that the section experienced only three crashes. This translated to an index of effectiveness of 0.56, indicating that the continuous shoulder rumble strip treatment helped improve safety in terms of single-vehicle ran-off-roadway crashes on these segments.

In the year 1999, a 15.69 mile portion of SR-604 was treated with rumble strips. This section of highway recorded 161 crashes during the four year period from 1995 to 1998. A comparison section of 7.5 miles length was considered to perform the comparison group analysis. This comparison group section recorded 12 crashes during the four year "before" period and 14 crashes were recorded during the four year "after" period. The comparison ratio of the section was 1.08. It expected that the treated section would experience at least 173 = (1.08 * 161) crashes if it were not treated with continuous shoulder rumble strips. After the section of this roadway was installed with rumble strips, it had only 127 crashes for the same duration. This indicated that the rumble strips were effective in reducing the single-vehicle crashes on this roadway. An index of effectiveness value of 0.73 (<1) also reaffirmed the effectiveness of the continuous shoulder rumble strip treatment.

4.2.2 Comparison of Poisson's Means

The methodology previously presented was adopted to compute the means of the crash rates before and after the installation of the continuous shoulder rumble strips. This method of analysis was applicable only to large numbers. Hence the analysis was performed treating each roadway facility as a single entity. During the year 1999, continuous shoulder rumble strips were deployed on 199 segments totaling 1,017 centerline miles of roadway. To explain the method of analysis, the analysis performed on US- 95 was described next.

On route US-95 a total of 363 centerlines of roadway were treated with continuous shoulder rumble strips. These 363 miles have experienced 688 crashes during the four year "before" period. After the rumble strip treatment on these segments, the number of crashes decreased to 458, showing a 33 percent improvement in the situation. To test the statistical significance of the improvement the hypothesis that $\lambda_b = \lambda_a$ was tested with a 95 percent confidence interval, λ_b, λ_a were rates of occurrence of crashes "before-after" rumble strip treatment. The 95 percent confidence interval for λ_b/λ_a was obtained using the following expression also described in the previous section: $t_2 (n_2 + 1/2) / t_1 (n_1 + 1/2)(FL) < \lambda_1/\lambda_2 < t_2 (n_2 + 1/2) / t_1 (n_1 + 1/2)(FU)$

The confidence interval for this case was given by $1.335 < \lambda_b/\lambda_a < 1.691$

The confidence interval being greater than one indicated the rate of occurrence of crashes in the "before" scenario, λ_b, was higher than the rate of occurrence of crashes in the "after" period, λ_a. The hypothesis tested all the other facilities that were treated with continuous shoulder rumble strips in the year 1999. A summary of the results were presented and discussed in Section 5.

5.0 RESULTS & DISCUSSION

The results of the various analyses and the findings from each method of analysis were discussed next.

5.1 Before-after Analysis

The results of the before and after analysis of single-vehicle ran-off-roadway crashes on roadway segments treated with continuous shoulder rumble strips were summarized in Table 49 and showed the crash rates aggregated by facility type (class).

An examination of Table 49 shows that for the crash rate of single-vehicle ran-off-roadway crashes reduced by 36.8 percent on I-15, and 41.5 percent on I-80. If crash density was considered, the reductions were 21.8 percent and 33.0 percent for I-15 and I-80, respectively. The routes US-95 and US-93 recorded reductions of 37 percent and 42.5 percent respectively for the crash rates after installation of rumble strips. These routes showed 36.0 percent and 40.0 percent reductions respectively in crash density for the "before-after" periods. All the other routes, including state routes treated with rumble strips, had a significant reduction in the single-vehicle ran-off-roadway crashes. Some of the state routes had zero crashes during the "before-after" periods, indicating no change. All of the state routes had very small numbers of roadway segments included in the analyses; and thus, it would not be prudent to place significant value on these results.

Table 49: Summary of Crash Rates on Facilities Treated with Rumble Strips

Facility	# Segments	CL Miles	# Crashes/Year		Crashes/Mile/Year			Crashes/MVMT		
			Before	After	Before	After	% Change	Before	After	% Change
I-15N	32	89.459	3.467	2.856	0.0390	0.0320	17.95	0.169	0.115	31.95
I-15S	32	91.732	2.862	2.076	0.0310	0.0230	25.81	0.140	0.081	42.14
I-15	64	181.191	3.160	2.472	0.0174	0.0136	21.80	0.155	0.098	36.75
I-80E	78	188.959	1.430	1.051	0.0076	0.0056	26.32	0.252	0.159	36.90
I-80W	75	176.834	1.273	0.759	0.0072	0.0043	40.28	0.228	0.121	46.93
I-80	153	365.793	1.353	0.907	0.0037	0.0025	32.95	0.241	0.141	41.51
US-95	48	382.596	3.825	2.463	0.0100	0.0064	36.00	0.362	0.228	37.02
US-93	9	142.807	5.669	3.359	0.0400	0.0240	40.00	0.379	0.218	42.48
US-50	12	98.414	4.068	2.979	0.0410	0.0300	26.83	0.435	0.297	31.72
US-6	4	35.507	2.162	2.427	0.0610	0.0680	-11.48	0.600	0.542	9.67
US-395	5	12.672	6.183	3.967	0.4880	0.3130	35.86	0.392	0.215	45.15
SR-766	3	11.595	0.674	0	0.0580	0.0000	100.00	0.175	0	100.00
SR-160	2	21.516	17.659	19.766	0.8210	0.9190	-11.94	0.848	0.683	19.46
SR-163	1	19.36	0	0	0	0	0.00	0	0	0.00
SR-221	1	0.337	0	0	0	0	0.00	0	0	0.00
SR-227	1	5.504	6.164	3.047	1.1200	0.5540	50.54	0.237	0.119	49.79
SR-228	1	4.732	0.743	0.609	0.1570	0.1290	17.83	1.227	0.947	22.82
SR-318	1	5.471	1.168	0.699	0.2140	0.1280	40.19	0.688	0.349	49.27
SR-604	1	15.69	41.150	31.89	2.6230	2.0330	22.49	1.611	1.576	2.17
Total	**306**	**1303.2**	**2.649**	**2.048**	**0.0020**	**0.0016**	**22.66**	**0.262**	**0.158**	**39.69**
Roadway Class	**#Segments**	**CL Miles**	**# Crashes/Year**		**Crashes/Mile/Year**			**Crashes/MVMT**		
			Before	**After**	**Before**	**After**	**% Change**	**Before**	**After**	**% Change**
Interstates	217	547	1.85	1.486	0.00338	0.00272	19.53	0.191	0.111	41.88
US Routes	78	672	4.147	2.73	0.00617	0.00406	34.20	0.382	0.24	37.17
State Routes	11	84.2	7.602	7.718	0.09028	0.09166	-1.53	0.571	0.491	14.01
SR without SR-160	9	62.684	5.655	3.610	0.09021	0.05758	36.17	0.477	0.369	22.59

An analysis based on roadway classes indicated that Interstates have seen the greatest crash rate reduction of all functional roadway classes with a reduction of 41.9 percent. The reduction in crash density on Interstate facilities was 19.5 percent.

On US routes there was a 37.2 percent reduction in crash rate. The crash density had a 34.2 percent decline.

All of the state routes had an overall reduction of 14 percent in the crash rate after installation of continuous shoulder rumble strips. This reduction was low because the crash rate on some sections of SR-160 saw no reductions. Similarly when crash density was compared for the "before-after" periods of rumble strips installation, it was found that the crash density increased by 1.5 percent. However, if SR-160 were not considered, the reduction was 22.6 percent and 28.3 percent for crash rate and crash density respectively. Several factors warranted excluding SR-160 from consideration. These related to the significant growth in traffic volumes, changes in land use, and other activities along the segments of SR-160 not included in this study.

Overall, for the entire 1,303 centerline miles of roadways evaluated, there was 39.7 percent reduction in the crash rate due to the installation of continuous shoulder rumble strips during the "after" period as compared to the "before" period. Similarly the reduction was 22.7 percent when the crash density was compared for these two periods. Thus, it was concluded that roadways with continuous shoulder rumble strips have fewer single-vehicle ran-off-roadway crashes.

5.2 Comparison Group Method

The crash rates on the test sections were compared with the crash rates on the untreated roadway sections for the same facility. The premise in this method of analysis was that had the test sections not been treated with continuous shoulder rumble strips, the test sections would have experienced the same trend of crash rates as experienced by the untreated comparison group. The value of comparison ratio was computed for each comparison group and it was assumed that the test sections would also have the same comparison ratio. The expected numbers of crashes for the "after" treatment were then predicted for the test sections using the comparison ratio. Then an index called the "index of effectiveness" was computed. The summary of the results of the comparison group analysis performed for 1,017 miles long roadway installed with rumble strips in the year 1999 was presented below.

5.2.1 Interstates

Interstate 15 had 178.14 miles of roadway treated with rumble strips in the year 1999. As mentioned earlier, there were few sections of I-15 left untreated with rumble strips. In order to obtain the comparison ration, four years of data before the installation was used, with two years as "before" and two years as "after" data. The comparison ratio with this arrangement was 1.278. Using this comparison ratio, the rumble strips proved effective on 44 of the 62 segments, which were 163 of the total 178 treated miles of I-15. Analysis performed with the 62 segments as a single entity and using the same comparison ratio as the rumble strips proved very effective with an index of effectiveness of 0.59. The significant reduction thresholds of 967.5 and 928.1 also indicated a highly significant improvement as the actual number of crashes during the "after" period was low at 617 single-vehicle crashes during the four year "after" period.

Though sufficient untreated sections were not available for the comparison group analysis; the comparison group analysis was performed with the available untreated sections as a single comparison group. The few untreated sections considered as a single comparison group resulted in a comparison ratio of 0.873. Using this comparison group for analysis found that 102 centerline miles of the treated 178 miles of roadway, which was 30 of the 62 segments on I-15, had an 'index of effectiveness' value of less than one. It implied that the treatment was effective on 58 percent of the continuous shoulder rumble strips treated on I-15.

Analysis of these 62 segments of I-15 as a single entity had an index of effectiveness value of 0.863, and a significant reduction threshold of 635.7 with an actual "after" crash number of 617, which indicated the improvement was significant.

The other interstate, I-80, showed results better than I-15 with 143 of the 208 treated miles having an index of effectiveness of less than one. The 64 segments when considered as a single entity had an index of effectiveness of 0.717. The results showed that the effect of rumble strips in reducing the single-vehicle crashes was highly significant with threshold values of 376 and 343 as compared to the actual 318 single-vehicle crashes.

Major US routes of US-95 and US-93 had significant improvements with 85 percent of treated US-95 and 97 percent of the treated US-93 having an index of effectiveness of less than one. Similar results were observed with all the other facilities except SR-160, which had an index of effectiveness of less than one.

Overall, with the entire treated roadway as a single unit, it was observed that the rumble strips were very effective in reducing the frequency of single-vehicle crashes. The continuous shoulder rumble strips treated network had an index of effectiveness of 0.702. The significant reduction threshold value of 2,360 and the highly significant threshold value of 2,712 as compared to the actual number of 1,907 indicated that the rumble strips were very effective in alerting the drifting drivers so as to keep themselves to the main roadway.

5.3 Poisson's Means

One of the statistical methods used to evaluate the effectiveness of continuous shoulder rumble strips consisted of conducting a hypothesis test that the Poisson's means of the number of crashes on each facility before and after the treatment of the facility with rumble strips were equal ($\lambda_b = \lambda_a$). In order to ensure that the test was accurate this method of hypothesis testing was only used in cases where large numbers of crashes were recorded. The literature suggested that the test might not be accurate in cases where the sample size was small; hence, the comparison was made for each facility rather than individual segments of the facility. The hypothesis test was also performed on all the remaining segments of roadway, which were treated with rumble strips and had unequal “before-after” periods. The results of analysis are presented in Table 51.

The results presented in Table 51 clearly showed that for all roadways evaluated with the exception of SR-160, the lower bound (or lower limit) of the 95 percent confidence interval for the ratio (λ_b / λ_a), which was greater than 1.0. This indicated that the crash rates in the “after” period were less than the crash rates in the “before” period. Observations from the number of crashes, as well as, the confidence interval showed that SR-160 experienced deterioration in the crash rate in the period following the continuous shoulder rumble strip treatment.

Table 50: Results of Poisson's Means Hypothesis Testing

Facility	CL Miles	#Segments	#Crashes 'before'(3yrs)	#Crashes 'after'(4yrs)	λ_b/λ_a Confidence Interval
Poisson's means hypothesis testing for facilities treated with CSRS in 1998-1999					
SR-160	16.18	1	77	98	$0.776 < \lambda_b/\lambda_a < 1.410$
I-80	32.78	28	66	56	$1.102 < \lambda_b/\lambda_a < 2.247$
Poisson's means hypothesis testing for facilities treated with CSRS in 1999					
Facility	**CL Miles**	**#Segments**	**#Crashes 'before'(4yrs)**	**#Crashes 'after'(4yrs)**	**λ_b/λ_a Confidence Interval**
I-80	208.00	64	473	318	$1.291 < \lambda_b/\lambda_a < 1.715$
I-15	178.14	61	819	617	$1.196 < \lambda_b/\lambda_a < 1.474$
US-95	363.28	47	688	458	$1.335 < \lambda_b/\lambda_a < 1.691$
US-93	92.57	6	146	83	$1.347 < \lambda_b/\lambda_a < 2.309$
US-50	98.48	11	175	126	$1.106 < \lambda_b/\lambda_a < 1.748$
US-395	12.67	5	121	80	$1.143 < \lambda_b/\lambda_a < 2.010$
SR-604	15.69	1	161	127	$1.005 < \lambda_b/\lambda_a < 1.601$
SR-160	5.34	1	38	65	$0.390 < \lambda_b/\lambda_a < 0.868$
Poisson's means hypothesis testing for facilities treated with CSRS in 1999-2000					
Facility	**CL Miles**	**#Segments**	**#Crashes 'before'(4yrs)**	**#Crashes 'after'(3yrs)**	**λ_b/λ_a Confidence Interval**
I-80		2	25	6	$1.356 < \lambda_b/\lambda_a < 8.066$
US-93		3	55	25	$1.039 < \lambda_b/\lambda_a < 2.675$
SR-766		3	9	0	$2.406 < \lambda_b/\lambda_a < 14133$
Poisson's means hypothesis testing for facilities treated with CSRS in 2000					
Facility	**CL Miles**	**#Segments**	**#Crashes 'before'(5yrs)**	**#Crashes 'after'(3yrs)**	**λ_b/λ_a Confidence Interval**
SR-227		1	32	8	$1.153 < \lambda_b/\lambda_a < 5.438$
Poisson's means hypothesis testing for facilities treated with CSRS in 2000-2001					
Facility	**CL Miles**	**#Segments**	**#Crashes 'before'(5yrs)**	**#Crashes 'after'(2yrs)**	**λ_b/λ_a Confidence Interval**
I-80	114.86	55	318	71	$1.392 < \lambda_b/\lambda_a < 2.329$
Poisson's means hypothesis testing for facilities treated with CSRS in 2001-2002					
Facility	**CL Miles**	**#Segments**	**#Crashes 'before'(6yrs)**	**#Crashes 'after'(1yrs)**	**λ_b/λ_a Confidence Interval**
US-95A	19.32	1	42	1	$1.442 < \lambda_b/\lambda_a < 65.949$

6.0 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

6.1 Summary

A high number of single-vehicle ran-off-roadway crashes had been recorded in Nevada since the early 1990s. In order to address this problem, the NDOT constructed continuous shoulder rumble strips over the past decade. The research efforts presented in this report summarize the evaluation of the effectiveness of continuous shoulder rumble strips in reducing such crashes in Nevada.

The research used single-vehicle ran-off-roadway crashes as indicators of safety experience on roadways in Nevada on which continuous shoulder rumble strips had been installed. The roadways studied included Interstate freeways, US routes, and state routes. The roadways were broken into individual segments for analyses - 306 individual segments corresponding to a total of 1,303 centerline miles of roadways. Data and results for such segments were aggregated to evaluate sections or roadways (routes). The aggregation of information for various routes within a roadway functional class (or type) yielded the information for that particular roadway class (or type). Data for the period from 1995 to 2003 were used for the analyses. Crash records in Nevada for this period included over 33,000 ran-off-roadway single-vehicle crashes of which 772 were fatal crashes, and 11,976 were injury crashes.

The crash frequency and rates of single-vehicle ran-off-roadway crashes were determined for periods "before-after" the installation of the continuous shoulder rumble strips. Descriptive analyses, as well as, statistical analyses were used to evaluate the effectiveness of the continuous shoulder rumble strips treatment. The descriptive analyses include comparisons of crash rates based on crash frequency, rate, and density. Simple linear regression models were developed in the analysis. The statistical analyses include Ezra Hauer's Comparison Group Method and Cox's Method of a Comparison of Poisson Means. Table 51 summarizes the results obtained from the above mentioned statistical analyses methods i.e. Ezra Hauer's Comparison Group Method and Cox's Method of a Comparison of Poisson Means.

Table 51: Summary of Statistical Analysis Methods Results

Facility	Statistical Analysis Method											
	Ezra Hauer Comparison Group Method						Poisson's Means Method					
	I-15	I-80	US-95	US-93	US-50	Others	I-15	I-80	US-95	US-93	US-50	Others
Number of Segments	61	64	47	6	11	9	61	149	48	9	11	12
No Significant Change	31	30	10	2	8	1	10	28	10	3	7	4
Significant Decrease	13	14	15	2	2	4	15	64	25	2	2	5
Highly Significant Decrease	17	20	22	2	1	4	36	57	13	4	2	3

6.2 Conclusions

The results of the study indicated that, overall, the continuous shoulder rumble strip treatment had been effective in reducing single-vehicle ran-off-roadway crashes and their corresponding crash rates. Improvement was shown in 68 percent of the individual roadway segments based on crashes, and these segments accounted for 83 percent of the centerline miles of the roadways. Likewise 11 percent of the segments (4 percent of centerline miles) showed no change in crash rates, and 21 percent of the segments (14 percent of the centerline miles) showed worse crash rates. The results, based on crash rates, were similar: 66 percent of the segments (81 percent of centerline miles) showed improvement, 12 percent of the segments (4 percent of centerline miles) showed no change and 23 percent of the segments (15 percent of centerline miles) experienced higher rates after the installation of rumble strips. The Interstate routes observed experienced lower crash rates as compared to the US routes and state routes.

Linear regression models developed to relate the crash rates during the "before" period to those during the "after" period clearly indicated that for any given crash rate the predicted "after" crash rate was lower. Though not clearly established, the models developed suggested a reduction in the crash rates with higher values of average daily traffic, wider shoulders, and higher speeds. Roadways with posted speed limits greater than 65 miles/hour (105 kilometers/hour) showed significant improvements after the installation of continuous shoulder rumble strips (based on crash density and crash rate). As the posted speed limit increased, the crash rates decreased. Statistical analyses of the data strongly supported the finding that the deployment of continuous shoulder rumble strips has been effective in reducing the single-vehicle ran-off-roadway crashes especially on high speed highways.

An application of Ezra Hauer's Comparison Group Method showed that the installation of continuous shoulder rumble strips resulted in significant reductions and, in several cases highly significant reductions, in the expected number of crashes on a vast majority of the roadways studied. These results showed that the rumble strips were effective in reducing the rates of single-vehicle crashes with an overall "index of effectiveness" of 0.702 (a value less than 1.0 indicated improvement). The use of this method resulted in the index of effectiveness for Interstates I-15 and I -80 to be 0.863 and 0.717 respectively. The index for US-95 and US-93 were 0.646 and 0.657 respectively. However, SR-160 had a worse crash rate even after the continuous shoulder rumble strip treatment. This result needs to be used with caution because of various extenuating circumstances related to traffic operations on SR-160 during the study period. At a disaggregate level, most of the individual segments had an index of effectiveness of less than one in the comparison group analysis proving the effectiveness of rumble strips. Cox's method of Comparing Poisson means also served as proof of the effectiveness of the rumble strips in reducing the crash rates on all roadways with the exception of SR-160.

6.3 Recommendations

This study focused on single-vehicle ran-off-roadway crashes using data obtained from crash records maintained by the NDOT. The study did not examine individual crash reports. An examination of individual crash reports could yield additional information that may be valuable to such analyses. For example, it could help identify details of crashes such as causal and contributing factors, information regarding on which side the vehicle left the roadway, and if the driver over corrected and returned to the travel lane before departing the roadway again). While the research efforts identified the need to evaluate the impacts of geometric design, such as horizontal and vertical alignments, these were beyond the scope of the present study. Performing these analyses could help shed further light on the effectiveness of continuous shoulder rumble strips treatments in reducing single-vehicle ran-off-roadway crashes. The study only considered shoulder rumble strips on the right side of the roadway. Additional efforts to evaluate centerline rumble strips and rumble strips on the left side of the road on freeways were suggested. Since only milled rumble strips were used in Nevada, it was the only type of rumble strips evaluated. These results could be compared with results for other types of rumble strips. The comparison group method used compared only the crash rates for equal “before-after” periods. Other methods suggested by Hauer could also be explored to compare data of unequal durations.

In general, the installation of continuous shoulder rumble strips on roadways in Nevada resulted in improved safety in terms of reduced number of single-vehicle ran-off-roadway crashes, crash frequency, rate, and density. The outcomes of this research will assist system managers in Nevada and nationwide to better understand the effectiveness of continuous shoulder rumble strips in reducing “ran-off-roadway” single-vehicle crashes, and identify opportunities for applications of these rumble strips.

Clearly, it is recommended that NDOT utilize continuous shoulder rumble strips whenever practical. Additionally, the use of wider shoulders with and without rumble strips is recommended. Other recommendations for NDOT to consider include: 1) examining individual crash reports to assess whether there is a tendency for drivers to over correct, 2) evaluating whether there is a relationship between geometric features, i.e. horizontal and vertical alignments, 3) examining the effectiveness of centerline rumble strips and rumble strips on the left shoulders of divided highways, and 4) comparing the results of this study on milled rumble strips against other types of rumble strips.

REFERENCES

1. Annino, Julie. Rumble Strips in Connecticut-A Before/After Analysis of Safety Benefits. Report No. CT-902-F-04-3, Final Report, Connecticut Department of Transportation, 2003.

2. Bucko, T. R. and Ahmed Khorashadi. Evaluation of Milled-In Rumble Strips, Rolled-In Rumble Strips, and Audible Edge Stripe. California Department of Transportation, May 2001.

3. Chaudoin, J. H. and G. Nelson. Interstate Routes 15 and 40 Shoulder Rumble Strips. Caltrans-08-85-1, Traffic Operations Branch – District 8, California Department of Transportation, August 1985.

4. Chen. A Study of Effectiveness of Various Shoulder Rumble Strips on Highway Safety. Virginia Department of Transportation, 1994.

5. Cheng, Eric, et al. Application and Evaluation of Rumble Strips on Highways. Utah Department of Transportation, August 1993.
   Online posting. http://safety.fhwa.dot.gov/roadway_dept/rumble/synthesis/exec_summary.htm.

6. Cheng, Eric, et al. Application and Evaluation of Rumble Strips on Highways. Utah Department of Transportation, August 2000.
   Online posting. http://safety.fhwa.dot.gov/rumblestrips/resources/chengite.htm.

7. Cox, D. R. Some Simple Approximate Tests for Poisson Variates. Biometrika, Vol. 40, No. 3/4, PP. 354 – 360, 1953.

8. Elefteriadou, Lily. et al. Bicycle-Tolerable Shoulder Rumble Strips. Final Report, Pennsylvania Department of Transportation, March 2000.

9. Griffith, Michael. Safety Evaluation of Rolled-in Continuous Shoulder Rumble Strips Installed on Freeways: Statistical Methods in Transportation and Safety Data Analysis for Highway Geometry, Design, and Operations. Transportation Research Record, No.1665, PP. 28-34, October 1999.

10. Hauer, Ezra.. Observational Before-After Studies in Road Safety. Elsevier Science Ltd., 1997.

11. Hickey Jr., John. Shoulder Rumble Strips Effectiveness: Drift-Off-Road Accident Reductions on the Pennsylvania Turnpike. Transportation Research Record, No. 1573, PP. 105-109, 1997.

12. Higgins, J. S. and W. Barbel. Rumble Strip Noise. Transportation Research Record, No. 983, PP 27-36, 1984.

13. Hirasawa et al. Developing Optimal Centerline Rumble Strips and Evaluating Their Safety Benefits on National Highways in Hokkaido, Japan. (Preprint), Transportation Research Board Annual Meeting, January 2005.
    Online posting. http://www.mdt.mt.gov/research/docs/trb_cd/Files/06-1968.pdf.

14. Khan, A. and A. Bacchus. Bicycle Use of Highway Shoulders. Transportation Research Record, No. 1502, PP. 8-21, 1995.

15. Khan, A. and A. Bacchus. Economic Feasibility and Related Issues of Highway Shoulder Rumble Strips. Transportation Research Record, No. 1498, PP. 92-101, 1995.

16. Ligon, C. M., E. C. Carter, D. B. Joost, and W. F. Wolman. Effects of Shoulder Texture Treatments on Safety. Federal Highway Administration, US Department of Transportation, Report No. FHWA/RD-85/027, May 1985.

17. Marvin & Associates. An Evaluation of Shoulder Rumble Strips in Montana. Montana Department of Transportation, March 2003.

18. Moeur, R.. Analysis of Gap Patterns in Longitudinal Rumble Strips to Accommodate Bicycle Travel. Transportation Research Record, No. 1705, Pedestrian and Bicycle Transportation Research, PP. 93-98, 2000.

19. Morgan, Rick and Dan McAuliffe. Effectiveness of Shoulder Rumble Strips: A Survey of Current Practice. New York State, Department of Transportation, Special Report 127, September 1997.
Online posting. http://safety.fhwa.dot.gov/roadway_dept/rumble/states/state_ny.htm

20. Noyce, David and Elango Vetri. Safety Evaluation of Centerline Rumble Strips: A Crash and Driver Behavior Analysis. Transportation Research Board Annual Meeting, 2004.

21. Outcalt, William. Bicycle-Friendly Rumble Strips. Colorado Department of Transportation, Report No. CDOT-DTD-R-2001-4, May 2001.

22. Perrillo, Kerry. The Effectiveness and Use of Continuous Shoulder Rumble Strips.
Online Library, Federal Highway Administration, August 1998.

23. Unknown. Rumble Strips Alert Drivers, Save Lives, and Money: Research Pays off. Transportation News, PP 20-21, March – April 1988.

24. Unknown. Facts, Statistics and Data. Federal Highway Administration, US Department of Transportation, Safety Section, 2002 (accessed in November 2006).
Online: http://fhwa.dot.gov/safety.pdf

25. Spring, Gary. Rumble Strips in Missouri. Missouri Department of Transportation, University of Missouri, Rolla, RDT 03-007, July 2003.

26. Taylor, Harry and Leonard Meczkowski. Safer Roadsides. Public Roads, Vol. 66, No.4, Jan-Feb 2003.

27. Walton. S and E. Meyer. The Effect of Rumble Strip Configuration on Sound and Vibration Level. ITE Journal, Vol. 72, Issue 12, PP 28 – 32, 2002.

28. Wood, Neal.. Shoulder Rumble Strips: A Method to Alert Drifting Drivers. Pennsylvania Turnpike Commission, January 1994.
Online posting. http://safety.fhwa.dot.gov/roadway_dept/docs/shoulderdrift.pdf.

29. Wood, Neal.. Rumble Strip Simulation Model Developed and Evaluated, September, 2006.
Online posting. http://safety.fhwa.dot.gov/roadway_dept/docs/shoulderdrift.pdf.

APPENDICES

APPENDIX 1

1.1. Computation of Safety Indicators

A comparison of the number of crashes during the period "before-after" continuous shoulder rumble strip treatment was a good indicator of the effectiveness. The 9-year study period was sufficient to provide high potential for change in key factors that might have direct or indirect influence in the rise / decline in the crash rate experience. However, considering just the number of crashes during the two periods of analysis can bias factors like average daily traffic (ADT) in which "change with time" was not considered. Estimates of the average daily traffic or annual average daily traffic were good indicators of "exposure" for determining crash rates. Thus, ADT was used to first determine vehicular travel on individual segments. This travel in million vehicle miles of travel (MVMT) was then divided into the crash frequency to compute the crash rate in crashes/MVMT. The vehicular travel on each segment was computed as the product of the average daily traffic and the centerline length of the roadway segment. Hence, to account for a variety of factors, which might have a bearing on the increase/reduction of the number of crashes; the analyses were carried out based on three indicators of safety for each segment, namely:

- Crash frequency in Crashes/Year
- Crash rate in Crashes/Million Vehicle Miles of Travel
- Crash density in Crashes/Mile/Year

1.2 Computation of Crash Frequency

The simplest of the aforementioned safety indicators was the crash frequency. This frequency was computed by dividing the total number of crashes recorded on each segment during the "before-after" period by their respective duration expressed in years. It was computed using the following equations:

$$Crashes/Year_{\,before} = \sum C_{ij\,before} / P_{i\,before}$$

$$Crashes/Year_{after} = \sum C_{ij\ after} / P_{i\ after}$$

Where

$C_{ij\ before}$ = Total number of crashes recorded on segment *i* in year j during the "before" period

$C_{ij\ after}$ = Total number of crashes recorded on segment *i* in year j during the "after" period

$P_{i\ before}$ = duration of the "before" period of segment *i* in years

$P_{i\ after}$ = duration of the "after" period of segment *i* in years

The computation of single-vehicle ran-off-roadway frequency was illustrated using the following example. Consider a 6.09 mile segment on I-15 north bound (segment code given 1007). The construction period lasted for 56 calendar days with January 4, 1999, as the start date and March 1, 1999, as the end date of construction. The single-vehicle ran-off-roadway crashes recorded on this segment were shown in Table A.

Table 52: Single-Vehicle Ran-off-roadway Crashes on Segment 1007 (I-15 northbound)

Year	1995	1996	1997	1998	1999_{before}	1999_{after}	2000	2001	2002	2003
# Crashes	2	4	3	6	0	2	3	2	6	5

$\sum C_{i\ before}$ = $\Sigma_j C_{1007,\ j}$ = 2+4+3+6+0 = 15

$\sum C_{i\ after}$ = $\Sigma_j C_{1007,\ j}$ = 2+3+2+6+5 = 18

$P_{i\ before}$ = 4.011 years

$P_{i\ after}$ = 4.836 years

$Crashes/Year_{before}$ = 15 / 4.011 = **3.740** SV ROR Crashes/Year

$Crashes/Year_{after}$ = 18 / 4.836 = **3.722** SV ROR Crashes/Year

% change = 100* ($Crash\ Rate_{before}$ - $Crash\ Rate_{after}$) / $Crash\ Rate_{before}$

% change = 100* (3.740 – 3.722) / 3.740

= 0.465 %

The analysis indicated that this section of roadway had seen a nominal improvement in terms of crash frequency after the treatment with continuous shoulder rumble strips.

The aggregation of individual segments led to sections, and likewise roadways, that were made up of sections. In order to compute the single-vehicle ran-off-roadway crash frequency on each section or roadway (facility), the total number of crashes on the facility and the average "before-after" periods were computed. The total number of crashes on each facility was obtained by the simple addition of the number of crashes on each constituent segment. Since different roadway segments have different construction periods, it was implied that the "before-after" periods were also different for many of these roadway segments. In order to compute the crash rate in terms of crashes/year, a weighted average of the "before-after" period was computed separately as described next:

Average "before" period (P_{before}) $= \sum L_i * P_{i\ before} / \sum L_i$

Where

L_i is the length of each segment

P_i is the "before" period of each segment

A similar computation was used to obtain the average "after" period (P_a). The crashes/year for each facility was computed as follows:

$$\text{Crashes/Year}_{\text{before}} = \Sigma_i \Sigma_j C_{ij\ before} / P_{before}$$

$$\text{Crashes/Year}_{\text{after}} = \Sigma_i \Sigma_j C_{ij\ after} / P_{after}$$

1.3 Computation of Crash Rate

The safety indicator in terms of crash rate was the ratio of the number of crashes/MVMT on a segment. The MVMT on a segment was estimated as a function of the ADT on the segment and the segment's length. The following equation was used to estimate MVMT on a segment:

$$MVMT_{ij} = ADT_{ij}*365*L_j / 1,000,000$$

Where

$MVMT_{ij}$ is the MVMT of segment i during year j

ADT_{ij} is the ADT of segment i during year j

L_i is the length of segment i *(in miles)*

If year j was the roadway section that was treated with rumble strips, then a *modified million vehicle miles of travel* was computed using the non-construction days during that year. The modified MVMT was given by:

$$Modified\ MVMT_{ij} = ADT_{ij} * (non\text{-}construction\ period\ in\ days) * L_j / 1{,}000{,}000$$

The modified MVMT was computed separately using data for the "before-after" periods and using the "before" and "after" non-construction days during the year of construction. The crash rate on the segment during the "before-after" period was then computed using the following equation:

$$\text{Crash Rate}_{before} = \Sigma_j \# C_{j\ before} / \Sigma MVMT_j$$

$$\text{Crash Rate}_{after} = \Sigma_j \# C_{j\ after} / \Sigma MVMT_j$$

Where C_j is the number of crashes during year j

Similarly the crash rates for each facility was computed as per the following equation

$$\text{Crash Rate}_{before} = \Sigma_i \Sigma_j \# C_{ij\ before} / \Sigma_i \Sigma_j MVMT_{ij}$$

$$\text{Crash Rate}_{after} = \Sigma_i \Sigma_j \# C_{ij\ after} / \Sigma_i \Sigma_j MVMT_{ij}$$

Where

C_{ij} is the number of crashes on segment i during year j

$MVMT_{ij}$ is the MVMT of segment i during year j

The crash rates for both "before-after" periods were computed and the percent change in the crash rate was computed to estimate the effectiveness of the continuous rumble strips. The MVMT, frequency, and crash rate calculated were illustrated as follows: Consider the same 6.09 mile long roadway segment on the I-15 north bound (segment code given 1007) as in the previous illustration. The construction period lasted for 56 calendar days with January 4, 1999, as start date and March 1, 1999, as end date of construction. The ADT, MVMT, and the frequency of crashes on the segment during the study period are shown in Table B.

Table 53: ADT, MVMT and SV ROR Crashes on Segment 1007 (I-15 northbound)

Year	1995	1996	1997	1998	1999_{before}	1999_{after}	2000	2001	2002	2003
ADT	13,595	13,275	13,945	14,975	15,790	15,790	16,700	17,880	18,600	18,100
MVMT	30.210	29.500	30.990	33.280	0.385	29.320	37.120	39.740	41.340	40.230
# Crashes	2	4	3	6	0	2	3	2	6	5

MVMT for the year 1995 was computed as follows:

$$MVMT_{1007,\ 1995} = 13{,}595*365*6.09/1{,}000{,}000 = 30.21$$

Similarly, the MVMT value for each year was computed as follows:

MVMT for the "before" period (4 days) during the year 1999 was given by

$$MVMT_{\ 1007,\ 1999\ before} = 15790*4*6.09/1{,}000{,}000 = 0.385$$

MVMT for the "after" period (305 days) during the year 1999 was given by

$$MVMT_{\ 1007,\ 1999\ after} = 15790*305*6.09/1{,}000{,}000 = 29.320$$

Frequency of crashes during "before" period (1995 – 1999) was given by

$$C_{1007\ before} = \Sigma C_{1007,\ j} = 2+4+3+6+0 = 15$$

$$C_{1007\ after} = \Sigma C_{1007,\ j} = 2+3+2+6+5 = 18$$

$$MVMT_{before} = \Sigma MVMT_{ij\ before} = 30.21+29.5+30.99+33.28+0.385 = 124.365$$

$$MVMT_{after} = \Sigma MVMT_{ij\ after} = 29.32+37.12+39.74+41.34+40.23 = 187.750$$

$$Crash\ Rate_{\ before} = \Sigma\ \#\ C_{ij\ before} / \Sigma MVMT_{ij\ before}$$

$$= 15/124.365 = \mathbf{0.121}\ SV\ ROR\ Crashes/MVMT$$

$$Crash\ Rate_{\ after} = \Sigma\ \#\ C_{ij\ after} / \Sigma MVMT_{ij\ after}$$

$$= 18/187.750 = \mathbf{0.096}\ SV\ ROR\ Crashes/MVMT$$

The percent change in crash rate was computed as follows:

$\% \text{ Change} = 100 * (\textit{Crash Rate}_{before} - \textit{Crash Rate}_{after}) / \textit{Crash Rate}_{before}$

$\% \text{ change} = 100 * (0.121 – 0.096) / 0.121 = 20.66\ \%$

After the treatment of this section of I-15 N with continuous shoulder rumble strips the crash rate for single-vehicle ran-off-roadway crashes has seen a 20.66 percent reduction in the crash rate.

1.4 Computation of Crash Density

The crash density safety indicator was computed as the crashes/year divided by the length of each segment. To compute the crash density for each facility as a single unit, the following expression was used:

$\text{Crashes/Mile/Year}_{\text{before}} = \Sigma_i \Sigma_j C_{ij\ before} / (\sum L_i * P_{i\ before})$

Where

C_{ij} = Number of crashes of segment i in year j

L_i = Length of segment i

$P_{i\ \text{“before”}}$ = “Before” period of analysis of segment i

APPENDIX 2

2.1 Ezra Hauer's Comparison Group Method

A sample calculation was illustrated for a roadway segment on I-80 eastbound. This roadway segment was treated with continuous shoulder rumble strips in the year 1999. A 10.02 mile long roadway segment on I-80 east was used as the 'comparison group' to estimate the 'index effectiveness' of this section of roadway. The crash data for this segment are shown in Table C.

Table 54: Sample Calculation for the Comparison Group Method of Analysis

	#Crashes during each year								(M) #Crashes 'Before'	(N) #Crashes 'After'
	1995	1996	1997	1998	2000	2001	2002	2003		
Treatment Group	10	7	10	9	3	11	5	2	36	21
Comparison Group	6	10	8	6	11	10	9	2	30	32
	"before" CSRS treatment				"after" CSRS treatment					

The analysis of the data presented in Table C follows.

#crashes for the comparison group during "after" period (N) = 32

#crashes for the comparison group during "before" period (M) = 30

Comparison ratio (r_c) = (N/M)/ (1+1/M)

= (32/30)/(1+1/30)

= 1.032

Expected # crashes on the treatment group had the roadway segment not been treated with rumble strips = (λ) x r_c

= 36 x 1.032

= 37.152

Thus, according to the 'comparison group' method, there would have been at least 37 crashes in 4 years if the roadway section was not treated with rumble strips.

The index of effectiveness (θ) = λ/π

= 21/31.152

= 0.565 (< 1)

As the index of effectiveness (θ) was less than one, it can be stated that the treatment of this section of I-80 with continuous shoulder rumble strips was effective in reducing the ran-off-roadway single-vehicle crashes.

<u>2.2 Comparison of Poisson's Means</u>

As an example, consider a 3.3 mile long roadway segment (segment code 1016) of northbound Interstate 15. Rumble strips were installed in the year 1999 on this roadway segment. Four years of crash data were available for each of the "before" and "after" periods.

$t_1 = t_2 = 4$

Number of Crashes before treatment $n_1 = 28$

Number of Crashes before treatment $n_2 = 9$

Degree of Freedom1 (DF_1) = $(2n_1+1) = 57$

Degree of Freedom 2 (DF_2) = $(2n_2+1) = 19$

$F = [t_1 (n_2 + 1/2) \lambda_1] / [t_2 (n_1 + 1/2)\lambda_2] = 0.3333$

For a 95% confidence interval (from the standard F-table),

FL = 0.506

FU = 2.276

$t_2 (n_2 + 1/2) \lambda_1 / t_1 (n_1 + 1/2)\lambda_2(FL) < \lambda_1/\lambda_2 < t_2 (n_2 + 1/2) \lambda_1 / t_1 (n_1 + 1/2)\lambda_2(FU)$

➔ $1.518 < \lambda_1/\lambda_2 < 6.829$

Since the ratio of the Poisson's means of the number of crashes before and after the installation of rumble strips was greater than one, the reduction in the number of crashes on this section of roadway was statistically significant. The data and methods presented in this section were used to evaluate the effectiveness of the continuous shoulder rumble strips treatment.

Jim Gibbons, Governor
Susan Martinovich, P.E. Director
Prepared by Research Division
Tie He, Research Division Chief
(775) 888-7803
the@dot.state.nv.us
Nevada Department of Transportation
1263 S. Stewart Street
Carson City, Nevada 89712