MT Committee

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Please see attached National Highway research on centerline and shoulder rumble strips.

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NCHRP

REPORT 641

NATIONAL
COOPERATIVE
HIGHWAY
RESEARCH
PROGRAM

Guidance for the Design and Application of Shoulder and Centerline Rumble Strips

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

N A T I O N A L   C O O P E R A T I V E   H I G H W A Y   R E S E A R C H   P R O G R A M

NCHRP REPORT 641

Guidance for the Design and Application of Shoulder and Centerline Rumble Strips

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Academies was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

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COOPERATIVE RESEARCH PROGRAMS

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FOREWORD

By Charles W. Niessner
Staff Officer
Transportation Research Board

This report provides guidance for the design and application of shoulder and centerline rumble strips as an effective crash reduction measure, while minimizing adverse effects for motorcyclists, bicyclists, and nearby residents. Using the results of previous studies and the research conducted under this project, safety effectiveness estimates were developed for shoulder rumble strips on rural freeways and rural two-lane roads and for centerline rumble strips on rural and urban two-lane roads. The report will be of particular interest to safety practitioners with responsibility for roadway design.

Shoulder rumble strips have demonstrated effectiveness in reducing lane-departure crashes on rural freeways. Because they have proven to be cost-effective countermeasures, state departments of transportation and local agencies want to expand the use of rumble strips along the shoulders of divided and undivided highways and along the centerline of undivided highways including two-lane roadways. However, installing rumble strips to reduce run-off-the-road or centerline crossover crashes, with no consideration of impacts to other users, may lead to unintended outcomes.

Some of the unresolved issues with installing either shoulder or centerline rumble strips include:

- Minimum dimensions of the rumble strips necessary for effective vehicular warning with least potential for adverse effects;
- Optimal placement, including minimum criteria for lane and shoulder widths;
- Optimal longitudinal gaps in rumble strips to provide accessibility for bicyclists while maintaining the effectiveness in reducing lane departures;
- Effectiveness and alternative designs for various speeds;
- Physical design of rumble strips with respect to "rideability" for motorcyclists and bicyclists; and
- Noise produced by rumble strips on adjacent residents.

The shoulders of the highway system are a diverse environment, with usage by bicyclists, pedestrians, mail carriers, school buses, and farm vehicles. There is great variability in shoulder widths, materials, and pavement depths, making uniform application difficult. The optimal placement of the rumble strips in relation to the edgeline is also in question. Further, shoulders are used for lane shifts during construction and maintenance operations, requiring vehicles to drive over the rumble strips which may result in driver discomfort and potential operational problems.

Although information is limited, there is evidence that centerline rumble strips are an effective countermeasure for reducing centerline crossover collisions. However, centerline rumble strips raise concerns regarding pavement durability at centerline joints, their use in passing zones, and their impact on motorcyclists.

Under NCHRP Project 17-32, "Guidance for the Design and Application of Shoulder and Centerline Rumble Strips," the research team led by Midwest Research Institute (MRI) investigated the (a) safety effectiveness of shoulder rumble strips on different types of roads, (b) optimal placement of shoulder rumble strips with respect to the edgeline, (c) optimal dimensions of shoulder rumble strips necessary for effective vehicular warning with least potential adverse effects, and (d) minimum level of stimuli necessary to alert a drowsy or inattentive driver. MRI also investigated the safety effectiveness of centerline rumble strips on different types of roads, for varying roadway geometry, and in combination with shoulder rumble strips.

The report includes estimates of the safety effectiveness of shoulder and centerline rumble strips, recommends the placement of shoulder rumble strips with respect to the edgeline, recommends sound level differences in the passenger compartment to alert drivers, and provides equations for determining rumble strip dimensions for a range of operating conditions.

CONTENTS

SUMMARY

Guidance for the Design and Application of Shoulder and Centerline Rumble Strips

The primary objective of this research was to develop guidance for the design and application of shoulder and centerline rumble strips as an effective motor vehicle crash reduction measure, while minimizing adverse effects for motorcyclists, bicyclists, and nearby residents. The focus of the research was on (1) summarizing previous research and existing policies on the design and application of shoulder and centerline rumble strips, (2) quantifying the safety effectiveness of shoulder rumble strips on different roadway types, (3) providing guidance on the safety effectiveness of shoulder rumble strips placed in varying locations with respect to the edgeline, (4) quantifying the safety effectiveness of centerline rumble strips on different roadway types, (5) quantifying the safety effectiveness of centerline rumble strips along varying roadway geometry, and (6) developing statistical models for predicting noise levels within the passenger compartment of a vehicle for use in designing rumble strip patterns. There are several shoulder and centerline rumble strip design and application guidelines that can be developed based on converging findings from the existing literature and results from this research.

Shoulder rumble strips may be considered for implementation on a range of roadway types, including urban and rural freeways, on- and off-ramps, multilane divided highways, multilane undivided highways, and two-lane roads. Criteria that may be considered for determining whether implementation is appropriate include shoulder width, lateral clearance, traffic volume, bicycles, pavement type, pavement depth, area type, speed limit, and crash experience. The most reliable and comprehensive estimates to date of the safety effectiveness of shoulder rumble strips are for freeways and rural two-lane roads. The safety effectiveness estimates for shoulder rumble strips and the standard errors (SE) for the estimates are the following:

Urban/Rural Freeways

- Rolled shoulder rumble strips [based on results from Griffith (*1*)]:
  - 18 percent reduction in single-vehicle run-off-road (SVROR) crashes (SE = 7) and
  - 13 percent reduction in SVROR fatal and injury (FI) crashes (SE = 12).

Rural Freeways

- Shoulder rumble strips [based on combined results from this research and Griffith (*1*)]:
  - 11 percent reduction in SVROR crashes (SE = 6) and
  - 16 percent reduction in SVROR FI crashes (SE = 8).

Rural Two-Lane Roads

- Shoulder rumble strips [based on results from this research and Patel et al. (*2*)]:
  - 15 percent reduction in SVROR crashes (SE = 7) and
  - 29 percent reduction in SVROR FI crashes (SE = 9)

Estimates on the safety effectiveness of shoulder rumble strips along rural multilane divided highways are also available but are not considered as reliable as the estimates for freeways and rural two-lane roads. The safety estimates for rural multilane divided highway are as follows:

Rural Multilane Divided Highways

- Shoulder rumble strips [based on results from Carrasco et al. (*3*)]:
  - 22 percent reduction in SVROR crashes and
  - 51 percent reduction in SVROR FI crashes.

The lack of reliable estimates on the safety effectiveness of shoulder rumble strips along other roadway types does not indicate that shoulder rumble strips are ineffective on these roadway types. Rather, their safety effects are not known at this time.

Transportation agencies specify different offset distances from the edgeline to install shoulder rumble strips. The safety evaluation performed during this research found statistically significant evidence that on rural freeways, rumble strips placed closer to the edgeline are more effective in reducing SVROR FI crashes compared to rumble strips placed further from the edgeline. Therefore, for rural freeways, it is recommended that shoulder rumble strips be placed as close to the edgeline as possible, taking into consideration other factors such as pavement joints. For other roadway types, such as rural two-lane roads, there is no statistically significant evidence to indicate that offset distance influences the safety effectiveness of shoulder rumble strips. Therefore, based strictly on safety, there is no current basis for recommending that transportation agencies change their current policies concerning the placement of shoulder rumble strips with respect to the edgeline on these other roadway types.

Centerline rumble strips may be considered for implementation on a range of roadway types, including urban and rural multilane undivided highways and rural two-lane roads. Criteria that may be considered for determining whether implementation is appropriate include lane width, traffic volume, pavement depth, area type, speed limit, and crash experience. The most reliable and comprehensive estimates to date on the safety effectiveness of centerline rumble strips are for those installed on urban and rural two-lane roads. The safety effectiveness estimates for milled centerline rumble strips and the standard errors for the estimates are as follows:

Urban Two-Lane Roads

- Centerline rumble strips (based on results from this research):
  - 40 percent reduction in total (TOT) target crashes (SE = 17) and
  - 64 percent reduction in FI target crashes (SE = 27).

Rural Two-Lane Roads

- Centerline rumble strips [based on combined results from this research and Persaud et al. (*4*)]:
  - 9 percent reduction in TOT crashes (SE = 2),
  - 12 percent reduction in FI crashes (SE = 3),
  - 30 percent reduction in TOT target crashes (SE = 5), and
  - 44 percent reduction in FI target crashes (SE = 6) (based on results from this research).

Target crashes are defined as head-on and opposite-direction sideswipe crashes.

Similar to shoulder rumble strips, the lack of reliable estimates on the safety effectiveness of centerline rumble strips along other roadway types does not indicate that centerline rumble strips are ineffective on these roadway types. Rather, their safety effects are not known at this time.

Prior to this research, it was not known whether the same safety benefits of centerline rumble strips should be expected along different roadway alignments. Results of this research show that the expected reductions in crashes due to the installation of centerline rumble strips on horizontal curves and tangents are very similar. Thus, it is concluded that the safety effectiveness of centerline rumble strips is for practical purposes the same for both curved and tangent alignments.

It is difficult to specify optimal dimensions of shoulder and centerline rumble strips because fundamental research has not been conducted on the stimuli levels necessary to alert inattentive, distracted, drowsy, or fatigued drivers. Based upon a review of previous research and existing practices, it is recommended that for roadways where bicyclists are not expected (e.g., freeways) that rumble strip patterns should be designed to produce sound level differences in the range of 10 to 15 dBA in the passenger compartment; on roadways where bicyclists can be expected or near residential or urban areas, rumble strip patterns should be designed to produce sound level differences in the range of 6 to 12 dBA in the passenger compartment. Several statistical models were developed as part of this research that predict the sound level difference in the passenger compartment when traversing rumble strips. Transportation agencies can utilize these models to develop rumble strip patterns for use on a range of roadway types and operating conditions. The independent variables of the predictive models include the four primary rumble strip dimensions (i.e., length, width, depth, and spacing), vehicle speed, angle of departure, pavement type (asphalt or concrete), pavement condition (wet or dry), rumble strip type (milled or rolled), and location (shoulder or centerline). In situations where it is desirable to provide more lateral clearance for bicyclists or for installing shoulder rumble strips on roads with very narrow shoulders, the predictive models indicate that rumble strips can be designed with relatively narrow lengths (e.g., 6 in. [152 mm]) and still generate the desired sound level differences of 6 to 12 dBA in the passenger compartment.

Further guidance is provided in the main text of the report concerning the design and application of shoulder and centerline rumble strips.

SECTION 1

Introduction

Background

To address the problem of single-vehicle run-off-road (SVROR) crashes, many transportation agencies use shoulder rumble strips to alert inattentive or drowsy motorists that their vehicles have drifted out of the travel lane. As motor vehicle tires pass over the rumble strips, the drifting motorists receive auditory and tactile warnings to correct their path of steering. Due to the expected safety benefits of shoulder rumble strips and their relatively low installation cost, transportation agencies are applying shoulder rumble strips on a widespread basis. Originally, rumble strips were installed primarily on rural freeways, but now transportation agencies are installing shoulder rumble strips along divided and undivided highways in both rural and urban areas, including along rural and urban two-lane roads.

The expected safety benefit of shoulder rumble strips has prompted transportation agencies to expand their application of rumble strips to include installations along the centerlines of undivided highways. The primary purpose of centerline rumble strips is to reduce head-on crashes, opposite-direction sideswipe crashes, and to some degree SVROR-to-the-left crashes; however, installing rumble strips either along the shoulder or on centerline, without considering the impacts on other highway users, may lead to unintended consequences.

In Section 5103 of the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU), enacted in August 2005, Congress recognized that Federally sponsored surface transportation research indicates that rumble strips improve safety. As such, Section 1401 of SAFETEA-LU lists the installation of rumble strips as a type of safety project that may be carried out under the provisions of a highway safety improvement program.

A significant amount of research has been conducted on shoulder rumble strips and a lesser amount on centerline rumble strips. However, there remain a number of key unresolved issues related to the design, placement, and unintended effects of shoulder and centerline rumble strips. This report presents results from the entire research effort to address key unresolved issues associated with shoulder and centerline rumble strips.

Research Objective and Scope

The primary objective of this research is to develop further guidance for the design and application of shoulder and centerline rumble strips as an effective motor vehicle crash reduction measure, while minimizing adverse effects for motorcyclists, bicyclists, and nearby residents. Guidance on the appropriate application of rumble strips on undivided and divided highways in both urban and rural areas is provided. This research focuses on addressing several key unresolved issues associated with shoulder and centerline rumble strips.

This research was conducted in three phases. The scope of Phase I was to develop a list of key unresolved issues associated with shoulder and centerline rumble strips and select the highest priority issues to be investigated as part of this research. Phase I was accomplished by summarizing completed and ongoing research, conducting a survey of transportation agencies to identify existing rumble strip policies and guidelines, identifying the gaps in research and practices, and selecting the highest priority issues for further investigation.

The scope of Phase II was to conduct research on key unresolved issues primarily associated with shoulder rumble strips, but several of the issues also relate to centerline rumble strip applications. The key issues investigated during Phase II included the following:

- Safety effectiveness of shoulder rumble strips on different types of roads,

- Optimal placement of shoulder rumble strips with respect to the edgeline,
- Optimum dimensions of shoulder rumble strips necessary for effective vehicular warning with least potential for adverse effects, and
- Minimum level of stimuli (i.e., sound or vibration) necessary to alert a drowsy or inattentive driver.

The scope of Phase III was to conduct research on key unresolved issues primarily associated with centerline rumble strips. The key issues investigated during Phase III included the following:

- Safety effectiveness of centerline rumble strips on different types of roads,
- Safety effectiveness of centerline rumble strips along varying roadway geometry,
- Safety effectiveness of centerline rumble strips installed in combination with shoulder rumble strips, and
- Difference in safety effectiveness of shoulder rumble strips installed along the right (outside) shoulder vs. the left (median) shoulder.

This research does not address transverse rumble strips. Transverse rumble strips are installed in travel lanes to warn motorists of approaching intersections, toll plazas, horizontal curves, traffic control devices, etc. In addition, this research does not specifically investigate the application of rumble strips within work zones. Several concepts and issues addressed in this report are potentially applicable to such installations, but this report does not go into detail on either the application of transverse rumble strips in travel lanes, nor installation of rumble strips in work zones.

Organization of This Report

This final report documents the entire research effort. The remainder of this report is organized as follows. Section 2 describes the magnitude and nature of highway safety concerns that could be addressed through the implementation of shoulder and centerline rumble strips. Section 3 presents the purpose, types, and dimensions of rumble strips. Section 4 summarizes the results of shoulder and centerline rumble strip research completed prior to, and during, the course of this research. Section 5 summarizes existing policies/guidelines concerning the design and application of shoulder and centerline rumble strips on rural and urban highways and, specifically, presents the results of the survey conducted as part of this research. Section 6 presents the results of a safety evaluation of shoulder rumble strips completed during this research. Section 7 presents the results of a safety evaluation of centerline rumble strips completed during this research. Section 8 presents details on minimum stimuli levels for effective rumble strips. Section 9 presents the results of the vehicle dynamics modeling and noise study. Section 10 provides design and applications guidance for rumble strips based on the results of the research findings. Section 11 presents the conclusions and recommendations of the research, including future research needs. Section 12 presents the references cited in the report. Appendix A presents a review of the literature in greater detail than Section 4. Appendix B presents the survey that was distributed as part of the research, and Appendix C presents a detailed summary of the survey results. Appendices D through H provide supplemental information related to the safety evaluations conducted as part of this research.

For practitioners who wish to focus on the findings of this research rather than the details of the research methodology, Sections 10 and 11 will be of particular interest.

SECTION 2

Magnitude and Nature of Highway Safety Concerns Related to Shoulder and Centerline Rumble Strips

The purpose of shoulder and centerline rumble strips is to alert motorists that their vehicles have drifted out of their intended travel lane. The primary purpose of shoulder rumble strips is to reduce SVROR crashes, and for centerline rumble strips, it is to reduce head-on crashes, opposite-direction sideswipe crashes, and to some degree SVROR-to-the-left crashes. Shoulder and centerline rumble strips can be expected to have the greatest impact on crashes where drivers drift from their travel lanes because they are inattentive, distracted, drowsy, or fatigued. In these situations, the auditory (and possibly tactile) stimuli generated while traversing the rumble strips can alert the inattentive, distracted, drowsy, or fatigued drivers to correct their vehicle trajectories. Shoulder or centerline rumble strips should not be expected to significantly impact those crashes where vehicles leave their intended travel lanes due to situations such as mechanical failures (e.g., tire blowouts), evasive maneuvers to avoid objects in the travel lane, or driver error due to medical conditions (e.g., heart attack or seizures). This section summarizes the magnitude and nature of the highway safety concerns related to SVROR, head-on, and fatigue-related crashes to put into perspective the extent of the problem and highlight the potential impact that shoulder and centerline rumble strips could have on reducing highway fatalities and injuries.

SVROR Crashes

Based upon a compilation of motor vehicle crash data from the Fatality Analysis Reporting System (FARS) and the General Estimates System (GES), 39,189 fatal crashes, 1,816,000 injury crashes, and 4,304,000 property-damage-only crashes occurred on the U.S. highway system in 2005, totaling 6,159,000 crashes (*5*). Table 1 presents these crashes by crash type, relation to roadway, and crash severity. It shows that of the 39,189 fatal crashes, 12,340 (31.5 percent) were single-vehicle crashes that occurred off the roadway. An additional 2,431 fatal crashes (6.2 percent) occurred on the shoulder, and 1,022 (2.6 percent) occurred on the median. Thus, of the 39,189 fatal crashes, 15,793 crashes (40.3 percent) occurred off the roadway, on the shoulder, or within the median. Of the injury crashes, 21 percent (382,000) were single-vehicle crashes that occurred off the roadway, on the shoulder, or within the median. Of the property-damage-only crashes, 16.5 percent (710,000) were single-vehicle crashes that occurred off the roadway, on the shoulder, or within the median. These numbers show that single-vehicle crashes that occur off the roadway, on the shoulder, or within the median account for a significant portion of all accidents (18 percent). It is also evident from the higher percentage of fatal and injury crashes that these crashes typically cause severe injuries or fatalities. It is these single-vehicle, off roadway (and possibly shoulder and median) crashes that rumble strips placed on the outside shoulder or median shoulder have the greatest potential to impact.

Table 2 presents 2005 crash data by first harmful event, manner of collision, and crash severity. It shows that of the 39,189 fatal crashes, 12,439 (31.7 percent) were single-vehicle collisions with fixed objects; while another 6,505 (16.6 percent) were single-vehicle collisions with objects that were not fixed. The single-vehicle collisions with fixed objects are potentially correctable by shoulder rumble strips, while it is not known what portion of the single-vehicle collisions with objects not fixed are potentially correctable by rumble strips because it is not known whether the collisions occurred on the roadway or off the roadway. It is also notable that the single-vehicle collisions with fixed objects are a high percent of the fatal crashes (31.7 percent).

A final note concerning Tables 1 and 2, these tables do not indicate where these crashes occurred relative to junctions (i.e., whether the crashes should be attributed to an intersection or to a roadway segment). In most cases, the SVROR types of crashes that could be remedied by shoulder rumble strips occur along roadway segments, not at intersection junctions. In addition, shoulder rumble strips are typically discontinued at

Table 1. Crashes by crash type, relation to roadway, and crash severity (*5*).

Crash type	Relation to roadway					Total
	On roadway	Off roadway	Shoulder	Median	Other/unknown	
Fatal Crashes						
Single Vehicle	6,507	12,340	2,431	1,022	353	22,653
Multiple Vehicle	15,647	297	302	198	92	16,536
Total	22,154	12,637	2,733	1,220	445	39,189
Injury Crashes						
Single Vehicle	154,000	320,000	14,000	48,000	28,000	564,000
Multiple Vehicle	1,235,000	7,000	1,000	7,000	2,000	1,252,000
Total	1,390,000	327,000	15,000	54,000	30,000	1,816,000
Property-Damage-Only Crashes						
Single Vehicle	328,000	598,000	31,000	81,000	277,000	1,314,000
Multiple Vehicle	2,957,000	11,000	3,000	14,000	5,000	2,990,000
Total	3,284,000	609,000	34,000	94,000	282,000	4,304,000
All Crashes						
Single Vehicle	488,000	930,000	48,000	129,000	306,000	1,901,000
Multiple Vehicle	4,208,000	18,000	5,000	21,000	7,000	4,258,000
Total	4,697,000	948,000	53,000	150,000	313,000	6,159,000

Table 2. Crashes by first harmful event, manner of collision, and crash severity (*5*).

First harmful event	Crash severity						Total	
	Fatal		Injury		Property damage only			
	Number	Percent	Number	Percent	Number	Percent	Number	Percent
Collision with Motor Vehicle in Transport:								
Angle	8,119	20.7	586,000	32.3	1,185,000	27.5	1,779,000	28.9
Rear-end	2,118	5.4	513,000	28.2	1,309,000	30.4	1,824,000	29.6
Sideswipe	958	2.4	71,000	3.9	392,000	9.1	463,000	7.5
Head-on	3,970	10.1	62,000	3.4	57,000	1.3	123,000	2.0
Other/unknown	192	0.5	*	*	4,000	0.1	4,000	0.1
Subtotal	15,357	39.2	1,232,000	67.8	2,947,000	68.5	4,195,000	68.1
Collision with Fixed Object:								
Pole/post	1,852	4.7	72,000	4.0	153,000	3.6	227,000	3.7
Culvert/curb/ditch	2,591	6.6	60,000	3.3	131,000	3.0	193,000	3.1
Shrubbery/tree	3,215	8.2	65,000	3.6	82,000	1.9	150,000	2.4
Guard rail	1,189	3.0	35,000	1.9	84,000	1.9	120,000	1.9
Embankment	1,444	3.7	25,000	1.4	28,000	0.6	54,000	0.9
Bridge	336	0.9	4,000	0.2	12,000	0.3	16,000	0.3
Other/unknown	1,812	4.6	65,000	3.6	165,000	3.8	232,000	3.8
Subtotal	12,439	31.7	326,000	18.0	653,000	15.2	992,000	16.1
Collision with Object Not Fixed:								
Parked motor vehicle	498	1.3	29,000	1.6	297,000	6.9	327,000	5.3
Animal	174	0.4	15,000	0.8	260,000	6.0	275,000	4.5
Pedestrian	4,520	11.5	59,000	3.3	1,000	*	64,000	1.0
Pedal cyclist	776	2.0	45,000	2.5	4,000	0.1	50,000	0.8
Train	204	0.5	1,000	*	1,000	*	2,000	*
Other/unknown	333	0.8	8,000	0.4	41,000	0.9	49,000	0.8
Subtotal	6,505	16.6	158,000	8.7	603,000	14.0	768,000	12.5
Noncollision:								
Rollover	4,266	10.9	87,000	4.8	49,000	1.1	141,000	2.3
Other/unknown	564	1.4	12,000	0.7	51,000	1.2	64,000	1.0
Subtotal	4,830	12.3	99,000	5.5	100,000	2.3	205,000	3.3
Total	**39,189	100.0	1,816,000	100.0	4,304,000	100.0	6,159,000	100.0

* Less than 500 or less than 0.05 percent.
** Includes 58 fatal crashes with an unknown first harmful event.

intersections, so shoulder rumble strips should not be expected to significantly impact SVROR crashes at intersections, such as those where a single vehicle strikes a signal pole.

Neuman et al. (*6*) analyzed the extent of the SVROR problem specifically related to two-lane, undivided, noninterchange, and nonjunction roadways using 1999 FARS data. On these roadways, Neuman et al. found that 24 percent of the fatal crashes were SVROR crashes. Figure 1 shows the distribution of SVROR crashes on two-lane roadways by roadway functional classification. Twice as many SVROR crashes occur on rural roads than on urban roads, partly due to higher speeds on rural roads and to the greater mileage. This suggests the expected safety effectiveness of shoulder rumble strips may likely be different on rural and urban two-lane roads due to the difference in crash distributions between rural and urban areas and probably on other roadway types as well.

Neuman et al. (*6*) also investigated the distribution of SVROR crashes between tangent and curved sections of highways. For all roadway types, they found that 42 percent of the SVROR crashes occurred on curves and 58 percent occurred on tangents. For rural two-lane roads, the distribution of SVROR crashes is equally distributed between tangents and curves (i.e., 50 percent on tangents and 50 percent on curves). It is clear that SVROR crashes are a significant problem along both types of alignments.

Head-On Crashes

Centerline rumble strips are intended to reduce head-on crashes, opposite-direction sideswipe crashes, and to some degree SVROR-to-the-left crashes. This section focuses on head-on crashes rather than opposite-direction sideswipe crashes and SVROR-to-the-left crashes because head-on crashes are typically more severe than sideswipe crashes, and often it is difficult to distinguish between SVROR-to-the-right and SVROR-to-the-left crashes using electronic crash data. Thus, this general discussion may underestimate the potential safety benefits of centerline rumble strips.

Neuman et al. (*7*) analyzed the extent of the problem of head-on crashes that could potentially be remedied by centerline rumble strips. Based upon 1999 FARS data, 18 percent of noninterchange, nonjunction fatal crashes were two vehicles colliding head on. In addition, the data revealed the following:

- 75 percent of head-on crashes occur on rural roads,
- 75 percent of head-on crashes occur on undivided two-lane roads, and
- 83 percent of two-lane undivided road crashes occur on rural roads.

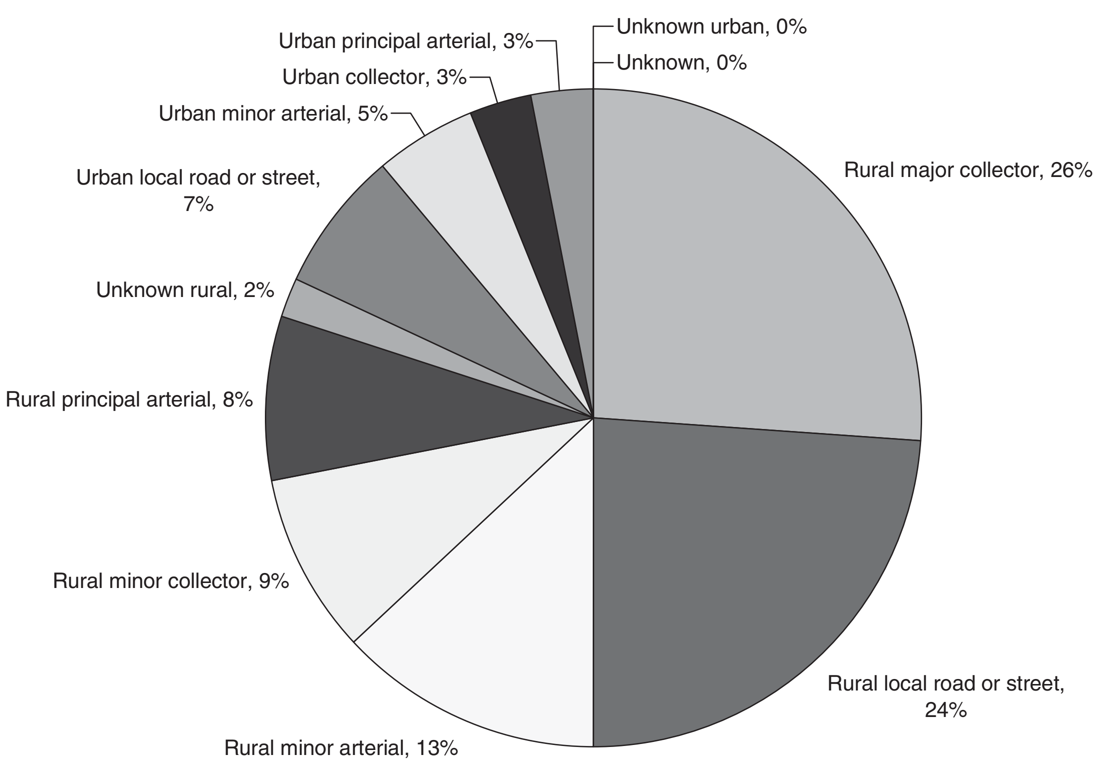


Figure 1. Distribution of SVROR fatalities on two-lane, undivided, noninterchange, nonjunction roads by highway type (6).

The high percentage of head-on crashes that occur on rural, undivided two-lane roads might suggest that many head-on crashes relate to failed passing maneuvers; however, of the 7,430 vehicles involved in head-on fatal crashes on two-lane, undivided roadways in 1997, only 4.2 percent involved a vehicle passing or overtaking another vehicle. This trend is consistent with two FHWA studies (*8, 9*).

It might be thought that most head-on crashes occur along horizontal curves rather than tangent sections of roadway because vehicles would be expected to cross the centerline more frequently on curves. However, the majority of head-on fatal crashes occur on tangent sections. For all roads, 67 percent of the head-on fatal crashes occur on tangents, and 33 percent occur on curves. On rural two-lane roads, similar percentages are found; 63 percent of the head-on fatal crashes occur on tangents, while 37 percent occur on curves. This most likely reflects that the tangent sections account for a significant portion of the total miles of roadway. Still, based on the percentages, head-on crashes on both curves and tangents represent a significant safety problem, particularly on rural two-lane roads.

Table 2 shows that head-on crashes account for approximately 10.1 percent of all fatal crashes and 3.4 percent of all injury crashes. In particular, the table shows head-on crashes are often fatal. As noted above, Table 2 does not indicate where these crashes occurred relative to junctions (i.e., whether the crashes should be attributed to an intersection or to a roadway segment) so this table does not show a complete picture of those accidents that could be remedied by centerline rumble strips. Centerline rumble strips should not be expected to impact head-on crashes that occur at intersections, in part because centerline rumble strips are typically discontinued at intersections, and although head-on crashes at intersections might be related to driver inattention or distraction, the stimuli generated by centerline rumble strips may not heighten the awareness of drivers in these situations.

Drowsy and Fatigued Driving

The discussion of SVROR and head-on crashes above does not illustrate a complete picture of the frequencies or proportions of crashes that are potentially remedied by shoulder and centerline rumble strips. What is missing is the driver behavior associated with these crashes. It is the SVROR and head-on crashes where the driver is inattentive, distracted, drowsy, or fatigued that have the greatest potential to be impacted by shoulder and centerline rumble strips. This section focuses on safety concerns related to drowsy and fatigued driving.

Drowsy and fatigued driving leads to crashes because it impairs a driver's performance. Drowsiness reduces reaction times and even small changes in reaction time can have a major repercussion, particularly at high speeds. Drowsiness also reduces vigilance and slows the driver's ability to process information. These limitations, working in combination, lead to a high number of serious crashes each year.

Several recent studies suggest that drowsy and fatigued driving is a serious concern for highway safety. The *2002 Sleep in America Poll* (*10*) found that 51 percent of drivers admitted to driving while drowsy, 17 percent admitted to dozing off while driving, and 1 percent reported having crashed due to dozing off or fatigue. A 2004 public opinion poll of Canadian drivers found that 20 percent of drivers admitted to falling asleep or nodding off at least once while driving in the past 12 months (*11*). In a study about factors associated with falling asleep at the wheel among long-distance truck drivers, 47 percent of the respondents admitted to falling asleep at the wheel of their trucks, and 25 percent had fallen asleep at the wheel in the past year (*12*). In the United States it is estimated that up to 20 percent of serious crashes may be due to drowsy or fatigued driving and that fatigue likely contributes to between 79,000 and 103,000 crashes and approximately 1,500 fatalities annually.

Typical crashes that are related to drowsiness/fatigue have the following characteristics (*13*):

- **Crashes occur during late-night hours**—Most crashes involving drowsiness/fatigue occur from midnight to the predawn hours with a small peak in the middle of the afternoon. This is consistent with human sleeping patterns.
- **Crashes happen at high speed**—Because more long trips occur on higher speed roadways, there is likely a higher proportion of drowsiness/fatigue crashes on roadways with speed limits of 55 to 65 mph (88 to 105 km/h).
- **Crashes are likely to be serious**—Injury and fatality rates are higher for drowsiness/fatigue crashes than with other types of crashes. The higher rates could be a factor of the crashes happening at higher speeds.
- **Single vehicle leaves the roadway**—A majority of drowsiness/fatigue crashes involve single vehicles leaving the roadway. Rear-end crashes and head-on crashes may also be increased due to drowsiness and fatigue.
- **No attempt to avoid crashes**—Evidence of avoiding actions such as skid marks or brake lights are less likely in drowsiness/fatigue crashes than in other types of crashes.
- **Driver is alone in vehicle**—Drowsiness/fatigue crashes often involve single-occupant vehicles.

Although no one is exempt from risk, the following three populations have a higher risk of being involved in a drowsiness/fatigue-related crash:

- **Young people, especially young men**—Drivers under age 30 are four times more likely than other drivers to be involved in a drowsy-driving crash. Men are five times more likely than women to be involved in a drowsy-driving crash.

- **Shift workers**—The information concerning shift workers and drowsiness/fatigue-related crashes has come from self-reporting and interviews rather than crash reports; but due to changing sleeping patterns, loss of sleep, and more driving done in the early morning hours, it is assumed that there is a greater risk of drowsiness/fatigue crashes among shift workers.
- **People with untreated sleep apnea syndrome and narcolepsy**—The total number of drowsiness/fatigue crashes involving drivers with sleep disorders is low, but the risk is higher among drivers with untreated sleep disorders than among other drivers.

Crashes and Heavy Vehicles

There has been some debate on the impact that shoulder and/or centerline rumble strips can have on reducing the number of crashes involving heavy vehicles. One issue is whether a sufficient amount of stimuli, either auditory or tactile, is generated within the passenger compartment to alert a truck driver; the second issue is whether heavy vehicles are involved in the types of crashes that could be remedied by shoulder and/or centerline rumble strips. This section addresses the second issue.

Based upon 2005 crash data, more that 94 percent of the 11 million vehicles involved in motor vehicle crashes were passenger cars or light trucks. Heavy vehicles accounted for 8 percent of vehicles involved in fatal crashes, 3 percent of vehicles involved in injury crashes, and 5 percent of vehicles involved in property-damage-only crashes. Of the 4,932 heavy vehicles involved in fatal crashes, 74 percent were combination trucks.

Table 3 presents 2005 crash data for heavy vehicles by first harmful event and crash severity. Of the 4,932 fatal crashes involving heavy vehicles, 175 crashes (3.5 percent) were single-vehicle collisions with fixed objects, and of the 82,000 injury crashes involving heavy vehicles, 2,000 crashes (2.9 percent) were single-vehicle collisions with fixed objects. This suggests that very few heavy vehicles are involved in fatal and injury crashes that could be remedied by shoulder rumble strips. Data from the California DOT (Caltrans) indicate similar results (*14*). Using accident data for the period from 1997 to 1999, a total of 929 fatal SVROR crashes were identified. A small portion of these fatal crashes involved single heavy vehicles with 3 axles or more (i.e., 41 fatal crashes or approximately 4 percent) and the remaining 888 fatal crashes (i.e., 96 percent) involved passenger vehicles. Of the 41 fatal truck crashes, only 4 crashes were attributed to the driver falling asleep. The remaining truck crashes were due to primary causes including driving under the influence (DUI), alcohol, speeding, etc. From the 888 passenger vehicle fatal crashes, 54 involved drivers falling asleep. This analysis showed that the incidence of SVROR crashes for trucks is very low. Bucko and Khorashadi (*14*) thought this might be due, in part, to stricter requirements for licensing of commercial vehicle drivers, as well as restrictions on the number of hours they are allowed to drive daily. It should be noted that the crash data contradict the drowsy and

Table 3. Heavy vehicles involved in crashes by most harmful event and crash severity (*5*).

First harmful event	Crash severity						Total	
	Fatal		Injury		Property damage only			
	Number	Percent	Number	Percent	Number	Percent	Number	Percent
Collision with Motor Vehicle in Transport by Initial Point of Contact:								
Front	2,309	46.8	29,000	35.3	74,000	20.8	105,000	23.8
Left side	417	8.5	12,000	14.7	50,000	14.0	62,000	14.1
Right side	212	4.3	12,000	14.5	55,000	15.6	67,000	15.2
Rear	740	15.0	14,000	17.6	58,000	16.5	74,000	16.7
Other/Unknown	33	0.7	*	0.3	*	0.1	1,000	0.1
Subtotal	3,711	75.2	68,000	82.3	237,000	66.9	309,000	69.9
Collision with Fixed Object:								
Subtotal	175	3.5	2,000	2.9	30,000	8.4	32,000	7.3
Collision with Object Not Fixed:								
Nonoccupant	405	8.2	1,000	1.2	*	*	1,000	0.3
Other	119	2.4	1,000	1.4	65,000	18.3	66,000	15.0
Subtotal	524	10.6	2,000	2.5	65,000	18.3	67,000	15.3
Noncollision:								
Subtotal	522	10.6	10,000	12.3	22,000	6.3	33,000	7.5
Total	4,932	100.0	82,000	100.0	354,000	100.0	442,000	100.0

* Less than 500 or less than 0.05 percent.

fatigued driving study of long-distance truck drivers, which suggests a good portion of these drivers are prone to falling asleep behind the wheel (*12*).

Focusing on the crashes that could potentially be remedied by centerline rumble strips, Table 3 shows that of the 4,932 fatal crashes involving heavy vehicles, 2,309 (46.8 percent) where head-on crashes, and of the 82,000 injury crashes involving heavy vehicles, 29,000 (35.3 percent) were head-on crashes. Looking at total percentages, if a large truck is involved in a crash, 23.8 percent of the time the front part of the truck collided with another motor vehicle in transport. It is not known whether the truck collided with the front, rear, or side of the other vehicle. Not knowing this information, assume that a collision with a motor vehicle in transport by initial point of contact (front) is the best surrogate for a head-on crash. This suggests that trucks should potentially be considered in the design and application of centerline rumble strips. Again, Table 3 does not indicate where these crashes occurred relative to junctions (i.e., whether the crashes should be attributed to an intersection or to a roadway segment), nor does Table 3 indicate whether the heavy vehicle crossed over the centerline or whether the other involved vehicle crossed the centerline.

Summary

The primary purpose of shoulder rumble strips is to reduce SVROR crashes, and the primary purpose of centerline rumble strips is to reduce head-on crashes, opposite-direction sideswipe crashes, and to some degree SVROR-to-the-left crashes. For centerline rumble strips, the focus above was on head-on crashes rather than opposite-direction sideswipe crashes and SVROR-to-the-left crashes because head-on crashes are typically more severe than sideswipe crashes, and often it is difficult to distinguish between SVROR-to-the-right and SVROR-to-the-left crashes.

Crash data show, in both frequency and proportion, that SVROR and head-on crashes are a problem on the U.S. highway system and deserve attention. Similarly, the data on drowsy and fatigued driving suggest a significant portion of drivers are behind the wheel while they are drowsy and fatigued, leading to impaired performance. The data do not support the need to design and install shoulder rumble strips for heavy vehicles but do potentially support the need to design and apply centerline rumble strips to reduce the frequency of head-on crashes involving heavy vehicles.

SECTION 3

Purpose, Types, and Dimensions of Rumble Strips

Purpose of Rumble Strips

A rumble strip is a raised or grooved pattern placed on the pavement surface of a travel lane or shoulder (*15*). Rumble strips are intended to provide motorists with an audible and tactile warning that they are approaching a decision point of critical importance to their safety or that their motor vehicles have partially or completely left the travel lane. Noise generated as the motor vehicle tires pass over the rumble strip provides an audible warning to the motorist, while vibration induced in the motor vehicle by the rumble strips provides a tactile warning. Although rumble strips alert motorists of potential decision points or hazards, rumble strips do not identify what type of action is appropriate.

Rumble strip applications fall into four general categories:

- **Shoulder Rumble Strips**—Shoulder rumble strips are placed on highway shoulders, outside of the travel lane. In some cases, the rumble strips may be installed along the edge-line of the roadway and may be referred to as edgeline rumble strips or rumble stripes. Shoulder rumble strips are designed primarily to mitigate SVROR-type crashes. On divided highways, shoulder rumble strips may be installed on the right (outside) shoulder and the left (median) shoulder. Figure 2 illustrates a typical shoulder rumble strip installation.
- **Centerline Rumble Strips**—Centerline rumble strips are placed on or near the centerline of the roadway. Centerline rumble strips are designed primarily to mitigate head-on crashes, opposite-direction sideswipe crashes, and to some degree SVROR-to-the-left crashes. Figure 3 illustrates a typical centerline rumble strip installation.
- **Midlane Rumble Strips**—Midlane rumble strips theoretically would be placed in the center of the travel lane (Figure 4). Midlane rumble strips so far are a concept that has been discussed, but no actual installations are known. Midlane rumble strips have the potential to mitigate both SVROR and crossover type crashes. They have primarily been discussed for use along roads with narrow or nonexistent shoulders.
- **Transverse Rumble Strips**—Transverse rumble strips are placed pretty much across the full width of the travel lanes (Figure 5), and their primary purpose is to alert motorists of approaching intersections, toll plazas, horizontal curves, work zones, or any other unexpected conditions. The current research does not address this type of rumble strip application.

Types of Rumble Strips

There are four types of rumble strips: milled, rolled, formed, and raised. They differ primarily by the installation method, their shapes, and sizes. Different amounts of vibration and noise levels are produced by each of the four types.

Milled rumble strips are currently the prevalent type of rumble strip among transportation agencies. They are easily installed on new or existing asphalt and Portland cement concrete (PCC) surfaces, and they produce a great amount of noise and vibration. This type of rumble strip is made by a milling machine, which cuts a groove in the pavement surface.

Rolled rumble strips must be installed when the constructed or reconstructed pavement surface is compacted. Grooves are pressed into the hot asphalt surface by a roller with steel pipes welded to the drums. Depressions are created as the roller passes over the hot asphalt surface.

Formed, or corrugated, rumble strips are installed along PCC surfaces. Grooves or indentations are formed into the concrete surface during the finishing process.

Raised rumble strips are strips of material that adhere to new or existing pavement surfaces. Different materials that have been used include asphalt bars and raised pavement markers. Use of raised rumble strips is usually restricted to warmer climates due to maintenance difficulties resulting from snow removal in the northern climates.

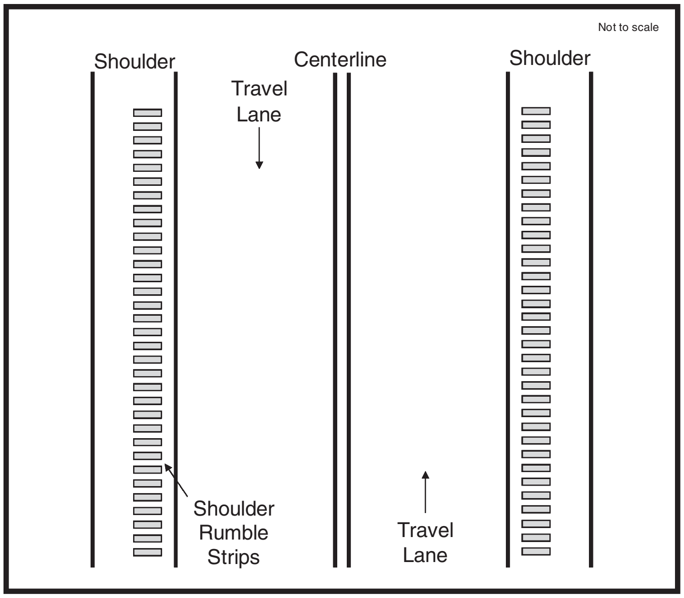


Figure 2. Typical shoulder rumble strip installation.

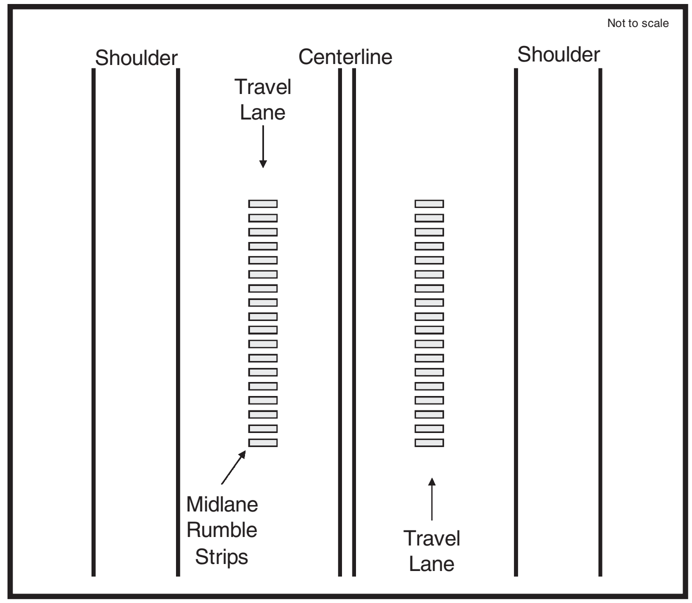


Figure 4. Midlane rumble strip concept.

Dimensions of Rumble Strips

Figure 6 illustrates an application of shoulder rumble strips along the right (outside) shoulder of a roadway. A variety of terms have been used to describe the dimensions of rumble strips. To minimize confusion as to which dimensions are being referred to throughout this report, the following terms are used to describe/define the dimensions as illustrated in Figure 6.

- **Offset (A):** Lateral distance from the edge of the travel way to the inside edge of the rumble strip.
- **Length (B):** Dimension of the rumble strip measured lateral to the travel way. This dimension is sometimes referred to as the transverse width.
- **Width (C):** Dimension of the rumble strip measured parallel to the travel lane.
- **Depth (D):** Dimension is the vertical distance measured from the top of the pavement surface to the bottom of a rumble strip pattern. This distance refers to the maximum depth of the cut or groove.
- **Spacing (E):** Distance measured between rumble strips patterns. Typically this dimension is measured from the

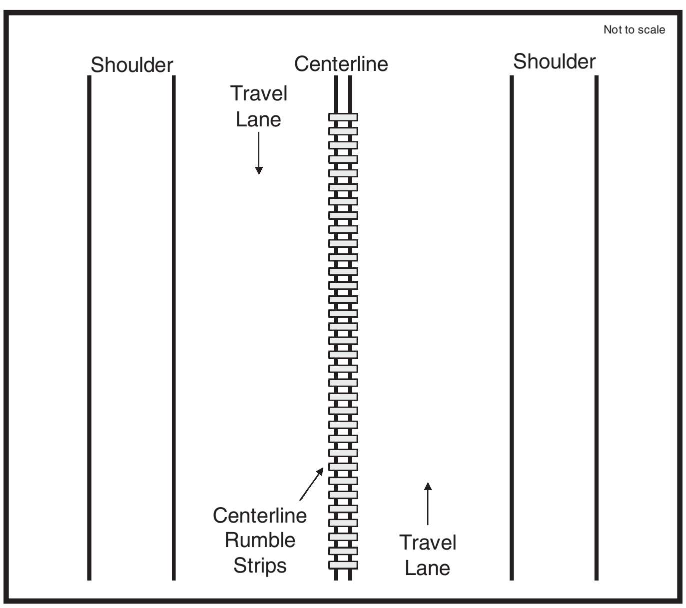


Figure 3. Typical centerline rumble strip installation.

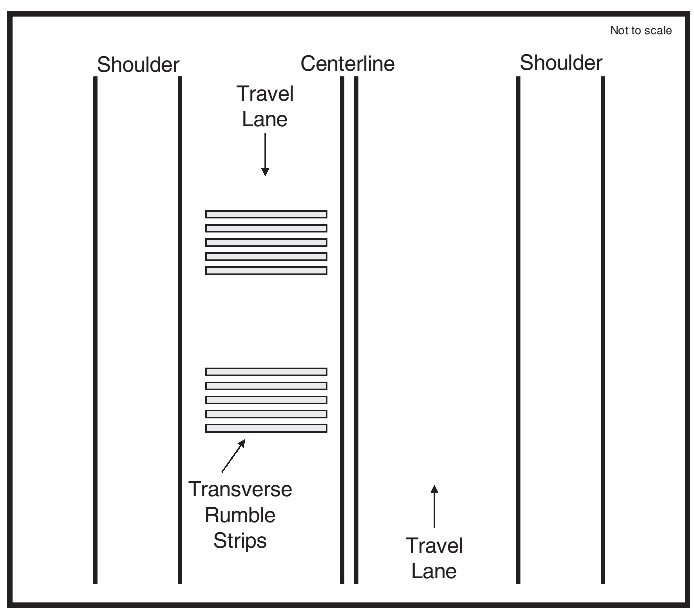


Figure 5. Typical transverse rumble strip installation.

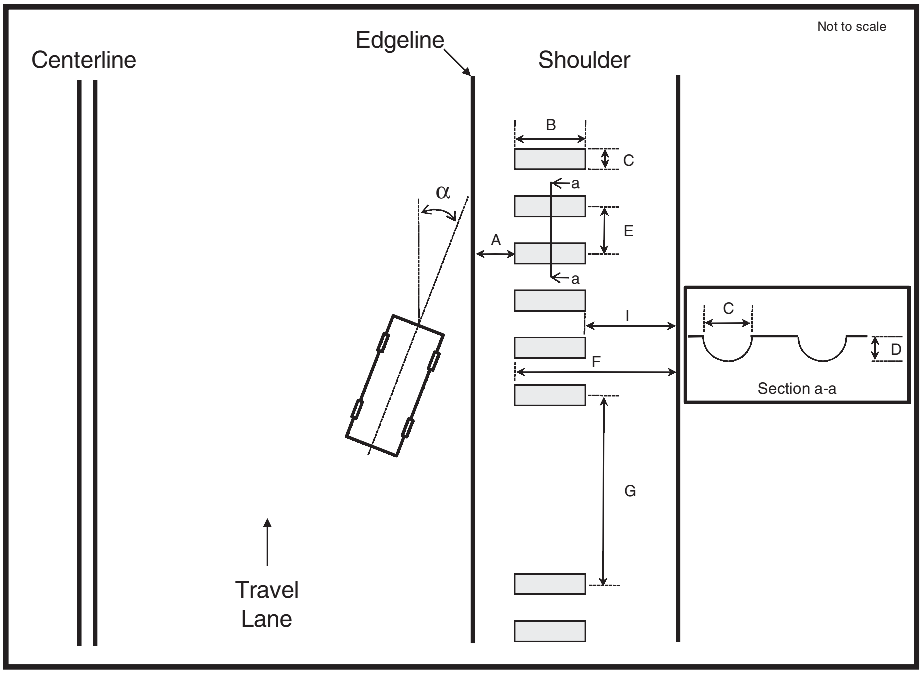


Figure 6. Design parameters associated with shoulder rumble strips.

center of one rumble strip to the center of the adjacent rumble strip, or it could be measured from the beginning of one rumble strip to the beginning of the adjacent rumble strip. Typical terms used to describe this dimension are on-center spacing, spacing on-center, center-to-center spacing, or simply "spacing."

- **Recovery Area (F):** Distance from the inside (i.e., left) edge of the rumble strip to the outside edge of the shoulder. The recovery area can also extend beyond the edge of the shoulder to the nearest roadside object.
- **Gap (G):** Distance, measured parallel to the roadway, between groups of rumble strip patterns. Gaps are designed primarily to allow bicyclists to navigate to the other side of the rumble strip pattern without having to encounter a rumble strip.
- **Height (H):** This dimension is not depicted in Figure 6, but it refers to the vertical distance measured from the pavement surface to the top of a raised rumble strip. This dimension corresponds to the depth dimension of milled, rolled, and formed rumble strips.
- **Lateral Clearance (I):** Distance from the outside (i.e., right) edge of the rumble strip to the outside edge of the shoulder. This is the portion of the shoulder to the right of the rumble strips available for bicyclists to ride along the shoulder without encountering the rumble strips. The lateral clearance can also be measured to the nearest roadside object rather than the outside edge of the shoulder.
- **Departure Angle (α):** Angle at which a motor vehicle departs from the roadway. This angle is a function of the steering angle and the curvature of the roadway.

Figure 6 illustrates an application of shoulder rumble strips. Essentially, the same terms [i.e., length (B), width (C), depth (D), and spacing (E)] are used to describe the dimensions of centerline rumble strips.

SECTION 4

Review of Completed Shoulder and Centerline Rumble Strip Research

This section summarizes the review of completed research on shoulder and centerline rumble strips. This review includes research completed by other agencies prior to and during the course of this research. The information is organized as follows:

- Safety impacts of shoulder rumble strips,
- Safety impacts of centerline rumble strips,
- Operational impacts of centerline rumble strips,
- Vehicle dynamics related to vibration and noise stimuli,
- Effects of rumble strips on specific types of highway users (i.e., motorists, motorcyclists, and bicyclists),
- Pavement performance issues, and
- Other potential adverse concerns.

A detailed review of the completed rumble strip research is provided in Appendix A.

Safety Impacts of Shoulder Rumble Strips

Safety evaluations of shoulder rumble strips have been conducted in many states, and in some cases the evaluations included data from multiple states. Table 4 summarizes the results of these safety evaluations, along with results from several unpublished materials. Table 4 shows the state/location of the evaluation, the type of facility where the rumble strips were installed, the types of collisions included in the analysis, the estimated safety effectiveness of the rumble strip application, and the type of analysis that was performed (i.e., if it could be determined from the reference material). The following are several key findings:

- Most of the studies evaluated the safety effectiveness of shoulder rumble strips installed along freeway facilities. Only a limited number of studies investigated the safety effectiveness of shoulder rumble strips along lower class roadways (i.e., nonfreeways).
- Most of the evaluations were limited to those collision types most directly affected by the installation of shoulder rumble strips (i.e., SVROR-type crashes). However, several studies did investigate the safety impact of shoulder rumble strips on total crashes.
- SVROR crashes were reduced by 10 to 80 percent due to shoulder rumble strips. The simple average percent reduction in SVROR crashes from these studies is 36 percent.
- Total crashes were reduced by 13 to 33 percent due to shoulder rumble strips. The simple average percent reduction in total crashes from these studies is 21 percent.

Concerning the safety effectiveness of shoulder rumble strips, *NCHRP Report 617: Accident Modification Factors for Traffic Engineering and ITS Improvements* (*28*) summarizes the status of crash reduction factors for a variety of treatments. In preparing *NCHRP Report 617*, a panel of safety experts assigned a level of predictive certainty to each accident modification factor (AMF) based upon a critical review of the published research. In assigning a single value or values of the safety effectiveness of shoulder rumble strips, the panel only referenced the 1999 study by Griffith (*1*) and assigned a medium-high level of predictive certainty to these estimates. *NCHRP Report 617* specifically states that the estimated safety effects are only applicable to freeways and not other types of roads (i.e., two-lane or multilane roads).

Finally, draft chapters of the forthcoming *Highway Safety Manual* (HSM) include AMFs for shoulder rumble strips for freeways and rural multilane divided highways. The AMFs for freeways are based upon research by Griffith (*1*) and Perrillo (*23*), and the AMFs for rural multilane divided highways are based upon research by Carrasco et al. (*3*).

Safety Impacts of Centerline Rumble Strips

Table 5 summarizes the results of safety evaluations that quantified the safety effectiveness of centerline rumble strips.

Table 4. Summary of safety benefits attributed to the installation of shoulder rumble strips.

State/location	Type of facility	Type of collisions targeted	Percent decrease (–) or percent increase (+) in target collision frequency from application of shoulder rumble strips (standard deviation)	Type of analysis
Arizona (*16*)	Interstate	SVROR	–80%	Cross–sectional comparison
California (*17*)	Interstate	SVROR Total	–49% –19%	Before–after with comparison sites
Connecticut (*18*)	Limited–access roadways	SVROR	–32%	Before–after with comparison sites
Florida (*16*)		Fixed object Ran–into–water	–41% –31%	Naïve before–after
Illinois and California (*1*)	Freeways Rural freeways	SVROR (total) SVROR (injury) SVROR (total) SVROR (injury)	–18% (±6.8%) –13% (±11.7%) –21.1% (±10.2%) –7.3% (±15.5 %)	Before–after with marked comparison sites and a comparison group
Kansas [unpublished; cited in Stutts (*19*)]	Freeways	SVROR	–34%	Unknown
Maine (*20*)	Rural freeways	Total	Inconclusive	Before–after with comparison sites
Massachusetts [unpublished; cited in Stutts (*19*)]		SVROR	–42%	Unknown
Michigan (*21*)		SVROR	–39%	Cross–sectional comparison
Minnesota (*3*)	Rural multilane divided highways	Total Injury SVROR (total) SVROR (injury) Total Injury SVROR (total) SVROR (injury)	–16% –17% –10% –22% –21% –26% –22% –51%	Naïve before–after Before–after with comparison sites
Minnesota (*2*)	Rural two–lane roads	SVROR (total) SVROR (injury)	–13% (8%) –18% (12%)	Before–after EB analysis with a reference group
Montana (*22*)	Interstate and primary highways	SVROR	–14%	Before–after with comparison sites
New Jersey [unpublished; cited in Stutts (*19*)]		SVROR	–34%	Unknown
New York (*23*)	Interstate Parkway	SVROR	–65% to 70%	Naïve before–after
Pennsylvania (*24*)	Interstate	SVROR	–60%	Naïve before–after
Tennessee (*25*)	Interstate	SVROR	–31%	Unknown
Utah (*26*)	Interstate	SVROR Total	–27% –33%	Before–after with comparison sites
Virginia (*27*)	Rural freeways	SVROR	–52%	Before–after with comparison sites
Washington (*15*)		Total	–18%	Naïve before–after
Multistate (*16*)	Rural freeways	SVROR	–20%	Before–after with comparison sites

These safety evaluations suggest that head-on collision frequency and rate decreased after installation of the centerline rumble strips. Several key findings are as follows:

- Most of the studies evaluated the safety effectiveness of centerline rumble strips installed along rural two-lane roads. Only one study investigated the safety effectiveness of centerline rumble strips along another type of roadway (i.e., rural multilane highways).
- Most of the evaluations were limited to those collision types most directly affected by the installation of centerline rumble strips (i.e., head-on or crossover-type crashes). However, several studies did investigate the safety impact of centerline rumble strips on total crashes.
- Head-on crashes were reduced by 34 to 95 percent due to centerline rumble strips. The simple average percent reduction in head-on crashes from these studies is 65 percent.

Concerning the safety effectiveness of centerline rumble strips, *NCHRP Report 617* (*28*) only referenced the Persaud et al. study (*4*) when assigning a single value or values of the safety effectiveness of centerline rumble strips and

Table 5. Summary of safety benefits attributed to installation of centerline rumble strips.

State/Location	Type of facility	Type of collisions targeted	Percent decrease (–) or percent increase (+) in target collision frequency from application of centerline rumble strips (95% confidence interval)	Type of analysis
California (*29*)	Rural two–lane road	Head-on (total) Head-on (fatal)	–42% –90%	Naïve before–after
Colorado (*30*)	Rural two–lane road	Head-on Sideswipe	–34% –36.5%	Naïve before–after
Delaware (*31*)	Rural two–lane road	Head-on Drove left of center PDO Injury Fatal Total	–95% –60% +13% +4% N/A –8%	Naïve before–after
Massachusetts (*32*)	Rural two–lane roads	Head-on Opposite-direction angle Opposite-direction sideswipe SVROR with centerline encounters	Inconclusive	Before–after with comparison group
Minnesota (*33*)	Rural two–lane roads	Total Total (fatal and severe injury) Head-on / opposite-direction sideswipe / SVROR–to–the–left (all severities) Head-on / opposite-direction sideswipe / SVROR–to–the–left (fatal and severe injury)	–42% –73% –43% 13%	Cross–sectional comparison
Missouri (*34*)	Rural two–lane roads	Total	–60%	Naïve before–after
Nebraska (*35*)	Rural two–lane roads	Cross–over crashes	–64%	Naïve before–after
Oregon (*36*)	Rural two– and four–lane highways	Cross–over crashes	–69.5% –79.6%	Naïve before–after Before–after with comparison group
Multistate (*4*)	Rural two–lane roads	Total Injury Frontal/opposite-direction sideswipe (total) Frontal/opposite-direction sideswipe (injury)	–14% (8–20%) –15% (5–25%) –21% (5–37%) –25% (5–45%)	Empirical Bayes (EB) before–after

assigned a medium-high level of predictive certainty to these estimates. *NCHRP Report 617* also specifically states that the estimated safety effects are only applicable to rural two-lane roads and not other types of roads (i.e., multilane roads).

Finally, draft chapters of the forthcoming HSM include AMFs for centerline rumble strips for rural two-lane roads, which strips are based upon research by Persaud et al. (*4*).

Operational Impacts of Centerline Rumble Strips

Lateral positioning and vehicle speed are the two measures most often considered when investigating the operational impacts to vehicular traffic due to the presence of centerline rumble strips. In most cases it was found that the installation of centerline rumble strips does impact the lateral positioning of vehicles and that the presence of centerline rumble strips causes drivers to move further away from the centerline (*37–42*), but at least one study (*33*) suggests that centerline rumble strips do not impact the lateral positioning of vehicles. Regarding encroachments, one study (*33*) suggests that centerline rumble strips reduce the number of encroachments, while another study (*39*) suggests otherwise. The results of five studies (*33,37,39,40,42*) suggest that centerline rumble strips do not change vehicle travel speeds, or if a change in vehicle speed does occur, the change is small or minimal.

Noyce and Elango (*32*) concluded, based on driver simulation studies, that motorists encountering centerline rumble strips do not always immediately steer their vehicles back to the right toward the intended travel lane. This finding is somewhat counterintuitive and is cause for concern. However, Miles et al. (*38*) indicate that centerline rumble strips do not significantly change driving behaviors in passing zones nor do they affect the driving environment adversely or induce unsafe driving practices.

Vehicle Dynamics Related to Vibration and Noise Stimuli

The noise and vibration created by rumble strips is the key feature in their use. Unlike most other visual-based traffic controls, rumble strips use noise and vibration to create a response from the driver. To determine optimum rumble strip dimensions, numerous studies have been conducted to detect the amount of vibration and noise generated by vehicles as they traverse different types and patterns of rumble strips.

Several recent studies (*14,43–45*) have focused on finding rumble strip dimensions that are a compromise between the alerting properties desirable for motorists and the negative benefits potentially experienced by bicyclists when encountering rumble strips. In general, higher vibration and noise levels generated by rumble strips are desirable to alert inattentive/drowsy motorists. On the other hand, lower vibration levels are desirable for bicyclists so that bicyclists do not experience discomfort and control problems while traversing the rumble strips. The more recent studies (*14,44,46,47*) have also collected vibration and noise data for more types of motor vehicles.

It is important to note that the transferability of results, or the ability to compare results between studies, is difficult primarily because the vibration data were collected in different ways. For example, Hirasawa et al. (*42*) measured vibrations at the steering column. Bucko and Khorashadi (*14*) measured the vibrational properties of the steering wheel. Outcalt (*44*) mounted accelerometers on the floor of the motor vehicle just behind the driver's seat at the spot where the floor was welded to the vehicle frame and to the steering wheel. Elefteriadou et al. (*45*) measured the vertical acceleration and pitch angular acceleration of the body frame of the motor vehicle. Chen (*48*) evaluated vibration based upon the International Roughness Index (IRI). Tye (*49*) measured the right front-wheel bounce.

The study conducted by Elefteriadou et al. (*45*) was unique in that it was the only study that utilized simulation modeling to investigate optimum dimensions of rumble strips, and it was the only study that tried to measure the impact of rumble strip patterns on the controllability of a bicycle by using an objective measure of control (i.e., the ability of a bicyclists to ride along a designated path while traversing the rumble strip).

Even though numerous studies have been conducted to investigate the optimum dimensions of rumble strips, there is no clear absolute answer to the issue. Several general points that may be concluded are the following:

- The sound levels generated by the various rumble strip configurations differ in the various test vehicles.
- In general, for milled rumble strips, wider and deeper cuts will generate higher levels of vibration and noise for all types of vehicles because of tire-drop capabilities; however, tire drop is dependent upon the properties of the tire, the speed of the vehicle, and the spacing of the cuts.

Effects of Rumble Strips on Specific Types of Highway Users

In most cases, the intended effect of shoulder and centerline rumble strips is to alert inattentive or drowsy drivers of motor vehicles that their vehicles have departed from the travel lane. However, shoulder and/or centerline rumble strips may also cause unintended behaviors or may negatively impact certain types of highway users such as motorcyclists and bicyclists. This section summarizes those studies in which participants subjectively rated the impact of rumble strips and, to the extent possible, focuses on the correlation between the alerting properties of the rumble strips (i.e., vibration and sound levels) and the reactions or behaviors of highway users to these stimuli.

Several studies investigated the effect that rumble strips have on drivers of passenger cars. In general it is assumed that rumble strips that generate 3 to 15 dBA of noise above the ambient noise level will alert drivers that their vehicles have drifted from the travel lane. Bucko and Khorashadi (*14*) rated the alerting properties of various sound levels, suggesting that increases in the range of 11 to 13.5 dBA have low to moderate alerting value compared to increases in the range of 16.7 to 19.9 dBA, which have high alerting properties. It is important to note that Bucko and Khorashadi (*14*) concluded that vibrations felt through the steering wheel are negligible in their alerting properties compared to the noise level produced in the passenger compartment. Therefore, when attempting to rate the alerting properties of rumble strips, Bucko and Khorashadi (*14*) only considered noise level. However, research conducted by Hirasawa et al. (*42*) suggests that both sound and vibration contribute to drivers' impressions from the rumble strips. None of the studies fully investigated the relationship of the alerting properties of rumble strips (i.e., vibration and sound levels) and the reactions or behaviors of drivers of passenger cars. The research conducted by O'Hanlon and Kelley (*50*) in the early 1970s could probably be considered the most comprehensive research that investigated the human factor issues associated with rumble strips; however, O'Hanlon and Kelley did not measure the vibration levels experienced by the drivers, so they too could not investigate the correlation between the alerting properties of rumble strips and drivers' reactions to these stimuli. [Note: The various studies and documents that report on either the desired noise levels to be generated by rumble strips or the field studies that document sound level intensities measured in the field alternate between expressing the sound levels in units of dB and dBA. The intensity of sound is measured in units called decibels (dB). Intensity is perceived as loudness. The notation dBA refers to decibels measured on a sound level meter using the A-weighting filter network. Once the A-weighting scale is selected, the meter mimics the way the human ear responds to sound. The A-weighting scale is the most commonly used family of curves relating to the measurement of sound (*51,52*). For consistency purposes, it is assumed that even when a reference reported a sound level in units of dB, the A-weighting was applied. Therefore, all units of sound level throughout this document are reported in units of dBA, even if the original reference reported the sound level in units of dB.]

Only one study (*14*) investigated truck drivers' reactions to rumble strips. The biggest difference between trucks and passenger cars is the level of stimuli experienced by truck drivers when traversing rumble strips. Bucko and Khorashadi note that in commercial vehicles, vibrations are dampened considerably because of the size and weight of the vehicles. Thus, the alerting properties of the vibration levels are essentially insignificant, so the noise in the passenger compartment of a commercial vehicle generated by rumble strips has a greater effect in alerting the driver than the vibration. Bucko and Khorashadi also note that increases in the sound level generated by rumble strips in the range of 1.88 to 4.72 dBA were considered to have low alerting value and increases in the range of 3.62 to 4.62 dBA were considered to have moderate alerting value.

Only a few studies included motorcycles as part of field experiments. The most detailed study on the interaction between motorcyclists and rumble strips was performed by Miller (*53*), who investigated motorcycle rider behavior on roads with centerline rumble strips. The research included a review of motorcycle crash records, an observational study of motorcyclists on roads with centerline rumble strips, and a closed course field study where 32 motorcyclists navigated across rumble strips. Miller concluded that centerline rumble strips add no measurable risk to motorcyclists. These results are consistent with findings from other studies (*14,42*).

The research conducted by Torbic *(54)* is the only investigation that truly looked at the correlation between the alerting properties of rumble strips and bicyclists' reactions to the stimuli. Torbic concluded that the relationship between whole-body vibration and a bicyclist's perception of comfort is linear; as vibration increases, comfort decreases. Torbic also concluded there is no clear relationship between whole-body vibration and the controllability of a bicycle. This research was also unique in that Torbic developed a methodology for quantifying whole-body vibration of bicyclists based upon guidelines in International Standard Organization (ISO) 2631 (*55*) to assess human response. In the other comprehensive studies that investigated bicyclists' reactions to rumble strips (*14,44,45*), bicyclists subjectively rated the comfort and control levels of bicycles while traversing various experimental rumble strip patterns, but no correlation was made between the vibration levels experienced by the bicyclists and the subjective comfort and control ratings. Finally, a general conclusion that can be drawn from the three most comprehensive studies that included bicycle and motor vehicle testing of various rumble strip designs (*14,44,45*) is that rumble strips providing the greatest amount of stimuli (noise and vibration) to alert an inattentive or drowsy driver also are the most uncomfortable for the bicyclists to traverse. Likewise, rumble strips that are the most comfortable for bicyclists generate the least amount of stimuli in a motor vehicle to alert an inattentive or drowsy driver. In all three studies, compromises were made when selecting the rumble strip design most compatible for both types of road users.

Very few pedestrians encounter rumble strips so, for all practical purposes, rumble strips have an insignificant effect on pedestrians.

Pavement Performance Issues

Several pavement performance concerns associated with shoulder and centerline rumble strips have been identified. Very little scientific-based research has been conducted to address these concerns, but through observational reports most of the pavement performance concerns appear to be unwarranted.

Several maintenance concerns associated with shoulder and centerline rumble strips have been reported. Maintenance crews reported concerns that heavy traffic would cause shoulder pavements with rumble strips to deteriorate faster and that the freeze-thaw cycle of water collecting in the grooves would crack the pavement. For the most part, these concerns have been shown to be unfounded. Most transportation agencies do advise against installing shoulder rumble strips on pavements that are rated as deformed or show high degrees of deformation and/or cracking.

Inclement weather also appears to have an insignificant impact on the durability of shoulder rumble strips. Field tests refute concerns about the effects of the freeze-thaw cycle as water collects in the grooves. In fact, field tests show that vibration and the action of wheels passing over the rumble strips knock debris, ice, and water out of the grooves. Snow plow drivers have also noted that they have come to depend on shoulder rumble strips to help them find the edge of the travel lane during heavy snow and other low visibility situations.

Shoulder rumble strips may also present a challenge to maintenance and rehabilitation crews when lane closures require traffic to be diverted to the shoulder. For long-term rehabilitation projects involving asphalt shoulders, most agencies simply mill a trench around the rumble strips and fill the trench with asphalt. Once construction is complete, the shoulder can be resurfaced and new rumble strips installed along the new asphalt overlay.

Similar to the experience with shoulder rumble strips, several agencies have expressed concerns about pavement deterioration associated with the installation of centerline rumble strips. However, none of these concerns have been validated.

The pavement performance issue that has received the most detailed investigation deals with the preparation of rumble strips prior to overlayment of the shoulder surface so that rideability and pavement integrity are not compromised. New Hampshire DOT (NHDOT) conducted research to develop a specification defining materials, sequences, and/or options to perform this operation successfully. Four test sections were prepared in the following manner for evaluation:

- Test Section A: Shim and overlay;
- Test Section B: Just overlay;
- Test Section C: Mill, inlay, and overlay; and
- Test Section D: Mill and overlay.

Test Sections C and D performed the best, showing no sign of reflection in the area of the former rumble strips, while Test Section A resulted in mild depressions, and Test Section B resulted in pronounced rumble strip reflection. Thus, preparing areas with rumble strips prior to overlayment either by (1) milling, inlaying, and overlaying or by simply (2) milling and overlaying is preferred over the other two preparation options, which would likely result in some degree of reflection in the area of the former rumble strips.

Other Potential Concerns

This section summarizes potential issues or concerns associated with shoulder and/or centerline rumble strips that were not previously addressed.

Impact of Noise on Nearby Residents

A common problem cited by transportation agencies concerning the use of rumble strips is noise that disturbs nearby residents (*15*). However, noise is generated relatively infrequently by rumble strips placed on the shoulders and on the centerlines of undivided highways. For shoulder and centerline rumble strips, noise is generated only by errant motor vehicles, not by every motor vehicle.

Although the noise produced by shoulder and centerline rumble strips is intermittent, transportation agencies continue to receive complaints from nearby residents. To address these complaints, some agencies have increased the offset of the rumble strip from the edgeline to decrease the incidence of vehicles falsely traversing the rumble strips. Other transportation agencies have completely removed the rumble strips. Another alternative is to construct noise barriers. It has been noted that some residents claim to be able to hear the noise generated from the rumble strips from up to 1.2 mi (2 km) away (*56*). Studies have also shown that when rumble strips are terminated 656 ft (200 m) prior to residential or urban areas, tolerable noise impacts are experienced; also at a distance of 1,640 ft (500 m), the noise generated from rumble strips is negligible (*57*). A recent survey to determine the opinions of residents in areas where centerline rumble strips had been placed showed that the majority of residents find the external noise produced from centerline rumble strips acceptable or tolerable and that the potential driver safety outweighed the effect of the external noise (*43*).

Bicycle Issues

Most studies that investigated the impact of rumble strips on bicyclists focused on the comfort and control problems that bicyclists may (or may not) experience while traversing rumble strips. However, bicyclists have several other concerns associated with rumble strips that have not necessarily been validated or dismissed through research. The severity or extent of these concerns is difficult to assess without the supporting research.

One concern with shoulder rumble strips is that they may encourage bicyclists to ride in the travel lane in situations where bicyclists would rather ride on the shoulder. Even though rumble strips are typically installed on only about half of the paved shoulder, the remaining area between the outer edge of the rumble strip and the outside edge of the shoulder is often littered with debris. The debris discourages bicyclists from utilizing that area. Therefore, bicyclists may prefer to ride in the travel lane. A possible solution to this dilemma is to move the rumble strip further from the travel lane to provide bicyclists with adequate room to ride between the travel lane and the rumble strip. This, however, decreases the recovery area available to errant motor vehicles. Another possibility is to make the rumble strips narrower. Yet, another possibility is to provide a gap in the rumble strip pattern to allow bicyclists to cross back and forth from the paved shoulder to the travel lane without having to encounter rumble strips.

A general concern with centerline rumble strips is that motorists may not provide sufficient clearance distance between the bicyclist and the motor vehicle when passing a bicyclist on a section of roadway with centerline rumble strips. In other words, the centerline rumble strips may force motorists away from the centerline (as has been shown in several studies) closer to bicyclists riding near the outside edge of the travel lane, leaving less distance between a bicyclist and motor vehicle during the actual passing maneuver. Another concern is that when motorists encounter centerline rumble strips during the passing maneuver, the noise generated by the rumble strips may startle bicyclists, which could result in an undesirable maneuver by the bicyclist.

Maintenance Concerns

Weather does cause problems with raised rumble strips. Snow plow blades passing over the rumble strips tend to scrape them off the pavement surface, which is why raised rumble strips are usually restricted to areas that do not contend with snow removal. When raised rumble strips get scraped from the pavement surface, a secondary concern is that the material could become a projectile.

Visibility/Retroreflectivity of Centerline and Edgeline Pavement Markings

Some transportation agencies have reported concerns over the visibility and retroreflectivity of centerline pavement markings installed on centerline rumble strips. This could potentially be a problem under nighttime conditions especially if snow, salt, sand, or debris collect in the grooves of the rumble strips. Visibility of pavement markings can also be an issue when rumble strips are installed along the edgeline.

Conflicting evidence as to whether this is an actual problem is found in the literature. However, the majority of studies suggest that visibility/retroreflectivity of pavement markings placed over rumble strips (i.e., rumble stripes) is higher compared to standard edgeline/centerline pavement markings, particularly during wet-night conditions. Rumble stripes also appear to be more resilient and durable than standard pavement markings, particularly in areas with winter maintenance activities.

SECTION 5

Existing Rumble Strip Practices and Policies

This section presents a summary of existing rumble strip practices and policies. This section focuses on the typical dimensions of shoulder and centerline rumble strips and the criteria that control installation practices of shoulder and centerline rumble strips. The information presented in this section is pulled from multiple sources. The primary source of information is the results of a survey conducted in fall 2005 as part of this research. The survey was distributed via email to the 50 U.S. state transportation agencies and 12 Canadian provincial transportation agencies to identify existing policies/guidelines governing the design and application of shoulder and centerline rumble strips on rural and urban highways. Responses from 27 U.S. state transportation agencies and 4 Canadian provincial transportation agencies were received. The survey asked questions related to the following topics:

- lateral placement with respect to edgeline/centerline,
- lane width,
- shoulder width,
- clear path,
- traffic volume,
- posted speed,
- crash history,
- pavement type,
- pavement depth,
- presence of designated bicycle route,
- spacing, and
- geometric configuration of the roadway.

A copy of the survey questionnaire is provided in Appendix B.

Since a number of recent surveys (*32,36,45,46,58–62*) on rumble strips have been conducted, the results of these surveys were reviewed prior to developing the survey for this research. This was done to avoid unnecessary duplication of questions. Thus, this section presents a compilation of information from these surveys as well. In addition, a number of recent syntheses documents have been published and so information from these documents serves as supplemental material for this section. These synthesis documents include:

- *Synthesis of Practices for the Implementation of Centerline Rumble Strips* (*56*),
- *NCHRP Synthesis 339: Centerline Rumble Strips* (*36*),
- *Synthesis of Best Practices for the Implementation of Shoulder and Centerline Rumble Strips* (*57*),
- *Synthesis of Shoulder Rumble Strip Practices and Policies* (*63*), and
- *Technical Advisory: Roadway Shoulder Rumble Strips* (*64*).

Typical Shoulder and Centerline Rumble Strip Practices in North America

Various types, patterns, and designs of shoulder rumble strips are used in most states within the United States, but not all Canadian provinces install shoulder rumble strips. Table 6 summarizes shoulder rumble strip practices within North America. Table 6 is divided into five sections. The first section (Column 1) simply indicates the state or Canadian province. The second section (Columns 2 to 4) provides information on pattern characteristics including information on the types of roadways where shoulder rumble strips are installed, the type of rumble strip (i.e., milled, rolled, formed, or raised), and details of a skip pattern if preferred over continuous placement. The third section (Columns 5 to 12) provides information concerning minimum requirements for installation as it relates to minimum shoulder widths, lateral clearances, average daily traffic (ADT), pavement depth, speed, accident frequencies/rates, bicycle considerations, and placement distances with respect to the edgeline of the travel lane. The fourth section (Columns 13 to 16) provides dimensions of the shoulder rumble strips used by the respective states. The final section (Column 17) indicates the effective date of the policy from which some, or all, of the information found in the table for the respective state was obtained. Because the response rate

Table 6. Summary of North American shoulder rumble strip practices.

State or province*	Pattern characteristics			Minimum requirements for installation								Dimensions				Date of policy
	Roadway type	Rumble type**	Skip Pattern	Shoulder width	Lateral clearance	ADT (vpd)	Pavement depth	Speed	Accident	Bicycle	Offset (A)	Length (B)	Width (C)	Depth (D)	Spacing (E)	
Alabama*	U frwy; U multilane divided; R freeway; R multilane divided; R multilane undivided; R two-lane	M	Continuous	N	N	N	N	N	N	N	18 in.	16 in.	7 in.	0.5 – 0.625 in.	12 in.	–
		RL	Continuous	N	N	N	N	N	N	N	0 in.	3 ft	1 in.	0.5 in.	8 in.	10/93
Alaska	U frwy; U expwy U two-lane R frwy R expwy R two-lane	M	6 ft Gap 40 ft Cycle 10 ft Gap (edgeline)	6 ft	4 ft	–	2 in.	45 mph	N	Y	2 in. for 6 in. shldr 6 in. for > 6 in. shldr	16 in.	7 in.	0.5 in.	12 in.	5/01
Arkansas*	U frwy; R frwy	M	Continuous	N	N	N	N	N	N	N	4 in.	16 in.	7 in.	0.5–0.625 in.	12 in.	–
Arizona*	R frwy; R multilane divided; R multilane undivided; R two-lane	M	10 ft Gap 40 ft Cycle	3–6 in.	2 in.	N	N	N	N	Y	0 in.	6 in.	7 in. ± 0.25 in.	0.375 in.	12 in. ± 1 in.	5/03
											10 in.	8 in. or 12 in.	7 in. ± 0.25 in.	0.375 in.	12 in. ± 1 in.	
California	R frwy R expwy R two-lane	M	Continuous	4 ft	5 ft	N	N	N	N	Y	6–12 in.	12 in.	5 in.	0.32 in. ± 125 in.	12 in.	9/02
		RL	Continuous	4 ft	5 ft	N	N	N	N	Y	6–12 in.	12 in.	2 in.	1 in.	8 in.	
		RS	Continuous	4 ft	5 ft	N	N	N	N	Y	6–12 in.	–	–	–	–	
Colorado*	R frwy; R frwy ramps R multilane divided; R multilane undivided; R two-lane	M	12 ft Gap 60 ft Cycle	4 ft	6 ft	N	Y	N	N	N	0 in.	12 in.	5 in.	0.375 in.	12 in.	10/00
		RL,F	12 ft Gap 60 ft Cycle	4 ft	6 ft	N	Y	N	N	N	0 in.	12 in.	2.375 in.	0.5–1 in.	4 in.	
Connecticut*	U frwy; R frwy	M	Continuous	3 ft	4 ft	N	N	N	N	N	6 in. (median) 12 in (outside)	16 in. ± 0.5 in.	7 in. ± 0.5 in.	0.5–0.625 in.	12 in. ± 0.5 in.	10/99

Delaware*	U frwy; U multilane divided; U multilane undivided; U two-lane; R freeway; R multilane divided; R multilane undivided; R two-lane	M	Continuous	N	N	N	N	N	N	Y	12 in.	16 in.	7 in.	0.5 in.	12 in.	–
Florida	U frwy R frwy	M	11 ft Gap 28 ft Cycle	N	N	N	N	N	N	N	16 in.	16 in.	7 in. ± 0.5 in.	0.5– 0.625 in.	12 in. ± 1 in.	–
		RS (asphalt)	–	N	N	N	N	N	N	N	0 in.	28 in.	2 in.	0.5 in.	12 in.	–
		RS (Thermoplastic)	–	N	N	N	N	N	N	N	0 in.	–	4 in. Min	0.5 in.	–	–
Georgia*	U frwy; U frwy ramps; U multilane divided; U multilane undivided; U two-lane; R frwy; R frwy ramps; R multilane divided; R multilane undivided; R two-lane	M	12 ft	4 ft	4 ft	400	N	N	N	N	8–12 in.	16 in.	7 in.	0.5– 0.625 in.	12 in.	–
Hawaii		–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Idaho*	R frwy; R multilane divided; R multilane undivided; R two-lane	M	12 ft Gap 60 ft Cycle	3 ft	N	N	N	N	N	N	0 in.	12– 18 in.	7 in. ± 0.5 in.	0.5– 0.625 in.	12 in.	5/05
Illinois	–	M	Continuous	–	Varies	–	–	–	–	–	12 in.	16 in.	7 in.	0.5 in.	12 in.	1/03

(continued on next page)

Table 6. (Continued).

State or province*	Pattern characteristics: Roadway type	Rumble type**	Skip Pattern	Minimum requirements for installation: Shoulder width	Lateral clearance	ADT (vpd)	Pavement depth	Speed	Accident	Bicycle	Dimensions: Offset (A)	Length (B)	Width (C)	Depth (D)	Spacing (E)	Date of policy
Indiana*	R frwy; R frwy ramps; R multilane divided; R multilane undivided	M	20 ft Gap 100 ft Cycle	4 ft	7 ft	N	5 in.	N	N	Y	0–6 in.	16 in.	7 in.	0.5 in.	12 in.	3/03
Iowa*	U frwy; U multilane divided; U multilane undivided; R freeway; R multilane divided; R multilane undivided; R two-lane	M	12 ft Gap 60 ft Cycle	4 ft	N	3,000	N	N	N	Y	0 in.	16 in.	7 in.	0.5–0.625 in.	12 in.	1/04 4/05
Kansas	R hwy	M	Intermittent	8–10 ft	N	N	1 in.	N	N	N	16 in.	16–17 in.	7–8 in.	0.5 in.	12 in.	3/01
Kentucky*	U frwy; U frwy ramps; U multilane divided; U multilane undivided; U two-lane; R frwy; R frwy ramps; R multilane divided; R multilane undivided; R two-lane	M	Continuous	N	N	N	Variable	N	N	N	12 in.	16 in.	7 in. ± 0.5 in.	0.5 in. ± 0.125 in.	12 in. ± 1 in.	–
		RL	Continuous	N	N	N	Variable	N	N	N	0 in.	24 in.	1.5 in. ± 0.25 in.	0.75 in. ± 0.25 in.	9 in. ± 1 in.	–
Louisiana	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Maine*	U frwy; R frwy	M	–	–	–	–	3 in.	–	–	–	0 in.	16 in.	7 in.	0.5–0.75 in.	12 in.	–
Maryland	–	M	Continuous	N	–	–	–	–	–	–	6–12 in.	16 in. Min	7 in. ± 0.5 in.	0.5–0.625 in.	12 in.	3/04

Massachusetts	U frwy; U multilane divided; U multilane undivided; R freeway; R multilane divided; R multilane undivided; R two-lane	M	Continuous	2 ft	N	N	N	40 mph	N	N	4 in.	16 in.	7 in.	0.5 in.	12 in.	12/04
Michigan	–	M	Continuous	4 ft	–	–	–	–	–	–	12 in.	16 in.	7 in.	0.5–0.625 in.	12 in.	8/04
Minnesota*	U frwy; U multilane divided; U multilane undivided; R freeway; R multilane divided; R multilane undivided; R two-lane	M	12 ft Gap 60 ft Cycle	6 ft	N	N	N	50 mph	N	Y	4 in.	12–16 in.	7 in. ± 0.5 in.	0.375–0.5 in.	12 in. ± 0.5 in.	5/00
Mississippi*	U frwy; U multilane divided; R frwy; R multilane divided	M	Continuous	2 ft	4 ft	N	N	N	N	N	0 in.	15 in.	7 in.	0.5–0.625 in.	12 in.	10/04
Missouri*	U frwy; U multilane divided; U multilane undivided; U two-lane; R freeway; R multilane divided; R multilane undivided; R two-lane	–	Continuous	2 ft	N	N	3.75 in.	50 mph	N	N	0 in.	–	–	–	–	–
Montana	Interstates Primary routes	M	Continuous	4 ft	N	N	N	N	N	N	6 in.	12–16 in.	7 in.	0.5–0.75 in.	12 in.	3/96

(continued on next page)

Table 6. (Continued).

State or province*	Pattern characteristics			Minimum requirements for installation								Dimensions				Date of policy
	Roadway type	Rumble type**	Skip Pattern	Shoulder width	Lateral clearance	ADT (vpd)	Pavement depth	Speed	Accident	Bicycle	Offset (A)	Length (B)	Width (C)	Depth (D)	Spacing (E)	
		F	Continuous	4 ft	N	N	N	N	N	N	6 in.	12–16 in.	2 in.	1 in.	4.5 in.	3/96
Nebraska	–	M	–	–	–	–	–	–	–	N	0 in.	16 in.	7 in.	0.5 in.	12 in.	–
Nevada*	R frwy; R multilane divided; R multilane undivided; R two-lane	M	Continuous	6 ft	N	N	N	N	N	Y	4 in.	16 in.	7 in.	0.5–0.625 in.	12 in.	1/01
New Hampshire	R frwy	M	Continuous	–	–	–	–	–	–	N	6–30 in.	16 in.	7 in.	0.5 in.	12 in.	–
New Jersey	U frwy R frwy	M	Continuous	3 ft (median) 8 ft (outside)	N	N	N	N	N	N	4 in.	16 in.	7 in.	0.5 in.	12 in.	–
New Mexico	R frwy R expwy R two-lane	M	Continuous	–	–	–	–	–	–	–	12 in.	16 in.	7 in. ± 0.5 in.	0.5–0.625 in.	12 in. Min	8/98
New York	R frwy U frwy	M	Continuous	N	34 in.	N	2.5 in.	N	N	Y	Varies	16 in.	7 in.	0.5–0.625 in.	–	6/97
North Carolina*	U frwy; U multilane divided; R freeway; R multilane divided; R two-lane	M	6 ft Gap 40 ft Cycle	6 ft	N	N	6 in.	N	N	Y	0 in.	16 in.	7 in.	0.5 in.	12 in.	3/05
North Dakota*	R frwy; R multilane divided; R multilane undivided; R two-lane	M	12 ft Gap 50 ft Cycle	4 ft	4 ft	2,000	N	45 mph	N	N	0 in.	Varies	6.5 in. ± 0.5 in.	0.5 in. ± 0.125 in.	12 in.	5/23/03
Ohio	R frwy U frwy	M	10 ft Gap 20 ft Cycle	4 ft	4 ft	–	–	–	0.25 acc/MVM	Y	4–6 in.	16 in.	7 in.	0.5 in.	12 in.	–
Oklahoma	Multilane Two-lane	M	Continuous	4 ft	N	N	2 in.	N	N	N	24 in. ± 3 in.	16 in. ± 1 in.	7 in. ± 1 in.	0.5–0.625 in.	12 in.	99
Oregon*	R frwy; R multilane divided; R multilane undivided; R two-lane	M	Continuous	–	4 ft	–	–	–	–	N	0 in.	–	5.5 in.	0.5 in. ± 0.125 in.	18 in.	5/05

Pennsylvania*	U frwy; U frwy ramps; U multilane divided; U multilane undivided; R frwy; R frwy ramps; R multilane divided; R multilane undivided; R two-lane	M (Interstate)	Continuous	4 ft (median) 8 ft (outside)	N	N	N	N	N	N	12 in. ± 0.5 in. (median) 18 in. ± 0.5 in. (outside)	16–17 in.	7 in. ± 0.5 in.	0.5–0.625 in.	12 in.	4/95
		M (non-Interstate)	Continuous	6 ft	4 ft	1,500	–	≥ 55 mph	N	Y	6 in.	16 in.	5 in. ± 0.5 in.	0.375 in. ± 0.0625 in.	12 in. ± 0.5 in.	
		M (non-Interstate)	Continuous	6 ft	4 ft	1,500	–	< 55 mph	N	Y	6 in.	16 in.	5 in. ± 0.5”	0.375 in. ± 0.0625 in.	11 in. ± 0.5 in.	3/02
		M (edgeline)	Continuous	4–6 ft	4 ft	N	N	N	N	Y	0 in.	6 in.	5 in. ± 0.5 in.	0.375 in. ± 0.0625 in.	12 in. ± 0.5 in.	
Rhode Island*	U frwy; U frwy ramps; U multilane divided; U multilane undivided; R frwy; R frwy ramps; R multilane divided; R multilane undivided; R two-lane	M	Continuous	N	N	N	N	N	N	N	4 in. (median) 12 in. (outside)	16 in.	7 in.	0.5 in.	12 in.	–
South Carolina	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
South Dakota	–	RL	Continuous	–	–	2,500	–	–	–	N	8 in.	36 in.	2 in.	1 in.	8 in.	–

(continued on next page)

Table 6. (Continued).

State or province*	Pattern characteristics			Minimum requirements for installation								Dimensions				Date of policy
	Roadway type	Rumble type**	Skip Pattern	Shoulder width	Lateral clearance	ADT (vpd)	Pavement depth	Speed	Accident	Bicycle	Offset (A)	Length (B)	Width (C)	Depth (D)	Spacing (E)	
Tennessee	R frwy U frwy	M	Continuous	N	–	–	–	–	N	N	6 in.	16 in. Min	6 in. ± 0.5”	0.375–0.5 in.	18 in. ± 0.5 in.	–
Texas*	R frwy; R multilane divided; R multilane undivided;	M	Continuous	4 ft (median) 8 ft (outside)	6 ft	–	–	–	–	Y	0 in.	16 in.	7 in. ± 0.5 in.	0.5–0.625 in.	12 in.	5/99
		RL	Continuous	4 ft (median) 8 ft (outside)	6 ft	–	–	–	–	Y	4–8 in.	24 in.	2 in.	1 in. ± 0.125 in.	8–9 in.	
		RS	Continuous	–	–	–	–	–	–	Y	–	–	–	–	–	
Utah*	U frwy; R frwy; R frwy ramps; R multilane divided; R multilane undivided; R two-lane	M	12 ft Gap 60 ft Cycle	N	4 in.	N	N	N	N	N	Varies	12 in.	8 in. ± 0.375 in.	0.625–0.75 in.	12 in.	1/05
Vermont*	U frwy; R frwy; R multilane divided; R multilane undivided	M	Continuous	N	4 ft	N	N	N	N	Y	6–30 in.	16 in.	7 in.	0.5 in.	12 in.	–
Virginia*	R frwy	M	Continuous	N	N	N	N	N	N	N	0 in.	16 in.	7 in.	0.5 in.	12 in.	–
Washington*	U frwy; R frwy; R multilane divided; R multilane undivided; R two-lane	M	12 ft Gap 40 ft Cycle; 12 ft Gap 60 ft Cycle; 16 ft Gap 64 ft Cycle	4 ft	N	N	Variable	45 mph	.6/mi or 34/100 MVMT	Y	6 in.	16 in.	7 in. ± 0.5 in.	0.5–0.625 in.	12 in.	8/04
West Virginia	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Wisconsin	R frwy R expwy U frwy U expwy	M	–	N	–	–	–	–	N	N	30 in.	16 in.	7 in.	0.5–0.625 in.	19 in. ± 1 in.	–
Wyoming*	R frwy; R multilane undivided; R two-lane	M	12 ft Gap 60 ft Cycle	2 ft	N	N	N	45 mph	N	N	6 in.	16 in.	7 in.	0.5–0.625 in.	12 in.	9/01

Canadian Provinces																
Alberta	–	M	12 ft Gap 24 ft Cycle	–	–	–	–	–	–	–	6–8 in.	12 in.	5–7 in.	0.32– 0.5 in.	11–14 in.	–
		RL	Continuous	–	–	–	–	–	–	–	3–6 in.	24 in.	1.5–2 in.	0.5– 0.625 in.	7.5–8.5 in.	–
British Columbia*	R frwy; R multilane divided; R two-lane	M	Continuous	5 ft	4 ft	N	N	N	N	N	4 in.	12 in. ± 0.375 in.	5.5 in. ± 0.75 in.	0.32 in. ± 0.125 in.	12 in.	4/04
New Brunswick	–	M	Continuous	–	–	–	–	–	–	–	8 in.	12 in.	6 in.	0.375– 0.5 in.	12 in.	–
Ontario*	R frwy; R two lane	M	Continuous	2 ft	3 ft	N	3 in.	N	N	Y	4 in.	12 in.	6 in. ± 0.75 in.	0.375 in. ± 0.125 in.	12 in.	10/00
Prince Edwards Island*	N/A	–	N/A	–	–	–	–	–	–	N	N/A	–	–	–	–	–
Quebec	–	M	Continuous	–	–	–	–	–	–	–	12 in.	16 in.	7 in.	0.5 in.	12 in.	–
Saskatchewan*	R frwy; R frwy ramps; R multilane divided; R multilane undivided; R two-lane	M	13 ft Gap 26 ft Cycle	6 ft	N	1,800	N	N	N	Y	6–7 in.	12 in.	6 in. ± 1 in.	0.32 in. ± 0.125 in.	12 in.	2/05
		RL	Continuous	6 ft	N	1,800	N	N	N	Y	0 in.	24 in.	1.5– 2.0 in.	0.5 in.	7.5–8.5 in.	–

* Indicates state/province responded to survey and information from the survey is reflected in this table.

** Rumble Strip Type Abbreviations: M = Milled RL= Rolled RS = Raised F = Formed.

of the survey conducted as part of this project was not 100 percent, and because the research team tried to utilize responses from the most recent surveys and syntheses, there is the possibility that some of the information presented in Table 6 may not reflect the most current practice of the respective state. However, Table 6 attempts to provide the most up-to-date and comprehensive information available on shoulder rumble strip practices in North America.

Table 7 summarizes centerline rumble strip practices within North America. Similar to Table 6, Table 7 is divided into five sections. The primary difference between the two tables is that under pattern characteristics for centerline rumble strips, there is no column for skip patterns, and Column 4 now indicates the lateral placement of the centerline rumble strip applications relative to the centerline pavement markings and lane. In addition, under minimum requirements for installation for centerline rumble strips, Column 5 indicates the minimum lane width requirements rather than the minimum shoulder width and lateral clearance requirements, which are more applicable to shoulder rumble strips.

Summary of Survey Responses

This section summarizes the responses to the survey conducted as part of this research received from 27 U.S. state transportation agencies and 4 Canadian provincial transportation agencies. As noted earlier, Tables 6 and 7 are based on a broader data set, because they also include information gathered in earlier surveys and from synthesis documents. Responses to categorical questions are summarized by showing both the percentage of the responses and the frequency/number of responses shown in parentheses. For those questions that asked transportation agencies to further explain an issue, the actual responses are provided in bullet form in Appendix C.

Survey Results: Shoulder Rumble Strip Policies and Practices

1. *Does your agency have a written policy concerning the installation/application of shoulder rumble strips?*

YES:	80.6%	(25)
NO:	19.4%	(6)

   If no, does your agency use shoulder rumble strips?

YES:	16.1%	(5)
NO:	3.2%	(1)

   Total agencies using shoulder rumble strips:

   96.8% (30)

   States/Provinces that have their policy information available on the Internet: Arizona, Iowa, Indiana, Minnesota, North Carolina, North Dakota, Nevada, Oregon, Pennsylvania, Texas, Utah, Virginia, Washington, and British Columbia.

2. *On what types of roadways does your agency install shoulder rumble strips?*

Urban freeways:	54.8%	(17)
Urban freeway on-ramps and off-ramps:	9.7%	(3)
Urban multilane divided highways (nonfreeways):	32.3%	(10)
Urban multilane undivided highways (nonfreeways):	22.6%	(7)
Urban two-lane roads:	12.9%	(4)
Rural freeways:	96.8%	(30)
Rural freeway on-ramps and off-ramps:	22.6%	(7)
Rural multilane divided highways (nonfreeways):	77.4%	(24)
Rural multilane undivided highways (nonfreeways):	71.0%	(22)
Rural two-lane roads:	71.0%	(22)
Other:	3.2%	(1)

3. *On roadways with medians, does your agency install shoulder rumble strips on both the right (outside) and left (median) shoulder?*

YES:	93.5%	(29)
NO:	6.5%	(2)

   If yes, does your policy differ between rumble strips installed on the right (outside) versus the left (median) shoulder?

YES:	35.5%	(11)
NO:	51.6%	(16)

   If your policy differs, what are the primary differences?

   - Typical responses included: (a) the offsets are different typically with smaller offsets on the left (median) shoulder and (b) rumble strips are installed continuously on the left (median) shoulder while intermittent gaps are provided on the right (outside) shoulder.

4. *Does your policy concerning shoulder rumble strips differ depending upon the type of shoulder surface?*

YES:	38.7%	(12)
NO:	54.8%	(17)

   If yes, please elaborate:

   - Several agencies only install shoulder rumble strips on asphalt shoulders and prohibit the use on PCC shoulders. Some agencies indicated that standards for placements differ, primarily to account for joints in PCC surfaces.

Table 7. Summary of North American centerline rumble strip practices.

State or province*	Pattern characteristics			Minimum requirements for installation						Dimensions				Date of policy
	Roadway type	Rumble type**	Placement	Lane width	ADT (vpd)	Speed	Accident	Pavement depth	Bicycle	Length (B)	Width (C)	Depth (D)	Spacing (E)	
Alabama*	R two-lane		Into lane	N	N	N	N	N	N	–	–	–	–	–
Alaska	–	M								12 in.	5–7 in.	0.5 in.	10–12 in.	–
Arkansas*	R two-lane		Within pm	N	N	N	N	N	N	–	–	–	–	–
Arizona*	R multilane undivided, R two-lane	M	Within pm Into lane	N	N	N	N	N	N	–	–	–	–	–
California	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Colorado*	R multilane undivided, R two-lane	M	Within pm	N	N	N	N	Varies	N	12 in.	5 in.	0.375 in.	12 in.	6/02
Delaware*	U multilane undivided; R multilane undivided, R two-lane	M	Into lane	N	N	N	N	N	N	16 in.	7 in.	0.5 in.	12 in.	–
Hawaii	–	M	–	–	–	–	–	–	–	18–24 in.	4 in.	–	24 in.	–
Idaho*	R multilane undivided, R two-lane	–	Within pm Into lane	N	N	N	Y	N	N	–	–	–	–	–
Iowa*	R two-lane	–	Into lane	N	N	N	N	N	N	–	–	–	–	–
Kansas		M	–	–	–	–	–	–	–	12 in.	6.5 in.	0.5 in.	12 in. 12 in. and 24 in.	–
Kentucky*	R two-lane	M	Into lane	N	N	N	Y	Varies	N	24 in.	7 in.	0.5–0.625 in.	24 in.	–
Maine*	B multilane undivided	–	Into lane	N	N	N	N	3 in.	N	–	–	–	–	–
Maryland	–	M	–	–	–	–	–	–	–	18–24 in.	4 in.	0.5 in.	varies	–
Massachusetts	–	M	–	–	–	–	–	–	–	16 in.	6 in.	0.5 in.	12 in.	–
Michigan	–	M	–	–	–	–	–	–	–	16 in.	7 in.	0.375 in.	19 in.	–
Minnesota*	R two-lane	M	Beside pm	N	N	50 mph	N	N	N	12–16 in.	7 in.	0.5 in.	19 in.	–
Missouri*	R two-lane	M	Within pm	N	N	N	N	3.75 in.	N	12 in.	6.5 in.	0.5 in.	12.5 in.	–
Nebraska	–	M	–	–	–	–	–	–	–	16 in.	7 in.	0.5–0.625 in.	12 in.	–
Nevada*	U multilane undivided; R multilane undivided, R two-lane	–	Into lane	N	N	N	Y	N	N	–	–	–	–	–
North Carolina*	R two-lane	–	Into lane Beside pm	N	N	N	N	6 in.	N	–	–	–	–	–
Oregon*	R multilane undivided, R two-lane	M	Within pm Into lane	N	N	N	N	N	N	16 in.	7 in.	0.5 in.	12 in.	–

(continued on next page)

Table 7. (Continued).

State or province*	Pattern characteristics			Minimum requirements for installation						Dimensions				Date of policy
	Roadway type	Rumble type**	Placement	Lane width	ADT (vpd)	Speed	Accident	Pavement depth	Bicycle	Length (B)	Width (C)	Depth (D)	Spacing (E)	
Pennsylvania*	U multilane undivided; R multilane undivided, U two-lane R two-lane	M	Within pm Into lane	10 ft	Y	N	Y	N	N	16 in.	7 in. ± 0.5 in.	0.5 in. ± 0.0625 in.	24 in. and 48 in.	3/02
		M	Within pm Into lane	10 ft	Y	N	Y	N	N	14–18 in.	7 in. ± 0.5 in.	0.5 in. ± 0.0625 in.	24 in.	
Texas*	R multilane undivided, R two-lane	M	Into lane	N	N	N	N	N	N	16 in.	7 in.	0.5 in.	17 in.	–
Utah*	R multilane undivided, R two-lane	M	Into lane	N	N	N	N	N	N	12 in.	8 in.	0.625–0.75 in.	12 in.	–
Virginia*	U multilane undivided; R multilane undivided, R two-lane	M, RS	Within pm	N	N	N	N	N	N	16 in.	7 in.	0.5 in.	12 in.	–
Washington*	R multilane undivided, R two-lane	M	Within pm	12 ft	N	N	N	Varies	N	16 in.	5 in.	0.375 in.	12 in.	–
Wisconsin	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Wyoming*	R two-lane	M	Into lane	–	N	N	N	–	N	12 in.	7.5 in.	0.5 in.	14.5 in.	–
Canadian Provinces														
														–
Alberta	–	M	–	–	–	–	–	–	–	12 in.	6–8 in.	0.2–0.35 in.	13–15 in.	–
British Columbia*	R multilane undivided, R two-lane	M	Within pm	> 11 ft Eng. review	N	N	N	N	N	12 in. ± 0.375 in.	5.5 in. ± 0.75 in.	0.32 in. ± 0.125 in.	12 in.	5/04
Ontario*	R two-lane	M	Within pm	N	N	N	N	3 in.	N	12 in.	6 in. ± 0.75 in.	0.375 in. ± 0.125 in.	12 in.	–
Saskatchewan*	R multilane undivided, R two-lane	M	Within pm Into lane	N	N	N	N	N	N	12 in.	4–7 in.	0.315 in. ± 0.079 in.	10–13 in.	–

* Indicates state/province responded to survey and information from the survey is reflected in this table.

** Rumble Strip Type Abbreviations: M = Milled RS = Raised

5. *How close to the edgeline does your agency install shoulder rumble strips?*

   - Responses ranged from flush against the edgeline (i.e., 0 in. [0 mm]) to 30 in. (762 mm) from the edgeline.

   If the lateral placement from the edgeline is variable, what specific features are considered in determining the lateral placement of the shoulder rumble strips?

   - Responses included: (a) snow plowing considerations, (b) whether the installation was on the right (outside) shoulder or the left (median) shoulder, and (c) shoulder width/lateral clearance requirements.

6. *At what specific features or areas along the shoulder/roadway (e.g., ramps or catch basins) are rumble strips discontinued to avoid adverse consequences (e.g., pavement deterioration, noise, etc.)?*

   - Responses included: (a) entrance and exit ramps; (b) when the lateral clearance is less than required; (c) when turn lanes are provided; (d) at intersections, driveways, and median crossings; (e) near residential areas; (f) near catch basins; (g) near pavement joints; (h) bicycle routes; (i) structures; (j) where curb and gutter are installed; (k) when posted speed is 45 mph (70 km/h) or less; and (l) in urban areas.

7. *What features directly affect installation requirements within your agency's shoulder rumble strip policy or guidelines?*

Roadway Type:	74.2%	(23)
Shoulder Width:	80.6%	(25)
Lateral Clearance:	41.9%	(13)
ADT:	29.4%	(6)
Bicycles:	54.8%	(17)
Pavement Type:	35.5%	(11)
Pavement Depth:	25.8%	(8)
Area Type (i.e., urban vs. rural):	58.1%	(18)
Speed Limit:	16.1%	(5)
Crash frequency/rate:	35.5%	(11)
Other:	16.1%	(5)

   - Other responses included: (a) condition of existing shoulder, and (b) scheduled upgrades for the facility.

8. *Does your agency have a minimum shoulder width requirement for the installation of shoulder rumble strips?*

YES:	61.3%	(19)
NO:	35.5%	(11)

   If YES, please elaborate:

   - Responses ranged from 2 to 6 ft (0.6 to 1.8 m), but 4 ft (1.2 m) and 6 ft (1.8 m) were the most common responses.

9. *Does your agency have a minimum lateral clearance requirement for the installation of shoulder rumble strips?*

YES:	45.2%	(14)
NO:	51.6%	(16)

   If YES, please elaborate:

   - Responses ranged from 2 to 7 ft (0.6 to 2.1 m), but 4 ft (1.2 m) was the most common response.

10. *Does your agency have a minimum traffic volume requirement for the installation of shoulder rumble strips?*

YES:	16.1%	(5)
NO:	83.9%	(26)

   If YES, please elaborate:

   - Responses ranged from 400 to 3,000 veh/day.

11. *Does your agency have a minimum pavement depth requirement for the installation of shoulder rumble strips?*

YES:	25.8%	(8)
NO:	74.2%	(23)

   If YES, please elaborate:

   - Responses ranged from 3 to 6 in. (76 to 152 mm). One respondent had a minimum requirement of 1.75 in. (44 mm) for the final surface. Also several respondents had a general depth requirement but no minimum depth specified.

12. *Does your agency have a minimum speed limit requirement for the installation of shoulder rumble strips?*

YES:	12.9%	(4)
NO:	83.9%	(26)

   If YES, please elaborate:

   - Minimum speeds ranged from 45 to 50 mph (70 to 80 km/h).

13. *Does your agency have a minimum crash frequency/rate requirement for the installation of shoulder rumble strips?*

YES:	6.5%	(2)
NO:	90.3%	(28)

   If YES, please elaborate:

   - Respondents indicated that they compared the SVROR crash frequency to the statewide average.

14. *Does your agency's policy change depending upon whether shoulder rumble strips will be installed along a designated bicycle route?*

YES:	38.7%	(12)
NO:	58.1%	(18)

If YES, please elaborate:

- Responses included: (a) rumble strips are not installed along designated bicycle routes, (b) need to consider available lateral clearance, (c) rumble strip patterns/dimensions change, and (d) gaps are provided rather than installing the rumble strips on a continuous basis.

15. *Does your agency's policy provide a gap in the shoulder rumble strip pattern to allow bicyclists to maneuver from the travel lane to the shoulder and back without traversing the rumble strips?*

YES: 35.5% (11)
NO: 54.8% (17)

If YES, please describe the gap pattern and whether it varies with the type of facility:

- Common responses were 10 or 12 ft (3.0 or 3.6 m) gaps in 40 or 60 ft (12 or 18 m) cycles. One respondent increases the gap and cycle lengths when longer rumble strips are installed.

16. *Most agencies that use shoulder rumble strips install them continuously along extended sections of roadway. Does your agency, in some cases, install shoulder rumble strips along specific shorter sections of roadway (e.g., specific horizontal curves)?*

YES: 29.0% (9)
NO: 71.0% (22)

If YES, please elaborate:

- Common responses included: (a) based upon crash history, and (b) at horizontal curves.

17. *Has your agency installed milled, rolled, or formed rumble strips directly on the edgeline of the traveled way?*

YES: 48.4% (15)
NO: 51.6% (16)

18. *Has your agency installed textured pavement edgeline markings (e.g., thermoplastic) to stimulate the driver with audible or tactile sensations (i.e., rumble stripes)?*

YES: 29.0% (9)
NO: 71.0% (22)

19. *Has your agency's policy/practice of installing shoulder rumble strips changed recently (i.e., within the last 3 to 5 years)?*

YES: 48.4% (15)
NO: 51.6% (16)

If YES, how has it changed?

- Common responses included: (a) now install intermittent gaps and (b) discontinued the use of rolled rumble strips.

20. *Do you anticipate that your agency's policy/practice of installing shoulder rumble strips will change in the next year or so (i.e., are changes planned or are modifications currently being drafted)?*

Yes: 29.0% (9)
NO: 71.0% (22)

If YES, please explain what type of modifications will be made or are anticipated?

- Responses included: (a) adopting a written policy when no policy previously existed, (b) adopting a policy for other roadway types, (c) modifying the depth dimension, and (d) changing the length of intermittent gaps.

Survey Results: Centerline Rumble Strip Policies and Practices

21. *Does your agency have a written policy or set of guidelines for the installation/application of centerline rumble strips on undivided roads?*

YES: 29.0% (9)
NO: 71.0% (22)

If NO, does your agency use centerline rumble strips?

YES: 45.2% (14)
NO: 25.8% (8)

- Total agencies using centerline rumble strips: 74.2% (23)

22. *Concerning the lateral placement of centerline rumble strips, check the type(s) of applications that have been installed by your agency?*

Centerline rumble strips within pavement markings: 38.7% (12)

Centerline rumble strips extend into travel lane: 48.4% (15)

Centerline rumble strips on either side of pavement markings: 6.5% (2)

23. *On what type of roadways does your agency install centerline rumble strips? (Select all that apply.)*

Urban multilane undivided highways (nonfreeways):	9.7%	(3)
Urban two-lane roads:	6.5%	(2)
Rural multilane undivided highways (nonfreeways):	38.7%	(12)
Rural two-lane roads:	71.0%	(22)
Other:	6.5%	(2)

24. *Does your agency have a minimum lane width requirement for the installation of centerline rumble strips?*

YES:	9.7%	(3)
NO:	71.0%	(22)

If YES, please elaborate:

- The responses were 10 ft (3.0 m), 11 ft (3.3 m), and 12 ft (3.6 m) (combined lane and shoulder width).

25. *Does your agency have a minimum traffic volume guideline for the installation of centerline rumble strips?*

YES:	3.2%	(1)
NO:	77.4%	(24)

If YES, please elaborate:

- 1,500 ADT

26. *Does your agency have a minimum speed limit guideline for the installation of centerline rumble strips?*

YES:	3.2%	(1)
NO	74.2%	(23)

If YES, please elaborate:

- 50 mph (80 km/h)

27. *Does your agency have a minimum crash frequency/rate guideline for the installation of centerline rumble strips?*

YES:	12.9%	(4)
NO:	67.7%	(21)

28. *Has your agency installed both centerline rumble strips and shoulder rumble strips along the same roadway?*

YES:	35.5%	(11)
NO:	38.7%	(12)

If YES, approximately how many miles of this dual application have been installed?

- Responses ranged from 5 to 50 mi (8 to 80 km)

Survey Results: General Issues

29. *Has your agency installed midlane rumble strips (i.e., rumble strips installed in the center of the travel lane)?*

YES:	0.0%	(0)
NO:	100.0%	(29)

If NO, what is the possibility that your agency would consider installing midlane rumble strips on an experimental basis?

Highly unlikely:	61.5%	(16)
Willing to consider:	34.6%	(9)
High likelihood:	3.8%	(1)

NOTE: Three states actually responded "YES" to this question, but after several follow-up telephone conversations, it was determined that either the respondent misunderstood the question or simply provided an incorrect response.

30. *Does your agency have statewide or district-level data in electronic format that contains information concerning the application of shoulder and/or centerline rumble strips (e.g., implementation dates, design information, etc.)?*

YES:	29.0%	(9)
NO:	58.1%	(18)

31. *Does your agency install rumble strips?*

Only as part of larger projects?	6.5%	(2)
As a stand-alone safety improvement?	6.5%	(2)
Both situations?	83.9%	(26)

32. *Does your agency have data on bicycle-only crashes or noncrash injuries related to rumble strip encounters?*

YES:	0%	(0)
NO:	100%	(31)

33. *We are currently setting priorities for the research in NCHRP Project 17-32. Your opinion would be appreciated. Please rank the priority for research to address gaps in knowledge associated with SHOULDER rumble strips. Please rank each research need on a 1 (Low Priority) to 5 (High Priority) scale.*

Table 8 presents the survey responses to Question 33 in prioritized order. The higher priority issues are provided at the top of the table, while the low priority issues are provided at the bottom of the table.

Table 8. Transportation agency responses concerning future research needs related to shoulder rumble strips.

Unresolved issue	Priority ranking		
	Avg. value	Min. value	Max. value
Determine minimum shoulder width	3.8	1	5
Better quantify safety effectiveness (along different types of roads)	3.7	1	5
Determine optimum lateral placement from the edgeline	3.6	1	5
Determine effect on pavement performance	3.4	1	5
Determine impact of noise produced by rumble strips on adjacent residents	3.3	1	5
Determine minimum level of stimuli (i.e., sound or vibration) necessary to alert a drowsy or inattentive driver	3.3	1	5
Determine effect on maintenance activities	3.1	1	5
Better quantify safety effectiveness (along varying roadside conditions—e.g., 10 ft clear zone vs. 20. ft clear zone vs. 30 ft clear zone)	3.1	0	5
Better quantify safety effectiveness (along varying roadway geometry)	3.0	1	5
Determine optimum dimensions (e.g., length, width, depth, spacing)	3.0	1	5
Determine optimum longitudinal gaps in rumble strips to provide accessibility for bicyclists	2.8	0	5
Improve physical design of rumble strips with respect to rideability for bicyclists and motorcyclists	2.8	1	5
Better quantify safety effectiveness (differences in rumble strips installed along the right (outside) vs. left (median) shoulders)	2.8	0	5
Better quantify safety effectiveness (along roadways with varying speeds or ADT)	2.8	1	5
Better quantify safety effectiveness (under varying conditions—e.g., wet vs. dry, light vs. dark, etc.)	2.7	0	5
Other—determine benefit of painting edgelines through shoulder rumble strips (1 respondent)	*4.0*	*4*	*4*
Other—determine effect of rumble strips in edgeline pavement marking from safety, visibility, and durability aspect (1 respondent)	*5.0*	*5*	*5*

34. *Please rank the priority for research to address gaps in knowledge associated with CENTERLINE rumble strips? Please rank each research need on a 1 (Low Priority) to 5 (High Priority) scale.*

    Table 9 presents the survey responses to Question 34 in prioritized order. The higher priority issues are provided at the top of the table, while the low priority issues are provided at the bottom of the table.

Summary of Key Findings From Existing Rumble Strip Practices and Policies

The following key points are drawn from the recent rumble strip surveys and synthesis documents:

- It is believed that at least 46 out of the 50 state transportation agencies within the United States install shoulder rumble strips on at least one type of roadway; however, several state transportation agencies do so without a written policy.
- Shoulder rumble strips are being installed on a wide variety of roadway types including urban freeways, urban freeway on-ramps and off-ramps, urban multilane divided highways (nonfreeways), urban multilane undivided highways (nonfreeways), urban two-lane roads, rural freeways, rural freeway on-ramps and off-ramps, rural multilane divided highways (nonfreeways), rural multilane undivided highways (nonfreeways), and rural two-lane roads. The majority of the installations are on rural roads compared to urban roads. It should be pointed out that the numbers shown in response to Question 2 of the survey may be somewhat misleading in terms of the total mileage of shoulder rumble strip installations along the respective roadway types. As part of the safety evaluation of shoulder rumble strips conducted during this research, several of the responding agencies that indicated in their survey response that they installed rumble strips on a wide range of the respective roadway types were contacted. However, in requesting sites with rumble strips for inclusion in the safety evaluation, several of the agencies had difficulty identifying sites with rumble strips covering the full range of roadway types or, in some cases, indicated that the mileage for certain roadway types was extremely low.

Table 9. Transportation agency responses concerning future research needs related to centerline rumble strips.

Unresolved issue	Priority ranking		
	Avg. value	Min. value	Max. value
Determine effect on visibility of pavement markings	3.8	1	5
Operational impacts on vehicular traffic (i.e., vehicle speeds and lateral placement)	3.7	1	5
Determine optimum dimensions (e.g., length, width, depth, spacing)	3.7	1	5
Assess advantages/disadvantages of installing centerline rumble strips in passing zones	3.6	1	5
Determine optimum placement with respect to the centerline markings	3.6	1	5
Better quantify safety effectiveness (along different types of roads—e.g., two-lane highway, multilane highways, etc.)	3.5	1	5
Determine effect on pavement performance	3.4	1	5
Better quantify safety effectiveness (along varying roadway geometry)	3.2	0	5
Better quantify safety effectiveness (installed in combination with shoulder rumble strips)	3.2	1	5
Determine impact of noise produced by rumble strips on adjacent residents	3.0	0	5
Determine effect on maintenance activities	3.0	1	4
Better quantify safety effectiveness (along roadways with varying speeds or ADT)	2.9	1	5
Better quantify safety effectiveness (under varying conditions)	2.8	0	5
Improve physical design of rumble strips with respect to rideability for bicyclists and motorcyclists	2.6	1	5
Other—potential effect of centerline rumble strips on longitudinal pavement joints (1 respondent)	*4.0*	*4*	*4*
Other—determine effect of rumble strips in edgeline pavement marking from safety, visibility, & durability aspect (1 respondent)	*5.0*	*5*	*5*

Based upon the survey results and our experience in trying to identify sites with shoulder rumble strips for inclusion in the safety evaluation, we found that a significant number of miles of shoulder rumble strips are installed along urban freeways, rural freeways, rural multilane divided highways, and rural two-lane roads, and significantly less mileage of shoulder rumble strips are installed along urban multilane divided highways, urban multilane undivided highways, urban two-lane roads, and rural multilane undivided highways.

- Written shoulder rumble strip policies and specifications differ considerably by the shoulder pavement surface type (i.e., concrete or asphalt).
- Rumble strip policies incorporate a wide range of criteria that directly impact installation requirements for shoulder rumble strips. These criteria include the following:
  - Roadway type
  - Shoulder width
    - 26 transportation agencies specify a minimum shoulder width requirement within their written policy.
    - Minimum requirements range from 2 to 10 ft (0.6 to 3.0 m), with 4 ft (1.2 m) being the most common value.
    - Several transportation agencies have different minimum requirements for different types of roads.
  - Lateral clearance
    - 16 transportation agencies specify a minimum lateral clearance requirement within their written policy.
    - Minimum requirements range from 2 to 7 ft (0.6 to 2.1 m), with 4 ft (1.2 m) and 6 ft (1.8 m) being the most common values.
    - Several transportation agencies specify both a minimum shoulder width requirement and a lateral clearance requirement, and in several cases the lateral clearance requirement is greater than the shoulder width requirement. For these cases, it must be assumed that the lateral clearance is measured to the closest fixed object on the roadside, beyond the outside edge of the paved shoulder.
  - ADT
    - 5 transportation agencies specify minimum ADT levels within their written policy.
    - Minimum ADT levels for rumble strips range from 400 to 3,000 veh/day, but a majority fall between 1,500 and 3,000 veh/day.
  - Bicycles
    - 16 transportation agencies address bicycle considerations in some manner within their written policy.

- Pavement type
  - Several transportation agencies only install shoulder rumble strips on asphalt shoulders.
  - Pavement type impacts the placement of the rumble strips because of joints in PCC surfaces.
- Pavement depth
  - 8 transportation agencies specify a minimum pavement depth requirement within their written policy.
  - Minimum requirements range from 1 to 6 in. (25 to 152 mm).
- Area type
  - Most transportation agencies install shoulder rumble strips in rural areas.
  - 27 transportation agencies install shoulder rumble strips in urban areas.
- Speed limit
  - 8 transportation agencies have a speed limit requirement in their written policy.
- Crash frequencies/rates
  - 2 transportation agencies have a crash frequency/rate requirement within their written policy.

• A variety of shoulder rumble strip types are used in North America. These include milled, rolled, raised, or formed. Based on noise and vibration research, milled rumble strips generally provide higher in-vehicle noise and vibration levels than rolled rumble strips. Currently, milled rumble strips are the preferred type among most transportation agencies.
• Transportation agencies have varying policies concerning where rumble strips are installed with respect to the edgeline. Offset distances range from 0 to 30 in. (0 to 762 mm). Eighteen transportation agencies have installed rumble strips on the edgeline of the travel way. Other common offset distances are 6 to 12 in. (152 to 305 mm). Only a few transportation agencies install shoulder rumble strips with an offset distance greater than 12 in. (305 mm). Several transportation agencies specify different offsets for rumble strips installed on the right (outside) shoulder and rumble strips installed on the left (median) shoulder. Typically, the offset for the left (median) shoulder is less than the offset for the right (outside) shoulder.
• Typical dimensions for milled shoulder rumble strips are the following:
  - Length: 16 in. (406 mm)
    - Several transportation agencies install rumble strips as short as 6, 8, or 12 in. (152, 203, or 305 mm), but 16 in. (406 mm) is definitely the most common length.
  - Width: 7 in. (178 mm)
    - Widths commonly range from 5 to 7 in. (127 to 178 mm), but 7 in. (178 mm) is by far the most common. At least one transportation agency installs rumble strips with a width of 8 in. (203 mm).
  - Depth: 0.5 to 0.625 in. (13 to 16 mm)
    - Many transportation agencies specify the depth to be between 0.5 to 0.625 in. (13 to 16 mm). A groove depth of 0.5 in. (13 mm) is also common. Several transportation agencies specify depths as small as 0.375 in. (10 mm).
  - Spacing: 12 in. (305 mm)
    - Most transportation agencies specify a spacing of 12 in. (305 mm). Some transportation agencies install rumble strips with 11 in. (280 mm) spacing, while others increase the spacing to 18 in. (457 mm).
• On non-controlled access highways, it is common for transportation agencies to provide periodic gaps in the rumble strips of 10 or 12 ft (3.0 or 3.6 m), in 40 or 60 ft (12 or 18 m) cycles, with the primary intention to allow bicyclists to maneuver from the travel lanes to the shoulder and back (i.e., from one side of the rumble strips to the other) without having to encounter the indentations/grooves.
• In addition to providing periodic gaps in continuous rumble strips to enable bicyclists to cross over the rumble strips without encountering the indentations/grooves, it is common practice to discontinue or interrupt shoulder rumble strips at specific features or areas to avoid adverse consequences (e.g., pavement deterioration, noise, etc.). Specific features or areas along the shoulder or roadway where it is common to discontinue or interrupt shoulder rumble strips include the following:
  - Intersections, driveways, and turn lanes;
  - Entrance and exit ramps;
  - Structures (i.e., bridges);
  - Areas where the lateral clearance drops below a specified value and/or areas where the lateral clearance is limited due to adjacent guardrail, curb, or other obstacles;
  - Residential areas;
  - Catch basins and drainage grates;
  - Pavement joints; and
  - Median crossings.
• Fewer transportation agencies use centerline rumble strips than shoulder rumble strips, and only a few transportation agencies that use centerline rumble strips have a written (i.e., formal) policy. The majority of centerline rumble strips have been installed on rural two-lane undivided roads; however, centerline rumble strips have been installed on rural multilane undivided highways and to a lesser degree on urban two-lane undivided roads and urban multilane undivided highways. The responses to Question 23 concerning the types of roadways where centerline rumble strips are installed may be misleading. While trying to identify sites with centerline rumble strips on urban multilane undivided highways, urban two-lane roads, rural multilane undivided highways, and rural two-lane roads, responding agencies that indicated they installed centerline rumble strips on such sites had difficulty

identifying any sites for inclusion in a safety evaluation for many of the roadway types. Based upon our experience and the survey responses, it is our opinion that centerline rumble strips are commonly installed along rural two-lane roads, and very few installations have occurred on the other three roadway types. In most cases, where centerline rumble strips have been installed along a rural multilane undivided highway, the installation was part of an extended project along a rural two-lane road, and rather than discontinuing the centerline rumble strips along shorter multilane sections within the limits of the entire project, the rumble strips were installed on the multilane sections as well.

- Although many transportation agencies incorporate a wide range of criteria that directly impact installation requirements for shoulder rumble strips, very few criteria are specified for the installation of centerline rumble strips. Two transportation agencies have a lane width requirement, one transportation agency has a traffic volume requirement, one transportation agency has a speed limit requirement, four transportation agencies have a crash frequency/rate requirement, six transportation agencies have a pavement depth requirement, and no state transportation agency directly addresses bicycle considerations for determining the installation of centerline rumble strips.
- Most transportation agencies install centerline rumble strips within the boundaries of the centerline markings or a portion of the rumble strips may extend slightly into the travel lane. Only two transportation agencies install centerline rumble strips on either side of the centerline pavement markings.
- All transportation agencies in North America that install centerline rumble strips use milled rumble strips.
- Typical dimensions for milled centerline rumble strips are as follows:
  - Length: 12 or 16 in. (305 to 406 mm)
    - This dimension varies considerably among transportation agencies. Lengths range from 12 to 24 in. (305 to 610 mm).
  - Width: 7 in. (178 mm)
    - Widths commonly range from 5 to 7 in. (127 to 178 mm), but 7 in. (178 mm) is by far the most common. At least one transportation agency installs rumble strips with a width of 8 in. (203 mm).
  - Depth: 0.5 in. (13 mm)
    - Many transportation agencies specify the depth to be 0.5 in. (13 mm). Several transportation agencies specify a range for the depth from 0.5 to 0.625 in. (13 to 16 mm). Several transportation agencies specify depths as small as 0.375 in. (10 mm).
  - Spacing: 12 in. (305 mm)
    - Many transportation agencies specify a 12-in. (305-mm) spacing, but this dimension varies considerably, ranging from 10 to 48 in. (254 to 1220 mm), among transportation agencies. Some transportation agencies also alternate the spacing between grooves.
- Midlane rumble strips are still a concept that no transportation agency has been willing to install, even on a trial or experimental basis. Several transportation agencies indicated that they would be willing to consider such a treatment.

SECTION 6

Safety Effectiveness of Shoulder Rumble Strips

The safety evaluation of shoulder rumble strips addresses two key unresolved issues: (a) the safety effectiveness of shoulder rumble strips on various roadway types, and (b) whether the placement of rumble strips with respect to the edgeline impacts the safety effectiveness of the treatment. Other issues that are addressed in lesser detail include determining the impact of shoulder rumble strips on heavy vehicle crashes, crashes that occur under adverse pavement conditions, and crashes that occur during low-lighting conditions.

Previous safety evaluations of shoulder rumble strips have focused on determining the safety effectiveness of this treatment installed along freeway facilities, primarily in rural areas, but, to a lesser degree, in urban areas as well. This is mainly because the initial use of shoulder rumble strips was primarily on rural freeways. As evident from the survey results in Section 5, in recent years shoulder rumble strips have been installed along all types of roadways. *NCHRP Report 617* (*28*) indicates that rolled shoulder rumble strips reduce all SVROR crashes by 21 percent on rural freeways and by 18 percent on all freeways (i.e., both rural and urban combined). It also reports that rolled shoulder rumble strips reduce SVROR-injury crashes by 7 percent on rural freeways and by 13 percent on all freeways. These safety estimates and others, including safety estimates for rural multilane divided highways, are incorporated in the draft chapters of the forthcoming HSM, but in most cases the safety estimates (i.e., AMFs) are not very reliable. In summary, reliable estimates of the safety effectiveness of shoulder rumble strips for different roadway types are not available, and in all likelihood the safety benefits of shoulder rumble strips vary by roadway type because the different types of roadways are built to varying standards (e.g., lane widths, shoulder widths, roadside), accommodate varying traffic volumes and distributions, serve different driver populations, and accommodate a range of operating speeds.

Also evident from the survey results, transportation agencies install rumble strips at various locations with respect to the edgeline. Typical offset distances range from 0 to 30 in. (0 to 762 mm) from the edgeline. By placing the shoulder rumble strips closer to the edgeline (or in some cases on the edgeline), drivers are alerted sooner that their vehicles have departed from the travel lane than if the rumble strips are placed further from the edgeline on the shoulder. More recovery area is also available on the shoulder when the rumble strips are located closer to the edgeline. On the other hand, when rumble strips are located closer to the edgeline, drivers are more likely to run over them in nonemergency situations. It is not known how the offset distance influences the safety effectiveness of rumble strips.

Other issues that have not been fully investigated in previous research concern the impact that shoulder rumble strips may have on specific target crashes, such as heavy vehicle crashes and/or crashes that occur under adverse pavement conditions or low-lighting (i.e., nighttime) conditions. The safety effect that shoulder rumble strips have on crashes involving heavy vehicles is of interest because (a) it is unclear whether the stimuli (i.e., noise and vibration) generated by rumble strips are sufficient to alert drivers of heavy vehicles, (b) designing rumble strip patterns specifically for heavy vehicles will likely conflict with needs of other road users such as bicyclists, and (c) it is difficult to assess the need or priority to specifically consider heavy vehicles in the design of shoulder rumble strips given the frequency of crashes involving heavy vehicles that would likely be affected by the installation of shoulder rumble strips. Finally, although the primary purpose of shoulder rumble strips is to alert inattentive and drowsy drivers that their vehicles have departed from the travel lanes, it is likely that this safety treatment also indirectly affects crashes that occur under adverse pavement conditions (i.e., rainy or snowy conditions) and during low-lighting (i.e., nighttime) conditions. For example, snow plow drivers have noted that they have come to depend on shoulder rumble strips to help them find the edge of the travel lane during heavy snow and other low-visibility situations, so in some situations when the lane lines (i.e., edgelines) might be difficult to see either because of precipitation or low retroreflectivity, shoulder rumble strips can serve to provide positive guidance to drivers who are not necessarily inattentive or drowsy, but may just find it difficult to follow the delineation of the roadway.

This section describes the general scope of the safety evaluation conducted to resolve these issues, the site selection process, the videolog data collection procedures, the database development, the analysis approach, and the analysis results.

Scope of Safety Evaluation

The primary objectives of the safety evaluation conducted as part of this research are to do the following:

- Quantify the safety effectiveness of milled shoulder rumble strips on specific types of roads including urban freeways, urban multilane divided highways (nonfreeways), urban multilane undivided highways (nonfreeways), urban two-lane roads, rural freeways, rural multilane divided highways (nonfreeways), rural multilane undivided highways (nonfreeways), and rural two-lane roads.
- Quantify the safety effectiveness of shoulder rumble strips placed in varying locations with respect to the edgeline.

The safety effectiveness evaluation is based on the change in crash frequency for total (TOT) crashes, fatal and injury (FI) crashes, SVROR crashes, and/or SVROR FI crashes. Depending upon the comparison, the data are analyzed using either an Empirical Bayes (EB) methodology for before-after analysis or a cross-sectional approach for analyses across treatment sites (i.e., sites with milled shoulder rumble strips) and non-treatment sites (i.e., sites without any type of shoulder rumble strip). The Analysis Approach part of this section describes the similarities and differences between these two analysis approaches. Additional analyses are performed to investigate the impact that shoulder rumble strips have on selected target SVROR crashes, including the following:

- Crashes involving heavy vehicles (i.e., trucks),
- Crashes occurring under adverse pavement conditions, and
- Crashes occurring during low-light conditions (i.e., dusk, dawn, or dark).

As part of the safety evaluation of shoulder rumble strips, steps were taken in an effort to quantify the difference in safety effectiveness between rumble strips installed on the right (outside) shoulder of a divided highway and rumble strips installed on the left (median) shoulder of a divided highway. A key element for being able to address this issue is the capability to distinguish the location of the crashes within the right-of-way. Rumble strips installed on the right (outside) shoulder are expected to reduce SVROR crashes to the right that occur on the roadside, while rumble strips installed on the left (median) shoulder are expected to reduce SVROR crashes to the left that occur within the median. Rules were developed to distinguish between SVROR-right and SVROR-left crashes from the electronic crash databases that had been assembled in conjunction with this safety evaluation. The accuracy of the rules was assessed by comparing the query results to a sampling of hard copies of the crash reports. Approximately 100 crash reports were reviewed during this process. Based upon the results of the sampling, SVROR-left and SVROR-right crashes could not be accurately distinguished in the electronic databases assembled. Because resources were too limited to review hard copies of the crash reports for all of the crashes (or a large sampling of the crashes) in the respective databases, a decision was made to terminate efforts to address this issue.

Based upon the safety evaluation of milled shoulder rumble strips on a range of roadway types, AMFs are developed for potential incorporation in HSM. The AMFs (and associated standard errors) are developed in a manner consistent with the method correction factor procedures developed for use in conjunction with the HSM (*65*).

Site Selection

Representatives from the Georgia, Kentucky, Minnesota, Missouri, and Pennsylvania DOTs were contacted to inquire about potentially including sites from their respective states in the safety evaluation. Types of information gathered to determine whether sites from a particular state would be appropriate for this study included the following:

- Has the agency installed shoulder rumble strips on a range of roadway types of interest for this study?
- Does the agency have the ability to identify locations where shoulder rumble strips have been installed?
- Does the agency have the ability to provide construction history information such as rumble strip installation dates and information about other improvements made during the study period?
- Does the agency keep a library of videologs that could be accessed by the research team?
- Is the agency willing to participate in the research and work with the research team to gather the necessary data for the safety evaluation?

Through a series of phone interviews and, in one case, a visit to the central office, it was determined to include sites from Minnesota, Missouri, and Pennsylvania in the safety evaluation. Subsequently, official requests were made to the respective DOTs to provide a list of locations where shoulder rumble strips had been installed. A list of selection criteria was provided and explained to the DOTs in an effort to develop a list of treatment sites that could be used in a before-after safety evaluation. The following were selection criteria for identifying candidate treatment sites:

- Roadway type—Identify locations along the following roadway types where shoulder rumble strips have been installed:
  - Urban freeways,
  - Urban multilane divided highways (nonfreeways),
  - Urban multilane undivided highways (nonfreeways),
  - Urban two-lane roads,
  - Rural freeways,
  - Rural multilane divided highways (nonfreeways),
  - Rural multilane undivided highways (nonfreeways), and
  - Rural two-lane roads.
- Installation date—Shoulder rumble strips should have been installed sometime between calendar years 1997 and 2003.
- Type of safety improvement:
  - 1st priority—Sites where installation of a shoulder rumble strip was the only recent improvement (safety or otherwise) made to the site.
  - 2nd priority—Sites where the shoulders (and/or travel lanes) were paved in conjunction with installing shoulder rumble strips (i.e., a resurfacing project followed by the installation of shoulder rumble strips). The shoulder widths before and after paving should be the same, and no other improvements (safety or otherwise) have been made recently.
- Type of rumble strip:
  - The focus of the study is on milled rumble strips, so a priority is placed on sites with milled rumble strips.
- Placement of the shoulder rumble strips with respect to the edgeline:
  - Sites should be identified with a range of offset distances (i.e., from edgeline rumble strips/stripes to offsets as far from the edgeline as the DOT's policy permits). Ideally, sites with a range of offsets within a roadway type (e.g., rural freeways) would be preferable.

The information provided by each state DOT based upon this initial inquiry for a list of treatment sites varied considerably. The following sections summarize the tasks conducted for the respective states to select treatment sites (i.e., sites with milled shoulder rumble strips) for inclusion in this safety evaluation. The next part on videolog data collection provides more details on how treatment and nontreatment sites (i.e., sites without any type of shoulder rumble strip, whether milled, rolled, formed, or raised) were identified for use in the analysis.

Minnesota Sites

Minnesota DOT (MnDOT) provided an initial list of treatment locations. The information provided with this list included the district, route type, route number, beginning and ending mileposts, installation dates, notes concerning the type of rumble strip installation, and dimension and offset information. The initial list contained many duplicate sites, and much of the information was incomplete. A series of telephone interviews were held with each district office to do the following:

- Learn more about the construction history of each site to determine whether the rumble strips were installed in conjunction with other improvements at the site or were a stand-alone improvement. In many cases, the shoulder rumble strips were installed as part of a resurfacing project, but the cross section of the roadway (e.g., lane widths and shoulder widths) remained unchanged.
- Verify the type of rumble strip installation (e.g., milled shoulder rumble strips). In some cases, candidate sites from the list were eliminated from further consideration because they included rolled rumble strips rather than milled rumble strips.
- Gather missing information, such as the installation dates of the rumble strips, and when possible, offset information.

Following the interviews, a comprehensive list of treatment sites was compiled, eliminating duplicate sites and only including those sites that appeared to be the most appropriate for inclusion in a before-after evaluation of milled shoulder rumble strips. Using roadway characteristic data available from the FHWA's Highway Safety Information System (HSIS), the treatment sites were categorized according to the eight roadway types of interest for the study.

After having compiled a prioritized list of sites for data collection, the research team reviewed each of the sites using MnDOT's videolog system. The next part on Videolog Data Collection provides detailed information on the actual data collection process performed for sites in Minnesota and the other states.

MnDOT's videolog system contains videologs for calendar years 2000–2006. Initially, the 2006 videologs were reviewed to confirm the presence or absence of the rumble strips at the locations. Subsequently, the 2001–2005 videologs were reviewed to confirm the installation dates of the rumble strips at each site where the rumble strips were installed during calendar years 2002–2005. In the prioritized list of candidate treatment sites, the installation dates of the rumble strips ranged from 1983 to 2006. Only those installation dates between calendar years 2002 and 2005 could be confirmed during this process by verifying the absence/presence of the shoulder rumble strips across multiple years.

This process of confirming installation dates revealed that approximately 50 percent of the dates obtained either from the initial list or during the interviews with district personnel were correct. This relatively poor accuracy level of the installation dates for the treatment sites caused serious concern, especially since it is reasonable to assume that the more recent installations would have more accurate information than the older installations. As a result of this finding, the following rules were applied concerning installation dates and the applicability of a site for inclusion in a before-after evaluation or a cross-sectional analysis:

- For those sites with installation dates prior to and including calendar year 2000, the site was automatically determined to be inappropriate for a before-after evaluation but appropriate for a cross-sectional analysis, and the analysis period was defined to extend from 2001 to 2005.
- For those sites with installation dates during calendar year 2001, if the rumble strips were confirmed to be present during the review of the 2001 videolog, then the site was determined to be inappropriate for a before-after evaluation but appropriate for a cross-sectional analysis, and the analysis period was defined to extend from 2001 to 2005. If the rumble strips were confirmed to be absent during the review of the 2001 videolog but were present during the review of the 2002 videolog, then the site was determined to be appropriate for a before-after evaluation, and the analysis period was defined to extend from 1997 to 2005 with an installation date of 2001.
- For those sites with installation dates during calendar years 2002 and 2005, installation dates were confirmed or modified based upon the absence and/or presence of the rumble strips from the yearly videologs. In some cases the videologs were recorded in the spring, while others were recorded in the fall so the date of the yearly videologs was taken into consideration when determining the calendar year of the installation.

Through this process, the treatment sites in Minnesota were selected for inclusion in this safety evaluation, the sites were classified as being appropriate for a before-after evaluation and/or a cross-sectional analysis, and the analysis periods were determined based upon the available crash data and construction history. More details are provided in Analysis Approach later in this section.

Table 10 shows the total mileage (by roadway type) of treatment and nontreatment sites from Minnesota considered for inclusion in the safety evaluation. This table reflects total mileage for treatment and nontreatment sites after a series of data quality checks were performed to ensure data were consistent and complete for each location. This table does not classify the mileage by installation dates, or by total mile-years that can be used for before- and after-period analyses in a before-after evaluation or the total mile-years that can be used in a cross-sectional analysis. This level of detail is provided in the descriptive statistics part of this section.

Missouri Sites

Missouri DOT (MoDOT) did not have an efficient manner to identify locations where milled shoulder rumble strips were present based upon the selection criteria provided. MoDOT's central office initially generated a list of locations where shoulder rumble strips were installed during 2001 through 2005; however, this list did not provide information on whether the rumble strips were installed as the only improvement to the site or in conjunction with other improvements, nor did the list identify the type of rumble strip (i.e., milled, rolled, or formed). Each district office was contacted to help provide this information. The district offices provided the requested infor-

Table 10. Total mileage of Minnesota treatment and nontreatment sites considered for inclusion in the safety evaluation of shoulder rumble strips.

Roadway type	Treatment sites (mi)	Nontreatment sites (mi)
Urban freeways	1.72	110.97
Urban multilane divided highways (nonfreeways)	8.48	60.82
Urban multilane undivided highways (nonfreeways)	0.00	1.90
Urban two-lane roads	2.41	0.00
Rural freeways	109.15	23.42
Rural multilane divided highways (nonfreeways)	123.32	73.17
Rural multilane undivided highways (nonfreeways)	0.00	0.61
Rural two-lane roads	284.72	86.66
Totals across all roadway types	529.80	357.55

mation to the best of their capability, but much of the information remained missing. For those sites where complete information had been provided and the site appeared appropriate for inclusion in the safety evaluation, and for those sites where installation dates and the construction history were incomplete, the research team turned to the videologs to gather this information. For those candidate treatment sites identified for videolog review, roadway characteristic data were obtained from MoDOT's Transportation Management System (TMS) database. Using the roadway characteristic data, the candidate treatment sites were grouped according to the eight roadway types of interest for the study.

Table 11 shows the total mileage (by roadway type) of treatment and nontreatment sites from Missouri considered for inclusion in the safety evaluation. Similar to the previous table, this table reflects total mileage for treatment and nontreatment sites after a series of data quality checks were performed to ensure data were consistent and complete for each location. This table does not classify the mileage by installation dates or by total mile-years. This level of detail is provided in the Descriptive Statistics part of this section.

Pennsylvania Sites

The Pennsylvania DOT (PennDOT) maintains a database of low-cost safety improvements made across the entire state of Pennsylvania. From this database, PennDOT provided a list of approximately 150 safety improvement projects where the installation of shoulder rumble strips was the only safety improvement made as part of the project. This list included the location of the safety projects on the state highway network and the installation date of the project. The research team reviewed the locations of these safety projects using PennDOT's videolog, accessible via the Internet. This review could only confirm that approximately 43 percent of the safety projects from the initial list were actually constructed. In some cases the research team could not confirm the presence of shoulder rumble strips because the quality of the videolog was poor, while in other instances, the quality of the videolog was high, but the videolog showed that milled shoulder rumble strips were not present at the site. Additional treatment sites were identified either through personal knowledge of the installations or during the process of identifying nontreatment sites for the evaluation. For those treatment sites included in the evaluation but not included in the initial list of safety improvement projects provided by PennDOT, the research team contacted the PennDOT district offices to inquire about the construction history of the sites. For some districts, PennDOT personnel provided the necessary information, while for other districts the research team visited the district offices and reviewed plans, contracts, and other documentation to gather the construction history and installation date data. Comparisons of the dates of the videologs and the installation dates were used to determine the appropriateness of the site for a before-after evaluation and/or a cross-sectional analysis.

Table 12 shows the total mileage (by roadway type) of treatment and nontreatment sites from Pennsylvania considered for inclusion in the safety evaluation. This table is similar to the tables for Minnesota and Missouri.

Summary of Sites Across All States

Table 13 shows the total mileage (by roadway type) of treatment and nontreatment sites summed across all three states (i.e., Minnesota, Missouri, and Pennsylvania) considered for inclusion in the safety evaluation of shoulder rumble strips. Based on the total mileage of both treatment and nontreatment sites across all three states, Table 13 suggests that analyses of the data for urban freeways, rural freeways, rural multilane divided

Table 11. Total mileage of Missouri treatment and nontreatment sites considered for inclusion in the safety evaluation of shoulder rumble strips.

Roadway type	Treatment sites (mi)	Nontreatment sites (mi)
Urban freeways	5.13	0.51
Urban multilane divided highways (nonfreeways)	1.56	6.95
Urban multilane undivided highways (nonfreeways)	0.00	1.92
Urban two-lane roads	0.00	3.15
Rural freeways	77.73	7.91
Rural multilane divided highways (nonfreeways)	21.43	15.04
Rural multilane undivided highways (nonfreeways)	0.00	0.31
Rural two-lane roads	12.85	77.20
Totals across all roadway types	118.70	112.99

Table 12. Total mileage of Pennsylvania treatment and nontreatment sites considered for inclusion in the safety evaluation of shoulder rumble strips.

Roadway type	Treatment sites (mi)	Nontreatment sites (mi)
Urban freeways	63.95	19.88
Urban multilane divided highways (nonfreeways)	0.23	2.47
Urban multilane undivided highways (nonfreeways)	0.00	0.46
Urban two-lane roads	1.23	26.88
Rural freeways	70.83	25.23
Rural multilane divided highways (nonfreeways)	5.36	3.43
Rural multilane undivided highways (nonfreeways)	0.00	0.00
Rural two-lane roads	23.34	99.49
Totals across all roadway types	164.94	177.84

highways (nonfreeways), and rural two-lane roads have the greatest potential to provide meaningful results.

Special attention should be drawn to the total nontreatment miles for rural freeways. During the site selection process it was very difficult to find appropriate nontreatment sites for this particular roadway type. Hundreds of miles of videologs were reviewed in each state to identify sections of rural freeways without some type of shoulder rumble strip. Because shoulder rumble strips (i.e., milled, rolled, or formed) are predominantly installed on rural freeways in Minnesota, Missouri, and Pennsylvania, identifying nontreatment sites for this particular roadway type was extremely difficult.

Videolog Data Collection

This section describes the videolog data collection effort conducted as part of the safety evaluation of shoulder rumble strips. The videolog review was briefly described above, but this section describes in more detail the types of information gathered during the videolog review.

The videolog review served several purposes. First, the videologs were reviewed to confirm the presence or absence of milled shoulder rumble strips at the candidate treatment and nontreatment sites. Second, site characteristic data obtained from roadway inventory databases were verified. Third, roadside data not available from the roadway inventory files were collected for each site. Fourth, offset distances of the rumble strips with respect to the edgeline were estimated or verified if such information had initially been provided for a site. Finally, the review served to confirm the construction history of a site when possible and to determine how a site should be considered during the analysis.

While reviewing sites to confirm the absence or presence of milled shoulder rumble strips, several issues were considered. For treatment sites, the focus of the safety evaluation is on milled shoulder rumble strips, so only those sites with

Table 13. Total mileage of treatment and nontreatment sites considered for inclusion in the safety evaluation of shoulder rumble strips (includes data from Minnesota, Missouri, and Pennsylvania).

Roadway type	Treatment sites (mi)	Nontreatment sites (mi)
Urban freeways	70.80	131.36
Urban multilane divided highways (nonfreeways)	10.27	70.24
Urban multilane undivided highways (nonfreeways)	0.00	4.28
Urban two-lane roads	3.64	30.03
Rural freeways	257.71	56.56
Rural multilane divided highways (nonfreeways)	150.11	91.64
Rural multilane undivided highways (nonfreeways)	0.00	0.92
Rural two-lane roads	320.91	263.35
Totals across all roadway types	813.44	648.38

milled shoulder rumble strips are included in the safety evaluation. During the review process, many sites were reviewed where the shoulder contained rolled or formed rumble strips. In some cases, these sites were recorded in the master databases, but these sites are not included in the analyses. Nontreatment sites consist of locations without any type of shoulder rumble strip, whether rolled, formed, or raised. Thus, the analyses compare the crash history of sites with milled shoulder rumble strips to sites without any type of shoulder rumble strip treatment (or any other type of shoulder treatment) intended to reduce SVROR-type crashes. Similarly, none of the sites included in the safety evaluation include centerline rumble strips. When confirming the presence of the milled shoulder rumble strip at a site, the beginning and ending locations of the milled shoulder rumble strips were recorded. For divided highways (i.e., freeways and multilane divided highways [nonfreeways]), a site was considered a valid treatment site when rumble strips were located on the right (outside) shoulder. When possible, the presence of shoulder rumble strips installed on the left (inside) shoulder was recorded as well. Most of the divided highways had rumble strips on both the right (outside) and left (median) shoulders.

The videologs were used to verify certain roadway characteristic data that were considered potentially important in explaining the safety effectiveness of shoulder rumble strips. Prior to the videolog data collection, roadway inventory data files were obtained for the three states involved in the safety evaluation. The roadway characteristic data verified during the videolog review included the following:

- Area type (rural vs. urban);
- Roadway type (i.e., freeway, multilane divided, multilane undivided, or two-lane);
- Number of lanes;
- Lane widths; and
- Shoulder widths.

During the videolog review, the roadside hazard rating (RHR) was recorded for both sides of the roadway. The RHR system was developed by Zegeer et al. (*66*) to characterize the accident potential for roadside designs found on two-lane roads. The roadside hazard is ranked on a 7-point categorical scale from 1 (safest and most traversable) to 7 (most dangerous and least traversable). For undivided roadways, the RHR was recorded separately for the right and left sides of the road, and for divided highways, the RHR was recorded separately for the right and left (median) sides of the road in both directions of travel. For Minnesota, which treats the separate directions of travel of divided highways as a single site, this meant that four RHRs were recorded for each site. For Missouri and Pennsylvania, which treat the separate directions of travel of divided highways as separate sites, this meant that two RHRs were recorded for each site on a divided highway.

The RHR system is a subjective measure for quantitatively characterizing the accident potential of the roadside. Several data collectors could view a given site and, based on their subjective opinion, assign a different RHR to the site. To minimize the variability between data collectors in assigning RHRs, several steps were taken. First, written and pictorial descriptions of the seven roadside hazard categories that distinguished the differences between categories were provided to each data collector involved in the study. These written and pictorial descriptions, provided in Appendix D, were taken from an FHWA report on the expected safety performance of two-lane roads (*67*) and from a website for the Interactive Highway Safety Design Model (IHSDM), but as noted above, the original categories/descriptions were developed by Zegeer et al. (*66*). Next, 10 sites were chosen for a pilot study in which each data collector independently reviewed the sites and assigned an RHR to each. Then the variability in ratings between data collectors was evaluated. In most cases, the differences in ratings were plus or minus 1 or 2. Then, 5 of the original 10 sites with the greatest variability in assigned RHR among reviewers were examined by the data collectors as a group to discuss what each data collector was considering when rating each site. During this group discussion, several members with the most experience in using the roadside hazard rating explained their thought process and how they would rate the sites. This pilot effort could not completely eliminate the variability between data collectors in assigning roadside hazard rating scores, but the exercise was designed to minimize that variability.

When reviewing the treatment sites, the offset distances of the rumble strips from the edgeline were estimated to the nearest inch. Estimating the offset distances from videologs was not the most accurate method of measurement, but resource limitations prohibited visiting each site in the field, which would have been the best approach for obtaining the most accurate measurements. The offset distances were judged taking into account relative distances of the travel lane widths, shoulder widths, the width of the rumble strips, and the width of the edgeline. The offset distance was measured relative to the inside edge of the edgeline separating the outside travel lane from the shoulder so, for example, if the rumble strip was installed on the edgeline, then the offset distance would be 0 in. (0 mm), while if the rumble strip was installed adjacent to the edgeline but not on the edgeline, then the offset distance was estimated to be 4 in. (102 mm) because most standard edgelines are 4 in. (102 mm) in width. Offset distances were only verified and/or estimated for rumble strips on the right (outside) shoulder. No attempt was made to estimate or verify the accuracy of the offset distance for rumble strips on the left shoulder because the perspectives of the videologs of the left (median) shoulders of divided highways made it very difficult to estimate these offset distances.

The videolog review also served to gather information concerning the construction history of sites and installation dates, which in turn was useful in determining the appropriateness of sites for a before-after EB analysis and/or a cross-sectional analysis and in determining analysis periods for individual sites. The dates of the videologs were compared to the installation dates to verify the accuracy of the data and/or establish new installation dates for the rumble strips. The videologs in some cases also revealed when sites were under construction, which was taken into consideration when determining the analysis periods for sites or served as justification for excluding a site from the analysis because there was some uncertainty about the construction history and potentially the accuracy of the roadway characteristic data. When possible, the videologs were used to assess the conditions of treatment sites prior to installation of the rumble strips. This information was useful for determining whether a treatment site could be included in an EB analysis using before-after data or to include the site only in a cross-sectional analysis because the data collector noticed something from the videolog that created uncertainty about the condition of the treatment site prior to installation of the milled shoulder rumble strips. For example, if adjacent segments upstream or downstream of a treatment site had formed rumble strips that appeared to have been present for years, but the treatment site with milled shoulder rumble strips had a relatively recent installation date, it is very possible that the conditions of the treatment site prior to installation of the milled shoulder rumble strips included formed shoulder rumble strips. In this instance, it would not be appropriate to include the treatment site in a before-after EB analysis because the before conditions likely included formed rumble strips on the shoulders. It would, however, be perfectly acceptable to include it as a treatment site in a cross-sectional analysis but consider only those years since installation of the milled shoulder rumble strips.

To identify nontreatment sites for possible inclusion in the safety evaluation, certain cross-sectional characteristics (e.g., lane widths and shoulder widths) and traffic volumes of each potential treatment site were reviewed. For those roadway types for which a reasonable amount of mileage of treatment locations had been identified, a list of locations was generated for review using roadway characteristics data. An attempt was made to generate a list of nontreatment locations for each roadway type with a range of lane widths, shoulder widths, and traffic volumes that matched the ranges of the respective characteristics of the treatment sites. This list was generated without knowledge of whether rumble strips were present at the respective locations. Therefore, the videologs were used to review these locations for the presence/absence of shoulder rumble strips. For certain roadway types, limited mileage of nontreatment sites were found after reviewing this initial list. In those instances, maps were used to identify selected routes and extensive lengths of roadway mileage were reviewed in an attempt to identify nontreatment locations for inclusion in the analysis. In other situations, nontreatment locations were identified while reviewing the videologs for treatment sites. When a potential treatment site was reviewed but no rumble strips were present at the sites, the appropriate data were collected for the site, and the site was classified as a nontreatment rather than a treatment site.

The following final points regarding the data collection effort, relevant to the analysis approach and analysis results, are noteworthy:

- For divided highways when rumble strips are present on the left (median) shoulder, it is always assumed that these rumble strips were installed during the same calendar year as the rumble strips on the right (outside) shoulder.
- Even when milled rumbles strips are installed continuously along a segment, there are many breaks in the rumble strips for various reasons such as bridges, speed-change lanes (i.e., deceleration and acceleration lanes), intersections, driveways, etc. Depending upon the roadway type and the policy of the individual states, the frequencies of these breaks vary considerably. For example, in some cases, shoulder rumble strips near interchanges are installed along the shoulder of a speed-change lane, and in other instances the rumble strips are dropped/begin at the beginning/end of the speed-change lane. Also the frequency/spacing of interchanges differs depending upon whether it is an urban or rural area. For those treatment sites where a significant length of contiguous mileage of shoulder rumble strip installations existed, long breaks in the rumble strips may have been recorded during the data collection process, but the boundaries of the treatment site were not modified to reflect the breaks in the rumble strips. Thus, there are locations along the roadways of treatments sites where shoulder rumble strips are not present. Only those treatment sites where shoulder rumble strips were not installed over a very long stretch of highway were the boundaries of the treatment sites modified to reflect numerous or significant breaks in the continuous shoulder rumble strips. Based purely on observation, the urban treatment sites tended to have more natural breaks within the sites compared to the rural treatment sites. To further explain how the data were collected, the following examples are provided:
  - Example 1: The treatment site is a 10 mi (16 km) segment along a rural freeway, and three interchanges occur within this 10 mi (16 km) segment. At each interchange, the shoulder rumble strips are discontinued at the beginning of the deceleration lane, are installed between the gore points, and continue after the end of the acceleration

lane. Even though the rumble strips are not installed along the full 10 mi (16 km) segment, the full 10 mi (16 km) segment would have been recorded as a treatment site.
  - Example 2: The treatment site is initially listed as a 0.5 mi (8 km) segment of rural two-lane road, but on one end of the treatment site there is a long bridge so the rumble strips were only installed over a 0.4 mi (0.64 km) segment of highway. In this case, the boundaries of the treatment site would have been defined to be 0.4 mi (0.64 km) in length.
- The ideal type of treatment site to include in a before-after analysis is one in which the only type of treatment made during the analysis period is the safety improvement (i.e., installation of shoulder rumble strips). For many of the treatment sites in Minnesota and Missouri, the shoulder rumble strips were installed as part of a resurfacing project. To the best of our ability, we obtained information through various means to confirm that the cross-sectional characteristics of the roadway did not change (i.e., number of lanes, lane widths, and shoulder widths). For those treatment sites where we could confirm that the cross-sectional characteristics did not change, the site was identified as being appropriate for use in a before-after analysis. If it was determined that the cross-sectional characteristics changed as a result of the resurfacing, then the treatment site was identified as being appropriate for a cross-sectional analysis. As a result of this decision, the safety effectiveness of shoulder rumble strips will be confounded to some degree with the safety effects of resurfacing a roadway.
- In Pennsylvania, the initial list of treatment sites was generated from a low-cost safety improvement database developed and maintained by PennDOT. This database includes information such as the project number, type of safety improvement, installation date, location of the improvement, etc. This database is an inventory of the low-cost safety improvements made by PennDOT throughout the entire state roadway network and includes many types of low-cost safety improvements, not just the installation of shoulder rumble strips. It is our understanding that PennDOT has a process for identifying high-crash locations, and through this process PennDOT programs the implementation of certain types of low-cost safety improvements such as shoulder rumble strips. Thus, the locations of some of the treatment sites in Pennsylvania were initially identified as being high-crash locations compared to the rest of the highway network. For the other treatment sites included in the safety evaluation but not initially identified through the low-cost safety improvement database, the rumble strips may or may not have been installed as part of a broader proactive safety policy to install shoulder rumble strips on certain types of roadways. For Minnesota and Missouri, the policy for determining the need and location for installation of shoulder rumble strips is not known. It is likely that for the nonfreeway roadways, each state has a procedure/program for identifying high-crash locations (e.g., locations with high frequencies of SVROR crashes) and that some of the rumble strip installations being analyzed as part of this evaluation were implemented as part of such a program.
- All milled rumble strips are treated as being equivalent in their alerting properties. Although an effort was made to obtain rumble strip dimensions for each treatment site, this information was very difficult to obtain, and in many cases when it was obtained, the validity of the data was questionable. Therefore, in the analysis, a site with rumble strip dimensions of 16, 6, 0.5, and 12 in. (406, 152, 13, and 305 mm) for the length, width, depth, and spacing would be treated the same as a site with rumble strip dimensions of 6, 5, 0.375, and 16 in. (152, 127, 10, and 406 mm) for the length, width, depth, and spacing.

Database Development

The final database(s) utilized for analysis consisted of the roadway characteristic data (including traffic volume), the primary data from the videolog data collection effort, and crash data. In summary, the database(s) for each state included the following roadway inventory and videolog data for a given site:

- Location reference information (i.e., beginning and ending mileposts/logpoints, or route, county, segment, and offsets);
- Area type (rural vs. urban);
- Roadway type (i.e., freeway, multilane divided, multilane undivided, or two-lane);
- Number of lanes;
- Lane widths;
- Shoulder widths;
- Presence/absence of milled shoulder rumble strips;
- Offset distance of rumble strips from edgeline;
- RHR;
- Analysis period(s) (including year(s) without rumble strips, installation year(s), and years with rumble strips); and
- ADT for each year in the analysis period(s).

Concerning the traffic volume data, the original roadway inventory files obtained from the states did not contain ADTs for all sites for each year in the analysis period(s). Therefore, rules were established for interpolating and extrapolating the ADT data so that the final database included ADTs for each site for each year of the analysis period(s). The analysis period(s) were determined based upon the construction history and installation data gathered and the years of available crash data for each state. Crash data were obtained for the following calendar years (inclusive) for each state:

- Minnesota (1997 through 2005),
- Missouri (1997 through 2006), and
- Pennsylvania (1997 through 2006).

The types of crash data in the final database(s) for potential use in the analyses consisted of the following:

- Crash report number or crash ID number,
- Date of crash,
- Location information (county, route, direction, segment and offset or logpoint),
- Number of vehicles involved,
- Crash severity,
- Accident type or manner of collision,
- Run-off-road indicator,
- Fatigue-related indicator,
- Heavy vehicle indicator,
- Adverse pavement indicator,
- Light condition indicator, and
- Alcohol/drug indicator.

The final database only included crashes assigned to roadway segments. Rules were established to eliminate (i.e., screen out) intersection-related crashes and crashes near interchanges that did not occur on or adjacent to the mainline freeway. For example, crashes that occurred on interchange ramps (i.e., the ramp proper) are not included in the database, while crashes that occurred within or adjacent to acceleration or deceleration lanes are included in the database.

Several other rules were established for developing the final database(s). Most of these rules pertained to establishing a rationale for combining adjacent sites to create longer homogeneous sites. Several of these rules pertained to:

- Selected roadway characteristic (e.g., lane widths, shoulder widths, number of lanes);
- ADT thresholds; and
- Desirable minimum lengths (e.g., 0.3 mi [0.48 km]).

The following section provides descriptive statistics of the information contained in the databases developed for the safety evaluation.

Descriptive Statistics

The basic study layout and descriptive statistics in either tabular and/or graphical form are provided for the independent variables (i.e., ADT, site geometrics) and dependent variables (i.e., crash data) of interest in the safety evaluation of shoulder rumble strips.

General study layout. Data at each site were collected over periods of varying lengths (i.e., number of years). For comparison, the site length and the number of years were combined into a single variable, mile-years, for each site. Throughout the remainder of this section on the safety evaluation of shoulder rumble strips, the four site types are encoded as follows for ease of readability:

- BA-No RS: Nontreatment site of the matched before-after site pair in the before period;
- BA-RS: Treatment site of the matched before-after site pair in the after period;
- CS-No RS: Nontreatment cross-sectional site; and
- CS-RS: Treatment cross-sectional site.

Table 14 summarizes the basic layout of the available data in the three states, separately for each roadway type and type of site: number of sites, total site length, and mile-years. Because of insufficient number of sites and mile-years or lack of comparison sites for a number of roadway types and states to conduct the safety evaluation, it was decided to focus the safety evaluation of shoulder rumble strips on the following four categories:

- Urban freeways in Pennsylvania only;
- Rural freeways in Missouri and Pennsylvania only;
- Rural multilane divided highways (nonfreeways) in all three states; and
- Rural two-lane roads in all three states.

The analysis for rural freeways does not include Minnesota data even though there appears to be a sufficient number of mile-years of cross-sectional sites with and without rumble strips for analysis purposes; however, rural freeways in Minnesota were not included in the analysis because the distribution of ADT was unbalanced between treatment and nontreatment sites. Many of the Minnesota sites with rumble strips had lower ADTs than the Minnesota sites without rumble strips. This unbalanced distribution occurred primarily due to the difficulty of finding rural freeway nontreatment sites (see earlier part on Site Selection in this Section).

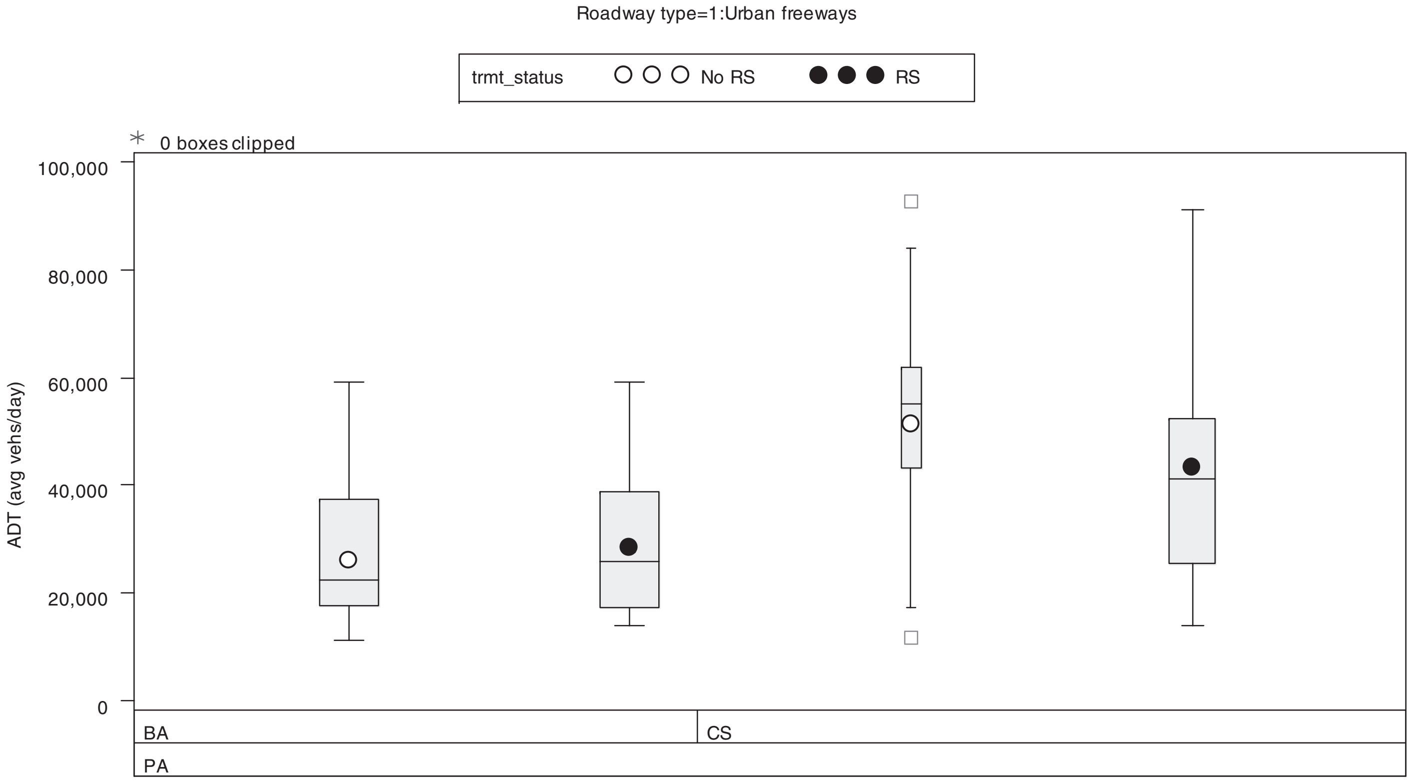
ADT volume. For each site, ADTs were first averaged across years within an analysis period. This allowed for a fair comparison of the distribution of ADTs across site types, analysis periods, and states since the sample size is reduced to the number of sites within each category and thus not unduly influenced by the length of the varying analysis periods.

Figures 7 through 10 show the ADT distributions in the form of side-by-side boxplots, separately for each of the four roadway types discussed above: urban freeways, rural freeways, rural multilane divided highways (nonfreeways), and rural two-lane roads. Within each figure, the data are organized by state when more than one state is included in the analysis; within each state, the data are ordered by site type—

Table 14. Summary study layout—total number of sites, site length, and mile-years by state, roadway type, and site type[a].

Roadway type	Site type	Minnesota			Missouri			Pennsylvania		
		Number of sites	Length (mi)	Mile-years	Number of sites	Length (mi)	Mile-years	Number of sites	Length (mi)	Mile-years
Urban freeways	BA-No RS	0			6	5.13	36.30	53	35.51	182.00
	BA-RS						9.87			129.60
	CS-No RS	49	110.97	998.75	2	0.51	5.07	37	19.88	194.50
	CS-RS	1	1.72	8.61	0			48	28.44	104.00
Urban multilane divided highways (nonfreeways)	BA-No RS	3	5.60	33.80	4	1.56	9.84	1	0.23	1.13
	BA-RS			10.98			4.20			0.91
	CS-No RS	30	60.82	547.34	7	6.95	69.50	7	2.47	23.64
	CS-RS	3	2.88	13.49	0			0		
Urban multilane undivided highways (nonfreeways)	BA-No RS	0			0			0		
	BA-RS									
	CS-No RS	2	1.90	17.08	1	1.92	19.20	1	0.46	4.58
	CS-RS	0			0			0		
Urban two-lane roads	BA-No RS	1	1.40	6.99	0			3	1.23	6.91
	BA-RS			4.19						3.69
	CS-No RS	0			3	3.15	31.50	29	26.88	261.60
	CS-RS	1	1.01	5.06	0			0		
Rural freeways	BA-No RS	0			29	52.08	313.00	18	15.43	80.09
	BA-RS						156.00			57.02
	CS-No RS	8	23.42	210.75	6	7.91	79.20	16	25.23	245.60
	CS-RS	28	109.15	495.67	12	25.65	77.90	41	55.40	146.30
Rural multilane divided highways (nonfreeways)	BA-No RS	6	20.00	100.00	14	19.11	109.00	5	4.18	32.57
	BA-RS			60.00			51.20			4.61
	CS-No RS	27	73.17	658.49	12	15.04	150.00	8	3.43	32.88
	CS-RS	27	103.32	508.56	1	2.32	2.32	4	1.18	2.35
Rural multilane undivided highways (nonfreeways)	BA-No RS	0			0			0		
	BA-RS									
	CS-No RS	1	0.61	5.46	1	0.31	3.13	0		
	CS-RS	0			0			0		
Rural two-lane roads	BA-No RS	28	95.51	478.41	5	10.52	64.00	20	23.34	136.20
	BA-RS			285.67			30.70			69.90
	CS-No RS	28	86.66	776.29	32	77.20	772.00	90	99.49	933.20
	CS-RS	53	179.21	851.60	1	2.33	2.33	0		

[a] Shaded cells are the focus of statistical analysis.



No. of sites	53	53	37	48
Mean	26,107	28,549	51,791	43,493
Std dev	12,434	12,553	18,400	20,725
Min	11,254	13,830	11,856	13,785
Median	22,517	25,659	54,982	41,283
Max	59,092	59,391	92,757	91,223

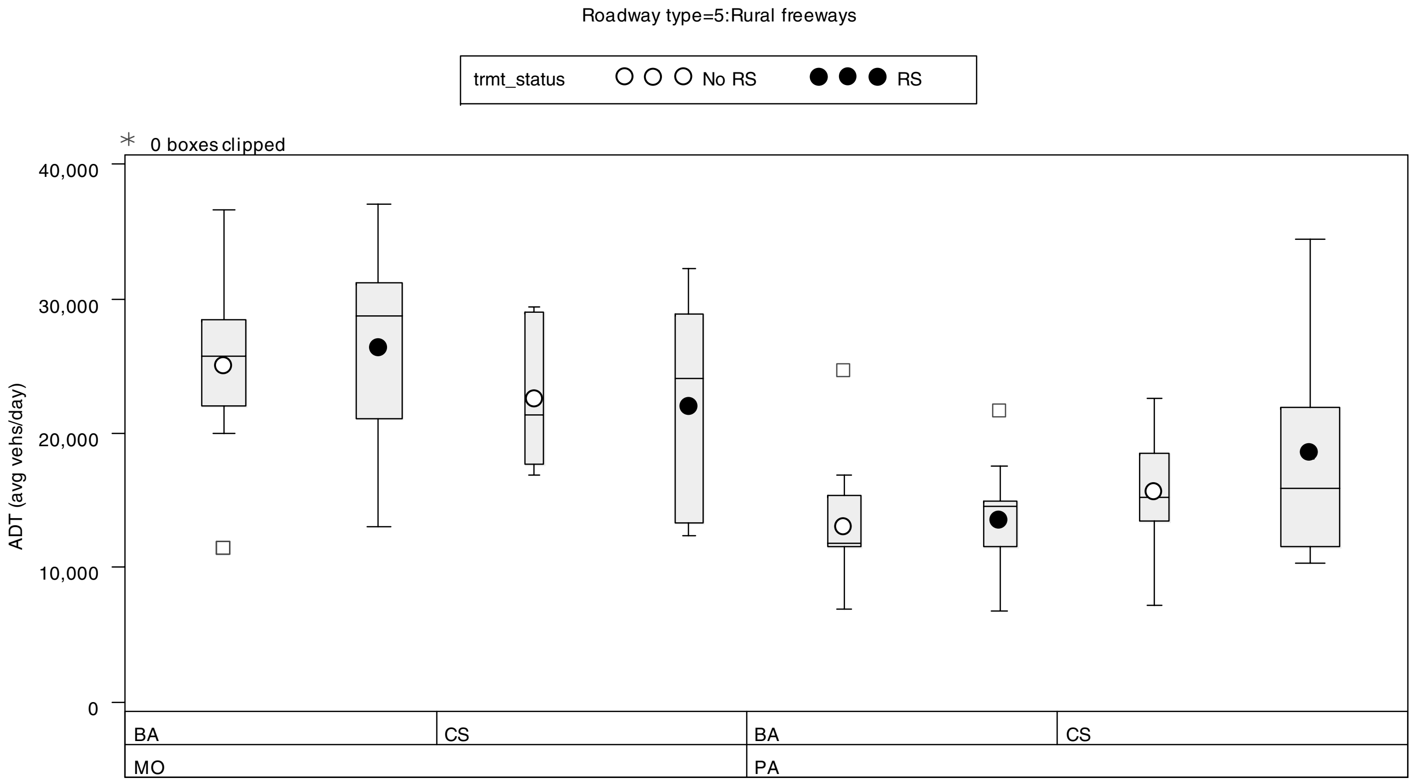
Figure 7. ADT distribution by site type for urban freeways in Pennsylvania.

before-after sites then cross-sectional sites. The mean ADTs of nontreatment sites are colored white; those of the treatment sites are black. Each figure also contains a table of basic descriptive ADT statistics: number of sites, mean, standard deviation, minimum, median, and maximum.

Lane width. Lane widths ranged from 7 to 20 ft (2.1 to 6.1 m) across all sites and states, with the majority of lanes being 12 ft (3.6 m) wide. The distribution of lane width is summarized in Table 15 by state and site type. Due to the lack of variability in lane width, it was decided to exclude this variable from all modeling efforts.

Outside and inside shoulder widths. Outside shoulder widths ranged from 1 to 14 ft (0.3 to 4.3 m) across sites and states, with slightly over half of outside shoulders being 10 ft (3.0 m) wide. The distribution of outside shoulder width is summarized in Table 16 by state and site type. For divided highway sites with an inside shoulder, inside shoulder widths ranged from 1 to 10 ft (0.3 to 3.0 m) across sites and states, with approximately 61 percent of inside shoulders being 4 ft (1.2 m) wide. The distribution of inside shoulder width is summarized in Table 17 by state and site type. Due to the lack of variability in either shoulder widths within a given roadway type and/or due to a high correlation with roadside hazard ratings, it was decided to exclude shoulder width from all modeling efforts. The use of RHRs discussed below addresses how shoulder width information is being captured in the statistical models.

RHR. Outside and inside (on divided highways) roadside hazard ratings were recorded as integers ranging from 1 (low RHR) to 7 (high RHR); both variables are treated as continuous variables in the statistical model development. Tables 18 (outside RHR) and 19 (inside RHR) present basic descriptive RHR statistics—number of sites and minimum, maximum, mean, and standard deviation—across sites within



No. of sites	29	29	6	12	18	18	16	41
Mean	25,118	26,450	22,634	22,013	13,091	13,615	15,680	18,572
Std dev	5,464	6,212	5,883	8,064	4,012	3,602	4,049	8,010
Min	11,539	13,079	16,870	12,438	6,963	6,777	7,192	10,319
Median	25,752	28,702	21,370	24,123	11,795	14,584	15,209	15,930
Max	36,643	37,112	29,410	32,354	24,752	21,755	22,571	34,406

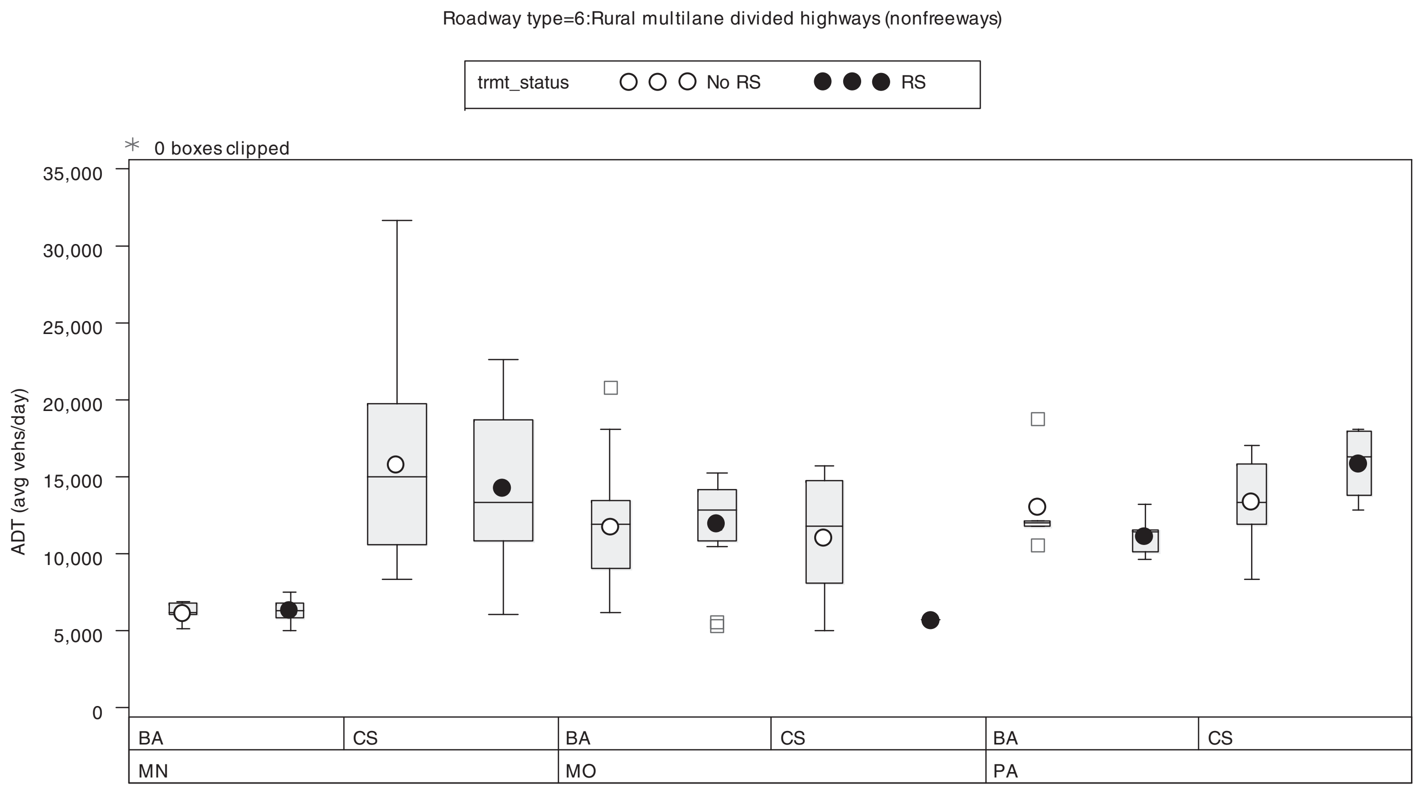
Figure 8. ADT distribution by site type for rural freeways in Missouri and Pennsylvania.

a given roadway type, state, and site type. Since RHR is related to shoulder width, these two explanatory variables are not statistically independent. Including RHR in the modeling effort and excluding shoulder width therefore solves the issue of non-independent variables; also, RHR accounts for additional variability in roadside factors that shoulder width does not. Non-integer values for minimums and maximums in Tables 18 and 19 are the result of combining adjacent segments into homogeneous sites for analysis purposes. When adjacent segments with different RHRs were combined into a single site for analysis purposes, a weighted average, based on segment length, of the RHR was calculated for the site.

Rumble strip offset. Rumble strip offset, measured in inches, is available for treatment sites only. A preliminary check of offset measurements on a continuous scale led to considering this variable as a categorical variable in two ways for the statistical analysis:

- Two categorical levels:
  - Edgeline rumble strips (i.e., offset distances of 0 to 8 in. [0 to 203 mm]), and
  - Non-edgeline rumble strips (i.e., offset distances of 9+ in. [229+ mm]).
- Three categorical levels:
  - 0 to 8 in. (0 to 203 mm),
  - 9 to 20 in. (229 to 508 mm), and
  - 21+ in. (533+ mm).

The distribution of rumble strip placement across the two offset levels is shown in Columns 3 and 4 of Table 20 by roadway type and state. The distribution of rumble strip offset across the three offset levels is shown in the last two columns of Table 20. Overall, just over half (56 percent) of the offset distances are in the 9 to 20 in. (229 to 508 mm) range; another 32 percent are in the 0 to 8 in. (0 to 203 mm) range; and the remaining 12 percent are in the 21+ in. (533+ mm) range.



No. of sites	6	6	27	27	14	14	12	1	5	5	8	4
Mean	6,193	6,292	15,827	14,316	11,781	11,945	11,074	5,725	13,041	11,185	13,421	15,876
Std dev	626	850	6,036	5,144	4,143	3,205	3,946	.	3,250	1,391	2,956	2,551
Min	5,110	4,959	8,349	6,005	6,192	5,326	4,956	5,725	10,587	9,653	8,267	12,874
Median	6,189	6,337	14,957	13,383	11,935	12,906	11,825	5,725	12,009	11,424	13,306	16,269
Max	6,875	7,459	31,692	22,665	20,763	15,198	15,725	5,725	18,753	13,195	17,018	18,093

Figure 9. ADT distribution by site type for rural multilane divided highways (nonfreeways) in Minnesota, Missouri, and Pennsylvania.

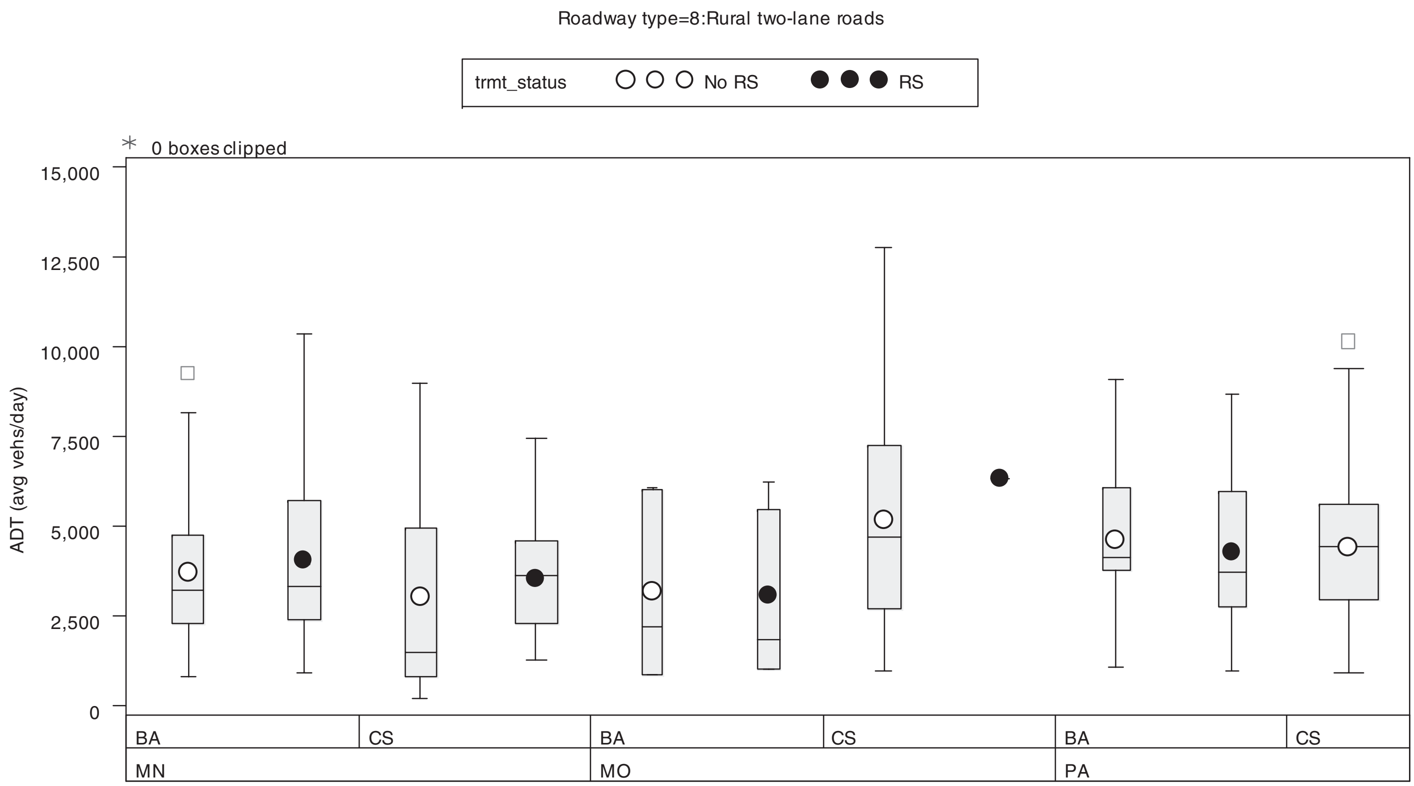
Recovery area. Recovery area at each treatment site was calculated as the difference between shoulder width and rumble strip offset. The final measurement is in feet. Based on the distribution of this variable, recovery area was treated as a categorical variable at two levels in the statistical models: 0 to 4 ft (0 to 1.2 m) and over 4 ft (1.2+ m). For nontreatment sites, the recovery area equals the shoulder width; therefore shoulder width was categorized in the same fashion: 0 to 4 ft (0 to 1.2 m) and over 4 ft (1.2+ m). Since recovery area was only used in conjunction with rumble strip offset in the statistical modeling to account for shoulder width, Table 21 presents the distribution of recovery area within each type of rumble strip placement (i.e., edgeline or non-edgeline). For nontreatment sites (shaded rows in Table 21), the table presents the distribution of shoulder width across the two levels. In summary, six combinations of rumble strip offset and recovery areas were considered:

1. RS edgeline and 4+ ft RA,
2. RS edgeline and 0–4 ft RA,
3. RS non-edgeline and 4+ ft RA,
4. RS non-edgeline and 0–4 ft RA,
5. No RS and 4+ ft shoulder width, and
6. No RS and 0–4 ft shoulder width.

Crash data. Four crash types are considered in the safety evaluation of shoulder rumble strips:

1. TOT crashes,
2. FI crashes,
3. SVROR crashes, and
4. SVROR FI crashes.

An SVROR crash was defined to be any single-vehicle crash that involved a vehicle leaving the travel way that was not intersection or ramp related.



No. of sites	28	28	28	53	5	5	32	1	20	20	90
Mean	3,736	4,081	3,040	3,563	3,206	3,087	5,211	6,348	4,642	4,299	4,445
Std dev	2,162	2,466	2,822	1,446	2,656	2,536	3,091	.	2,086	2,373	2,319
Min	782	921	180	1,285	861	983	952	6,348	1,081	948	910
Median	3,216	3,334	1,471	3,633	2,203	1,821	4,681	6,348	4,111	3,734	4,422
Max	9,288	10,386	8,981	7,431	6,077	6,205	12,776	6,348	9,067	8,674	10,177

Figure 10. ADT distribution by site type for rural two-lane roads in Minnesota, Missouri, and Pennsylvania.

Analyses of TOT crashes are performed primarily because several previous safety evaluations of shoulder rumble strips analyzed this crash type. However, analyses of TOT crashes include many other crash types besides SVROR crashes (i.e., the target crash type). No strong argument can be made to support why shoulder rumble strips would affect crashes other than SVROR crashes. Analyses based on FI crashes were also conducted because there is great interest in reducing crashes that result in fatalities and injuries, but again, analyses of FI crashes include many other crash types besides the target crashes. Analyses of SVROR crashes are expected to produce more reliable results than analyses of TOT and FI

Table 15. Distribution of lane width by state and site type.

Lane width (ft)	Minnesota			Missouri			Pennsylvania		
	Before–after sites	Cross-sectional sites		Before–after sites	Cross-sectional sites		Before–after sites	Cross-sectional sites	
		Untreated	Treated		Untreated	Treated		Untreated	Treated
7								1	
10				2	14			9	
11	1	8	1		4		12	50	
12	31	44	76	46	32	14	83	78	90
13	1	2	1					5	
14+	1	1	2				1	8	3

Table 16. Distribution of outside shoulder width by state and site type.

Outside shoulder width (ft)	Minnesota			Missouri			Pennsylvania		
	Before–after sites	Cross-sectional sites		Before–after sites	Cross-sectional sites		Before–after sites	Cross-sectional sites	
		Untreated	Treated		Untreated	Treated		Untreated	Treated
0								10	
1		3						2	
2	1						2	11	
3		1			7			10	
4	5	7	6	1	2		10	32	1
5		1	3		1			10	
6	1	7	4	3	9		2	10	
7	1	5	7					4	1
8	8	16	22	3	3		10	15	6
9	3	4	3		4				1
10	15	11	35	40	24	14	72	44	77
11				1				3	4
12									2
14									1

crashes because the analyses include only those crashes expected to be most directly impacted by shoulder rumble strips. Finally, analyses based on SVROR FI crashes are of interest because these analyses address the more severe target crashes.

The crash data across all years are summarized in Table 22 and are shown as both total number of crashes and crash frequency (crashes/mi/yr), separately for each type of site of a given roadway type within a given state. The two statistics are organized within each crash type in the following order: TOT, FI, SVROR, and SVROR FI crashes. This breakdown of the data is the level at which the statistical analyses are performed. Table 22 also provides the number of sites and their total length and mile-years to facilitate comparison between groups of data. For before-after site pairs (i.e., same site paired in time), number of sites and length are shown only once since the sites are the same before and after treatment; however, since the study periods changed from site to site, mile-years vary between nontreatment and treatment before-after site pairs.

The crash data are summarized by roadway type, state, site type, and rumble strip position (edgeline, non-edgeline, and no rumble strips) in Table 23. The crash count and frequency for TOT, FI, SVROR, and SVROR FI are presented.

The crash summaries for the supplemental analyses conducted for heavy vehicle, adverse pavement condition, and low-light condition crashes are presented in Table 24. The data are for SVROR crashes only and are summarized by roadway type, state, site type, and treatment status. Adverse pavement condition crashes are defined as crashes that occurred under wet, snow, slush, ice, standing or moving water, muddy, debris, or oily road surface conditions. Low-light condition crashes are defined as crashes that occurred during dawn, dusk, or dark.

Table 17. Distribution of inside shoulder width by state and site type.

Inside shoulder width (ft)	Minnesota			Missouri[a]			Pennsylvania		
	Before–after sites	Cross-sectional sites		Before–after sites	Cross-sectional sites		Before–after sites	Cross-sectional sites	
		Untreated	Treated		Untreated	Treated		Untreated	Treated
0		2	2				4	14	7
1							1	4	2
2			1				1	2	3
3	6	15	19				3		1
4		7	4				60	35	70
5		1	1				7	1	1
6		2						2	3
7								1	
8									1
9									2
10								2	3

[a] Inside shoulder width data not available for Missouri sites.

Table 18. Outside RHR statistics by roadway type, state, and site type.

Roadway type	State	Site type	Outside RHR: Number of sites	Minimum	Maximum	Mean	Standard deviation
Urban freeways	PA	BA	53	1.0	4.0	3.3	0.7
		CS-No RS	37	1.0	5.0	3.6	1.0
		CS-RS	48	2.7	4.0	3.6	0.4
Rural freeways	MO	BA	29	2.0	4.0	3.0	0.5
		CS-No RS	6	3.0	3.7	3.2	0.3
		CS-RS	12	2.0	4.0	3.0	0.4
	PA	BA	18	2.0	4.0	3.4	0.6
		CS-No RS	16	2.0	4.0	3.2	0.7
		CS-RS	41	2.2	4.1	3.6	0.5
Rural multilane divided highways (nonfreeways)	MN	BA	6	2.0	2.0	2.0	0.0
		CS-No RS	27	2.0	4.0	2.9	0.9
		CS-RS	27	1.0	3.3	2.2	0.6
	MO	BA	14	2.0	3.1	2.9	0.4
		CS-No RS	12	2.0	4.0	3.0	0.7
		CS-RS	1	3.0	3.0	3.0	
	PA	BA	5	3.0	4.0	3.5	0.5
		CS-No RS	8	2.8	4.4	3.5	0.6
		CS-RS	4	3.0	4.0	3.3	0.5
Rural two-lane roads	MN	BA	28	1.0	3.0	2.0	0.6
		CS-No RS	28	1.0	5.0	2.6	1.4
		CS-RS	53	1.0	4.0	2.3	0.8
	MO	BA	5	3.0	4.0	3.6	0.4
		CS-No RS	32	3.0	5.5	3.8	0.7
		CS-RS	1	3.6	3.6	3.6	
	PA	BA	20	2.5	5.0	3.5	0.7
		CS-No RS	90	1.7	6.0	4.1	1.0

Analysis Approach

The safety evaluation of shoulder rumble strips is based on the comparison of crash frequencies between treatment and nontreatment sites. This comparison is made separately for each combination of crash type—TOT, FI, SVROR, and SVROR FI crashes—and roadway type of interest. Comparisons of the crash frequencies are made separately for each state and across states for three of the four roadway types of interest. The following two statistical approaches are used to evaluate whether installing shoulder rumble strips has an effect on crash frequencies:

Table 19. Inside RHR statistics by roadway type, state, and site type.

Roadway type	State	Site type	Inside RHR: Number of sites	Minimum	Maximum	Mean	Standard deviation
Urban freeways	PA	BA	53	1.0	5.0	2.5	0.9
		CS-No RS	37	2.0	5.0	3.7	1.2
		CS-RS	48	1.0	5.3	3.3	1.2
Rural freeways	MO	BA	29	1.0	4.1	3.3	1.0
		CS-No RS	6	2.0	5.0	3.4	1.3
		CS-RS	12	2.0	4.0	3.0	1.0
	PA	BA	18	1.0	5.0	3.1	1.3
		CS-No RS	16	2.0	4.0	2.6	0.7
		CS-RS	41	1.0	5.0	3.6	1.0
Rural multilane divided highways (nonfreeways)	MN	BA	6	2.0	2.0	2.0	0.0
		CS-No RS	27	2.0	4.0	2.9	0.9
		CS-RS	27	1.0	3.4	2.2	0.6
	MO	BA	14	2.0	3.4	2.5	0.5
		CS-No RS	12	0.5	3.2	2.4	0.9
		CS-RS	1	3.0	3.0	3.0	
	PA	BA	5	4.0	5.0	4.4	0.5
		CS-No RS	8	3.0	5.0	4.2	0.7
		CS-RS	4	3.0	3.8	3.6	0.4

Table 20. Distribution of rumble strip placement and offset by roadway type and state.

Roadway type	State	Rumble strip placement	Number of sites	Offset (in.)	Number of sites
Urban freeways	PA	Edgeline	0	0-8	0
		Non-edgeline	101	9-20	101
				21+	0
Rural freeways	MO	Edgeline	24	0-8	24
		Non-edgeline	17	9-20	2
				21+	15
	PA	Edgeline	4	0-8	4
		Non-edgeline	55	9-20	51
				21+	4
Rural multilane divided highways (nonfreeways)	MN	Edgeline	7	0-8	7
		Non-edgeline	26	9-20	20
				21+	6
	MO	Edgeline	5	0-8	5
		Non-edgeline	10	9-20	0
				21+	10
	PA	Edgeline	1	0-8	1
		Non-edgeline	8	9-20	7
				21+	1
Rural two-lane roads	MN	Edgeline	61	0-8	61
		Non-edgeline	20	9-20	17
				21+	3
	MO	Edgeline	1	0-8	1
		Non-edgeline	5	9-20	0
				21+	5
	PA	Edgeline	15	0-8	15
		Non-edgeline	5	9-20	5
				21+	0

- A before-after comparison using the EB method applied to the before-after sites, and
- A cross-sectional analysis using a generalized linear model (GLM) approach based on crash data from:
  - all treatment and nontreatment sites (i.e., before-after and cross-sectional sites); and
  - all before-after sites and all cross-sectional nontreatment sites (i.e., cross-sectional treatment sites are excluded).

The rationale, differences, and similarities of the two methods are discussed next.

Before-After EB Analysis to Determine the Safety Effectiveness of Shoulder Rumble Strips on Different Roadway Types

The EB method is now the most widely used method to evaluate the safety effectiveness of a countermeasure given a set of matched before-after sites and a set of reference sites. The EB method, which adjusts for the effects of regression to the mean, is based on the comparison of observed crash frequencies in the after period to predicted crash frequencies in the after period had the treatment not been implemented.

To implement the EB methodology, it is crucial to develop a safety performance function (SPF) for each crash type on a particular roadway type based on crash data from a set of nontreatment reference sites.

The EB method used in this analysis is the method used in the countermeasure evaluation tool of the FHWA *Safety Analyst* software (*68*). The EB methodology is described in a white paper available on the *SafetyAnalyst* web site (www.safetyanalyst.org); a revised white paper presenting the EB methodology is currently under development (*69*). The EB methodology is based on methods recommended by Hauer (*70*) and Hauer et al. (*71*). The sequence of steps in applying the EB methodology is as follows:

- Obtain data for the observed crash frequency on each treatment site during both the before and after periods.
- Using the reference group data (i.e., sites that were not improved during the study period) for the entire period during which data are available, develop SPFs that model crash frequencies as a function of site parameters (e.g., traffic volumes and site geometrics). This is generally done by means of negative binomial (NB) regression analysis.
- Estimate the predicted crash frequency at each treatment site during the before period using the SPF developed for that type of site.
- Compute a weighted-average of the predicted and observed crash frequencies at each treatment site during the before

Table 21. Distribution of combined rumble strip placement and recovery area or shoulder width by roadway type and state.

Roadway type	State	Rumble strip placement	Recovery area (ft) or shoulder with (ft)[a]	Number of sites
Urban freeways	PA	Non-edgeline	4+	100
			0-4	1
		No rumble strips	4+	82
			0-4	8
Rural freeways	MO	Edgeline	4+	24
		Non-edgeline	4+	17
		No rumble strips	4+	35
	PA	Edgeline	4+	4
		Non-edgeline	4+	53
			0-4	2
		No rumble strips	4+	32
			0-4	2
Rural multilane divided Highways (nonfreeways)	MN	Edgeline	4+	7
		Non-edgeline	4+	26
		No rumble strips	4+	33
	MO	Edgeline	4+	4
			0-4	1
		Non-edgeline	4+	10
		No rumble strips	4+	25
			0-4	1
	PA	Edgeline	4+	1
		Non-edgeline	4+	8
		No rumble strips	4+	12
			0-4	1
Rural two-lane roads	MN	Edgeline	4+	51
			0-4	10
		Non-edgeline	4+	15
			0-4	5
		No rumble strips	4+	39
			0-4	17
	MO	Edgeline	4+	1
		Non-edgeline	4+	2
			0-4	3
		No rumble strips	4+	28
			0-4	9
	PA	Edgeline	4+	5
			0-4	10
		Non-edgeline	4+	5
		No rumble strips	4+	44
			0-4	66

[a] Column indicates recovery area for treatment sites; shoulder width for nontreatment sites.

period. This crash frequency is referred to as the EB-adjusted expected crash frequency.

- Using the EB-adjusted expected crash frequency at each site during the before period, make an estimate of the expected crash frequency at each treatment site during the after period had no change been made. This step of the analysis accounts for changes in traffic volumes between the before and after periods.
- Compare the observed after crash frequencies at the treatment sites to the expected after crash frequencies at the treatment sites had the change not been made. The difference between these observed and expected crash frequencies is an estimate of the safety effectiveness of the treatment.

SPFs were developed for each crash type, roadway type, and state considered based on all nontreatment sites, that is, all before sites and all nontreatment cross-sectional sites. The decision to include the before sites into the reference group was made to use the maximum number of sites and thus to capitalize on the maximum amount of information to develop the functions. Since, as evidenced by the crash rates, the treatment sites were unlikely to be selected based on a high crash count in the before period, this approach, on balance, seemed reasonable.

Of the independent variables summarized in the previous section, an attempt was made to incorporate as many variables as possible in the SPF, in addition to ADT, to obtain the best possible function to predict crashes at sites without shoulder

Table 22. Crash statistics by roadway type, state, site type, and treatment status.

Roadway type	State	Site type	Treatment status	Number of sites	Length (mi)	Mile-years	Crash type: TOT Total number of crashes	TOT Crash frequency (crashes/mi/yr)	FI Total number of crashes	FI Crash frequency (crashes/mi/yr)	SVROR Total number of crashes	SVROR Crash frequency (crashes/mi/yr)	SVROR FI Total number of crashes	SVROR FI Crash frequency (crashes/mi/yr)
Urban freeways	PA	BA	No RS	53	35.51	182.02	524	2.88	231	1.27	298	1.64	131	0.72
			RS			129.58	394	3.04	162	1.25	198	1.53	97	0.75
		CS	No RS	37	19.88	194.52	1,325	6.81	648	3.33	556	2.86	265	1.36
			RS	48	28.44	103.98	601	5.78	314	3.02	281	2.70	143	1.38
Rural freeways	MO	BA	No RS	29	52.08	313.07	1,324	4.23	417	1.33	617	1.97	248	0.79
			RS			155.69	827	5.31	241	1.55	300	1.93	115	0.74
		CS	No RS	6	7.91	79.15	310	3.92	102	1.29	177	2.24	63	0.80
			RS	12	25.65	77.90	200	2.57	64	0.82	107	1.37	42	0.54
	PA	BA	No RS	18	15.43	80.09	130	1.62	60	0.75	107	1.34	52	0.65
			RS			57.02	107	1.88	44	0.77	63	1.10	28	0.49
		CS	No RS	16	25.23	245.62	429	1.75	207	0.84	273	1.11	136	0.55
			RS	41	55.40	146.29	302	2.06	126	0.86	215	1.47	102	0.70
Rural multilane divided highways (nonfreeways)	MN	BA	No RS	6	20.00	100.00	72	0.72	30	0.30	33	0.33	20	0.20
			RS			60.00	59	0.98	16	0.27	28	0.47	10	0.17
		CS	No RS	27	73.17	658.49	1,770	2.69	550	0.84	567	0.86	248	0.38
			RS	27	103.32	508.56	1,205	2.37	373	0.73	476	0.94	193	0.38
	MO	BA	No RS	14	19.11	109.02	264	2.42	108	0.99	123	1.13	70	0.64
			RS			51.18	196	3.83	66	1.29	114	2.23	44	0.86
		CS	No RS	12	15.04	150.37	458	3.05	122	0.81	152	1.01	65	0.43
			RS	1	2.32	2.32	5	2.16	2	0.86	3	1.29	2	0.86
	PA	BA	No RS	5	4.18	32.57	47	1.44	19	0.58	35	1.07	13	0.40
			RS			4.61	6	1.30	2	0.43	4	0.87	2	0.43
		CS	No RS	8	3.43	32.88	113	3.44	62	1.89	79	2.40	48	1.46
			RS	4	1.18	2.35	6	2.55	2	0.85	3	1.28	1	0.43
Rural two-lane roads	MN	BA	No RS	28	95.51	478.41	296	0.62	100	0.21	61	0.13	24	0.05
			RS			285.67	220	0.77	70	0.25	43	0.15	15	0.05
		CS	No RS	28	86.66	776.29	515	0.66	199	0.26	162	0.21	76	0.10
			RS	53	179.21	851.60	511	0.60	174	0.20	177	0.21	88	0.10
	MO	BA	No RS	5	10.52	63.97	77	1.20	27	0.42	41	0.64	19	0.30
			RS			30.67	73	2.38	15	0.49	33	1.08	6	0.20
		CS	No RS	32	77.20	771.97	1,630	2.11	567	0.73	499	0.65	207	0.27
			RS	1	2.33	2.33	2	0.86	0	0.00	0	0.00	0	0.00
	PA	BA	No RS	20	23.34	136.18	171	1.26	101	0.74	118	0.87	64	0.47
			RS			69.90	86	1.23	56	0.80	41	0.59	24	0.34
		CS	No RS	90	99.49	933.20	1,080	1.16	617	0.66	643	0.69	345	0.37

Table 23. Crash statistics by roadway type, state, site type, and edgeline vs. non-edgeline.

Roadway type	State	Site type	Offset	Number of sites	Length (mi)	Mile-years	Crash type: TOT Total number of crashes	TOT Crash frequency (crashes/mi/yr)	FI Total number of crashes	FI Crash frequency (crashes/mi/yr)	SVROR Total number of crashes	SVROR Crash frequency (crashes/mi/yr)	SVROR FI Total number of crashes	SVROR FI Crash frequency (crashes/mi/yr)
Urban freeways	PA	BA	Non-edgeline	53	35.51	129.58	394	3.04	162	1.25	198	1.53	97	0.75
			No RS	53	35.51	182.02	524	2.88	231	1.27	298	1.64	131	0.72
		CS	Non-edgeline	48	28.44	103.98	601	5.78	314	3.02	281	2.70	143	1.38
			No RS	37	19.88	194.52	1,325	6.81	648	3.33	556	2.86	265	1.36
Rural freeways	MO	BA	Edgeline	16	28.42	47.10	288	6.11	68	1.44	114	2.42	41	0.87
			Non-edgeline	13	23.66	108.58	539	4.96	173	1.59	186	1.71	74	0.68
			No RS	29	52.08	313.07	1,324	4.23	417	1.33	617	1.97	248	0.79
		CS	Edgeline	8	13.46	16.97	85	5.01	23	1.36	35	2.06	9	0.53
			Non-edgeline	4	12.19	60.93	115	1.89	41	0.67	72	1.18	33	0.54
			No RS	6	7.91	79.15	310	3.92	102	1.29	177	2.24	63	0.80
	PA	BA	Edgeline	3	3.14	3.14	2	0.64	1	0.32	1	0.32	0	0.00
			Non-edgeline	15	12.29	53.88	105	1.95	43	0.80	62	1.15	28	0.52
			No RS	18	15.43	80.09	130	1.62	60	0.75	107	1.34	52	0.65
		CS	Edgeline	1	0.94	1.89	1	0.53	0	0.00	0	0.00	0	0.00
			Non-edgeline	40	54.46	144.40	301	2.08	126	0.87	215	1.49	102	0.71
			No RS	16	25.23	245.62	429	1.75	207	0.84	273	1.11	136	0.55
Rural multilane divided highways (nonfreeways)	MN	BA	Edgeline	3	10.40	31.20	28	0.90	7	0.22	11	0.35	4	0.13
			Non-edgeline	3	9.60	28.80	31	1.08	9	0.31	17	0.59	6	0.21
			No RS	6	20.00	100.00	72	0.72	30	0.30	33	0.33	20	0.20
		CS	Edgeline	4	14.24	67.19	189	2.81	49	0.73	44	0.65	18	0.27
			Non-edgeline	23	89.08	441.37	1,016	2.30	324	0.73	432	0.98	175	0.40
			No RS	27	73.17	658.49	1,770	2.69	550	0.84	567	0.86	248	0.38
	MO	BA	Edgeline	5	5.72	7.50	15	2.00	2	0.27	11	1.47	2	0.27
			Non-edgeline	9	13.39	43.69	181	4.14	64	1.46	103	2.36	42	0.96
			No RS	14	19.11	109.02	264	2.42	108	0.99	123	1.13	70	0.64
		CS	Non-edgeline	1	2.32	2.32	5	2.16	2	0.86	3	1.29	2	0.86
			No RS	12	15.04	150.37	458	3.05	122	0.81	152	1.01	65	0.43

	PA	BA	Edgeline	1	1.16	1.16	3	2.59	1	0.86	1	0.86	1	0.86
			Non-edgeline	4	3.02	3.45	3	0.87	1	0.29	3	0.87	1	0.29
			No RS	5	4.18	32.57	47	1.44	19	0.58	35	1.07	13	0.40
		CS	Non-edgeline	4	1.18	2.35	6	2.55	2	0.85	3	1.28	1	0.43
			No RS	8	3.43	32.88	113	3.44	62	1.89	79	2.40	48	1.46
Rural two-lane roads	MN	BA	Edgeline	19	62.33	174.00	116	0.67	38	0.22	19	0.11	6	0.03
			Non-edgeline	9	33.18	111.68	104	0.93	32	0.29	24	0.21	9	0.08
			No RS	28	95.51	478.41	296	0.62	100	0.21	61	0.13	24	0.05
		CS	Edgeline	42	140.01	655.58	413	0.63	141	0.22	154	0.23	74	0.11
			Non-edgeline	11	39.20	196.02	98	0.50	33	0.17	23	0.12	14	0.07
			No RS	28	86.66	776.29	515	0.66	199	0.26	162	0.21	76	0.10
	MO	BA	Edgeline	1	3.80	3.80	3	0.79	0	0.00	1	0.26	0	0.00
			Non-edgeline	4	6.72	26.88	70	2.60	15	0.56	32	1.19	6	0.22
			No RS	5	10.52	63.97	77	1.20	27	0.42	41	0.64	19	0.30
		CS	Non-edgeline	1	2.33	2.33	2	0.86	0	0.00	0	0.00	0	0.00
			No RS	32	77.20	771.97	1,630	2.11	567	0.73	499	0.65	207	0.27
	PA	BA	Edgeline	15	18.38	59.97	79	1.32	54	0.90	39	0.65	24	0.40
			Non-edgeline	5	4.96	9.92	7	0.71	2	0.20	2	0.20	0	0.00
			No RS	20	23.34	136.18	171	1.26	101	0.74	118	0.87	64	0.47
		CS	No RS	90	99.49	933.20	1,080	1.16	617	0.66	643	0.69	345	0.37

Table 24. Crash statistics for supplemental analyses of SVROR crashes by roadway type, state, site type, and treatment status.

							Crash type							
							Total (SVROR)		Heavy vehicle		Adverse pavement		Low light	
Roadway type	State	Site type	Treatment status	Number of sites	Length (mi)	Mile-years	Total number of crashes	Crash frequency (crashes/ mi/yr)	Total number of crashes	Crash frequency (crashes/ mi/yr)	Total number of crashes	Crash frequency (crashes/ mi/yr)	Total number of crashes	Crash frequency (crashes/ mi/yr)
Urban freeways	PA	BA	No RS	53	35.51	182.02	298	1.64	6	0.03	131	0.72	128	0.70
			RS			129.58	198	1.53	3	0.02	79	0.61	82	0.63
		CS	No RS	37	19.88	194.52	556	2.86	15	0.08	236	1.21	246	1.27
			RS	48	28.44	103.98	281	2.70	42	0.40	111	1.07	133	1.28
Rural freeways	MO	BA	No RS	29	52.08	313.07	617	1.97	146	0.47	255	0.82	235	0.75
			RS			155.69	300	1.93	51	0.33	108	0.69	103	0.66
		CS	No RS	6	7.91	79.15	177	2.24	26	0.33	76	0.96	82	1.04
			RS	12	25.65	77.90	107	1.37	15	0.19	39	0.50	34	0.44
	PA	BA	No RS	18	15.43	80.09	107	1.34	27	0.34	49	0.61	48	0.60
			RS			57.02	63	1.11	5	0.09	34	0.60	23	0.40
		CS	No RS	16	25.23	245.62	273	1.11	15	0.06	115	0.47	125	0.51
			RS	41	55.40	146.29	215	1.47	15	0.10	125	0.85	90	0.62
Rural multilane divided highways (nonfreeways)	MN	BA	No RS	6	20.00	100.00	33	0.33	5	0.05	21	0.21	13	0.13
			RS			60.00	28	0.47	1	0.02	24	0.40	5	0.08
		CS	No RS	27	73.17	658.49	567	0.86	14	0.02	308	0.47	266	0.40
			RS	27	103.32	508.56	476	0.94	14	0.03	320	0.63	211	0.42
	MO	BA	No RS	14	19.11	109.02	123	1.13	4	0.04	49	0.45	44	0.40
			RS			51.18	114	2.23	6	0.12	51	1.00	53	1.04
		CS	No RS	12	15.04	150.37	152	1.01	8	0.05	55	0.37	57	0.38
			RS	1	2.32	2.32	3	1.29	1	0.43	2	0.86	1	0.43
	PA	BA	No RS	5	4.18	32.57	35	1.08	1	0.03	16	0.49	14	0.43
			RS			4.61	4	0.87	1	0.22	2	0.43	1	0.22
		CS	No RS	8	3.43	32.88	79	2.40	12	0.37	40	1.22	33	1.00
			RS	4	1.18	2.35	3	1.28	0	0.00	3	1.28	0	0.00
Rural two-lane roads	MN	BA	No RS	28	95.51	478.41	61	0.13	7	0.02	27	0.06	34	0.07
			RS			285.67	43	0.15	5	0.02	25	0.09	23	0.08
		CS	No RS	28	86.66	776.29	162	0.21	3	0.00	68	0.09	68	0.09
			RS	53	179.21	851.60	177	0.21	10	0.01	119	0.14	77	0.09
	MO	BA	No RS	5	10.52	63.97	41	0.64	4	0.06	17	0.27	9	0.14
			RS			30.67	33	1.08	3	0.10	19	0.62	8	0.26
		CS	No RS	32	77.20	771.97	499	0.65	26	0.03	160	0.21	192	0.25
			RS	1	2.33	2.33	0	0.00	0	0.00	0	0.00	0	0.00
	PA	BA	No RS	20	23.34	136.18	118	0.87	4	0.03	48	0.35	60	0.44
			RS			69.90	41	0.59	2	0.03	19	0.27	22	0.32
		CS	No RS	90	99.49	933.20	643	0.69	28	0.03	281	0.30	322	0.35

rumble strips. A basic negative binomial model was used with PROC GENMOD of SAS to estimate the regression coefficients. A forward selection procedure was used to determine which variables to include in the SPF for each roadway type and state. The available variables are: ADT, outside RHR, and for divided highways, inside RHR. The following steps were used for variable selection:

- Step 1: Estimate the intercept only.
- Step 2: Estimate the intercept and the coefficient for the natural log of the ADT (lnADT). If the coefficient for lnADT is positive, then include it in the SPF and continue to Step 3.
- Step 3: Estimate the intercept and coefficients for lnADT and outside RHR (RHR_{Out}). If the coefficient for lnADT is positive and the coefficient for RHR_{Out} is positive and has a p-value less than 0.15, then include lnADT and RHR_{Out} in the SPF. If not, include lnADT only in the SPF. For divided roads, if RHR_{Out} is included in the model, then continue to Step 4.
- Step 4: Estimate the intercept and coefficients for lnADT, RHR_{Out}, and inside RHR (RHR_{In}). If the coefficient for lnADT is positive, the coefficient for RHR_{Out} is positive and has a p-value less than 0.15, and the coefficient for RHR_{In} is positive and has a p-value less than 0.15, then include lnADT, RHR_{Out}, and RHR_{In} in the SPF. If not, include lnADT and RHR_{Out} only in the SPF.

In some cases, neither the coefficient of RHR_{Out} nor that of RHR_{In} met the above criteria; in those cases, the SPF reduces to the standard ADT-only model. In a few instances, the coefficient of ADT did not meet the above criteria. In those cases, an intercept-only or means model was selected for the SPF.

The EB analysis was performed using the sum of the yearly crash frequencies at a given site during the before or after period. A factor was added to the model to account for the number of years at each site.

Cross-Sectional Analysis Using Generalized Linear Model Analysis to Determine the Safety Effectiveness of Shoulder Rumble Strips on Different Roadway Types

The evaluation of the safety effectiveness of shoulder rumble strips in the EB analysis discussed above is based solely on the comparison of sites with information from before and after the installation of rumble strips. Many additional sites are available that only have the information after the installation of the rumble strips (i.e., cross-sectional treatment sites). Since these sites provide additional information on the effectiveness of shoulder rumble strips, modeling efforts were undertaken to capitalize on all available information.

A GLM with a negative binomial distribution and a log link was used to model the yearly crash counts. A repeated measures correlation structure was included to account for the relationship in crashes at a given site across years (temporal correlation). A compound symmetry covariance structure was used. General estimating equations (GEE) were used to determine the final regression parameter estimates. The GEE regression model estimation technique has been demonstrated by Lord and Persaud (*72*). The selection of variables in the mean model was performed as described above with the addition of a factor for the presence of rumble strips (a 0,1 indicator variable) and a convergence criteria for the GEE.

The GLM analysis was performed on two sets of sites:

- All treatment and nontreatment sites (before-after and cross-sectional sites).
- All before-after sites and all cross-sectional nontreatment sites (i.e., cross-sectional treatment sites are excluded).

The first GLM analysis was performed to take advantage of all the data collected on the selected roadway types. The second GLM analysis was performed to provide a more direct comparison with the EB analysis results. In essence, the two methods use the same types of sites: the EB uses all nontreatment sites in the development of the SPFs and then the before and after sites in the safety evaluation; the second GLM analysis uses all nontreatment sites and the after sites more directly in the safety evaluation. A comparison of the three sets of results is discussed later in Analysis Results.

Cross-Sectional Analysis to Determine the Impact of Rumble Strip Placement on the Safety Effectiveness of Shoulder Rumble Strips

The analysis of the effect of rumble strip placement was performed using the same GLM approach used for the safety evaluation of shoulder rumble strips on different roadway types. All available site types were included in this analysis. The impact of offset distance was evaluated separately and then in combination with the recovery area. These analyses focused on SVROR FI crashes only. The rationale for this will become evident after reviewing the results of the safety evaluations of shoulder rumble strips for TOT, FI, SVROR, and SVROR FI crashes for the four roadway types of interest. Both offset and recovery area were used as categorical variables as discussed earlier part in Descriptive Statistics.

Three incrementally more detailed offset analyses were performed, based on various treatments of the offset and recovery area variables:

- Comparison of edgeline and non-edgeline rumble strips against the no rumble strip category (i.e., no offset or nontreatment sites) (see Columns 3 and 4 in Table 20);

- Comparison of rumble strip offset at each of the three levels (0 to 8 in. [0 to 203 mm]; 9 to 20 in. [229 to 508 mm]; 21+ in. [533+ mm]) against the no rumble strip category (i.e., no offset or nontreatment sites) (see Columns 5 and 6 in Table 20); and
- Comparison of the combination of rumble strip placement (i.e., edgeline; non-edgeline) and the recovery area at each of the five levels, including nontreatment sites with 4+ ft (1.2+ m) shoulders, against the nontreatment sites with 0 to 4 ft (0 to 1.2 m) shoulders (see Table 21).

In all cases, a mean crash model was developed using the forward selection procedure discussed earlier and included ADT, RHR_{Out}, RHR_{In}, and the presence of rumble strips as long as their coefficients met the above criteria.

Supplement Analysis for SVROR Crash Types

Supplemental analyses of specific SVROR crash types (i.e., heavy vehicle, adverse pavement condition, and low-light condition) were also conducted using both the EB methodology and the cross-sectional GLM methodology. For the EB methodology, separate SPFs were not developed for each crash type as described above. Instead, the SVROR SPF was used along with the percentage of crashes of the selected type to produce an SPF for each crash subtype. For crash type *i*, the SPF was defined as

$$SPF_i = PCT_i \times SPF_{SVROR}$$

The percent (PCT_i) is based on the accident count for site-years without rumble strips (i.e., the before period for before-after sites and cross-sectional sites without rumble strips) and is computed for each roadway type and state. The EB methodology is then carried out as described above. The cross-sectional GLM methodology was carried out in the same manner as for the roadway type evaluation, both with and without the cross-sectional rumble strip sites.

The analysis of SVROR crashes involving heavy vehicles does not specifically account for heavy vehicle exposure. The ADT variable in the SPFs is for total traffic, including both passenger cars and heavy vehicles. Without specifically accounting for heavy vehicle exposure, the baseline assumption of the analysis is that the percentage of heavy vehicle traffic, relative to the total traffic volume, remained constant throughout the analysis period.

Similarly, the analysis of SVROR crashes during adverse pavement conditions does not specifically account for the variability in weather from year to year. Without specifically accounting for variability in weather, the baseline assumption of the analysis is that traffic is exposed to the same weather conditions from year to year throughout the analysis period.

Analysis Results

Analysis results are first presented for estimating the safety effectiveness of shoulder rumble strips on different roadway types, followed by the analysis results for estimating the impact that rumble strip placement has on the safety effectiveness of shoulder rumble strips. The results of the supplemental analyses focusing on heavy vehicle, adverse pavement condition, and low-lighting condition crashes are presented last.

Estimating the Safety Effectiveness of Shoulder Rumble Strips on Different Roadway Types

Before-After EB Analysis Results

The EB analysis consisted of the following two steps:

- Develop SPF models based on all nontreatment sites.
- Using the SPFs, evaluate the safety effectiveness of shoulder rumble strips using crash data from the before-after sites only.

SPF results. The approach discussed in the previous section was implemented for each crash type, separately for each roadway type and state. SPFs were developed for each crash type in each category, using ADT and RHR as predictor variables. An attempt was made to include both outside and inside RHR in SPFs for divided highways. For undivided highways (i.e., rural two-lane roads in this analysis), only the outside RHR was included, if statistically significant. All nontreatment sites (i.e., nontreatment cross-sectional sites and before sites) were used for SPF development. Tables E-1 through E-4 in Appendix E summarize the crash frequency models for TOT, FI, SVROR, and SVROR FI crashes, respectively. The statistics shown for each roadway type and state SPF include the following:

- Number of nontreatment sites;
- Intercept: estimate and standard error;
- lnADT coefficient: estimate, standard error, and p-value (or significance level); for example, a p-value of 0.05 or less indicates that the coefficient is significantly different from 0 at the 0.05 significance (or 95 percent confidence) level;
- Outside RHR: estimate, standard error, and p-value;
- Inside RHR (divided highways only): estimate, standard error, and p-value;
- Model dispersion parameter: estimate and standard error; and
- Model R^2_{LR} value: the likelihood ratio R^2_{LR}, a measure of model fit between 0 and 1. The closer the value is to 1, the better the fit of the model is to the data.

Each SPF is represented by the following equations:

Divided highways:

$$\text{Expected crashes/mi/yr} = \exp\left(a + b\ln ADT + cRHR_{Out} + dRHR_{In}\right) \quad (1)$$

Rural two-lane roads:

$$\text{Expected crashes/mi/yr} = \exp\left(a + b\ln ADT + cRHR_{Out}\right) \quad (2)$$

where

ADT = average daily traffic volume for both directions of travel combined (veh/day)

RHR_{Out} = average roadside hazard rating for the outside (right) side of a divided highway

RHR_{In} = average roadside hazard rating for the inside (median) side of a divided highway

a,b,c,d = coefficients whose estimates are shown in Tables E-1 through E-4 in Appendix E

ADT was included in all models, regardless of its significance, as long as its coefficient was positive. A decision was made to select an ADT model with a nonsignificant positive slope rather than a simple means model after comparing their predicted crash frequencies over the range of ADTs in a given category. Including the before sites of the before-after site pairs in the SPF modeling ensured that no extrapolation outside an ADT range would occur since ADTs changed only slightly from year to year. In only 6 of the 36 SPFs was ADT not significant at the 0.15 level.

Outside and inside RHRs were only included in the SPF model for divided highways if they were significant at the 0.15 significance level. The selection of these two explanatory variables was such that inside RHR was only included if it was significant <u>and</u> if outside RHR was significant and both were in the expected direction. Outside RHR was generally significant for Pennsylvania urban freeways and Minnesota and Missouri rural two-lane roads. Inside RHR was significant for selected crash types on Pennsylvania urban freeways only. Including RHR in the SPF allowed for a more accurate prediction of crashes in the after period, had no shoulder rumble strips been installed, as compared to using an ADT model only. In those cases where RHR was significant, not including it in the model could potentially result in wrongly attributing a safety improvement effect to rumble strips.

The analyses of SVROR crashes included SVROR crashes to the right and to the left of the road. No effort was made to distinguish crashes by side of the road; however, by including RHR for both the outside and inside shoulder of divided highways, the analyses tried to account for the differences between SVROR crashes to the right and left. Also, it should be noted that for the states that treated both sides of a divided highway as separate sites (i.e., Missouri and Pennsylvania), the RHR variables in the models represent the values for a single side of the divided highway. When both sides of a divided highway were treated as a single site (i.e., Minnesota sites), the RHR variables in the model represent average values for both directions of travel. Similarly, the RHR variable in the model for rural two-lane roads represents the average RHR for both sides of the roadway. Thus, the analysis tried to account for SVROR right and SVROR left crashes, without necessarily distinguishing between the two crash types.

Safety effectiveness results. For each crash type, roadway type, and state, the safety effectiveness of shoulder rumble strips was estimated in accordance with the approach discussed earlier. The final results are shown in Tables 25 through 28 for TOT, FI, SVROR, and SVROR FI crashes, respectively. For each crash type, 12 separate analyses were performed across the four roadway types of interest, based on data for individual states and/or combined data across states. The statistics shown for each crash type, roadway type, and state (single or combined) are:

- Number of treatment sites;
- Total site length;
- Percent change due to shoulder rumble strips: estimate and standard error;
- Test statistic; and
- An indication of whether rumble strips had a significant effect on the crash type of intercept.

Four relevant findings from the EB analyses are noteworthy:

- Of the 12 analyses based on TOT crashes (Table 25), 7 yield significant results at the 90 or 95 percent confidence level. Six of the seven analyses that indicate significant changes in crashes due to shoulder rumble strips result in counterintuitive results, suggesting an increase in TOT crashes when shoulder rumble strips are installed.
- Of the 12 separate analyses based on FI crashes (Table 26), only the analysis of Pennsylvania urban freeway data yields statistically significant results, indicating a decrease in FI crashes when shoulder rumble strips are installed on urban freeways.
- Five of the 12 analyses based on SVROR crashes (Table 27) indicate that shoulder rumble strips have a statistically significant effect on SVROR crash frequency. Three of the statistically significant results indicate a decrease in SVROR crashes when shoulder rumble strips are installed, while two indicate an increase in SVROR crashes when shoulder rumble strips are installed.
- Six of the 12 analyses based on SVROR FI (Table 28) crashes indicate a statistically significant decrease in SVROR FI

Table 25. Safety effectiveness of shoulder rumble strips on TOT crashes using the EB method.

Roadway type	State	Number of sites	Total length (mi)	Percent change in crash frequency from before to after rumble strip installation (%) Estimate[a]	SE[b]	Test statistic[c]	Significance
Urban freeways	PA	53	35.5	–1.38	5.72	0.24	Not significant at 90% CL
Rural freeways	Combined	47	67.5	7.02	3.91	1.80	Significant at 90% CL
	MO	29	52.1	7.89	4.13	1.91	Significant at 90% CL
	PA	18	15.4	0.33	11.80	0.03	Not significant at 90% CL
Rural multilane divided highways (nonfreeways)	Combined	25	43.3	18.09	7.80	2.32	Significant at 95% CL
	MN	6	20.0	10.22	14.68	0.70	Not significant at 90% CL
	MO	14	19.1	22.00	9.46	2.32	Significant at 95% CL
	PA	5	4.2	–13.29	35.64	0.37	Not significant at 90% CL
Rural two–lane roads	Combined	53	129.4	5.93	5.74	1.03	Not significant at 90% CL
	MN	28	95.5	14.38	8.01	1.80	Significant at 90% CL
	MO	5	10.5	40.49	18.00	2.25	Significant at 95% CL
	PA	20	23.3	–24.40	8.61	2.83	Significant at 95% CL

[a] A negative percent change indicates a decrease in crash frequency while a positive percent change indicates an increase in crash frequency.
[b] SE: standard error of estimate.
[c] Test statistic = abs(Estimate/SE); not significant at 90% CL if < 1.7; significant at 90% CL if ≥ 1.7; significant at 95% CL if ≥ 2.

Table 26. Safety effectiveness of shoulder rumble strips on FI crashes using the EB method.

Roadway type	State	Number of sites	Total length (mi)	Percent change in crash frequency from before to after rumble strip installation (%) Estimate[a]	SE[b]	Test statistic[c]	Significance
Urban freeways	PA	53	35.5	–16.01	7.25	2.21	Significant at 95% CL
Rural freeways	Combined	47	67.5	–6.88	5.88	1.17	Not significant at 90% CL
	MO	29	52.1	–5.84	6.41	0.91	Not significant at 90% CL
	PA	18	15.4	–12.61	14.62	0.86	Not significant at 90% CL
Rural multilane divided highways (nonfreeways)	Combined	25	43.3	–10.16	10.22	0.99	Not significant at 90% CL
	MN	6	20.0	–22.21	19.63	1.13	Not significant at 90% CL
	MO	14	19.1	–5.25	12.31	0.43	Not significant at 90% CL
	PA	5	4.2	–40.12	42.52	0.94	Not significant at 90% CL
Rural two–lane roads	Combined	53	129.4	–7.99	8.04	0.99	Not significant at 90% CL
	MN	28	95.5	5.13	12.66	0.41	Not significant at 90% CL
	MO	5	10.5	–19.24	21.82	0.88	Not significant at 90% CL
	PA	20	23.3	–17.97	11.59	1.55	Not significant at 90% CL

[a] A negative percent change indicates a decrease in crash frequency while a positive percent change indicates an increase in crash frequency.
[b] SE: standard error of estimate.
[c] Test statistic = abs(Estimate/SE); not significant at 90% CL if < 1.7; significant at 90% CL if ≥ 1.7; significant at 95% CL if ≥ 2.

Table 27. Safety effectiveness of shoulder rumble strips on SVROR crashes using the EB method.

Roadway type	State	Number of sites	Total length (mi)	Percent change in crash frequency from before to after rumble strip installation (%)		Test statistic[c]	Significance
				Estimate[a]	SE[b]		
Urban freeways	PA	53	35.5	–5.81	7.32	0.79	Not significant at 90% CL
Rural freeways	Combined	47	67.5	–9.68	5.21	1.86	Significant at 90% CL
	MO	29	52.1	–7.91	5.71	1.38	Not significant at 90% CL
	PA	18	15.4	–17.71	12.27	1.44	Not significant at 90% CL
Rural multilane divided highways (nonfreeways)	Combined	25	43.3	40.01	12.40	3.23	Significant at 95% CL
	MN	6	20.0	38.36	26.62	1.44	Not significant at 90% CL
	MO	14	19.1	44.78	14.79	3.03	Significant at 95% CL
	PA	5	4.2	–25.46	37.44	0.68	Not significant at 90% CL
Rural two–lane roads	Combined	53	129.4	–16.17	8.07	2.01	Significant at 95% CL
	MN	28	95.5	10.72	17.07	0.63	Not significant at 90% CL
	MO	5	10.5	16.87	21.76	0.78	Not significant at 90% CL
	PA	20	23.3	–43.59	9.13	4.77	Significant at 95% CL

[a] A negative percent change indicates a decrease in crash frequency while a positive percent change indicates an increase in crash frequency.
[b] SE: standard error of estimate.
[c] Test statistic = abs(Estimate/SE); not significant at 90% CL if < 1.7; significant at 90% CL if ≥ 1.7; significant at 95% CL if ≥ 2.

Table 28. Safety effectiveness of shoulder rumble strips on SVROR FI crashes using the EB method.

Roadway type	State	Number of sites	Total length (mi)	Percent change in crash frequency from before to after rumble strip installation (%)		Test statistic[c]	Significance
				Estimate[a]	SE[b]		
Urban freeways	PA	53	35.5	–7.43	9.93	0.75	Not significant at 90% CL
Rural freeways	Combined	47	67.5	–17.14	7.30	2.35	Significant at 95% CL
	MO	29	52.1	–15.64	8.22	1.90	Significant at 90% CL
	PA	18	15.4	–23.20	15.71	1.48	Not significant at 90% CL
Rural multilane divided highways (nonfreeways)	Combined	25	43.3	–2.64	13.51	0.20	Not significant at 90% CL
	MN	6	20.0	–10.29	28.63	0.36	Not significant at 90% CL
	MO	14	19.1	0.16	15.84	0.01	Not significant at 90% CL
	PA	5	4.2	–19.86	56.95	0.35	Not significant at 90% CL
Rural two–lane roads	Combined	53	129.4	–36.42	9.71	3.75	Significant at 95% CL
	MN	28	95.5	–32.41	17.61	1.84	Significant at 90% CL
	MO	5	10.5	–44.59	23.16	1.93	Significant at 90% CL
	PA	20	23.3	–36.66	13.35	2.75	Significant at 95% CL

[a] A negative percent change indicates a decrease in crash frequency while a positive effect indicates an increase in crash frequency.
[b] SE: standard error of estimate.
[c] Test statistic = abs(Estimate/SE); not significant at 90% CL if < 1.7; significant at 90% CL if ≥ 1.7; significant at 95% CL if ≥ 2.

crashes when shoulder rumble strips are installed. The statistically significant results are obtained for rural freeways and rural two-lane roads.

Cross-Sectional GLM Analysis Results

The safety effectiveness of shoulder rumble strips was also evaluated using a repeated measures analysis of variance approach based on all treatment and nontreatment sites as discussed in the Analysis Approach part of this section. This approach takes advantage of crash information on all study sites of interest.

For each crash type, roadway type, and state, a regression model was developed to estimate crash frequency as a function of ADT, outside RHR (and inside RHR when applicable), and the presence of rumble strips. Similar to the development of SPFs, a stepwise selection procedure was implemented to assess the significance of these variables, as discussed in the Analysis Approach part of this section.

The GLM regression results for each crash type, roadway type, and state are shown in Tables F-1 through F-4 in Appendix F. These tables present the estimates of the regression coefficients and their precision (standard error) along with their significance level, and the dispersion parameter statistics. The introduction to Appendix F provides details on how to read and use these tables.

The safety effectiveness of shoulder rumble strips is evaluated in Tables 29 through 32 for the four crash types of interest. These tables are directly obtained from Tables F-1 through F-4 by calculating the percent change due to rumble strips from the rumble strip coefficient shown in Appendix F. For each crash type (i.e., TOT, FI, SVROR, and SVROR FI crashes), 12 separate analyses were performed across the roadway types of interest, based on data for individual states and/or combined data across states. The statistics shown in Tables 29 through 32 for TOT, FI, SVROR, and SVROR FI crashes, respectively, include:

- Number of sites (all treatment and nontreatment sites);
- Number of site-years;
- Percent change due to shoulder rumble strip: estimate and lower and upper 95 percent confidence limits;
- Associated Type 3 p-value; and
- An indication of whether rumble strips had a significant effect on the crash type of interest.

A negative percent change in crash frequency indicates that crash frequencies decreased due to the shoulder rumble strip treatment; conversely, a positive change indicates an increase in crash frequencies. The 95 percent confidence limits of the percent change provide an assessment of whether the change, positive or negative, is statistically significant at the 95 percent confidence level: if the interval contains zero, then the change is not statistically significant (i.e., not different from zero) at the 95 percent confidence level; if the interval does not contain zero, then the change is statistically significant (i.e., different from zero) at the 95 percent confidence level.

The Type 3 p-values in the last column of Tables 29 through 32 also provide an indication of whether rumble strips have a significant effect on crash frequencies. These p-values correspond to the score statistics produced in the Type 3 GEE analysis and are generally more conservative than the p-values associated with the computation of the 95 percent confidence limits, which are computed with the Wald statistic. Generally, these two p-values are in agreement with each other; however, when the two disagree, the Type 3 p-value should be the one on which to base conclusions (*73,74*). In most cases in Tables 29 through 32, the Type 3 p-value is no more than 0.10 when the p-value associated with the confidence limits is 0.05.

Several relevant findings from the cross-sectional GLM analyses based on all treatment and nontreatment sites are as follows:

- Of the 12 analyses of TOT crashes (Table 29), 3 yield significant results at the 90 or 95 percent confidence level based on the Type 3 p-value. Each of the statistically significant results is for rural multilane divided highways (nonfreeways), and each result is counterintuitive, indicating an increase in TOT crashes when shoulder rumble strips are installed.
- Of the 12 analyses of FI crashes (Table 30), 2 yield significant results at the 90 or 95 percent confidence level based on the Type 3 p-value. Both results indicate a decrease in FI crashes when shoulder rumble strips are installed.
- Of the 12 analyses of SVROR crashes (Table 31), 6 yield significant results at the 90 or 95 percent confidence level based on the Type 3 p-value. Three of the analyses indicate a decrease in SVROR crashes when shoulder rumble strips are installed, while the other three analysis results are counterintuitive. All of the counterintuitive results are based on data for rural multilane divided highways (nonfreeways).
- Of the 12 analyses of SVROR FI crashes (Table 32), 3 yield significant results at the 90 or 95 percent confidence level based on the Type 3 p-value. All three results indicate a decrease in SVROR FI crashes when shoulder rumble strips are installed.

The GLM method was then repeated using a smaller set of sites consisting of all nontreatment sites and cross-sectional nontreatment sites. Thus, the cross-sectional treatment sites were excluded from the previous analysis. This analysis approach most resembles that of the EB analysis in that the two approaches use crash and site information from the same types of sites.

Table 29. Safety effectiveness of shoulder rumble strips on TOT crashes based on all site types using the GLM method.

Roadway type	State	Number of sites	Number of site-years	Percent difference in crash frequency with rumble strips present			Type 3 p-value	Significance
				Estimate (%)	Lower 95% CL	Upper 95% CL		
Urban freeways	PA	138	999	–3.8	–13.9	7.5	0.51	Not significant at 90% CL
Rural freeways	Combined	122	776	1.0	–11.8	15.5	0.89	Not significant at 90% CL
	MO	47	351	8.3	–4.8	23.3	0.26	Not significant at 90% CL
	PA	75	425	7.9	–12.6	33.1	0.50	Not significant at 90% CL
Rural multilane divided highways (nonfreeways)	Combined	104	788	20.1	2.8	40.2	0.03	Significant at 95% CL
	MN	60	424	16.4	–0.2	35.8	0.07	Significant at 90% CL
	MO	27	239	27.8	2.9	58.7	0.07	Significant at 90% CL
	PA	17	125	–19.2	–49.6	29.4	0.43	Not significant at 90% CL
Rural two-lane roads	Combined	257	2,124	–14.0	–30.9	7.1	0.14	Not significant at 90% CL
	MN	109	726	–3.7	–16.2	10.6	0.59	Not significant at 90% CL
	MO	38	366	–16.7	–85.2	369.5	0.71	Not significant at 90% CL
	PA	110	1,032	–24.4	–48.1	10.1	0.14	Not significant at 90% CL

Table 30. Safety effectiveness of shoulder rumble strips on FI crashes based on all site types using the GLM method.

Roadway type	State	Number of sites	Number of site-years	Percent difference in crash frequency with rumble strips present			Type 3 p-value	Significance
				Estimate (%)	Lower 95% CL	Upper 95% CL		
Urban freeways	PA	138	999	–9.2	–22.2	6.0	0.23	Not significant at 90% CL
Rural freeways	Combined	122	776	–7.5	–19.7	6.6	0.28	Not significant at 90% CL
	MO	47	351	–2.6	–17.6	15.2	0.77	Not significant at 90% CL
	PA	75	425	–11.7	–30.8	12.7	0.32	Not significant at 90% CL
Rural multilane divided highways (nonfreeways)	Combined	104	788	0.6	–18.4	24.0	0.96	Not significant at 90% CL
	MN	60	424	6.9	–11.0	28.5	0.47	Not significant at 90% CL
	MO	27	239	5.3	–29.5	57.4	0.79	Not significant at 90% CL
	PA	17	125	–41.5	–65.4	–1.2	0.09	Significant at 90% CL
Rural two-lane roads	Combined	257	2,124	–27.5	–42.4	–8.6	0.01	Significant at 95% CL
	MN	109	726	–12.7	–27.6	5.3	0.16	Not significant at 90% CL
	MO	38	366	–39.7	–86.1	162.4	0.32	Not significant at 90% CL
	PA	110	1,032	–16.4	–45.6	28.5	0.36	Not significant at 90% CL

Table 31. Safety effectiveness of shoulder rumble strips on SVROR crashes based on all site types using the GLM method.

Roadway type	State	Number of sites	Number of site-years	Percent difference in crash frequency with rumble strips present			Type 3 p-value	Significance
				Estimate (%)	Lower 95% CL	Upper 95% CL		
Urban freeways	PA	138	999	–3.7	–17.4	12.2	0.63	Not significant at 90% CL
Rural freeways	Combined	122	776	–9.5	–21.6	4.5	0.19	Not significant at 90% CL
	MO	47	351	–6.5	–19.0	7.9	0.40	Not significant at 90% CL
	PA	75	425	–2.1	–24.8	27.4	0.88	Not significant at 90% CL
Rural multilane divided highways (nonfreeways)	Combined	104	788	41.4	12.0	78.4	0.00	Significant at 95% CL
	MN	60	424	38.5	9.8	74.6	0.01	Significant at 95% CL
	MO	27	239	69.6	23.5	132.9	0.01	Significant at 95% CL
	PA	17	125	–23.3	–44.9	6.8	0.10	Significant at 90% CL
Rural two-lane roads	Combined	257	2,124	–29.4	–49.0	–2.1	0.03	Significant at 95% CL
	MN	109	726	19.3	–7.8	54.4	0.19	Not significant at 90% CL
	MO	38	366	–8.9	–80.5	325.7	0.83	Not significant at 90% CL
	PA	110	1,032	–45.0	–64.6	–14.5	0.03	Significant at 95% CL

Table 32. Safety effectiveness of shoulder rumble strips on SVROR FI crashes based on all site types using the GLM method.

Roadway type	State	Number of sites	Number of site-years	Percent difference in crash frequency with rumble strips present			Type 3 p-value	Significance
				Estimate (%)	Lower 95% CL	Upper 95% CL		
Urban freeways	PA	138	999	1.7	–15.7	22.6	0.87	Not significant at 90% CL
Rural freeways	Combined	122	776	–13.8	–27.0	1.7	0.09	Significant at 90% CL
	MO	47	351	–12.4	–27.6	6.0	0.20	Not significant at 90% CL
	PA	75	425	–13.0	–36.4	19.0	0.40	Not significant at 90% CL
Rural multilane divided highways (nonfreeways)	Combined	104	788	4.7	–19.9	36.7	0.72	Not significant at 90% CL
	MN	60	424	12.2	–14.1	46.6	0.39	Not significant at 90% CL
	MO	27	239	18.5	–21.7	79.2	0.41	Not significant at 90% CL
	PA	17	125	–32.9	–61.3	16.4	0.18	Not significant at 90% CL
Rural two-lane roads	Combined	257	2,124	–37.3	–54.3	–13.9	0.01	Significant at 95% CL
	MN	109	726	3.6	–26.4	45.7	0.85	Not significant at 90% CL
	MO	38	366	–59.4	–97.3	510.3	0.25	Not significant at 90% CL
	PA	110	1,032	–37.4	–61.1	0.8	0.06	Significant at 90% CL

The GLM regression results of this cross-sectional analysis are presented in Tables F-5 through F-8 in Appendix F for the four types of crashes. The structure of these tables is identical to that of Tables F-1 through F-4. The safety effectiveness of shoulder rumble strips is evaluated in Tables 33 through 36 for the four crash types of interest. These tables are directly obtained from Tables F-5 through F-8 by calculating the percent change due to rumble strips from the rumble strip coefficient shown in Appendix F. The general discussion of Tables 29 through 32 also applies to Tables 33 through 36. Similar to the previous two types of analysis, for each crash type (i.e., TOT, FI, SVROR, and SVROR FI crashes), 12 analyses are performed across the four roadway types of interest, based on data for individual states and/or combined data across states.

The following relevant findings from the cross-sectional GLM analyses based on all before-after sites and all nontreatment cross-sectional sites (thus excluding cross-sectional treatment sites) are noteworthy:

- Of the 12 analyses based on TOT crashes (Table 33), 3 yield significant results at the 90 or 95 percent confidence level based on the Type 3 p-value. Each of these results is counterintuitive.
- Of the 12 analyses based on FI crashes (Table 34), 2 yield significant results at the 90 or 95 percent confidence level based on the Type 3 p-value. Both results indicate a decrease in FI crashes when shoulder rumble strips are installed.
- Of the 12 analyses based on SVROR crashes (Table 35), 4 yield significant results at the 90 or 95 percent confidence level based on the Type 3 p-value. Three of these results are counterintuitive.
- Of the 12 analyses based on SVROR FI crashes (Table 36), 3 yield significant results at the 90 or 95 percent confidence level based on the Type 3 p-value. All three results indicate a decrease in SVROR FI crashes when shoulder rumble strips are installed.

Comparison of Results from the Different Analysis Approaches

The previous discussion covers two statistical methods—EB and GLM—applied to three different sets of data to assess the safety effectiveness of shoulder rumble strips on different roadway types. A direct comparison of the three sets of results is presented in Tables 37 through 40 for the four crash types, respectively. These tables are simply a side-by-side compilation of Tables 25 through 36, highlighting the relevant statistics for each crash type, roadway type, and state combination. A row is shaded in gray whenever a percent change obtained from any of the three analyses shows a statistically significant rumble strip effect at the 95 or 90 percent confidence level.

Table 37 compares the results from the three analysis approaches to estimate the safety effectiveness of shoulder rumble strips based on TOT crashes. Comparisons of these results yield the following findings:

- Analyses for rural multilane divided highways (nonfreeways) yield the most consistent results across the three analysis approaches. Analyses for rural multilane divided highways (nonfreeways) based on the combined data for all three states and based on Missouri data yield statistically significant results; however, the results are counterintuitive.
- Of the 36 analyses performed on TOT crashes using the three analysis approaches, only one (the EB analysis of rural two-lane roads based on Pennsylvania data) yields statistically significant results that appear intuitive (i.e., indicate a decrease in TOT crashes when shoulder rumble strips are installed).
- Of the 36 analyses performed on TOT crashes using the three analysis approaches, 12 yield statistically significant results that are counterintuitive.
- The largest range between the statistically significant estimates for the percent change due to rumble strips across analysis approaches is from 18.1 to 28.0 percent for rural multilane divided highways (nonfreeways) based on combined data. All analysis approaches indicate a significant increase in TOT crashes when shoulder rumble strips are installed.

Table 38 compares the results from the three analysis approaches to estimate the safety effectiveness of shoulder rumble strips based on FI crashes. Comparisons of these results yield the following findings:

- Of the 36 analyses performed on FI crashes using the three analysis approaches, 5 yield statistically significant results at the 95 or 90 percent confidence level. All of these results indicate a significant decrease in FI crashes when shoulder rumble strips are installed.
- The largest range between the statistically significant estimates for the percent change due to rumble strips across analysis approaches is from −16.0 to −20.4 percent for urban freeways based on Pennsylvania data, suggesting close agreement between analysis approaches when statistically significant results are obtained.

Table 39 compares the results from the three analysis approaches to estimate the safety effectiveness of shoulder rumble strips based on SVROR crashes. Comparisons of these results yield the following findings:

- Of the 36 analyses performed on SVROR crashes across the three analysis approaches, 15 yield statistically significant

Table 33. Safety effectiveness of shoulder rumble strips on TOT crashes based on before-after sites and nontreatment cross-sectional sites using the GLM method.

Roadway type	State	Number of sites	Number of site-years	Percent difference in crash frequency with rumble strips present			Type 3 p-value	Significance
				Estimate (%)	Lower 95% CL	Upper 95% CL		
Urban freeways	PA	90	825	–5.2	–15.7	6.6	0.39	Not significant at 90% CL
Rural freeways	Combined	69	636	6.8	–7.4	23.2	0.36	Not significant at 90% CL
	MO	35	321	11.4	–2.5	27.4	0.15	Not significant at 90% CL
	PA	34	315	6.4	–20.6	42.5	0.69	Not significant at 90% CL
Rural multilane divided highways (nonfreeways)	Combined	72	646	28.0	8.4	51.2	0.02	Significant at 95% CL
	MN	33	291	16.7	–7.1	46.5	0.31	Not significant at 90% CL
	MO	26	238	27.7	2.7	58.8	0.08	Significant at 90% CL
	PA	13	117	–25.7	–59.6	36.4	0.37	Not significant at 90% CL
Rural two-lane roads	Combined	203	1,871	–5.5	–27.7	23.5	0.65	Not significant at 90% CL
	MN	56	474	17.9	–0.6	39.7	0.09	Significant at 90% CL
	MO	37	365	–15.3	–86.2	421.0	0.74	Not significant at 90% CL
	PA	110	1,032	–24.4	–48.1	10.1	0.14	Not significant at 90% CL

Table 34. Safety effectiveness of shoulder rumble strips on FI crashes based on before-after sites and nontreatment cross-sectional sites using the GLM method.

Roadway type	State	Number of sites	Number of site-years	Percent difference in crash frequency with rumble strips present			Type 3 p-value	Significance
				Estimate (%)	Lower 95% CL	Upper 95% CL		
Urban freeways	PA	90	825	–20.4	–34.2	–3.7	0.02	Significant at 95% CL
Rural freeways	Combined	69	636	–4.1	–19.2	13.8	0.63	Not significant at 90% CL
	MO	35	321	–1.3	–18.3	19.1	0.89	Not significant at 90% CL
	PA	34	315	–8.6	–32.2	23.2	0.56	Not significant at 90% CL
Rural multilane divided highways (nonfreeways)	Combined	72	646	5.1	–24.3	45.8	0.75	Not significant at 90% CL
	MN	33	291	–17.7	–42.1	17.0	0.33	Not significant at 90% CL
	MO	26	238	1.9	–32.3	53.2	0.93	Not significant at 90% CL
	PA	13	117	–43.8	–68.0	–1.2	0.10	Significant at 90% CL
Rural two-lane roads	Combined	203	1,871	–14.4	–34.1	11.2	0.23	Not significant at 90% CL
	MN	56	474	7.0	–20.0	43.1	0.66	Not significant at 90% CL
	MO	37	365	–35.4	–85.5	188.1	0.40	Not significant at 90% CL
	PA	110	1,032	–16.4	–45.6	28.5	0.36	Not significant at 90% CL

Table 35. Safety effectiveness of shoulder rumble strips on SVROR crashes based on before-after sites and nontreatment cross-sectional sites using the GLM method.

Roadway type	State	Number of sites	Number of site-years	Percent difference in crash frequency with rumble strips present			Type 3 p-value	Significance
				Estimate (%)	Lower 95% CL	Upper 95% CL		
Urban freeways	PA	90	825	–9.6	–26.6	11.2	0.33	Not significant at 90% CL
Rural freeways	Combined	69	636	–9.5	–22.7	5.9	0.23	Not significant at 90% CL
	MO	35	321	–5.6	–18.8	9.7	0.50	Not significant at 90% CL
	PA	34	315	–13.0	–39.5	24.9	0.45	Not significant at 90% CL
Rural multilane divided highways (nonfreeways)	Combined	72	646	66.4	27.1	118.0	0.00	Significant at 95% CL
	MN	33	291	34.4	11.1	62.6	0.06	Significant at 90% CL
	MO	26	238	66.8	21.2	129.4	0.01	Significant at 95% CL
	PA	13	117	–22.7	–45.1	8.9	0.12	Not significant at 90% CL
Rural two-lane roads	Combined	203	1,871	–25.9	–52.0	14.5	0.12	Not significant at 90% CL
	MN	56	474	12.1	–21.1	59.3	0.54	Not significant at 90% CL
	MO	37	365	–5.8	–80.1	346.1	0.89	Not significant at 90% CL
	PA	110	1,032	–45.0	–64.6	–14.5	0.03	Significant at 95% CL

Table 36. Safety effectiveness of shoulder rumble strips on SVROR FI crashes based on before-after sites and nontreatment cross-sectional sites using the GLM method.

Roadway type	State	Number of sites	Number of site-years	Percent difference in crash frequency with rumble strips present			Type 3 p-value	Significance
				Estimate (%)	Lower 95% CL	Upper 95% CL		
Urban freeways	PA	90	825	–9.5	–29.4	16.0	0.42	Not significant at 90% CL
Rural freeways	Combined	69	636	–17.5	–32.2	0.3	0.06	Significant at 90% CL
	MO	35	321	–13.7	–30.5	7.1	0.22	Not significant at 90% CL
	PA	34	315	–22.0	–47.0	14.7	0.22	Not significant at 90% CL
Rural multilane divided highways (nonfreeways)	Combined	72	646	14.7	–22.7	70.4	0.46	Not significant at 90% CL
	MN	33	291	–14.8	–41.1	23.4	0.40	Not significant at 90% CL
	MO	26	238	11.6	–25.8	67.7	0.59	Not significant at 90% CL
	PA	13	117	–21.5	–47.4	17.1	0.32	Not significant at 90% CL
Rural two-lane roads	Combined	203	1,871	–39.6	–59.5	–9.9	0.02	Significant at 95% CL
	MN	56	474	–22.6	–52.5	26.1	0.36	Not significant at 90% CL
	MO	37	365	–56.9	–97.4	617.0	0.29	Not significant at 90% CL
	PA	110	1,032	–37.4	–61.1	0.8	0.06	Significant at 90% CL

Table 37. Comparison of results from three approaches to estimate safety effectiveness of shoulder rumble strips on TOT crashes.

Roadway type	State	EB results (Table 25)				GLM results using BA and nontreatment CS sites (Table 33)					GLM results using all sites (Table 29)				
		Number of sites	Percent change in crash frequency from before to after rumble strip installation (%): Estimate	Percent change in crash frequency from before to after rumble strip installation (%): SE	Test statistic	Number of sites	Percent difference in crash frequency with rumble strips present (%): Estimate (%)	Lower 95% CL	Upper 95% CL	Type 3 p-value	Number of sites	Percent difference in crash frequency with rumble strips present (%): Estimate (%)	Lower 95% CL	Upper 95% CL	Type 3 p-value
Urban freeways	PA	53	–1.4	5.7	0.24	90	–5.2	–15.7	6.6	0.39	138	–3.8	–13.9	7.5	0.51
Rural freeways	Combined	47	7.0	3.9	1.80	69	6.8	–7.4	23.2	0.36	122	1.0	–11.8	15.5	0.89
	MO	29	7.9	4.1	1.91	35	11.4	–2.5	27.4	0.15	47	8.3	–4.8	23.3	0.26
	PA	18	0.3	11.8	0.03	34	6.4	–20.6	42.5	0.69	75	7.9	–12.6	33.1	0.50
Rural multilane divided highways (nonfreeways)	Combined	25	18.1	7.8	2.32	72	28.0	8.4	51.2	0.02	104	20.1	2.8	40.2	0.03
	MN	6	10.2	14.7	0.70	33	16.7	–7.1	46.5	0.31	60	16.4	–0.2	35.8	0.07
	MO	14	22.0	9.5	2.32	26	27.7	2.7	58.8	0.08	27	27.8	2.9	58.7	0.07
	PA	5	–13.3	35.6	0.37	13	–25.7	–59.6	36.4	0.37	17	–19.2	–49.6	29.4	0.43
Rural two-lane roads	Combined	53	5.9	5.7	1.03	203	-5.5	–27.7	23.5	0.65	257	–14.0	–30.9	7.1	0.14
	MN	28	14.4	8.0	1.80	56	17.9	–0.6	39.7	0.09	109	–3.7	–16.2	10.6	0.59
	MO	5	40.5	18.0	2.25	37	–15.3	–86.2	421.0	0.74	38	–16.7	–85.2	369.5	0.71
	PA	20	–24.4	8.6	2.83	110	–24.4	–48.1	10.1	0.14	110	–24.4	–48.1	10.1	0.14

Table 38. Comparison of results from three approaches to estimate safety effectiveness of shoulder rumble strips on FI crashes.

Roadway type	State	EB results (Table 26)				GLM results using BA and nontreatment CS sites (Table 34)					GLM results using all sites (Table 30)				
		Number of sites	Percent change in crash frequency from before to after rumble strip installation (%): Estimate	Percent change in crash frequency from before to after rumble strip installation (%): SE	Test statistic	Number of sites	Percent difference in crash frequency with rumble strips present (%): Estimate (%)	Lower 95% CL	Upper 95% CL	Type 3 p-value	Number of sites	Percent difference in crash frequency with rumble strips present (%): Estimate (%)	Lower 95% CL	Upper 95% CL	Type 3 p-value
Urban freeways	PA	53	–16.0	7.2	2.21	90	–20.4	–34.2	–3.7	0.02	138	–9.2	–22.2	6.0	0.23
Rural freeways	Combined	47	–6.9	5.9	1.17	69	–4.1	–19.2	13.8	0.63	122	–7.5	–19.7	6.6	0.28
	MO	29	–5.8	6.4	0.91	35	–1.3	–18.3	19.1	0.89	47	–2.6	–17.6	15.2	0.77
	PA	18	–12.6	14.6	0.86	34	–8.6	–32.2	23.2	0.56	75	–11.7	–30.8	12.7	0.32
Rural multilane divided highways (nonfreeways)	Combined	25	–10.2	10.2	0.99	72	5.1	–24.3	45.8	0.75	104	0.6	–18.4	24.0	0.96
	MN	6	–22.2	19.6	1.13	33	–17.7	–42.1	17.0	0.33	60	6.9	–11.0	28.5	0.47
	MO	14	–5.2	12.3	0.43	26	1.9	–32.3	53.2	0.93	27	5.3	–29.5	57.4	0.79
	PA	5	–40.1	42.5	0.94	13	–43.8	–68.0	–1.2	0.10	17	–41.5	–65.4	–1.2	0.09
Rural two-lane roads	Combined	53	–8.0	8.0	0.99	203	–14.4	–34.1	11.2	0.23	257	–27.5	–42.4	–8.6	0.01
	MN	28	5.1	12.7	0.41	56	7.0	–20.0	43.1	0.66	109	–12.7	–27.6	5.3	0.16
	MO	5	–19.2	21.8	0.88	37	–35.4	–85.5	188.1	0.40	38	–39.7	–86.1	162.4	0.32
	PA	20	–18.0	11.6	1.55	110	–16.4	–45.6	28.5	0.36	110	–16.4	–45.6	28.5	0.36

Table 39. Comparison of results from three approaches to estimate safety effectiveness of shoulder rumble strips on SVROR crashes.

Roadway type	State	EB results (Table 27): Number of sites	EB results (Table 27): Percent change in crash frequency from before to after rumble strip installation (%) Estimate	EB results (Table 27): Percent change in crash frequency from before to after rumble strip installation (%) SE	EB results (Table 27): Test statistic	GLM results using BA and nontreatment CS sites (Table 35): Number of sites	GLM results using BA and nontreatment CS sites (Table 35): Percent difference in crash frequency with rumble strips present (%) Estimate (%)	GLM results using BA and nontreatment CS sites (Table 35): Percent difference in crash frequency with rumble strips present (%) Lower 95% CL	GLM results using BA and nontreatment CS sites (Table 35): Percent difference in crash frequency with rumble strips present (%) Upper 95% CL	GLM results using BA and nontreatment CS sites (Table 35): Type 3 p-value	GLM results using all sites (Table 31): Number of sites	GLM results using all sites (Table 31): Percent difference in crash frequency with rumble strips present (%) Estimate (%)	GLM results using all sites (Table 31): Percent difference in crash frequency with rumble strips present (%) Lower 95% CL	GLM results using all sites (Table 31): Percent difference in crash frequency with rumble strips present (%) Upper 95% CL	GLM results using all sites (Table 31): Type 3 p-value
Urban freeways	PA	53	–5.8	7.3	0.79	90	–9.6	–26.6	11.2	0.33	138	–3.7	–17.4	12.2	0.63
Rural freeways	Combined	47	–9.7	5.2	1.86	69	–9.5	–22.7	5.9	0.23	122	–9.5	–21.6	4.5	0.19
	MO	29	–7.9	5.7	1.38	35	–5.6	–18.8	9.7	0.50	47	–6.5	–19.0	7.9	0.40
	PA	18	–17.7	12.3	1.44	34	–13.0	–39.5	24.9	0.45	75	–2.1	–24.8	27.4	0.88
Rural multilane divided highways (nonfreeways)	Combined	25	40.0	12.4	3.23	72	66.4	27.1	118.0	0.00	104	41.4	12.0	78.4	0.00
	MN	6	38.4	26.6	1.44	33	34.4	11.1	62.6	0.06	60	38.5	9.8	74.6	0.01
	MO	14	44.8	14.8	3.03	26	66.8	21.2	129.4	0.01	27	69.6	23.5	132.9	0.01
	PA	5	–25.5	37.4	0.68	13	–22.7	–45.1	8.9	0.12	17	–23.3	–44.9	6.8	0.10
Rural two-lane roads	Combined	53	–16.2	8.1	2.01	203	–25.9	–52.0	14.5	0.12	257	–29.4	–49.0	–2.1	0.03
	MN	28	10.7	17.1	0.63	56	12.1	–21.1	59.3	0.54	109	19.3	–7.8	54.4	0.19
	MO	5	16.9	21.8	0.78	37	–5.8	–80.1	346.1	0.89	38	–8.9	–80.5	325.7	0.83
	PA	20	–43.6	9.1	4.77	110	–45.0	–64.6	–14.5	0.03	110	–45.0	–64.6	–14.5	0.03

Table 40. Comparison of results from three approaches to estimate safety effectiveness of shoulder rumble strips on SVROR FI crashes.

Roadway type	State	EB results (Table 28): Number of sites	EB results (Table 28): Percent change in crash frequency from before to after rumble strip installation (%) Estimate	EB results (Table 28): Percent change in crash frequency from before to after rumble strip installation (%) SE	EB results (Table 28): Test statistic	GLM results using BA and nontreatment CS sites (Table 36): Number of sites	GLM results using BA and nontreatment CS sites (Table 36): Percent difference in crash frequency with rumble strips present (%) Estimate (%)	GLM results using BA and nontreatment CS sites (Table 36): Percent difference in crash frequency with rumble strips present (%) Lower 95% CL	GLM results using BA and nontreatment CS sites (Table 36): Percent difference in crash frequency with rumble strips present (%) Upper 95% CL	GLM results using BA and nontreatment CS sites (Table 36): Type 3 p-value	GLM results using all sites (Table 32): Number of sites	GLM results using all sites (Table 32): Percent difference in crash frequency with rumble strips present (%) Estimate (%)	GLM results using all sites (Table 32): Percent difference in crash frequency with rumble strips present (%) Lower 95% CL	GLM results using all sites (Table 32): Percent difference in crash frequency with rumble strips present (%) Upper 95% CL	GLM results using all sites (Table 32): Type 3 p-value
Urban freeways	PA	53	–7.4	9.9	0.75	90	–9.5	–29.4	16.0	0.42	138	1.7	–15.7	22.6	0.87
Rural freeways	Combined	47	–17.1	7.3	2.35	69	–17.5	–32.2	0.3	0.06	122	–13.8	–27.0	1.7	0.09
	MO	29	–15.6	8.2	1.90	35	–13.7	–30.5	7.1	0.22	47	–12.4	–27.6	6.0	0.20
	PA	18	–23.2	15.7	1.48	34	–22.0	–47.0	14.7	0.22	75	–13.0	–36.4	19.0	0.40
Rural multilane divided highways (nonfreeways)	Combined	25	–2.6	13.5	0.20	72	14.7	–22.7	70.4	0.46	104	4.7	–19.9	36.7	0.72
	MN	6	–10.3	28.6	0.36	33	–14.8	–41.1	23.4	0.40	60	12.2	–14.1	46.6	0.39
	MO	14	0.2	15.8	0.01	26	11.6	–25.8	67.7	0.59	27	18.5	–21.7	79.2	0.41
	PA	5	–19.9	56.9	0.35	13	–21.5	–47.4	17.1	0.32	17	–32.9	–61.3	16.4	0.18
Rural two-lane roads	Combined	53	–36.4	9.7	3.75	203	–39.6	–59.5	–9.9	0.02	257	–37.3	–54.3	–13.9	0.01
	MN	28	–32.4	17.6	1.84	56	–22.6	–52.5	26.1	0.36	109	3.6	–26.4	45.7	0.85
	MO	5	–44.6	23.2	1.93	37	–56.9	–97.4	617.0	0.29	38	–59.4	–97.3	510.3	0.25
	PA	20	–36.7	13.3	2.75	110	–37.4	–61.1	0.8	0.06	110	–37.4	–61.1	0.8	0.06

results at the 95 or 90 percent confidence level. Seven of the statistically significant results indicate a significant decrease in SVROR crashes when shoulder rumble strips are installed, while eight indicate a significant increase in SVROR crashes when shoulder rumble strips are installed. All of the statistically significant results that are counterintuitive are for rural multilane divided highways (nonfreeways).

- The EB analysis is the only analysis approach that yields a significant result for rural freeways based on the combined data, indicating a significant reduction in SVROR crashes at the 90 percent confidence level.
- When comparing the estimated percent change due to rumble strips between the analyses which yielded statistically significant results, in several cases the estimated percent changes are very close. For example, the EB analysis indicates a 43.6 percent reduction in SVROR crashes for rural two-lane roads based on Pennsylvania data, while both GLM analyses indicate a 45 percent reduction in crashes. In other instances, the estimates are far apart. For example, the EB analysis indicates a 44.8 percent increase in SVROR crashes for rural multilane divided highways (nonfreeways) based on Missouri data, while the GLM analysis using all sites indicates a 69.6 percent increase in SVROR crashes.
- When more than one analysis approach yields a significant result for a given analysis, the results are always in the same direction, either indicating a significant decrease (or increase) in crashes due to shoulder rumble strips.

Table 40 compares the results from the three analysis approaches to estimate the safety effectiveness of shoulder rumble strips based on SVROR FI crashes. Comparisons of these results yield the following findings:

- Of the 36 analyses performed on SVROR FI crashes using the three analysis approaches, 12 yield statistically significant results at the 95 or 90 percent confidence level, and all of the statistically significant results indicate a significant decrease in SVROR FI crashes when shoulder rumble strips are installed.
- The EB and the GLM analyses for both data sets yield statistically significant results for the same three roadway types (i.e., rural freeways—combined data; rural two-lane roads—combined data; and rural two-lane roads—Pennsylvania data). The confidence levels among the analysis approaches (i.e., the EB analyses and the two GLM analyses) are slightly different, but the estimated percent change due to rumble strips for a given analysis (i.e., rural freeways—combined data; rural two-lane roads—combined data; and rural two-lane roads—Pennsylvania data) is relatively consistent across the three analysis approaches.

From the comparison of the results from the three analysis approaches to estimate the safety effectiveness of shoulder rumble strips for the four crash types of interest (i.e., TOT, FI, SVROR, and SVROR FI crashes), it is recommended that the focus of the analyses be on SVROR and SVROR FI crash results. The rationale for this recommendation is as follows. First, the primary purpose of shoulder rumble strips is to reduce SVROR crashes. Second, as indicated in the earlier part on Descriptive Statistics, no strong argument can be made to support why shoulder rumble strips would affect crashes other than SVROR crashes. Third, many of the analysis results for TOT crashes are counterintuitive. Therefore, the analysis results for TOT and FI crashes should be viewed with caution. In summary, the conclusions of safety evaluations of shoulder rumble strips will be based on results for SVROR and SVROR FI crashes. The conclusions also will focus on results obtained from analyses of combined data sets, rather than results for an individual state. In general, the results from across the three analysis approaches are most consistent when based on the combined data.

The conclusions of the safety evaluation of shoulder rumble strips will further focus on results obtained from the EB analyses. The EB method is typically the method of choice to evaluate the safety effectiveness of a treatment when data are available for sites before and after a treatment. The steps of the method are straightforward; the method accounts for regression to the mean effects, and most researchers in the field of safety analysis consider this the most appropriate evaluation method. It is also the preferred method described in the forthcoming HSM for conducting safety evaluations. The GLM with the GEE estimation technique is less well known to non-statisticians, is less straightforward in its implementation, and thus is used less frequently in the field of safety analysis. However, the GLM method has a number of advantages over the EB method in that it uses site-year data and yearly changes in ADT; allows for quantification of site variability across years; does not rely on strict before-after data with a separate group of reference sites; accounts for sample size when testing for statistical significance; and is based on statistical theory. The decision to draw conclusions of the safety evaluations of shoulder rumble strips based upon the EB analyses was made primarily because this analysis approach is the preferred method of the forthcoming HSM, but analyzing the data using both the EB and GLM methods (and the two data sets for the GLM method) proved valuable in showing that the analysis approach can significantly impact the results of an evaluation; it also helped to illustrate concerns about drawing conclusions based upon TOT and FI crashes.

In summary, the average safety effects of installing milled shoulder rumble strips on the following roadway types and their associated standard errors (SE) are estimated to be the following:

Rural Freeways:
- 10 percent reduction in SVROR crashes (SE = 5) and
- 17 percent reduction in SVROR FI crashes (SE = 7).

Rural Two-Lane Roads:
- 16 percent reduction in SVROR crashes (SE = 8) and
- 36 percent reduction in SVROR FI crashes (SE = 10).

The EB and GLM methods applied to these two crash types and roadway types provide very similar results, with the largest difference in results being for SVROR crashes on rural two-lane roads. Even though the results of the EB analysis of SVROR crashes for rural multilane divided highways show a statistically significant result at the 95-percent confidence level, the result is counterintuitive. This appears to be an anomaly in the data for this roadway type. This anomaly cannot be fully explained at this time. In part, a number of factors working in combination could provide this result, such as (a) the unreliability related to PDO crash records, (b) the design features of this roadway type (e.g., roadside features, speed limit), or (c) the driver population along this roadway type. Also the sample size for this roadway type is relatively small, making it difficult to control for confounding factors. Thus, because the result of the EB analysis of SVROR crashes on rural multilane divided highways does not pass a face validity test (i.e., the results are in the expected direction and the magnitude appears reasonable), the result is viewed as an anomaly in the data and is not presented as a credible result.

Comparison of Results with Previous Results

The remainder of this section compares the results of the safety evaluation of milled shoulder rumble strips performed during this research to results from several previous studies. Two types of roadway were considered: rural freeways and rural two-lane roads.

- **Rural Freeways.** Results from Griffith (*1*), believed to be the most reliable and definitive previous safety evaluation of shoulder rumble strips for rural freeways as indicated in *NCHRP Report 617* (*28*), are compared to the results from this research. The following present both the crash reduction effectiveness estimates for shoulder rumble strips and their standard errors:
  - Results from Griffith (*1*):
    - 21 percent reduction in SVROR crashes (SE = 10) and
    - 7 percent reduction in SVROR FI crashes (SE = 15).
  - Results from this research
    - 10 percent reduction in SVROR crashes (SE = 5) and
    - 17 percent reduction in SVROR FI crashes (SE = 7).

  Griffith (*1*) suggests greater reductions in SVROR crashes compared to results from this research, while this research suggests greater reductions in SVROR FI crashes than Griffith (*1*). Three points of interest when comparing the results from this research and Griffith (*1*) pertain to the analysis approaches, the standard errors, and the rumble strip type. The results from this research are based on the EB analysis methodology (and a cross-sectional approach) to analyze the data, while Griffith (*1*) utilized a comparison group (C-G) before-after study with yoked comparison sites to analyze the data. Additionally, the standard errors reported in this research are smaller than the standard errors reported by Griffith (*1*) for both crash types, indicating greater reliability in the results. It should also be noted that although Griffith reported an expected reduction of 7 percent in SVROR FI crashes on rural freeways due to the installation of shoulder rumble strips, the standard error of the reduction is 15 percent, indicating that statistically the reduction is not significantly different from zero. Griffith (*1*) also reported results for all freeways (i.e., both rural and urban combined); since this type of analysis was not performed under this research, no comparison is made for this category. Finally, Griffith (*1*) analyzed sites with rolled rumble strips, while for this research, all treatment sites had milled rumble strips, so the rumble strip type differed between the two studies.
- **Rural Two-Lane Roads.** Results from this research for rural two-lane roads are presented with the results reported by Patel et al. (*2*), the only previous safety evaluation of shoulder rumble strips on rural two-lane roads. Both analyses used the EB method to analyze the data. The following present both the crash reduction effectiveness estimates for shoulder rumble strips and their standard errors:
  - Results from Patel et al. (*2*):
    - 13 percent reduction in SVROR crashes (SE = 8) and
    - 18 percent reduction in SVROR FI crashes (SE = 12).
  - Results from this research:
    - 16 percent reduction in SVROR crashes (SE = 8) and
    - 36 percent reduction in SVROR FI crashes (SE = 10).

  The two safety evaluations report similar expected reductions in SVROR due to shoulder rumble strips, while the results from this research indicate more than double the safety effectiveness of shoulder rumble strips in reducing SVROR FI crashes along rural two-lane roads compared to that reported by Patel et al. (*2*). The standard errors reported for both safety evaluations are comparable, but the expected values for SVROR FI crashes are considerably different. It should also be noted that Patel et al. (*2*) analyzed only Minnesota data, while the analysis for this research was based on data from Minnesota, Missouri, and Pennsylvania. There does not appear to be any overlapping of Minnesota sites being used in both studies, and both studies are based upon sites with milled shoulder rumble strips.

Considering that (a) *NCHRP Report 617* (*28*) states that the Griffith (*1*) study is the most definitive study on the safety effects of shoulder rumble strips, (b) results from Griffith (*1*) are already incorporated into draft chapters of the forthcoming HSM, and (c) the likelihood that results from Patel et al. (*2*) could eventually be incorporated in the HSM, Table 41 presents updated AMFs for the safety effectiveness of shoulder rumble strips. Results from this research are combined with results from Griffith (*1*) and Patel et al. (*2*) in an effort to provide reliable and comprehensive estimates on the safety effectiveness of shoulder rumble strips on rural freeways and rural two-lane highways. The results are combined in a manner consistent with the procedures for combining study results for incorporation in the HSM (*65*). Table 41 presents the safety effectiveness estimates of shoulder rumble strips in the form of AMFs for potential inclusion in future editions of the HSM. These estimates are viewed as the most comprehensive and reliable estimates for the safety effectiveness of shoulder rumble strips to date.

The safety effectiveness estimates for rural freeways in Table 41 are indicated as applying to shoulder rumble strips in general, rather than specifically to milled or rolled rumble strips. Milled rumble strips are currently used by most highway agencies and, therefore, most recent studies, including the current study, have focused on milled rumble strips. The previous research by Griffith (*1*), which has been viewed as the definitive research on this topic, addressed rolled rumble strips. While the alerting properties of milled and rolled rumble strips may differ to some extent, these differences would not be expected to have a major influence on the safety effectiveness of shoulder rumble strips. Furthermore, when the Griffith results were combined with the results of this research, only minor differences in the safety effectiveness estimates were found. Therefore, it appears that the combined results from the Griffith study and the current research provide the best overall estimate for the safety effectiveness of shoulder rumble strips on rural freeways.

Determine the Impact of Rumble Strip Placement on the Safety Effectiveness of Shoulder Rumble Strips

The effect of shoulder rumble strip offset on SVROR FI crashes was evaluated based on all treatment and nontreatment sites using the approach discussed previously in the Analysis Approach part of this section. The analysis focused on SVROR FI crashes because this crash type and severity level yielded the most consistent results when analyzing the safety effectiveness of shoulder rumble strips on different roadway types. The results of the three types of offset analyses (i.e., cross-sectional GLM analysis) are presented next.

Edgeline vs. non-edgeline rumble strip effect as compared to no rumble strips. The effect of rumble strip placement (i.e., edgeline defined as consisting of offset distances of 0 to 8 in. [0 to 203 mm] vs. non-edgeline defined as consisting of offset distances of 9 in. [229 mm] and greater) was evaluated against the absence of rumble strips. This analysis was performed separately for each roadway type and state and all states combined.

The GLM regression results of this cross-sectional analysis pertaining to ADT and outside RHR are presented in Table G-1; an introduction to Appendix G provides details on how to read and use this table. The structure of this table is identical to that of Tables F-1 through F-8. The remainder of the regression model, that is, the rumble strip placement statistics, is presented in Table 42. For each combination of roadway type, state (combined or single), and rumble strip placement category, Table 42 shows the offset regression coefficient, its 95 percent confidence limits and p-value, and the Type 3 p-value. The discussion of significance provided for Tables 29 through 36 also applies to Table 42. For this offset analysis, a number of GLM models did not converge and therefore no reliable regression coefficients could be obtained. This is most often the case when only a few sites of a given type in a given state were available (refer to Tables 20 and 21).

In Table 42, two sets of analyses are presented for rural two-lane roads. In the one analysis, all of the available data from Minnesota, Missouri, and Pennsylvania are included, resulting in a combined analysis based on 257 sites. The data

Table 41. AMFs for shoulder rumble strips recommended for inclusion in the HSM.

Treatment	Roadway type	Accident type and severity	AMF	SE
Shoulder rumble strips[a]	Rural freeways	SVROR	0.89	0.1
		SVROR FI	0.84	0.1
Shoulder rumble strips[b]	Rural two-lane roads	SVROR	0.85	0.1
		SVROR FI	0.71	0.1

[a] AMF/SE based upon combined results for rolled shoulder rumble strips from Griffith (*1*) and for milled shoulder rumble strips from this research.

[b] AMF/SE based upon combined results from Patel et al. (*2*) and this research.

Table 42. Safety effectiveness of rumble strip placement on SVROR FI crashes based on all sites using GLM method.

Roadway type	State	Number of sites	Number of site–years	Rumble strip placement	Regression coefficient of rumble strip placement	Percent difference in crash frequency with rumble strips present (%)[a]			P–value	Type 3 p–value
						Estimate	Lower 95% CL	Upper 95% CL		
Urban freeways	PA	138	999	Non–edgeline	0.02	1.7	–15.7	22.6	0.86	0.87
Rural freeways	Combined	122	776	Edgeline	–0.34	–28.8	–51	3.5	0.08	0.07[b]
				Non–edgeline	–0.09	–8.9	–23.7	8.6	0.30	
	MO	47	351	Edgeline	–0.29	–24.8	–49.5	12	0.16	0.22
				Non–edgeline	–0.03	–2.9	–17.5	14.3	0.73	
	PA[c]	75	425	Edgeline						
				Non–edgeline						
Rural multilane divided highways (nonfreeways)	Combined	104	788	Edgeline	–0.29	–25.1	–46.5	4.9	0.09	0.16
				Non–edgeline	0.10	10.3	–17.3	47.1	0.50	
	MN	60	424	Edgeline	–0.35	–29.6	–50.6	0.5	0.05	0.05[d]
				Non–edgeline	0.21	23.4	–6.3	62.5	0.14	
	MO	27	239	Edgeline	–0.54	–41.7	–63.5	–6.8	0.02	0.13
				Non–edgeline	0.25	28.3	–17.8	100.2	0.27	
	PA	17	125	Edgeline	0.27	31	11.6	53.9	<.001	0.09[b]
				Non–edgeline	–0.65	–47.7	–73.5	3.2	0.06	
Rural two-lane roads	Combined	257	2,124	Edgeline	–0.41	–33.3	–53.1	–5.2	0.02	0.03[d]
				Non–edgeline	–0.63	–46.5	–67.1	–13.1	0.01	
	MN	109	726	Edgeline	0.08	8.3	–25.8	58	0.68	0.82
				Non–edgeline	–0.09	–8.2	–43.9	50.4	0.74	
	MO[c]	38	366	Edgeline						
				Non–edgeline						
	PA[c]	110	1,032	Edgeline						
				Non–edgeline						
Rural two-lane roads[e]	Combined	204	1,872	Edgeline	–0.50	–39.2	–62.5	–1.5	0.04	0.05[d]
				Non–edgeline	–0.54	–41.9	–69.4	10.0	0.10	
	MN	56	474	Edgeline	–0.56	–42.9	–70.5	10.5	0.10	0.27
				Non–edgeline	0.10	10.5	–42.3	111.8	0.76	

[a] Percent change is relative to no RS.
[b] Significant at 90-percent confidence level.
[c] GLM algorithm did not converge.
[d] Significant at 95-percent confidence level.
[e] Excludes 53 Minnesota nontreatment cross-sectional sites.

for rural two-lane roads were also analyzed without the 53 nontreatment cross-sectional Minnesota sites since these sites account for almost half of the Minnesota rural two-lane roads (see Table 14) and could unduly influence the results. This exclusion impacts only the Minnesota and the combined analysis results for rural two-lane roads, presented in the last two rows of Table 42.

The most interesting results from this analysis are for rural freeways (combined) and for rural two-lane roads (combined). For rural freeways, the analysis of the combined data shows statistically significant results at the 90 percent confidence level based upon the Type 3 p-value. The estimates for the percent change due to offset of a given distance are the following:

- 28.8 percent reduction in SVROR FI crashes for edgeline rumble strips and
- 8.9 percent reduction in SVROR FI crashes for non-edgeline rumble strips.

For rural freeways, these results provide evidence that offset distance impacts the safety effectiveness of shoulder rumble strips. The results suggest that by alerting drivers sooner that their vehicles have left the travel lane, drivers are allotted more time to gain control of their vehicles and return safely to the roadway. As the rumble strips are placed farther from the edgeline, by the time drivers are alerted that their vehicles have left the travel lane they have less time to avoid hitting a roadside object, and therefore rumble strips placed further from the edgeline are less effective in reducing SVROR FI crashes.

The analysis results of the combined data for rural two-lane roads indicate a slightly different safety effect of offset distance than for rural freeways. Focusing first on the analysis of combined data using all available sites (i.e., 257 combined sites), the results indicate a significant reduction in crashes for either edgeline or non-edgeline shoulder rumble strips. On average, a 33.3 percent reduction in SVROR FI crashes is found for edgeline shoulder rumble strips, while a 46.5 percent reduction in SVROR FI crashes is found for non-edgeline shoulder rumble strips. Given the relative magnitude of the difference between these two estimates, there is not much difference as compared to the difference between the two estimates for rural freeways. The minimal difference between the two estimates for edgeline vs. non-edgeline shoulder rumble strips is clearer in the analysis based upon the 204 combined sites that excludes the 53 Minnesota nontreatment cross-sectional sites. The analysis results based upon 204 combined sites indicate a 39.2 percent reduction in SVROR FI crashes for edgeline rumble strips compared to a 41.9 percent reduction for non-edgeline rumble strips. Essentially, there is a 3 percent difference between the two estimates, but for practical matters this analysis indicates that offset distance does not impact the safety effectiveness of shoulder rumble strips along rural two-lane roads.

Possible explanations for the difference in results between rural freeways and rural two-lane roads include the following:

- Different driving populations;
- Differences in driving behavior while driving along a multilane divided roadway where opposing traffic is separated by a median and adjacent traffic is traveling in the same direction versus driving along a two-lane road without any type of physical separation between opposing vehicles traveling in the opposite direction;
- Differences in design standards (e.g., related to horizontal and vertical alignments); and
- Extreme differences in the roadside characteristics that cannot be fully explained in the analyses.

In an effort to account for differences between roadway types, an analysis of the effect of edgeline rumble strips versus non-edgeline rumble strips, as compared to no rumble strips, was performed by combining the data for all the roadway types. State and roadway type differences were accounted for in the statistical model by fitting the intercept, lnADT coefficient, and outside RHR coefficient for each individual combination of state and roadway type. This was accomplished by including a number of interactions in the model in addition to the main effect, that is, rumble strip placement (i.e., edgeline, non-edgeline, and no rumble strips).

The GLM regression results of this cross-sectional analysis, for all 621 sites combined, pertaining to ADT and outside RHR are presented in Table G-2. Since this cross-sectional analysis is based on a modification of previous models, a separate introduction to Table G-2 provides details on how to read and use this table. The remainder of the regression model, that is, the rumble strip placement statistics, is presented in Table 43. For each rumble strip placement, the table shows the regression coefficient on the natural log-scale and as percent change, its 95 percent confidence limits and p-value, and overall Type 3 p-value.

Overall, the presence of rumble strips across all states and roadway types, while accounting for state, roadway type, ADT, and RHR differences, does not significantly impact SVROR FI crashes as indicated by the Type 3 p-value of 0.26. Table 43 does suggest the following:

- Although only marginally statistically significant (i.e., p-value of 0.12), installing rumble strips within 0 to 8 in. (0 to 203 mm) of the edgeline reduces SVROR FI crashes by 14.4 percent as compared to not installing rumble strips.
- On the other hand, placing rumble strips 9+ in. (229+ mm) or more from the edgeline has no overall effect on SVROR

Table 43. Overall safety effectiveness of rumble strip placement on SVROR FI crashes based on all sites combined using the GLM method.

Number of sites	Number of site-years	Rumble strip placement	Regression coefficient of rumble strip placement	Percent difference in crash frequency with rumble strips present (%)[a] Estimate	Lower 95% CL	Upper 95% CL	P-value	Type 3 p-value
621	4,687	Edgeline	–0.156	–14.4	–29.6	3.9	0.12[b]	0.26
		Non-edgeline	0.0001	0.0	–10.3	11.5	0.999	

[a] Percent change is relative to no RS.
[b] Significant at 85 percent confidence level.

FI crashes as compared to not installing rumble strips (p-value of 0.999.)

- Combined, these two points could be interpreted to indicate that edgeline rumble strips are more effective than non-edgeline rumble strips because the edgeline rumble strips provide a reduction in SVROR FI crashes, while non-edgeline rumble strips have no effect (i.e., 0 percent reduction). However, the overall results are not statistically significant (i.e., Type 3 p-value = 0.26), so this analysis does not provide definitive results regarding the impact that placement has on the safety effectiveness of shoulder rumble strips.

Effect of offset distance at three levels as compared to no rumble strips. The effect of offset distance in three ranges was evaluated against the absence of rumble strips:

- 0 to 8 in. (0 to 203 mm),
- 9 to 20 in. (229 to 508 mm), and
- 21+ in. (533+ mm).

The GLM regression results of this cross-sectional analysis, pertaining to ADT and outside RHR, are presented in Table G-3. The structure of this table is identical to that of Table G-1 in Appendix G. The remainder of the regression model is presented in Table 44. For each combination of roadway type, state (combined or single), and offset category, Table 44 shows the offset regression coefficient, its 95 percent confidence limits and p-value, and the Type 3 p-value.

Table 44 presents the results of the analyses designed to determine the impact that rumble strip placement measured at three levels has on the safety effectiveness of shoulder rumble strips. The two most interesting results from this analysis are for rural freeways (combined data) and for rural two-lane roads (combined data). For rural freeways, the results from the combined data are not statistically significant at the 90 percent confidence level, but a Type 3 p-value of 0.14 indicates borderline significance (i.e., at the 85 percent confidence level). The estimates of the percent change due to offset of a given distance as compared to no rumble strips show the following:

- 28.8 percent reduction in SVROR FI crashes when rumble strips are placed within 0 to 8 in. (0 to 203 mm) of the edgeline,
- 10.4 percent reduction in SVROR FI crashes when rumble strips are placed within 9 to 20 in. (229 to 508 mm) of the edgeline, and
- 7.4 percent reduction in SVROR FI crashes when rumble strips are placed 21+ in. (533+ mm) from the edgeline.

Although these results are not statistically significant, the results are consistent with the analyses of edgeline vs. non-edgeline rumble strips for rural freeways shown in Table 42.

The analysis results for rural two-lane roads (combined data) suggest, at first, the opposite effect from that for rural freeways. The estimates (in this case statistically significant at the 90 percent confidence level based on the Type 3 p-value) of the percent change due to offset of a given distance as compared to no rumble strips show the following:

- 33.2 percent reduction in SVROR FI crashes when rumble strips are placed within 0 to 8 in. (0 to 203 mm) of the edgeline;
- 37.7 percent reduction in SVROR FI crashes when rumble strips are placed within 9 to 20 in. (229 to 508 mm) of the edgeline; and
- 56.7 percent reduction in SVROR FI crashes when rumble strips are placed 21+ in. (533+ mm) from the edgeline.

These results suggest that installing the rumble strips further away from the edgeline improves the safety effectiveness of the rumble strips, which is counterintuitive to some extent. Upon further review, the p-value associated with the offset range of 21+ in. (533+ mm) is 0.12, indicating a marginally significant result. This result is likely due to sample size issues, in which case it makes sense to combine the two categorical offset ranges of 9 to 20 in. (229 to 508 mm) and

Table 44. Safety effectiveness of rumble strip offset on SVROR FI crashes based on all sites using the GLM method.

Roadway type	State	Number of sites	Number of site-years	Offset (in.)	Offset regression coefficient	Percent difference in crash frequency with offset of given distance (%)[a]			P-value	Type 3 p-value
						Estimate	Lower 95% CL	Upper 95% CL		
Urban freeways	PA	138	999	9-20	0.02	1.7	–15.7	22.6	0.86	0.87
Rural freeways	Combined	122	776	0-8	–0.34	–28.8	–51.0	3.6	0.08[d]	0.14
				9-20	–0.11	–10.4	–32.7	19.2	0.45	
				21+	–0.08	–7.4	–21.4	9.0	0.35	
	MO	47	351	0-8	–0.28	–24.6	–49.5	12.6	0.17	0.13
				9-20	–0.72	–51.1	–56.2	–45.4	<.001[c]	
				21+	0.02	2.0	–13.1	19.8	0.81	
	PA[b]	75	425	0-8						
				9-20						
				21+						
Rural multilane divided highways (nonfreeways)	Combined	104	788	0-8	–0.30	–25.8	–46.9	3.8	0.08[d]	0.31
				9-20	0.06	6.4	–18.0	38.1	0.64	
				21+	0.15	15.8	–29.5	90.4	0.56	
	MN	60	424	0-8	–0.35	–29.2	–50.2	0.4	0.05[c]	0.02[c]
				9-20	0.26	29.9	–1.0	70.6	0.06[d]	
				21+	–0.30	–25.9	–47.8	5.2	0.09[d]	
	MO	27	239	0-8	–0.54	–41.7	–63.5	–6.8	0.02[c]	0.13
				21+	0.25	28.3	–17.8	100.2	0.27	
	PA[b]	17	125	0-8						
				9-20						
				21+						
Rural two-lane roads	Combined	257	2,124	0-8	–0.40	–33.2	–53.1	–4.9	0.03[c]	0.07[d]
				9-20	–0.47	–37.7	–60.4	–2.0	0.04[c]	
				21+	–0.84	–56.7	–84.8	23.4	0.12	
	MN	109	726	0-8	0.10	10.0	–24.9	61.2	0.63	0.54
				9-20	–0.24	–21.2	–55.3	39.0	0.41	
				21+	0.45	57.5	–26.0	234.9	0.24	
	MO[b]	38	366	0-8						
				21+						
	PA[b]	110	1,032	0-8						
				9-20						

[a] Percent change is relative to no rumble strip.
[b] GLM algorithm did not converge.
[c] Significant at 95 percent confidence level.
[d] Significant at 90 percent confidence level.

21+ in. (533+ mm) into a single categorical level, as presented in Table 42.

Effect of combination of offset and recovery area as compared to nontreatment sites with narrow shoulders. The analyses described above consider the safety effect of rumble strip offset without considering the potential impact of the width of the recovery area. Therefore, the data were further analyzed to estimate the combined effect of rumble strip offset and recovery area on SVROR FI crashes. The effect of five combinations of offset distance and recovery area (or shoulder width for nontreatment sites) on SVROR FI crashes was evaluated against the absence of rumble strips (category No. 6 below). The six combinations of rumble strip offset and recovery areas evaluated are as follows:

No.	RS	Offset, in. (mm)	Recovery area, ft (m)
1.	Edgeline	0 to 8 (0 to 203)	4+ (1.2+)
2.	Edgeline	0 to 8 (0 to 203)	0–4 (0–1.2)
3.	Non-edgeline	9+ (229+)	4+ (1.2+)
4.	Non-edgeline	9+ (229+)	0–4 (0–1.2)
5.	No RS	NA	4+ (1.2+) (shoulder width)
6.	No RS	NA	0–4 (0–1.2) (shoulder width)

The GLM regression results of this cross-sectional analysis pertaining to ADT and outside RHR are presented in Table G-4 in Appendix G. The structure and discussion of this table is identical to that of Table G-1. The remainder of the regression model, that is, the statistics for the offset-recovery area combination, is presented in Table 45. For each combination of roadway type, state (combined or single), and offset and recovery area combination, Table 45 shows the regression coefficient, the estimated safety effect and its 95 percent confidence limits and p-value, and the Type 3 p-value. As before, a number of GLM models did not converge, and therefore no reliable regression coefficients could be obtained for these cases. In general, no trends concerning the safety impacts of the interaction between offsets and recovery distances are observed from this analysis.

In summary, comparing results from all the previous analyses (i.e., Tables 42 through 45) performed to assess the impact that placement has on the safety effectiveness of shoulder rumble strips, it appears that Table 42 provides the most reliable results. The results of the analysis of edgeline rumble strips versus non-edgeline rumble strips as compared to no rumble strips reveals the following:

- On rural freeways, edgeline rumble strips are more effective in reducing SVROR FI crashes than non-edgeline rumble strips, and
- On rural two-lane roads, there is no difference in the safety effect of rumble strips placed close to the edgeline (i.e., edgeline rumble strips) compared to rumble strips placed further from the edgeline (i.e., non-edgeline rumble strips).

The following is the rationale for determining that these results are the most definitive:

- For rural freeways, all of the analyses were in agreement as to the direction of the effect that placement has on the safety effectiveness of shoulder rumble strips, whether the results are statistically significant at the 90 percent confidence level or higher, marginally significant, or not significant. With the exception of one result based on a single state (MO in Table 44), all of the analyses (Tables 42 through 45) indicate that edgeline rumble strips are more effective in reducing SVROR FI crashes than non-edgeline rumble strips. Additionally, Table 42 provides statistically significant results (i.e., Type 3 p-value = 0.07), based upon the combined data.
- The results for rural freeways are logical in that it makes sense that by alerting drivers sooner rather than later, they have more time to correct their steering and return to the travel lanes before encountering a roadside object. The high design policies for roadsides along rural freeways and high design policies for rural freeway alignments further support these results.
- The primary issue to be addressed is determining whether rumble strips placed closer to the edgeline are more effective in reducing SVROR FI crashes than shoulder rumble strips placed further away from the edgeline. The analysis of edgeline rumble strips versus non-edgeline rumble strips as compared to no rumble strips serves the purpose of answering this primary issue. The analyses on the "effect of offset distance at three levels as compared to no rumble strips" and the "effect of combinations of offset and recovery area as compared to nontreatment sites with narrow shoulders" are an attempt to further investigate and explain this issue; however, they are unnecessary in answering the primary issue at hand. The apparent conflict in the results for rural two-lane roads for Tables 42 and 44 is not an issue. Based upon the database available, the data do not support categorizing offset distance at three levels. Sample size issues limit the statistical validity of the results for Tables 44 and 45.

Finally, the results for rural freeways and rural two-lane roads should not be viewed as being in conflict with one another. Rather, the results for rural freeways should be viewed as statistically significant results indicating that edgeline rumble strips are more effective in reducing SVROR FI crashes (i.e., a 28.8 percent reduction) than non-edgeline rumble strips (i.e., a 8.9 percent reduction), whereas for rural two-lane roads, the estimates of the safety effects of edgeline and non-edgeline rumble strips are so close (i.e., 39.2 percent reduction compared to a 41.9 percent reduction) that, for all practical purposes, the placement of shoulder

Table 45. Safety effectiveness of combined rumble strip offset and recovery area on SVROR FI crashes based on all sites using the GLM method.

Roadway type	State	Number of sites	Number of site–years	Offset x RA Combination	Coefficient of offset by RA combination	Percent difference in crash frequency with combined effects of offset and recovery area (RA) (%)[a] Effect (%)	Lower 95% CL	Upper 95% CL	P–value	Type 3 p–value
Urban freeways	PA	138	999	Non–edgeline, 5 ft RA	–0.38	–31.5	–54.0	2.1	0.06	0.36
				Non–edgeline, 0–4 ft RA	–0.42	–34.0	–53.0	–7.4	0.02	
				No RS, 5+ ft shoulder	–0.45	–36.2	–56.2	–6.9	0.02	
Rural freeways	Combined[b]	122	776	Edgeline, 5+ ft RA						
				Non–edgeline, 5 ft RA						
				Non–edgeline, 0–4 ft RA						
				No RS, 5+ ft shoulder						
	MO[c]	47	351	Edgeline, 5+ ft RA	–0.29	–24.8	–49.5	12.0	0.16	0.22
				Non–edgeline, 5 ft RA	–0.03	–2.9	–17.5	14.3	0.73	
	PA[b]	75	425	Edgeline, 5+ ft RA						
				Non–edgeline, 5 ft RA						
				Non–edgeline, 0–4 ft RA						
				No RS, 5+ ft shoulder						
Rural multilane divided highways (nonfreeways)	Combined	104	788	Edgeline, 5+ ft RA	–1.07	–65.7	–86.4	–13.7	0.02	0.21
				Edgeline, 0–4 ft RA	–0.04	–3.6	–29.3	31.6	0.82	
				Non–edgeline, 5 ft RA	–0.65	–47.5	–78.2	26.0	0.15	
				No RS, 5+ ft shoulder	–0.76	–53.1	–80.5	13.1	0.09	
	MN[c]	60	424	Edgeline, 5+ ft RA	–0.35	–29.6	–50.6	0.5	0.05	0.05[d]
				Non–edgeline, 5 ft RA	0.21	23.4	–6.3	62.5	0.14	
	MO	27	239	Edgeline, 5+ ft RA	–0.78	–54.2	–72.9	–22.6	0.00	0.33
				Edgeline, 0–4 ft RA	0.10	10.4	0.9	20.8	0.03	
				Non–edgeline, 5 ft RA	0.34	40.7	1.9	94.5	0.04	
				No RS, 5+ ft shoulder	0.09	9.8	–22.1	54.9	0.59	
	PA	17	125	Edgeline, 5+ ft RA	–0.66	–48.2	–66.2	–20.7	0.00	0.14
				Non–edgeline, 5 ft RA	–1.53	–78.4	–88.5	–59.4	<.001	
				No RS, 5+ ft shoulder	–0.97	–62.0	–79.3	–30.3	0.00	

Rural two–lane roads	Combined	257	2,124	Edgeline, 5+ ft RA	–0.57	–43.4	–65.1	–8.2	0.02	0.10[e]
				Edgeline, 0–4 ft RA	–0.63	–46.5	–75.4	16.3	0.12	
				Non–edgeline, 5 ft RA	–0.78	–54.4	–72.8	–23.6	0.00	
				Non–edgeline, 0–4 ft RA	–1.05	–65.2	–96.0	204.7	0.34	
				No RS, 5+ ft shoulder	–0.32	–27.3	–50.8	7.4	0.11	
	MN	109	726	Edgeline, 5+ ft RA	0.11	11.3	–51.7	156.6	0.80	0.98
				Edgeline, 0–4 ft RA	0.24	27.1	–54.2	253.0	0.65	
				Non–edgeline, 5 ft RA	–0.08	–7.8	–61.7	121.7	0.86	
				Non–edgeline, 0–4 ft RA	0.19	20.9	–61.4	279.1	0.75	
				No RS, 5+ ft shoulder	0.07	6.9	–54.9	153.4	0.88	
	MO[b]	38	366	Edgeline, 5+ ft RA						
				Non–edgeline, 5 ft RA						
				Non–edgeline, 0–4 ft RA						
				No RS, 5+ ft shoulder						
	PA[b]	110	1,032	Edgeline, 5+ ft RA						
				Edgeline, 0–4 ft RA						
				Non–edgeline, 5 ft RA						
				No RS, 5+ ft shoulder						

RA = Recovery Area

[a] Percent change is relative to no RS with 0–4 ft shoulder unless otherwise noted.

[b] GLM algorithm did not converge.

[c] Percent change is relative to no RS with 5+ ft shoulder.

[d] Significant at 95 percent confidence level.

[e] Significant at 90 percent confidence level.

rumble strips on rural two-lane roads has no impact on their safety effectiveness.

Supplemental Analyses

Additional analyses of SVROR crashes were performed to investigate the safety effect that shoulder rumble strips may have on the following:

- Crashes involving heavy vehicles,
- Crashes that occur under adverse pavement conditions, and
- Crashes that occur during low-lighting conditions.

Both the EB methodology and the cross-sectional GLM methodology were used in these supplemental analyses, as described in the Analysis Approach earlier in this section. Analyses results are provided for rural freeways and rural two-lane roads only.

Heavy Vehicle Crashes

Analysis results showing the safety effectiveness of shoulder rumble strips on SVROR crashes involving heavy vehicles are presented in Table 46. The results suggest that shoulder rumble strips installed on rural freeways reduce SVROR crashes involving heavy vehicles by 41 percent (based on the EB analysis). No significant effect is found for rural two-lane roads. As indicated earlier, the results of this analysis should be viewed cautiously because the analysis does not specifically account for heavy vehicle exposure, but rather assumes that the percentage of heavy vehicle volume, relative to the total traffic volume, remained constant throughout the analysis period.

Given the level of detail of this analysis, the major findings should be viewed in the following manner:

- The primary issue to be resolved is whether shoulder rumble strips should be designed specifically taking into consideration heavy vehicles. One cannot state with certainty whether current rumble strip dimensions have been designed specifically based upon the needs of drivers of heavy vehicles. This is because it is still unclear, from a human factors perspective, what stimuli levels are necessary to alert drivers. In addition, the dynamic properties of passenger cars and trucks vary widely. What can be clearly stated, however, is that given the current dimensions of shoulder rumble strips installed along rural freeways that vary to some degree, the analysis results suggest a reduction in SVROR crashes involving heavy vehicles due to the installation of shoulder rumble strips. This implies that the current dimensions of shoulder rumble strips installed along rural freeways provide sufficient levels of stimuli to alert inattentive and/or drowsy drivers of heavy vehicles and that it is not necessary to design rumble strip patterns that are "more aggressive" based strictly on the needs of drivers of heavy vehicles.
- Concerning the accuracy of the estimated safety effect of shoulder rumble strips on SVROR crashes involving heavy vehicles (i.e., approximately a 40 percent reduction), it should be viewed with caution given the level of detail and assumptions of the analysis, but at this point it is the best estimate available for this crash type of interest. It should also be noted that all three analysis approaches provide very similar crash reduction estimates.
- Concerning the safety effectiveness of shoulder rumble strips impacting SVROR crashes involving heavy vehicles on rural two-lane roads, it is not clear whether the non-statistically significant results are due to sample size issues, exposure, some combination of the two, or some other issues, but at this point there is no evidence that shoulder rumble strips installed along rural two-lane highways impact SVROR crashes involving heavy vehicles.

Crashes Under Adverse Pavement Conditions

Analysis results showing the safety effectiveness of the shoulder rumble strips on SVROR crashes occurring during adverse pavement conditions (i.e., wet, snow, ice) are presented in Table 47. Statistically significant effects were found for both rural freeways and rural two-lane roads. In some cases, a significant reduction in SVROR crashes occurring under adverse pavement conditions was found, while in other cases a significant increase was found. Given that the analysis does not account for the potential differences in weather conditions from year to year, no definitive conclusions can be drawn from this analysis concerning the impact that shoulder rumble strips may have on SVROR crashes that occur under adverse pavement conditions.

Crashes in Low-Lighting Conditions

Analysis results showing the safety effectiveness of the shoulder rumble strips on SVROR crashes occurring during low-lighting conditions (i.e., dusk, dawn, dark) are presented in Table 48. Statistically significant effects were found for both rural freeways and rural two-lane roads. In all cases, a significant reduction in SVROR crashes occurring during low-light conditions was found. The EB results indicate that shoulder rumble strips installed on rural freeways reduce SVROR crashes that occur during low-lighting conditions by 27 percent. Similar estimates are provided for both GLM analyses. Considering that many inattention and drowsy driver crashes occur during late-night hours, these analysis results are confounded in that it cannot be distinguished

Table 46. Safety effectiveness of shoulder rumble strips on SVROR crashes involving heavy vehicles.

Roadway type	State	EB results: Number of sites	EB results: Percent change in crash frequency from before to after rumble strip installation (%): Estimate[a] (%)	SE	Test statistic	GLM results using BA and nontreatment CS sites: Number of sites	Percent difference in crash frequency with rumble strips present (%): Estimate[a] (%)	Lower 95% CL	Upper 95% CL	Type 3 p–value	GLM results using all sites: Number of sites	Percent difference in crash frequency with rumble strips present (%): Estimate[a] (%)	Lower 95% CL	Upper 95% CL	Type 3 p–value
Rural freeways	Combined[b]	47	–41.54	8.01	5.19	69	–41.6	–60.9	–12.9	0.01	122	–45.5	–61.9	–22.1	0.00
	MO[b]	29	–41.66	8.38	4.97	35	–40.6	–56.4	–19.0	0.02	47	–41.3	–56.0	–21.6	0.01
	PA	18	–40.81	26.97	1.51	34	–44.2	–94.1	426.5	0.53	75	–43.9	–84.5	103.0	0.36
Rural two–lane roads	Combined[c]	53	82.64	58.41	1.41	203					257				
	MN[c]	28	181.99	126.29	1.44	56					109				
	MO[c]	5	138.52	142.01	0.98	37					38				
	PA [c]	20	–19.12	57.52	0.33	110					110				

[a] A negative percent change indicates a decrease in crash frequency while a positive percent change indicates an increase in crash frequency.
[b] Shaded cells indicate a significant rumble strip effect at the 95 or 90 percent confidence level.
[c] Empty cells indicate that the GLM algorithm did not converge.

Table 47. Safety effectiveness of shoulder rumble strips on SVROR crashes under adverse pavement conditions.

Roadway type	State	EB results: Number of sites	EB results: Percent change in crash frequency from before to after rumble strip installation (%): Estimate[a] (%)	SE	Test statistic	GLM results using BA and nontreatment CS sites: Number of sites	Percent difference in crash frequency with rumble strips present (%): Estimate[a] (%)	Lower 95% CL	Upper 95% CL	Type 3 p–value	GLM results using all sites: Number of sites	Percent difference in crash frequency with rumble strips present (%): Estimate[a] (%)	Lower 95% CL	Upper 95% CL	Type 3 p–value
Rural freeways	Combined[b]	47	–17.86	7.30	2.45	69	–10.9	–29.9	13.4	0.37	122	–5.9	–23.9	16.5	0.60
	MO[b]	29	–23.13	7.75	2.99	35	–13.8	–32.3	9.6	0.30	47	–15.1	–32.8	7.4	0.23
	PA[b]	18	4.30	20.02	0.21	34	3.2	–39.1	74.9	0.91	75	39.6	–1.8	98.3	0.10
Rural two–lane roads	Combined	53	17.90	15.38	1.16	203	5.2	–31.5	61.7	0.81	257	5.0	–20.7	39.0	0.73
	MN[b]	28	50.15	30.23	1.66	56	37.9	–14.8	123.1	0.23	109	74.5	24.3	145.0	0.00
	MO[b]	5	98.10	49.14	2.00	37	135.0	–43.9	885.1	0.27	38	118.0	–45.6	773.1	0.29
	PA[b]	20	–30.43	16.42	1.85	110	–27.8	–57.9	23.7	0.17	110	–27.8	–57.9	23.7	0.17

[a] A negative percent change indicates a decrease in crash frequency while a positive percent change indicates an increase in crash frequency.
[b] Shaded cells indicate a significant rumble strip effect at the 95 or 90 percent confidence level.

Table 48. Safety effectiveness of shoulder rumble strips on SVROR crashes under low-lighting conditions.

Roadway type	State	EB results				GLM results using BA and nontreatment CS sites					GLM results using all sites				
		Number of sites	Percent change in crash frequency from before to after rumble strip installation (%)		Test statistic	Number of sites	Percent difference in crash frequency with rumble strips present (%)			Type 3 p–value	Number of sites	Percent difference in crash frequency with rumble strips present (%)			Type 3 p–value
			Estimate[a] (%)	SE			Estimate[a] (%)	Lower 95% CL	Upper 95% CL			Estimate[a] (%)	Lower 95% CL	Upper 95% CL	
Rural freeways	Combined[b]	47	–27.10	6.84	3.96	69	–23.3	–38.5	–4.5	0.02	122	–21.8	–35.1	–5.8	0.01
	MO[b]	29	–25.86	7.64	3.38	35	–18.0	–36.3	5.6	0.15	47	–20.7	–36.0	–1.8	0.05
	PA[b]	18	–32.62	15.16	2.15	34	–28.3	–52.1	7.4	0.11	75	–30.0	–52.7	3.5	0.07
Rural two–lane roads	Combined[b]	53	–11.44	12.54	0.91	203	–24.3	–49.8	14.1	0.15	257	–30.1	–49.2	–3.8	0.03
	MN	28	27.28	26.71	1.02	56	11.2	–30.1	77.0	0.67	109	11.2	–21.1	56.7	0.55
	MO	5	19.71	44.60	0.44	37	54.7	–72.8	781.1	0.63	38	40.5	–75.0	688.6	0.70
	PA[b]	20	–37.54	13.71	2.74	110	–40.0	–64.9	2.5	0.05	110	–40.0	–64.9	2.5	0.05

[a] A negative percent change indicates a decrease in crash frequency while a positive percent change indicates an increase in crash frequency.
[b] Shaded cells indicate a significant rumble strip effect at the 95 or 90 percent confidence level.

between crashes where poor delineation may have been a primary factor versus crashes where inattention and/or drowsiness may have been a primary factor. Also, no attempt was made in this analysis to account for adverse pavement conditions. Given the level of detail of this analysis and the confounding issues, only a general conclusion can be drawn stating that shoulder rumble strips likely result in a positive safety benefit during low-lighting conditions by providing positive guidance along the travel lanes.

Summary of Key Findings

The primary objectives of the safety evaluation of shoulder rumble strips are to do the following:

- Quantify the safety effectiveness of milled shoulder rumble strips on specific types of roads, and
- Quantify the safety effectiveness of shoulder rumble strips placed in varying locations with respect to the edgeline.

Supplemental analyses of SVROR crashes were performed to investigate the safety effect that shoulder rumble strips have on crashes that (a) involve heavy vehicles, (b) occur under adverse pavement conditions, and (c) occur during low-lighting conditions. Based upon the analysis results, the key findings from the safety evaluation of shoulder rumble strips are summarized as the following:

- The most reliable and comprehensive estimates to date of the safety effectiveness of shoulder rumble strips on rural freeways and rural two-lane highways are as follows:
  Rural Freeways:
  – Shoulder rumble strips [based on combined results from this research and Griffith (*1*)]:
    - 11 percent reduction in SVROR crashes (SE = 6) and
    - 16 percent reduction in SVROR FI crashes (SE = 8).

  Rural Two-Lane Roads:
  – Shoulder rumble strips [based on combined results from this research and Patel et al. (*2*)]:
    - 15 percent reduction in SVROR crashes (SE = 7) and
    - 29 percent reduction in SVROR FI crashes (SE = 9).
- Analyses for urban freeways and rural multilane divided highways (nonfreeways) did not show statistically significant decreases in crash frequencies with the installation of shoulder rumble strips.
- Limited mileage of shoulder rumble strips along urban multilane divided highways (nonfreeways), urban multilane undivided highways (nonfreeways), urban two-lane roads, and rural multilane undivided highways (nonfreeways) prohibited formal evaluation of the safety effectiveness of this treatment along these roadway types.
- On rural freeways, rumble strips placed closer to the edgeline (i.e., edgeline rumble strips) are more effective in reducing SVROR FI crashes than rumble strips placed further from the edgeline (i.e., non-edgeline rumble strips).
- On rural two-lane roads, there is no difference in the safety effect of rumble strips placed closer to the edgeline (i.e., edgeline rumble strips) as compared to rumble strips placed further from the edgeline (i.e., non-edgeline rumble strips).
- On rural freeways, shoulder rumble strips resulted in an estimated reduction of SVROR crashes involving heavy vehicles of approximately 40 percent.
- On rural two-lane roads, there is no evidence that suggests shoulder rumble strips may result in a reduction of SVROR crashes involving heavy vehicles.
- Mixed results were observed from the analysis of SVROR crashes that occur under adverse pavement conditions, but it should be noted that the study did not attempt to account for the frequency of adverse pavement condition occurrences.
- Shoulder rumble strips appear to provide a positive safety benefit during low-lighting conditions.

SECTION 7

Safety Effectiveness of Centerline Rumble Strips

The safety evaluation of centerline rumble strips addresses two key unresolved issues: (1) the safety effectiveness of centerline rumble strips on different roadway types, and (2) the safety effectiveness of centerline rumble strips along varying roadway geometry. Also addressed in lesser detail is the safety effectiveness of dual applications of rumble strips (i.e., centerline and shoulder rumble strips installed along the same roadway section).

Previous safety evaluations of centerline rumble strips have focused on the effectiveness of this treatment on rural two-lane roads. *NCHRP Report 617* (*28*) indicates that centerline rumble strips reduce all crashes by 14 percent and reduce head-on and opposite-direction sideswipe crashes by 21 percent on rural two-lane roads. It also indicates that centerline rumble strips reduce all injury crashes by 15 percent and all injury head-on and opposite-direction sideswipe crashes by 25 percent on rural two-lane roads. *NCHRP Report 617* specifically states that these expected safety estimates are only applicable to rural two-lane roads and are not applicable to other roadway types. As evident from the survey results in Section 5 of this report, in more recent years centerline rumble strips have been installed along other types of roadways, including urban multilane undivided highways (nonfreeways), urban two-lane roads, and rural multilane undivided highways (nonfreeways). Prior to the current research, it was not known whether the same safety benefits of centerline rumble strips should be expected on these other types of roadways. In all likelihood, the safety benefits of centerline rumble strips vary by roadway type because the different types of roadways are built to varying standards (i.e., lane widths, shoulder widths, etc.), accommodate varying traffic volumes and distributions, and serve different driver populations.

Studies concerning the safety effectiveness of centerline rumble strips have not distinguished between the safety effectiveness of centerline rumble strips along tangent sections as compared to horizontal curve sections. It should be recognized that the effectiveness of centerline rumble strips in reducing head-on and opposite-direction sideswipe crashes is dependent upon various elements, including the frequency with which vehicles cross the centerline, the angle at which vehicles cross the centerline, vehicle speed, lane width, and traffic volume (i.e., directional distribution). It should also be recognized that approximately 35 percent of all fatal accidents occur along horizontal curves as compared to 65 percent on tangent sections (7). Thus, there is reason to believe the safety benefits of centerline rumble strips differ along varying roadway geometry.

Previous safety evaluations of rumble strips have focused on one type of application per study (i.e., either shoulder or centerline rumble strips). No study has investigated the combined safety effectiveness of installing both centerline and shoulder rumble strips along the same section of roadway. As evident from the survey results in Section 5, several state transportation agencies have been installing both shoulder and centerline rumble strips along the same section of roadway, but the safety effectiveness of this dual application treatment has not yet been determined.

A safety evaluation was conducted to address the following key unresolved safety issues related to centerline rumble strips:

- Do centerline rumble strips have the same safety effectiveness when installed along different types of roadways?
- Does the safety effectiveness of centerline rumble strips differ depending upon the roadway geometry (i.e., tangent vs. curve)?
- What is the safety effectiveness when centerline rumble strips are installed in conjunction with shoulder rumble strips along the same roadway?

This section describes the general scope of the safety evaluation conducted to resolve these issues, the site selection process, the videolog data collection procedures, the database development, the analysis approach, and the analysis results.

In general the same methodology used to perform the safety evaluation of shoulder rumble strips was used to perform the safety evaluation of centerline rumble strips.

Scope of Safety Evaluation

The primary objectives of the safety evaluation conducted as part of this research are to do the following:

- Quantify the safety effectiveness of centerline rumble strips on specific types of roads including urban multilane undivided highways (nonfreeways), urban two-lane roads, rural multilane undivided highways (nonfreeways), and rural two-lane roads;
- Quantify the safety effectiveness of centerline rumble strips along varying roadway geometry (i.e., tangent vs. horizontal curve); and
- Quantify the safety effectiveness of dual applications of rumble strips (i.e., centerline and shoulder rumble strips installed on the same road section).

From the survey conducted in Phase I, the research team identified six states to initially contact to gather more information concerning their potential involvement in the safety evaluation of centerline rumble strips. The intent was to involve up to three states so that data could be collected over a wide range of roadway types, ideally in different regions of the country. The primary data collection effort involved review of videologs to verify the presence or absence of centerline rumble strips (and in some cases shoulder rumble strips) and to collect (or verify) roadway characteristic data. The data were analyzed using the EB methodology for before-after analysis, similar to the EB methodology used in safety evaluation of shoulder rumble strips.

Site Selection

Representatives from Missouri, Oregon, Pennsylvania, Utah, Virginia, and Washington DOTs were initially contacted to inquire about potentially including sites from their respective states in the centerline rumble strip safety evaluation. A similar site selection process was followed for the centerline safety evaluation as previously described for the shoulder rumble strip safety evaluation. The type of information gathered to determine whether sites from a particular state would be appropriate for this study included the following:

- Has the agency installed centerline rumble strips covering the range of roadway types of interest for this study and has the agency installed any dual applications of both centerline and shoulder rumble strips at the same site (preferably installed in the same year)?
- Does the agency have the ability to identify locations where centerline rumble strips and the dual applications have been installed?
- Does the agency have the ability to readily provide construction history information, such as rumble strip installation dates and information about other improvements made during the study period?
- Does the agency keep a library of videologs that could be accessed by the research team?
- Is the agency willing to participate in the research and work with the research team to gather the necessary data for the safety evaluation?

The research team found during these initial inquiries that most state transportation agencies (a) had no readily available means to identify the locations of the installations such that they could not even provide an initial list of potential treatment sites for further investigation by the research team, (b) had only installed a limited number of miles of centerline rumble strips on roadways other than rural two-lane roads and in some cases the centerline rumble strips were installed on the other roadway types as part of a pilot project, or (c) provided locations of the potential treatment limited strictly to rural two-lane roads.

Through these initial inquiries, a list of potential treatment sites with centerline rumble strips was obtained from Pennsylvania and Washington. The list of potential treatment sites for Pennsylvania included sites for all four roadway types of interest, and the list for Washington included primarily sites for rural two-lane roads, but also included a few sites on the other roadway types of interest. In a final effort to find additional sites with centerline rumble strips on roadways other than rural two-lane roads, MnDOT was contacted. MnDOT indicated in their survey response that they only installed centerline rumble strips on rural two-lane roads, but due to prior experience with the shoulder rumble strip safety evaluation and MnDOT's proactive approach concerning both shoulder and centerline rumble strips, further inquiries were made. This inquiry yielded a list of potential treatment sites but only for rural two-lane roads in Minnesota. To ensure a geographically representative set of sites, the decision was made to include sites from Minnesota, Pennsylvania, and Washington in the safety evaluation of centerline rumble strips.

The information provided by all three state DOTs with the list of potential treatment sites included location information and installation dates of the centerline rumble strips. The roadway type was determined from the states' roadway inventory data. For each state, it was also understood that the installations of the centerline rumble strips were the only recent improvements (safety or otherwise) made to the sites. The following sections summarize the tasks conducted for the respective states to select treatment sites (i.e., sites with centerline rumble strips or sites with centerline and shoulder rumble strips) for inclusion in this safety evaluation. The Videolog Data Collection part of this section provides detailed information on the actual data collection process performed for treatment site and nontreatment sites (i.e., sites without any type of centerline or shoulder rumble strips) for inclusion in this safety evaluation.

Minnesota Sites

MnDOT provided an initial list of treatment locations. The information provided with this list included the district, route type, route number, beginning and ending mileposts, and installation dates. The research team reviewed each of the sites using MnDOT's videolog system, which contains videologs for calendar years 2001–2006. Initially, the 2006 videologs were reviewed to confirm the presence or absence of the centerline rumble strips at the locations. Subsequently, the 2001–2005 videologs were reviewed to confirm the installation dates of the rumble strips at each site where the centerline rumble strips were installed during calendar years 2002–2005. In the list of treatment sites, the installation dates of the centerline rumble strips ranged from 1996 to 2004. Only those installation dates between calendar years 2002 and 2005 could actually be confirmed through this process by verifying the absence/presence of the centerline rumble strips across multiple years. This process of confirming the installation dates revealed that most of the installation dates from the initial list were correct. Therefore, it appeared reasonable that the older installation dates were accurate for the centerline rumble strip treatment sites.

Nontreatment sites in Minnesota identified during the safety evaluation of shoulder rumble strips were also used in the safety evaluation of centerline rumble strips. The videologs of the nontreatment sites were reviewed again as part of this safety evaluation to collect horizontal alignment data.

Table 49 shows the total mileage (by roadway type) of treatment and nontreatment sites from Minnesota considered for inclusion in the safety evaluation. This table reflects total mileage for treatment and nontreatment sites after a series of data quality checks to make sure data were consistent and complete for each location. The table includes data for treatment sites with centerline rumble strips only, dual application treatment sites (i.e., sites with both centerline and shoulder rumble strips), and nontreatment sites (i.e., sites without either centerline or shoulder rumble strips). This table does not classify the mileage by installation dates, or by total mile-years that can be used for before- and after-period analyses in a before-after evaluation. This level of detail is provided later in the part on Descriptive Statistics in this section.

Pennsylvania Sites

PennDOT maintains a database of low-cost safety improvements made across the entire state of Pennsylvania. From this database, a list of approximately 300 safety improvement projects were identified where the installation of centerline rumble strips was the only safety improvement made as part of the project. This list included the location of the safety projects on the state highway network and the installation date of the project. The installation dates ranged from 2000 to 2005. The research team reviewed the locations of these safety projects using PennDOT's videolog, accessible via the Internet.

Several dual applications sites were identified during the videolog review. To further verify the installation date of the centerline rumble strips and to determine the installation date of the shoulder rumble strips, archived videologs were reviewed at PennDOT's Central Office.

Table 50 shows the total mileage (by roadway type) of treatment and nontreatment sites from Pennsylvania considered for inclusion in the safety evaluation. This table is similar to Table 49 above for Minnesota sites.

Washington Sites

Washington State DOT (WSDOT) provided an initial list of treatment locations. The information provided with this list included the route number, beginning and ending mileposts, installation dates, and construction information. The initial list included approximately 85 potential treatment locations with installation dates ranging from 1996 to 2007. Using WSDOT's videolog system, the research team focused on reviewing sites where centerline rumble strips were installed between 2002 and 2005.

Table 49. Total mileage of Minnesota treatment and nontreatment sites considered for inclusion in the safety evaluation of centerline rumble strips.

Roadway type	Treatment sites (mi)	Nontreatment sites (mi)	Dual application treatment sites (mi)
Urban multilane undivided highways (nonfreeways)	0.00	0.00	0.00
Urban two-lane roads	0.00	0.00	0.00
Rural multilane undivided highways (nonfreeways)	0.00	0.00	0.00
Rural two-lane roads	181.85	82.98	0.00
Totals across all roadway types	181.85	82.98	0.00

Table 50. Total mileage of Pennsylvania treatment and nontreatment sites considered for inclusion in the safety evaluation of centerline rumble strips.

Roadway type	Treatment sites (mi)	Nontreatment sites (mi)	Dual application treatment sites (mi)
Urban multilane undivided highways (nonfreeways)	3.00	3.73	0.00
Urban two-lane roads	25.50	40.70	0.00
Rural multilane undivided highways (nonfreeways)	4.74	1.84	0.00
Rural two-lane roads	180.78	236.40	3.80
Totals across all roadway types	214.02	282.67	3.80

Table 51 shows the total mileage (by roadway type) of treatment and nontreatment sites from Washington considered for inclusion in the safety evaluation. This table is similar to Tables 49 and 50 above for Minnesota and Pennsylvania sites.

Summary of Sites Across All States

Table 52 shows the total mileage (by roadway type) of treatment and nontreatment sites summed across all three states (Minnesota, Pennsylvania, and Washington) for use in the safety evaluation of centerline rumble strips. Based on the total available mileage of both treatment and nontreatment sites across all three states, Table 52 suggests that analyses of the data for rural and urban two-lane roads have the greatest potential to provide reliable results for investigating the safety effectiveness of centerline rumble strips by themselves. Formal analyses of dual application sites were not performed due to limited mileage of dual applications sites. Crash statistics of the dual application sites are presented later in the section along with general observations of the data.

Videolog Data Collection

Data were collected in a similar manner as the videolog data collection effort conducted to assess the safety effectiveness of shoulder rumble strips (see Section 6), with some variations. The primary purposes of the videolog data collection effort for the safety evaluation of centerline rumble strips were to (a) confirm the absence/presence of the centerline rumble strips, (b) confirm the absence/presence of both centerline and shoulder rumble strips, (c) record the beginning and ending locations of the centerline rumble strips, (d) col-

Table 51. Total mileage of Washington treatment and nontreatment sites considered for inclusion in the safety evaluation of centerline rumble strips.

Roadway type	Treatment sites (mi)	Nontreatment sites (mi)	Dual application treatment sites (mi)
Urban multilane undivided highways (nonfreeways)	1.08	0.00	0.00
Urban two-lane roads	4.14	4.39	0.00
Rural multilane undivided highways (nonfreeways)	0.00	0.12	0.00
Rural two-lane roads	53.44	68.59	2.50
Totals across all roadway types	58.66	73.10	2.50

Table 52. Total mileage of treatment and nontreatment sites considered for inclusion in the safety evaluation of centerline rumble strips (includes data from Minnesota, Pennsylvania, and Washington).

Roadway type	Treatment sites (mi)	Nontreatment sites (mi)	Dual application treatment sites (mi)
Urban multilane undivided highways (nonfreeways)	4.08	3.73	0.00
Urban two-lane roads	29.64	45.09	0.00
Rural multilane undivided highways (nonfreeways)	4.74	1.96	0.00
Rural two-lane roads	416.07	387.97	6.30
Totals across all roadway types	454.53	438.75	6.30

lect horizontal alignment data, (d) collect roadside hazard ratings for each site, (e) verify certain roadway characteristic data, and (f) gather information concerning the construction history of sites and installation dates.

The main difference between the videolog data collection effort for the safety evaluation of centerline rumble strips compared to the safety evaluation of shoulder rumble strips is the collection of horizontal alignment data. Horizontal alignment data were specifically collected to assess the safety effectiveness of centerline rumble strips along varying roadway geometry. From the videologs, the beginning and ending locations of tangents and horizontal curves were recorded through manual observations. The sharpness of a curve was noted based upon the presence or absence of a curve warning sign, and the direction of the curve (i.e., left vs. right) in the direction of increasing milepost/offset was recorded as well. In summary, the following horizontal alignment data were gathered during the videolog data collection effort for each state:

- Beginning and ending mileposts/offsets of tangents,
- Beginning and ending mileposts/offsets of horizontal curves,
- Sharpness of curve (i.e., presence/absence of curve warning signs), and
- Direction of curve (left vs. right).

Some final points regarding the data collection effort, relevant to the analysis approach and analysis results, are the following:

- Even when centerline rumbles strips are installed continuously along a segment, there are many breaks in the rumble strips for various reasons such as bridges, intersections, driveways, etc. Depending upon the roadway type and the policy of the individual states, the frequencies of these breaks vary considerably. For those treatment sites where a significant length of contiguous mileage of centerline rumble strip installation existed, long breaks in the rumble strips may have been recorded during the data collection process, but the boundaries of the treatment site were not modified to reflect the breaks in the rumble strips. Thus, there are locations along the roadways of treatments sites where centerline rumble strips are not present. Only for those treatment sites where centerline rumble strips were not installed over a very long stretch of highway were the boundaries of the treatment sites modified to reflect numerous or significant breaks in the centerline rumble strips.
- The ideal type of treatment site to include in a before-after analysis is one in which the only type of treatment made during the analysis period is the safety improvement (i.e., installation of centerline rumble strips). To the best of our knowledge, the only improvements made to the treatment sites during the analysis period were the installation of the centerline rumble strips (and shoulder rumble strips in the case of dual application treatment sites).
- In Pennsylvania, the initial list of treatment sites was generated from the low-cost safety improvement database developed and maintained by PennDOT. Thus, it is likely that many of the treatment sites in Pennsylvania were initially identified as being high-crash locations compared to the rest of the highway network. For Minnesota and Washington, the policy for determining the need and location for installation of centerline rumble strips is not known.
- All centerline rumble strips are treated as being equivalent in their alerting properties. No effort was made to obtain either rumble strip dimensions for each treatment site or information concerning the placement of the centerline rumble strips relative to the centerline pavement markings.
- No information was recorded concerning the presence of passing zones for either treatment or nontreatment sites. Based upon the written or unwritten centerline rumble strip policies in the three states, several of the treatment sites do include passing zones, but as indicated no information was recorded concerning the presence of passing zones, so neither the percentage of sites with passing zones nor the total mileage of sites with or without passing zones can be determined. The decision to not collect passing zone information was based upon previous research (*38*) indicating that centerline rumble strips have minimal impact on driver behavior in passing zones.

Database Development

The final database(s) utilized for analysis consisted of the roadway characteristic data (including traffic volume), the videolog data, and crash data. In summary, the database(s) for each state included the following roadway inventory and videolog data for a given site:

- Location reference information (i.e., beginning and ending mileposts/logpoints, or route, county, segment, and offsets),
- Presence/absence of milled centerline rumble strips,
- Presence/absence of dual application (i.e., both centerline and shoulder rumble strips),
- Area type (rural vs. urban),
- Roadway type (i.e., multilane undivided or two-lane),
- Number of lanes,
- Lane widths,
- Shoulder widths,
- RHR,
- Horizontal alignment (i.e., tangent or curve),
- Sharpness of curve (i.e., presence/absence of curve warning signs),
- Direction of curve (i.e., left or right),

- Analysis period(s) (including year(s) without rumble strips, installation year(s), and years with rumble strips), and
- ADT for each year in the analysis period(s).

The original roadway inventory files obtained from the states did not contain ADTs for all sites for each year in the analysis period(s). Therefore, rules were established for interpolating and extrapolating the ADT data so that the final database included ADTs for each site and year in the analysis periods. The analysis periods were determined based upon the construction history and installation data gathered and the years of available crash data for each state. Crash data were obtained for the following calendar years (inclusive) for each state:

- Minnesota (1997 through 2006),
- Pennsylvania (1997 through 2006), and
- Washington (2001 through 2006).

The crash data available for use in the analyses consisted of the following:

- Crash report number or crash ID number,
- Date of crash,
- Location information (county, route, direction, segment and offset or logpoint),
- Number of vehicles involved,
- Crash severity, and
- Accident type or manner of collision.

The final database only included crashes assigned to roadway segments. Rules were established to eliminate (i.e., screen out) intersection-related crashes. As a final note concerning the crash data, logic was developed to identify SVROR-left and SVROR-right crashes from the electronic crash data for Pennsylvania. The accuracy of the results was assessed by reviewing about 100 sample crash reports. Based upon the results of the sampling, it was determined that SVROR-left and SVROR-right crashes could not be accurately determined from the electronic files for Pennsylvania. Therefore, SVROR-left crashes are not included in analyses of target crashes for centerline rumble strips. At least one study (*75*) indicated that SVROR-left crashes should potentially be considered as target crashes of centerline rumble strips.

Several other rules were established for developing the final database(s). Most of these rules pertained to establishing a rationale for combining adjacent sites to create longer homogeneous sites. Several of these rules pertained to the following:

- Selected roadway characteristics (e.g., lane widths, shoulder widths, number of lanes) and
- Desirable minimum lengths (e.g., 0.1 mi [0.16 km]).

The following section provides descriptive statistics of the information contained in databases developed for the safety evaluation of centerline rumble strips.

Descriptive Statistics

To address the three objectives of this safety evaluation of centerline rumble strips, a database has been assembled such that data from a given site could be used to address one or more of the objectives. This section provides descriptive statistics in either tabular and/or graphical form for the independent variables (i.e., ADT, site geometrics) and dependent variables (i.e., crash data) of interest in the safety evaluation of centerline rumble strips. The data are presented in several layouts, designed to provide basic summaries of the available information.

The data for each site were collected over time periods of varying lengths. For comparison, the site length and the number of years were combined into a single variable, mile-years, for each site. The following is nomenclature used in the safety evaluation of centerline rumble strips to describe the types of sites included in the evaluation:

- BA-No RS: Nontreatment site of the matched before-after site pair in the before period;
- BA-RS: Treatment site of the matched before-after site pair in the after period; and
- NT-No RS: Nontreatment reference site.

Table 53 summarizes the basic layout of the available data in the three states for evaluation of the safety effectiveness of centerline rumble strips on specific types of roads. The data provided separately for each state, roadway type, and type of site are the number of sites, total site length, and mile-years. Due to an insufficient number of treatment sites and mile-years for a number of roadway types and states, it was decided to focus the safety evaluation on the following roadway types:

- Urban two-lane roads and
- Rural two-lane roads.

For urban two-lane roads a decision was made to only analyze data from Pennsylvania and not include data from Washington because the number of mile-years of data from Pennsylvania was far greater than for Washington. The Pennsylvania data would likely dominate the analysis such that including data from Washington would not contribute to the results. Thus, the analysis for urban two-lane roads is based on data from Pennsylvania only.

ADT volume. For each site, ADTs were averaged across years within an analysis period. This allowed for a fair

Table 53. Summary study layout—total number of sites, site length, and mile-years by state, roadway type, and site type[a].

Roadway type	Site type	Treatment status	Minnesota			Pennsylvania			Washington		
			Number of sites	Length (mi)	Mile-years	Number of sites	Length (mi)	Mile-years	Number of sites	Length (mi)	Mile-years
Urban multilane undivided highways (nonfreeways)	BA	No RS	0			0			0		
		RS									
	NT	No RS	0			8	3.73	37.28	0		
Urban two-lane roads	BA	No RS	0			74	25.50	138.78	6	4.14	12.90
		RS						90.64			7.40
	NT	No RS	0			85	40.70	407.01	22	4.39	21.95
Rural multilane undivided highways (nonfreeways)	BA	No RS	0			0			0		
		RS									
	NT	No RS	0			4	1.84	18.42	0		
Rural two-lane roads	BA	No RS	301	181.85	1,033.15	526	180.78	893.14	135	53.44	190.88
		RS			603.48			722.28			53.97
	NT	No RS	243	82.98	747.82	518	236.40	2,364.01	206	68.59	342.95

[a] Shaded cells are focus of statistical analysis.

comparison of the distribution of ADTs across site types, analysis periods, and states since the sample size is reduced to the number of sites within each category and thus not unduly influenced by the length of the varying analysis periods.

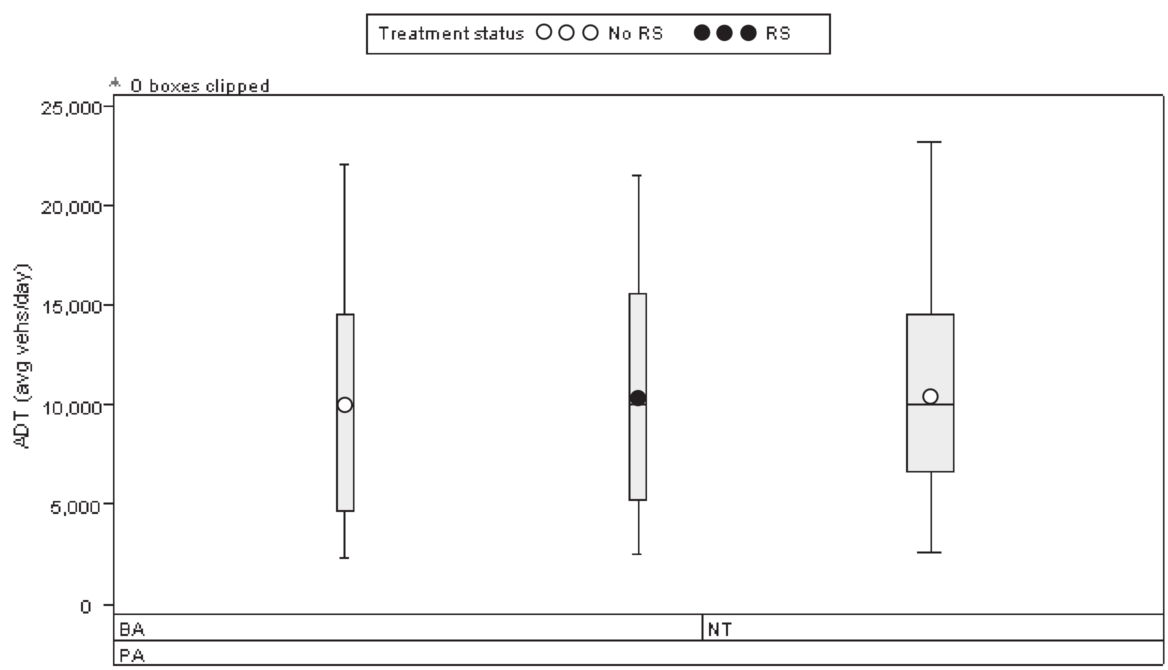
Figures 11 and 12 show the ADT distributions in the form of side-by-side boxplots for both urban and rural two-lane roads. Within each figure, the data are organized by the states included in the analysis; within each state, the data are ordered by site type—before-after sites then nontreatment sites; the mean ADTs of nontreatment sites are colored white; those of the treatment sites are black. Each figure also contains a table of basic descriptive ADT statistics for number of sites, mean, standard deviation, minimum, median, and maximum.

Lane width. Lane widths ranged from 10 to 14+ ft (3.0 to 4.3+ m) across all sites and states, with the majority of lanes being 11 or 12 ft (3.3 or 3.6 m) wide. The distribution of lane width is summarized in Table 54 by state and site type.

Shoulder width. Outside shoulder widths ranged from 0 to 10+ ft (0.0 to 3.0+ m) across sites and states. The distribution of shoulder width is summarized in Table 55 by state and site type.

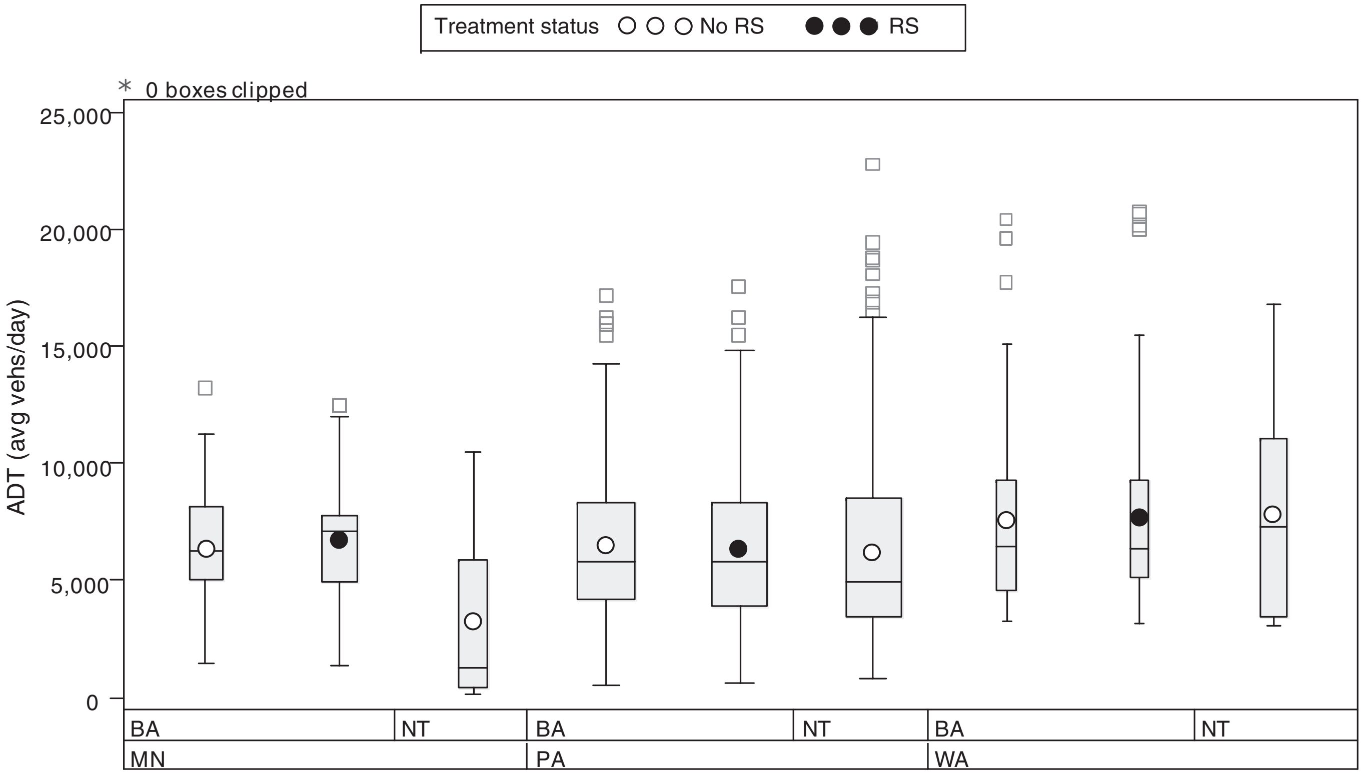
RHR. Roadside hazard ratings were recorded as integers ranging from 1 (low RHR) to 7 (high RHR); it is treated as a continuous variable in the statistical model development. Table 56 presents basic descriptive RHR statistics (i.e., number of sites and minimum, maximum, mean, and standard deviation) by state and site type. Non-integer values for minimums and maximums in Table 56 are the result of combining adjacent segments into homogeneous sites for analysis purposes. When adjacent segments with different RHRs were combined into a single site for analysis purposes, a weighted average, based on segment length, of the RHR was calculated for the site.

Horizontal alignment. Table 57 provides the mile-years and number of horizontal curve sites and tangent sites, respectively, used to assess the safety effectiveness of centerline rumble strips along varying roadway geometry. The analysis of the safety effectiveness of centerline rumble strips along varying roadway geometry is based upon data strictly from rural two-lane roads. Sites in Minnesota and Washington are defined slightly different than sites in Pennsylvania. The SPFs for Pennsylvania nontreatment sites were also developed in a slightly different manner than the



No. of sites	74	74	85
Mean	10,023	10,277	10,440
Std dev	5,751	5,884	5,001
Min	2,338	2,539	2,634
Median	9,952	10,071	9,999
Max	22,076	21,466	23,140

Figure 11. ADT distribution by site type for urban two-lane roads in Pennsylvania.



No. of sites	301	301	243	526	526	518	135	135	206
Mean	6,407	6,773	3,265	6,510	6,359	6,204	7,602	7,746	7,851
Std dev	2,591	2,700	3,121	3,315	3,220	3,794	3,644	3,902	3,723
Min	1,495	1,336	176	574	596	777	3,222	3,167	3,097
Median	6,307	7,145	1,247	5,821	5,760	4,992	6,495	6,394	7,300
Max	13,240	12,478	10,508	17,205	17,591	22,794	20,448	20,784	16,749

Figure 12. ADT distribution by site type for rural two-lane roads in Minnesota, Pennsylvania, and Washington.

SPFs for Minnesota and Washington. The differences are as follows:

- For Minnesota and Washington treatment and nontreatment sites, curve sites begin at the beginning of a curve and end at the end of a curve. Similarly, tangent sites begin at the beginning of a tangent and end at the end of a tangent.
- For Pennsylvania sites, treatment sites were classified as a horizontal curve if 75 percent or more of the length was on a horizontal curve, and treatment sites were classified as a tangent if 100 percent of the length was on a straight portion of roadway (i.e., without any horizontal curves). Treatment sites with less than 75 percent of the length on a horizontal curve were not included in either classifica-

Table 54. Distribution of lane width by state and site type[a].

Lane width (ft)	Minnesota		Pennsylvania		Washington	
	Before–after sites	Nontreatment sites	Before–after sites	Nontreatment sites	Before–after sites	Nontreatment sites
9	–	–	–	–	–	–
10	–	–	48	68	–	33
11	36	20	313	304	61	96
12	251	218	208	155	74	71
13	7	5	7	17	–	2
14+	7	–	24	59	–	4

[a] Includes data for all roadway types for which analyses are conducted.

Table 55. Distribution of shoulder width by state and site type[a].

Average shoulder width (rounded) (ft)	Minnesota		Pennsylvania		Washington	
	Before–after sites	Nontreatment	Before–after sites	Nontreatment	Before–after sites	Nontreatment
0	–	2	4	53	–	3
1	–	60	–	9	–	2
2	9	-	11	41	7	26
3	8	27	66	50	63	17
4	37	48	155	139	27	50
5	–	-	70	93	11	10
6	31	10	123	74	22	41
7	22	33	49	20	–	4
8	100	59	91	91	–	39
9	31	3	8	3	1	6
10+	63	1	23	30	4	8

[a] Includes data for all roadway types for which analyses are conducted.

Table 56. RHR statistics by roadway type, state, and site type[a].

State	Site type	RHR				
		Number of sites	Minimum	Maximum	Mean	Standard deviation
MN	BA	301	2	5.5	3.55	1.14
	Nontreatment	243	2	6	3.50	1.23
PA	BA	600	2	5	3.57	0.57
	Nontreatment	603	2	6	3.67	0.83
WA	BA	135	2	5	3.72	0.49
	Nontreatment	206	3	5	4.21	0.43

[a] Includes data for all roadway types for which analyses are conducted.

tion. During the SPF development for nontreatment sites, all nontreatment sites were included in the model and a curve/tangent independent variable was considered. The curve/tangent variable proved to be not significant; therefore, all Pennsylvania nontreatment sites, whether they included a horizontal curve or tangent sections were considered appropriate for analysis as nontreatment sites. Thus, the number of sites, length, and mile-years for nontreatment sites for Pennsylvania rural two-lane roads in Tables 53 and 57 are equivalent.

More details on the analysis approach to quantifying the safety effectiveness of centerline rumble strips along varying roadway geometry are provided on the next page in Analysis Approach.

Dual application sites. Table 58 provides the number of sites, length, and mile-years for the dual application sites found in Pennsylvania and Washington. For these sites, the centerline and shoulder rumble strips were installed during the same calendar year. No dual application sites were found

Table 57. Summary study layout—total number of horizontal curve and tangent sites, site length, and mile-years by state and site type.

Roadway type	Site type	Treatment status	Minnesota			Pennsylvania			Washington		
			Number of sites	Length (mi)	Mile-years	Number of sites	Length (mi)	Mile-years	Number of sites	Length (mi)	Mile-years
Horizontal Curve Sites											
Rural two-lane roads	BA	No RS	135	28.41	162.06	144	29.32	134.10	62	10.42	41.08
		RS			93.07			125.84			11.02
	NT	No RS	105	14.89	134.04	518	236.40	2,364.01	104	17.07	85.35
Tangent Sites											
Rural two-lane roads	BA	No RS	166	153.44	871.09	73	23.25	110.67	73	38.55	149.80
		RS			509.87			98.24			42.95
	NT	No RS	138	68.09	612.79	518	236.40	2,364.01	102	51.52	257.60

Table 58. Summary study layout—total number of dual application sites, site length, and mile-years by state and site type.

Roadway type	Site type	Treatment status	Minnesota			Pennsylvania			Washington		
			Number of sites	Length (mi)	Mile-years	Number of sites	Length (mi)	Mile-years	Number of sites	Length (mi)	Mile-years
Rural two-lane roads	BA	No RS	0			11	3.80	22.8	5	2.50	5.0
		RS						11.4			7.5

in Minnesota. Due to limited mileage and mile-years of treatment sites, a detailed safety evaluation of dual applications was not performed, but crash statistics are presented below followed by several general observations of the crash statistics in the section on Analysis Results.

Crash data. Four crash types are analyzed as part of the safety evaluation of centerline rumble strips:

- TOT crashes,
- FI crashes,
- Total head-on and sideswipe opposite-direction (TOT target) crashes, and
- Fatal and injury head-on and sideswipe opposite-direction (FI target) crashes.

Analyses of TOT crashes are performed primarily because several previous safety evaluations of centerline rumble strips analyzed this crash type. However, analyses of TOT crashes include many other crash types besides head-on and opposite-direction sideswipe crashes (i.e., the target crash types). No strong argument can be made to support why centerline rumble strips should affect crashes other than the primary target crashes (i.e., head-on and opposite-direction sideswipe crashes), with the possible exception of SVROR-left crashes. Analyses of FI crashes were also conducted because there is great interest in reducing crashes that result in fatalities and injuries, but again, analyses of FI crashes include many other crash types besides the target crashes. Analyses of head-on and opposite-direction sideswipe crashes are expected to produce more reliable results than analyses of TOT and FI crashes because the analyses include only those crashes expected to be most directly impacted by centerline rumble strips. Finally, analyses based on head-on and opposite-direction sideswipe FI crashes are of interest because these analyses address the more severe target crashes.

The crash data across all years are summarized in Table 59 and are shown as both total number of crashes and crash frequency (crashes/mi/yr) and separately for each type of site of a given roadway type within a given state. The two statistics are presented separately for TOT crashes, head-on crashes, and sideswipe opposite-direction crashes. Table 59 also provides the number of sites and their total length and mile-years to facilitate comparison between groups of data. For before-after site pairs (i.e., same site paired in time), the number of sites and length are shown only once since the sites are the same before and after treatment; however, since the study periods changed from site to site, mile-years vary between nontreatment and treatment before-after site pairs.

The crash data are summarized by roadway type, state, site type, and treatment status in Table 60 for all FI crashes and the target crashes. Crash counts and average frequencies per mile per year are presented.

Table 61 summarizes crash data used to evaluate the safety effectiveness of centerline rumble strips along varying roadway geometry. TOT crashes and the target crashes are presented for horizontal curve sites and tangent sites for rural two-lane roads by state, site type, and treatment status. Crash counts and average frequencies per mile per year are presented. Table 62 presents the corresponding data for FI crashes.

Table 63 summarizes crash data for dual application sites in Pennsylvania and Washington. Data are presented for TOT crashes, FI crashes, and TOT target crashes for before-after sites only, for rural two-lane roads. For dual application sites, the target crashes include head-on, sideswipe opposite-direction, and SVROR crashes. Crash counts and average frequencies per mile per year are presented.

Analysis Approach

The EB methodology, as described in Section 6, Analysis Approach, was used to evaluate the safety effectiveness of centerline rumble strips on different roadway types and along varying roadway geometry. The evaluations included analyses of TOT, FI, and TOT target crashes. Due to small sample sizes, analyses of FI target crashes were performed in the evaluation of centerline rumble strips on different roadway types, based upon proportions. Rather than developing SPFs for FI target crashes, the SPF for TOT target crashes was used along with the percentage of FI target crashes to TOT target crashes. The same approach for analyzing FI target crashes for centerline rumble strips was used as in the supplemental analyses of shoulder rumble strips (see Analysis Approach, Section 6). No analyses of FI target crashes were performed in the evaluation of centerline rumble strips along varying roadway geometry due to extremely small sample sizes.

Table 59. Crash statistics by roadway type, state, site type, treatment status, and severity (TOT crashes).

Roadway type	State	Site type	Treatment status	Number of sites	Length (mi)	Mile-years	TOT: Total number of crashes	TOT: Crash frequency (crashes/mi/yr)	Head-on: Total number of crashes	Head-on: Crash frequency (crashes/mi/yr)	Sideswipe opposite-direction: Total number of crashes	Sideswipe opposite-direction: Crash frequency (crashes/mi/yr)
Urban two-lane roads	PA	BA	No RS	74	25.50	138.78	395	2.85	30	0.22	19	0.14
			RS			90.64	222	2.44	7	0.08	6	0.07
		NT	No RS	85	40.70	407.01	1,168	2.87	82	0.20	17	0.04
	WA	BA	No RS	6	4.14	12.90	89	6.90	2	0.16	4	0.31
			RS			7.40	31	4.19	0	0.00	1	0.08
		NT	No RS	22	4.39	21.95	43	1.96	0	0.00	1	0.23
Rural two-lane roads	MN	BA	No RS	301	181.85	1,033.15	1,000	0.97	64	0.06	35	0.03
			RS			603.48	523	0.87	39	0.06	16	0.03
		NT	No RS	243	82.98	747.82	445	0.60	39	0.05	16	0.02
	PA	BA	No RS	526	180.78	893.14	1,936	2.17	209	0.23	67	0.08
			RS			722.28	1,256	1.74	54	0.08	40	0.06
		NT	No RS	518	236.40	2,364.01	4,140	1.75	301	0.13	117	0.05
	WA	BA	No RS	135	53.44	190.88	429	2.25	13	0.07	15	0.08
			RS			53.97	133	2.46	2	0.04	3	0.06
		NT	No RS	215	69.85	349.25	967	2.77	19	0.05	28	0.08

Table 60. Crash statistics by roadway type, state, site type, treatment status, and severity (FI crashes).

Roadway type	State	Site type	Treatment status	Number of sites	Length (mi)	Mile-years	All FI: Total number of crashes	All FI: Crash frequency (crashes/mi/yr)	Head-on: Total number of crashes	Head-on: Crash frequency (crashes/mi/yr)	Sideswipe opposite-direction: Total number of crashes	Sideswipe opposite-direction: Crash frequency (crashes/mi/yr)
Urban two-lane roads	PA	BA	No RS	74	25.50	138.78	239	1.72	27	0.20	12	0.09
			RS			90.64	116	1.28	2	0.02	4	0.04
		NT	No RS	85	40.70	407.01	600	1.47	40	0.10	2	0.00
	WA	BA	No RS	6	4.14	12.90	43	3.33	1	0.08	2	0.16
			RS			7.40	11	1.49	0	0.00	0	0.00
		NT	No RS	22	4.39	21.95	20	0.91	0	0.00	0	0.00
Rural two-lane roads	MN	BA	No RS	301	181.85	1,033.15	397	0.38	47	0.04	19	0.02
			RS			603.48	193	0.32	15	0.02	9	0.01
		NT	No RS	243	82.98	747.82	179	0.24	23	0.03	7	0.01
	PA	BA	No RS	526	180.78	893.14	1114	1.25	168	0.19	38	0.04
			RS			722.28	664	0.92	44	0.06	24	0.03
		NT	No RS	518	236.40	2,364.01	2,237	0.95	83	0.04	13	0.00
	WA	BA	No RS	135	53.44	190.88	222	1.16	13	0.07	15	0.08
			RS			53.97	63	1.17	2	0.04	2	0.04
		NT	No RS	215	69.85	349.25	424	1.21	18	0.05	19	0.05

Table 61. Crash statistics for curve/tangent sites by roadway type, state, site type, treatment status, and severity (TOT crashes).

Roadway type	State	Site type	Treatment status	Number of sites	Length (mi)	Mile-years	Crash type: TOT – Total number of crashes	TOT – Crash frequency (crashes/mi/yr)	Head-on – Total number of crashes	Head-on – Crash frequency (crashes/mi/yr)	Sideswipe opposite-direction – Total number of crashes	Sideswipe opposite-direction – Crash frequency (crashes/mi/yr)
Horizontal Curve Sites												
Rural two-lane roads	MN	BA	No RS	135	28.41	162.06	200	1.23	15	0.09	11	0.07
			RS			93.07	98	1.05	9	0.10	2	0.02
		NT	No RS	105	14.89	134.04	113	0.84	7	0.05	7	0.05
	PA	BA	No RS	144	29.32	134.10	248	1.85	41	0.31	8	0.06
			RS			125.84	223	1.77	7	0.06	8	0.06
		NT	No RS	518	236.40	2,364.01	4,140	1.75	301	0.13	117	0.05
	WA	BA	No RS	62	10.42	41.08	96	2.34	2	0.05	3	0.07
			RS			11.02	27	2.45	1	0.91	1	0.09
		NT	No RS	104	17.07	85.35	288	3.37	4	0.05	9	0.10
Tangent Sites												
Rural two-lane roads	MN	BA	No RS	166	153.44	871.09	800	0.92	49	0.06	24	0.03
			RS			509.87	425	0.83	30	0.06	14	0.03
		NT	No RS	138	68.09	612.79	332	0.54	32	0.05	9	0.02
	PA	BA	No RS	73	23.25	110.67	235	2.12	20	0.18	4	0.04
			RS			98.24	160	1.63	6	0.06	4	0.04
		NT	No RS	518	236.40	2,364.01	4,140	1.75	301	0.13	117	0.05
	WA	BA	No RS	73	38.55	149.80	333	2.24	11	0.07	12	0.08
			RS			42.95	106	2.47	1	0.02	2	0.05
		NT	No RS	102	51.52	257.60	636	2.47	15	0.06	18	0.07

Table 62. Crash statistics for curve/tangent sites by roadway type, state, site type, treatment status, and severity (FI crashes).

Roadway type	State	Site type	Treatment status	Number of sites	Length (mi)	Mile-years	Crash type					
							All FI		Head-on		Sideswipe opposite-direction	
							Total number of crashes	Crash frequency (crashes/mi/yr)	Total number of crashes	Crash frequency (crashes/mi/yr)	Total number of crashes	Crash frequency (crashes/mi/yr)
Horizontal Curve Sites												
Rural two-lane roads	MN	BA	No RS	135	28.41	162.06	94	0.58	12	0.07	6	0.04
			RS			93.07	34	0.36	2	0.02	1	0.01
		NT	No RS	105	14.89	134.04	42	0.31	4	0.03	2	0.02
	PA	BA	No RS	144	29.32	134.10	158	1.18	32	0.24	3	0.02
			RS			125.84	120	0.95	6	0.05	6	0.05
		NT	No RS	518	236.40	2,364.01	2,237	0.95	83	0.04	13	0.00
	WA	BA	No RS	62	10.42	41.08	56	1.36	1	0.02	3	0.07
			RS			11.02	10	0.91	1	0.09	3	0.27
		NT	No RS	104	17.07	85.35	130	1.52	10	0.12	7	0.08
Tangent Sites												
Rural two-lane roads	MN	BA	No RS	166	153.44	871.09	303	0.35	35	0.04	13	0.02
			RS			509.87	159	0.31	13	0.02	8	0.02
		NT	No RS	138	68.09	612.79	137	0.22	19	0.03	5	0.01
	PA	BA	No RS	73	23.25	110.67	137	1.24	19	0.17	3	0.03
			RS			98.24	79	0.80	6	0.06	2	0.02
		NT	No RS	518	236.40	2,364.01	2,237	0.95	83	0.04	13	0.00
	WA	BA	No RS	73	38.55	149.80	166	1.11	8	0.05	6	0.04
			RS			42.95	53	1.23	2	0.05	1	0.02
		NT	No RS	102	51.52	257.60	274	1.06	14	0.05	13	0.05

Table 63. Crash statistics for dual application sites by roadway type, state, site type, treatment status, and severity.

Roadway type	State	Site type	Treatment status	Number of sites	Length (mi)	Mile-years	Crash type					
							TOT		FI		TOT Target (head-on, sideswipe opposite-direction, and SVROR)	
							Total number of crashes	Crash frequency (crashes/mi/yr)	Total number of crashes	Crash frequency (crashes/mi/yr)	Total number of crashes	Crash frequency (crashes/mi/yr)
Rural two-lane roads	PA	BA	No RS	11	3.80	22.8	83	3.64	45	1.97	25	1.10
			RS			11.4	30	2.63	18	1.58	2	0.18
	WA	BA	No RS	5	2.50	5.0	17	3.40	7	1.40	5	1.00
			RS			7.5	30	4.00	16	2.13	12	1.60

Due to limited mileage and mile-years of dual application sites, a detailed safety evaluation of dual applications was not performed. Crash statistics are presented in Descriptive Statistics above; general observations of these data are presented in the next section.

Cross-sectional analyses using GLM were not used to assess the safety effectiveness of centerline rumble strips since all treatment sites had before-period information. Regarding the dual application sites, several sites were found during data collection that initially had shoulder rumble strips installed for several years, followed by the installation of centerline rumble strips. Thus, rather than having a before-treatment period without any centerline and shoulder rumble strips, the before-treatment period had shoulder rumble strips present for a significant number of years. A decision was made to report only those sites where the before-treatment period had no shoulder rumble strips present and the after period had both centerline and shoulder rumble strips present.

The SPFs developed for use in the EB methodology to evaluate the safety effectiveness of centerline rumble strips were based on negative binomial regression. Model estimation used PROC GENMOD in SAS. Variable selection was done for each state and roadway type based on trials with various combinations of logical potential dependent variables. Each potential model was assessed based on the statistical significance of the variable coefficients and overall model fit.

Several final points follow that concern the analysis approach to the safety evaluation of centerline rumble strips on different roadway types and along varying roadway geometry:

- It has been noted that the research by Persaud et al. (*4*) is the most comprehensive and reliable evaluation on the safety effectiveness of centerline rumble strips on rural two-lane roads. The research team had access to the raw data collected by Persaud et al. (*4*) for the Insurance Institute for Highway Safety (IIHS) and also the EB calculations. This enabled the data collected for rural two-lane roads during this research and the IIHS to be combined to provide reliable and comprehensive estimates on the safety effectiveness of centerline rumble strips on rural two-lane roads.
- In the evaluation of the safety effectiveness of centerline rumble strips along varying roadway geometry, horizontal curve and tangent sites were defined in a slightly different manner for Minnesota and Washington than for Pennsylvania. The differences in the way horizontal curve and tangent sites were defined were due to differences in the location referencing systems for Minnesota and Washington compared to Pennsylvania. The information on rumble strip placement in Minnesota and Washington was used to define curve and tangent segments when overlapped with the roadlog location referencing system. For Pennsylvania, a similar exercise would have resulted in many very short roadway segments, which would not be reliable for analysis. For Pennsylvania, a horizontal curve treatment site was classified as being a horizontal curve site if 75 percent or more of the segment length was curvilinear. Only treatment sites with at least 75 percent or more of the segment length being curvilinear were included in the analysis of the safety effectiveness of centerline rumble strips along horizontal curves. A tangent treatment site was classified as a tangent site if 100 percent of the segment length was on a straight portion of roadway without any horizontal curves. During the SPF development of nontreatment sites in all states, models were developed in which all sites (i.e., horizontal curves and tangents) were included and a curve/tangent indicator variable was included as a predictor (i.e., independent) variable in the model. The curve/tangent variable was not significant; therefore, all nontreatment sites, whether they included horizontal curves, tangents, or both were considered appropriate for analysis as nontreatment sites. Although the data for the nontreatment sites did not support different models for curve and tangent sites, the empirical Bayes procedure does reflect differences between sites when combining SPF predictions and observed crash counts and therefore would reflect actual differences between the two groups should they exist. Even though horizontal curve and tangent sites were defined slightly differently for Minnesota and Washington than for Pennsylvania, the results for all three states were combined in the separate analyses for horizontal curves and tangents, and the combined results from all three states are considered the most reliable and comprehensive compared to the individual results by state.

Analysis Results

Analysis results are first presented for estimating the safety effectiveness of centerline rumble strips on different roadway types and then followed by the analysis results for estimating the safety effectiveness of centerline rumble strips along varying roadway geometry. Finally, several general observations on the safety effectiveness of dual application sites based on the basic crash statistics are presented.

Estimating the Safety Effectiveness of Centerline Rumble Strips on Different Roadway Types

The EB analysis consisted of two steps:

1. Develop SPF models based on all nontreatment sites, and
2. Using the SPFs, evaluate the safety effectiveness of centerline rumble strips using crash data from the before-after sites only.

SPF results. Negative binomial regression models were developed for total crashes and the proportion of FI and target crashes were applied to the models to predict for these crash types, thus combining data for horizontal curve sites and tangent sites. For Minnesota and Washington, the curve/tangent characteristic was not a statistically significant variable for rural two-lane roads, while for Pennsylvania, curvature was not known for all of the reference sites used. For Washington, ADT was the only variable used in the model, while Minnesota also included roadside hazard rating and Pennsylvania included roadside hazard rating, posted speed, and road width as predictor variables. Only nontreatment sites were used for SPF development. Tables H-1 through H-3 in Appendix H summarize the crash frequency models for TOT, FI, and TOT target crashes, respectively. The statistics shown for each state SPF are as follows:

- Number of nontreatment sites;
- Intercept: estimate and standard error;
- lnADT coefficient: estimate, standard error, and p-value (or significance level); for example, a p-value of 0.05 or less indicates that the coefficient is significantly different from zero at the 0.05 significance (or 95 percent confidence) level;
- Model dispersion parameter: estimate and standard error; and
- Model R^2_{LR} value: the likelihood ratio R^2_{LR}, a measure of model fit between 0 and 1. The closer the value is to 1, the better the fit of the model is to the data.

The SPF is represented by the following general equation:

$$\text{Expected crashes/mi/yr} = \exp(1 + b\ln ADT + cRHR + dWidth + eSPD) \quad (3)$$

where

RHR = the average roadside hazard rating,
SPD = 1 if the posted speed is less than 55 mph and 0 otherwise,
Width = the roadway width in feet, and
a, b, c, d and e = coefficients whose estimates are shown in Tables H-1 through H-3 in Appendix H.

The SPFs were recalibrated to provide a yearly factor for each year to account for time trends in crash counts. These factors were based on total crashes.

Safety effectiveness results. For each crash type, roadway type, and state, the safety effectiveness of centerline rumble strips was estimated. The final results are shown in Tables 64 through 67 for TOT, FI, TOT target, and FI target crashes, respectively. For each crash type, separate analyses were performed across the two roadway types of interest, based on data for individual states and combined across states. The statistics shown for each crash type, roadway type, and state (single or combined) are as follows:

- Number of treatment sites,
- Total site length,
- Percent change due to centerline rumble strips: estimate and standard error,
- Test statistic, and
- An indication of whether rumble strips had a significant effect on the crash type of interest.

Several relevant findings from the EB analyses are as follows:

- Of the five analyses based on TOT crashes (Table 64), one yields statistically significant results at the 90 or 95 percent

Table 64. Safety effectiveness of centerline rumble strips on TOT crashes using the EB method.

Roadway type	State	Number of sites	Total length (mi)	Percent change in crash frequency from before to after rumble strip installation (%)		Test statistic[c]	Significance
				Estimate[a]	SE[b]		
Urban two–lane roads	PA	74	25.50	1.5	8.0	0.19	Not significant at 90% CL
Rural two–lane roads	Combined	962	416.06	–4.1	2.6	1.58	Not significant at 90% CL
	MN	301	181.84	–11.1	5.8	1.91	Significant at 90% CL
	PA	526	180.78	–1.6	3.3	0.48	Not significant at 90% CL
	WA	135	53.44	2.3	8.1	0.28	Not significant at 90% CL

[a] A negative percent change indicates a decrease in crash frequency while a positive percent change indicates an increase in crash frequency.
[b] SE: standard error of estimate.
[c] Test statistic = abs(Estimate/SE); not significant at 90% CL if < 1.7; significant at 90% CL if ≥ 1.7; significant at 95% CL if ≥ 2.

Table 65. Safety effectiveness of centerline rumble strips on FI crashes using the EB method.

Roadway type	State	Number of sites	Total length (mi)	Percent change in crash frequency from before to after rumble strip installation (%)		Test statistic[c]	Significance
				Estimate[a]	SE[b]		
Urban two–lane roads	PA	74	25.50	–9.3	9.5	0.98	Not significant at 90% CL
Rural two–lane roads	Combined	962	416.06	–9.4	3.5	2.57	Significant at 95% CL
	MN	301	181.84	–21.8	6.6	3.30	Significant at 95% CL
	PA	526	180.78	–6.2	4.2	1.48	Not significant at 90% CL
	WA	135	53.44	4.1	14.6	0.28	Not significant at 90% CL

[a] A negative percent change indicates a decrease in crash frequency while a positive percent change indicates an increase in crash frequency.
[b] SE: standard error of estimate.
[c] Test statistic = abs(Estimate/SE); not significant at 90% CL if < 1.7; significant at 90% CL if ≥ 1.7; significant at 95% CL if ≥ 2.

Table 66. Safety effectiveness of centerline rumble strips on TOT target crashes using the EB method.

Roadway type	State	Number of sites	Total length (mi)	Percent change in crash frequency from before to after rumble strip installation (%)		Test statistic[c]	Significance
				Estimate[a]	SE[b]		
Urban two–lane roads	PA	74	25.50	–40.2	17.0	2.36	Significant at 95% CL
Rural two–lane roads	Combined	962	416.06	–37.0	5.3	6.98	Significant at 95% CL
	MN	301	181.84	–48.9	7.3	6.69	Significant at 95% CL
	PA	526	180.78	–25.8	17.9	1.44	Not significant at 90% CL
	WA	135	53.44	–35.4	29.2	1.21	Not significant at 90% CL

[a] A negative percent change indicates a decrease in crash frequency while a positive percent change indicates an increase in crash frequency.
[b] SE: standard error of estimate.
[c] Test statistic = abs(Estimate/SE); not significant at 90% CL if < 1.7; significant at 90% CL if ≥ 1.7; significant at 95% CL if ≥ 2.

Table 67. Safety effectiveness of centerline rumble strips on FI target crashes using the EB method.

Roadway type	State	Number of sites	Total length (mi)	Percent change in crash frequency from before to after rumble strip installation (%)		Test statistic[c]	Significance
				Estimate[a]	SE[b]		
Urban two–lane roads	PA	74	25.50	–63.7	26.9	2.36	Significant at 95% CL
Rural two–lane roads	Combined	962	416.06	–44.5	6.4	6.98	Significant at 95% CL
	MN	301	181.84	–44.7	6.7	6.69	Significant at 95% CL
	PA	526	180.78	–44.4	30.8	1.44	Not significant at 90% CL
	WA	135	53.44	–35.4	29.2	1.21	Not significant at 90% CL

[a] A negative percent change indicates a decrease in crash frequency while a positive percent change indicates an increase in crash frequency.
[b] SE: standard error of estimate.
[c] Test statistic = abs(Estimate/SE); not significant at 90% CL if < 1.7; significant at 90% CL if ≥ 1.7; significant at 95% CL if ≥ 2.

confidence level. This single significant result for rural two-lane roads in Minnesota indicates a decrease in TOT crashes when centerline rumble strips are installed.

- Of the five separate analyses based on FI crashes (Table 65), two yield statistically significant results at the 90 or 95 percent confidence level. Each significant result for rural two-lane roads indicates a decrease in FI crashes when centerline rumble strips are installed.
- Of the five separate analyses based on TOT target crashes (Table 66), three yield statistically significant results at the 90 or 95 percent confidence level. The significant results for both urban and rural two-lane roads indicate a decrease in TOT target crashes when centerline rumble strips are installed.
- Of the five separate analyses based on FI target crashes (Table 67), three yield statistically significant results at the 90 or 95 percent confidence level. The significant results for both urban and rural two-lane roads indicate a decrease in FI target crashes when centerline rumble strips are installed.

Combined results from this research and the IIHS study. For rural two-lane roads, Table 68 presents results on the safety effectiveness of centerline rumble strips from this research, the IIHS study (*4*), and both combined. The IIHS study was an EB evaluation of 98 rural sites in 6 states with a total of 211 mi (340 km) of centerline rumble strip installations. Because comparisons between the two studies appear favorable, at least in terms of direction and general order of magnitude of the effects, the two sets of results were combined. The results of this research are the combined results from all three states. It should also be made clear that the combined results are based upon raw data from both studies, and the combined results are based upon the EB methodology. Because the raw data from the IIHS study were available, procedures for combining study results for incorporation in the HSM (*65*) were not used. The combined results estimate reductions of 8.7, 11.7, and 30.2 percent are expected for TOT, FI, and TOT target crashes, respectively, with the installation of centerline rumble strips.

Estimating the Safety Effectiveness of Centerline Rumble Strips Along Varying Roadway Geometry

The same SPFs used to estimate the safety effectiveness of centerline rumble strips on different roadway types were used to estimate the safety effectiveness of centerline rumble strips along varying roadway geometry.

Safety effectiveness results. For each horizontal alignment category, crash type, and state, the safety effectiveness of centerline rumble strips was estimated. The final results for horizontal curves are shown in Tables 69 through 71 for TOT, FI, and TOT target crashes, respectively, and the final results for tangents are shown in Tables 72 through 74 for TOT, FI, and TOT target crashes, respectively. For each crash type, separate analyses were performed based on data for individual states and combined across states. The statistics shown for each horizontal alignment category, crash type, and state (single or combined) are as follows:

- Number of treatment sites;
- Total site length;
- Percent change due to centerline rumble strips: estimate and standard error;
- Test statistic; and
- An indication of whether rumble strips had a significant effect on the crash type of interest.

Several relevant findings from the EB analyses are as follows:

- Of the four analyses based on TOT crashes for horizontal curve sites (Table 69), two yield statistically significant results at the 90 or 95 percent confidence level. One significant result indicates TOT crashes decrease when centerline rumble strips are installed along horizontal curves, while the other indicates an increase in TOT crashes when centerline rumble strips are installed along horizontal curves.
- Of the four analyses based on FI crashes for horizontal curve sites (Table 70), one yields statistically significant results at the 90 or 95 percent confidence level. The one significant result indicates a decrease in FI crashes when centerline rumble strips are installed along horizontal curves.
- Of the four analyses based on TOT target crashes for horizontal curve sites (Table 71), three yield statistically significant results at the 90 or 95 percent confidence level. All three significant results indicate a decrease in TOT target crashes when centerline rumble strips are installed along horizontal curves.
- Of the four analyses based on TOT crashes for tangent sites (Table 72), two yield statistically significant results at the 90 or 95 percent confidence level. Both significant results indicate a decrease in TOT crashes when centerline rumble strips are installed along tangents.
- Of the four analyses based on FI crashes for tangent sites (Table 73), three yield statistically significant results at the 90 or 95 percent confidence level. All three significant results indicate a decrease in FI crashes when centerline rumble strips are installed along tangents.
- Of the four analyses based on TOT target crashes for tangent sites (Table 74), all four yield statistically significant results at the 90 or 95 percent confidence level. All four significant results indicate a decrease in TOT target crashes when centerline rumble strips are installed along tangents.

Table 68. Safety effectiveness of centerline rumble strips on rural two-lane roads—comparison and amalgamation with results from the IIHS EB study.

Crash type	Study	Number of sites	Total length (mi)	Mile years (and crashes) Before	Mile years (and crashes) After	Percent change in crash frequency from before to after rumble strip installation (%) Estimate[a]	SE[b]	Test statistic[c]	Significance
TOTAL	Combined	1060	626.86	3239.8 (5875)	1952.1 (3393)	–8.7	2.0	4.3	Significant at 95% CL
	17–32	962	416.06	2117.2 (3365)	1380.1 (1912)	–4.1	2.6	1.6	Not significant at 90% CL
	IIHS	98	210.8	1122.6 (2510)	572.3 (1481)	–14.1	3.0	4.7	Significant at 95% CL
FI	Combined	1060	626.86	3239.8 (2615)	1952.1 (1456)	–11.7	2.8	4.2	Significant at 95% CL
	17–32	962	416.06	2117.2 (1733)	1380.1 (920)	–9.4	3.5	2.7	Significant at 95% CL
	IIHS	98	210.8	1122.6 (882)	572.3 (536)	–15.5	4.5	3.4	Significant at 95% CL
TOTAL TARGET	Combined	1060	626.86	3239.8 (733)	1952.1 (301)	–30.2	4.5	6.7	Significant at 95% CL
	17–32	962	416.06	2117.2 (403)	1380.1 (154)	–37.0	5.3	7.0	Significant at 95% CL
	IIHS	98	210.8	1122.6 (330)	572.3 (147)	–21.4	7.8	2.7	Significant at 95% CL

[a] A negative percent change indicates a decrease in crash frequency while a positive percent change indicates an increase in crash frequency.
[b] SE: standard error of estimate.
[c] Test statistic = abs(Estimate/SE); not significant at 90% CL if < 1.7; significant at 90% CL if ≥ 1.7; significant at 95% CL if ≥ 2.

Table 69. Safety effectiveness of centerline rumble strips on TOT crashes at horizontal curve sites using the EB method.

Roadway type	State	Number of sites	Total length (mi)	Percent change in crash frequency from before to after rumble strip installation (%) Estimate[a]	SE[b]	Test statistic[c]	Significance
Rural two–lane roads	Combined	331	68.15	+3.5	6.5	0.54	Not significant at 90% CL
	MN	135	28.41	–17.1	9.6	1.78	Significant at 90% CL
	PA	144	29.32	+16.0	9.2	1.74	Significant at 90% CL
	WA	62	10.42	+2.7	16.0	0.17	Not significant at 90% CL

[a] A negative percent change indicates a decrease in crash frequency while a positive percent change indicates an increase in crash frequency.
[b] SE: standard error of estimate.
[c] Test statistic = abs(Estimate/SE); not significant at 90% CL if < 1.7; significant at 90% CL if ≥ 1.7; significant at 95% CL if ≥ 2.

Table 70. Safety effectiveness of centerline rumble strips on FI crashes at horizontal curve sites using the EB method.

Roadway type	State	Number of sites	Total length (mi)	Percent change in crash frequency from before to after rumble strip installation (%)		Test statistic[c]	Significance
				Estimate[a]	SE[b]		
Rural two–lane roads	Combined	331	68.15	–6.4	8.1	0.79	Not significant at 90%
	MN	135	28.41	–36.7	11.6	3.16	Significant at 95% CL
	PA	144	29.32	+9.8	11.4	0.86	Not significant at 90%
	WA	62	10.42	–20.7	12.9	1.60	Not significant at 90%

[a] A negative percent change indicates a decrease in crash frequency while a positive percent change indicates an increase in crash frequency.
[b] SE: standard error of estimate.
[c] Test statistic = abs(Estimate/SE); not significant at 90% CL if < 1.7; significant at 90% CL if ≥ 1.7; significant at 95% CL if ≥ 2.

Table 71. Safety effectiveness of centerline rumble strips on TOT target crashes at horizontal curve sites using the EB method.

Roadway type	State	Number of sites	Total length (mi)	Percent change in crash frequency from before to after rumble strip installation (%)		Test statistic[c]	Significance
				Estimate[a]	SE[b]		
Rural two–lane roads	Combined	331	68.15	–47.1	9.9	4.76	Significant at 95% CL
	MN	135	28.41	–52.1	13.6	3.83	Significant at 95% CL
	PA	144	29.32	–46.9	13.9	3.37	Significant at 95% CL
	WA	62	10.42	+45.5	102.9	0.44	Not significant at 90% CL

[a] A negative percent change indicates a decrease in crash frequency while a positive percent change indicates an increase in crash frequency.
[b] SE: standard error of estimate.
[c] Test statistic = abs(Estimate/SE); not significant at 90% CL if < 1.7; significant at 90% CL if ≥ 1.7; significant at 95% CL if ≥ 2.

Table 72. Safety effectiveness of centerline rumble strips on TOT crashes at tangent sites using the EB method.

Roadway type	State	Number of sites	Total length (mi)	Percent change in crash frequency from before to after rumble strip installation (%)		Test statistic[c]	Significance
				Estimate[a]	SE[b]		
Rural two–lane roads	Combined	312	215.24	–8.0	4.3	1.86	Significant at 90% CL
	MN	166	153.44	–9.7	5.5	1.76	Significant at 90% CL
	PA	73	23.25	–9.9	8.4	1.18	Not significant at 90% CL
	WA	73	38.55	2.0	9.3	0.22	Not significant at 90% CL

[a] A negative percent change indicates a decrease in crash frequency while a positive percent change indicates an increase in crash frequency.
[b] SE: standard error of estimate.
[c] Test statistic = abs(Estimate/SE); not significant at 90% CL if < 1.7; significant at 90% CL if ≥ 1.7; significant at 95% CL if ≥ 2.

Table 73. Safety effectiveness of centerline rumble strips on FI crashes at tangent sites using the EB method.

Roadway type	State	Number of sites	Total length (mi)	Percent change in crash frequency from before to after rumble strip installation (%)		Test statistic[c]	Significance
				Estimate[a]	SE[b]		
Rural two–lane roads	Combined	312	215.24	–14.9	5.9	2.53	Significant at 95% CL
	MN	166	153.44	–17.8	7.8	2.28	Significant at 95% CL
	PA	73	23.25	–21.8	10.0	2.18	Significant at 95% CL
	WA	73	38.55	+10.2	17.3	0.59	Not significant at 90% CL

[a] A negative percent change indicates a decrease in crash frequency while a positive percent change indicates an increase in crash frequency.
[b] SE: standard error of estimate.
[c] Test statistic = abs(Estimate/SE); not significant at 90% CL if < 1.7; significant at 90% CL if ≥ 1.7; significant at 95% CL if ≥ 2.

Table 74. Safety effectiveness of centerline rumble strips on TOT target crashes at tangent sites using the EB method.

Roadway type	State	Number of sites	Total length (mi)	Percent change in crash frequency from before to after rumble strip installation (%)		Test statistic[c]	Significance
				Estimate[a]	SE[b]		
Rural two–lane roads	Combined	312	215.24	–49.3	6.9	7.14	Significant at 95% CL
	MN	166	153.44	–48.8	7.9	6.18	Significant at 95% CL
	PA	73	23.25	–43.3	18.4	2.35	Significant at 95% CL
	WA	73	38.55	– 67.3	19.0	3.54	Significant at 95% CL

[a] A negative percent change indicates a decrease in crash frequency while a positive percent change indicates an increase in crash frequency.
[b] SE: standard error of estimate.
[c] Test statistic = abs(Estimate/SE); not significant at 90% CL if < 1.7; significant at 90% CL if ≥ 1.7; significant at 95% CL if ≥ 2.

Estimating the Safety Effectiveness of Dual Applications of Rumble Strips

Based upon the crash statistics in Table 63, no observable trends are apparent concerning the safety effectiveness of dual applications of both centerline and shoulder rumble strips along the same roadway. In some cases, the crash frequencies are greater in the after period compared to the before period, and in other cases the reverse is true. This observation is very likely due to limited sample sizes of the data.

Summary of Key Findings

The primary objectives of the safety evaluation of centerline rumble strips are as follows:

- Quantify the safety effectiveness of centerline rumble strips on specific types of roads including urban multilane undivided highways (nonfreeways), urban two-lane roads, rural multilane undivided highways (nonfreeways), and rural two-lane roads.
- Quantify the safety effectiveness of centerline rumble strips along varying roadway geometry (i.e., tangent vs. horizontal curve).
- Quantify the safety effectiveness of dual applications of rumble strips (i.e., centerline and shoulder rumble strips installed on the same road section).

Based upon the analysis results, the key findings from the safety evaluation of centerline rumble strips are as follows:

- The most reliable and comprehensive estimates of the safety effectiveness of centerline rumble strips on urban and rural two-lane roads with their associated standard errors are:

  Urban Two-Lane Roads
  - Centerline rumble strips (based on results from this research):
    - 40 percent reduction in TOT target crashes (SE = 17) and
    - 64 percent reduction in FI target crashes (SE = 27).

  Rural Two-Lane Roads
  - Centerline rumble strips [based on combined results from this research and Persaud et al. (*4*)]:
    - 9 percent reduction in TOT crashes (SE = 2),
    - 12 percent reduction in FI crashes (SE = 3),
    - 30 percent reduction in TOT target crashes (SE = 5), and
    - 44 percent reduction in FI target crashes (SE = 6) (based on results from this research).
- Limited mileage of centerline rumble strips along urban multilane undivided highways (nonfreeways) and rural multilane undivided highways (nonfreeways) prohibited formal evaluation of the safety effectiveness of this treatment along these respective roadway types.
- The safety benefits of centerline rumble strips on horizontal curves and tangents, based on TOT target crashes, are remarkably similar with estimated 47 percent and 49 percent reductions in TOT target crashes, respectively. This result would indicate that the safety effectiveness of centerline rumble strips is for practical purposes the same for both curved and tangent alignments.
- Limited mileage of dual applications of rumble strips (i.e., centerline and shoulder rumble strips installed on the same road section) along rural two-lane roads prohibited formal evaluation of the safety effectiveness of this treatment along this respective roadway type.

SECTION 8

Stimuli Levels for Effective Rumble Strips

The minimum level of stimuli generated by a shoulder or centerline rumble strip able to alert an inattentive, distracted, drowsy, or fatigued driver is a key human factor issue for which there is little understanding. Without knowing this, it is difficult to recommend minimum or optimum dimensions for rumble strips. Based on the safety evaluations conducted as part of this research and from previous safety research, we know many rumble strip patterns generate sufficient stimuli levels to alert inattentive, distracted, drowsy, or fatigued drivers, but it is not known to what extent the dimensions of these rumble strips could be modified while still maintaining their effectiveness. The complexity of this issue rests at several levels.

Current practice suggests rumble strips that generate at least 3 to 6 dBA above the ambient sound level are sufficient to stimulate an inattentive or drowsy driver. This is based on research that investigated just noticeable differences (jnd) in sound levels. In other words, an attentive person can distinguish the difference between 2 sound levels when the difference is at least 3 to 6 dBA. Research by Watts (*76*) also suggests a recommended duration for the sound level, but the focus of current practice is based on changes in magnitude, and not necessarily duration or frequency.

Another level to this issue relates to the fact that rumble strips generate both vibration and sound. There is conflicting evidence that suggests the sound component may be more vital to alerting drivers than the vibration component. Bucko and Khorashadi (*14*) suggest that vibrations felt through the steering wheel are negligible in their alerting properties compared with the noise level produced in the passenger compartment. On the other hand, Anund et al. (*77*) suggest that both sound and vibration contributed to drivers' impressions of the rumble strips. Even though there is not necessarily agreement, current state of the practice focuses on sound levels generated by rumble strips because, even though the rationale for the recommended thresholds are difficult to determine, minimum sound level thresholds are provided in the literature (e.g., 3 to 6 dBA). However, similar minimum thresholds for vibration levels necessary to alert inattentive drivers do not currently exist in the literature and have not been applied in practice. In reality, it is probably a combination of both sound and vibration stimuli that provide the alerting properties of rumble strips. The weight of the contribution of either component (i.e., sound and vibration) to the alerting properties of rumble strips is unknown. To add to the complexity of the issue, the alerting properties of the sound component are likely a function of magnitude, frequency, and duration, whereas with the vibration component, the alerting properties are a function of the magnitude, frequency, direction, location, and duration. In previous research where vibration data have been collected, the focus has been on vibration magnitude and to a lesser degree on frequency and location.

Location of vibration measurements is an important issue. Vibration levels of motor vehicles have been measured at numerous locations (e.g., steering wheel, right-front wheel, vehicle frame, and base of seat). Drivers experience the vibration component generated from the rumble strip at their feet, seat-surface, back, and hands. Previous motor vehicle research has focused primarily on one or two of these components. With the exception of research conducted by Torbic (*54*) on whole-body vibration experienced by bicyclists, no efforts have been made to combine the vibration or sound components experienced by drivers of motor vehicles into a single-weighted value to rate the alerting properties of rumble strip dimensions. All of the vibration magnitudes reported in the literature are not directly comparable because of the different locations and directions of where the vibration levels were measured.

Finally, research conducted by O'Hanlon and Kelley (*50*) suggests that the persistence of arousal following impacts with shoulder treatments was very brief. This indicates that it is not merely sufficient to establish minimum stimulation thresholds that simply arouse drivers for a short period of time, but rather it is desirable to alert a driver such that the driver's arousal level is maintained for some extended period of time.

As part of this research, the research team reviewed several studies that discussed the issue associated with minimum stimuli levels necessary to alert inattentive, distracted, drowsy, or fatigued drivers. The literature review did not provide definitive answers to this issue; however, the research team was not fully convinced that this topic has not been researched in other disciplines such as ITS crash avoidance, drowsy driver, and/or sleep deprivation research. There is a wealth of literature in these various disciplines, and so additional time and effort in this research was spent on reviewing the documented research related to ITS crash avoidance, drowsy driver, and sleep deprivation to determine if a definitive answer on the minimum level of stimuli necessary to alert an inattentive, distracted, drowsy or fatigued driver has been provided elsewhere. The research team contacted agencies such as the FMCSA, the FHWA, and the National Sleep Foundation (NSF) to inquire about related research. The remainder of this section presents the results of this effort.

Overview

The purpose of shoulder and centerline rumble strips is to inform drivers as they inadvertently leave the travel lane that they are in danger of running off the road or colliding with oncoming vehicles. The information provided to drivers as they encounter a rumble strip comes in the form of vibration. That vibration can be functionally separated into two physical sensations: auditory vibration (hereafter called *noise*) heard as an increase in sound magnitude (i.e., volume) and a change in frequency (i.e., pitch); and haptic or tactile vibration (hereafter called simply *vibration*) felt through the driver's seat, foot pedals, floor, and steering wheel. The two types of vibration occur simultaneously and act in concert to attract driver attention.

Research on in-vehicle lane departure warning devices, or so-called "electronic rumble strips," has shown that drivers perform differently when exposed to rumble strip noise alone, vibration alone, and a combination of noise and vibration (*78*). However, as the noise and vibration produced by rumble strips that are part of the fixed roadway infrastructure will always operate jointly to alert drivers that they have left the travel lane, it is not ecologically valid to separately optimize the two vibration types. In other words, it does not make sense to determine the minimum noise level and the minimum vibration level necessary to alert a driver, as the two vibration types will never occur in isolation, and their impact on driver perception is not independent. The goal is to find the combination of vibration intensity level and noise magnitude and frequency that together will accomplish the following:

- Optimize the probability that the driver will notice the rumble strip without causing a startle response;
- Not result in damage to vehicles or infrastructure;
- Not annoy residents in neighboring communities; and
- Not cause problems for other highway uses (i.e., primarily bicyclists and/or motorcyclists).

It must be understood that a driver's detection of a rumble strip's presence depends not on the absolute characteristics of the stimuli, but rather on the driver noticing a change in ambient sensation. To attract driver attention, the alerting stimuli must break through the ambient "noise" that the driver is experiencing (auditory and tactile). This ambient noise level will vary due to environmental characteristics, user characteristics, and mental states.

The goal is really, therefore, to determine the combined stimulus characteristics of a rumble strip that, as Gustav Fechner (*125*) said over a century ago, "Lift the sensation or sensory difference over the threshold of consciousness." Crossing the threshold of consciousness experienced by drivers as they encounter a rumble strip is a function of numerous variables, including the following:

- Environmental variables:
  - Vehicle suspension, weight, and speed;
  - Pavement type;
  - Pavement profile characteristics (e.g., International Roughness Index [IRI]); and
  - Rumble strip dimensions (i.e., length, width, depth, and spacing).
- User variables:
  - Adaptation,
  - Attention,
  - Hearing, and
  - Physical condition.

Psychophysics

Psychophysics is a subdiscipline of psychology dealing with the relationship between physical stimuli and their perception. Ernst Weber along with his student, Gustav Fechner, founded psychophysics while at the University of Leipzig in the mid-1800s. This field of study is concerned with determining through experimentation how perception changes as a function of changes in physical intensity. For example, if something weighs (physical measurement) twice as much as another thing, is it perceived to be twice as heavy? For every physical stimulus there is a physical measure of intensity associated with a psychological perception for each sense modality (light intensity yields brightness; weight yields heaviness, etc.). Early work in this field resulted in the development of Weber's law or the Weber-Fechner Law expressed as a very simple equation that can be used to determine the difference threshold (or difference limen—from which the term "subliminal" or below threshold is derived) between two stimuli. This is what Fechner called the just noticeable difference (jnd). In Weber's Law, the ability to notice a change in stimulus intensity is a function of the intensity level of the original stimulus: $\frac{\Delta I}{I} = k$ where "I" is the initial stimulus intensity, "ΔI" is the change in intensity or "difference threshold," and "k" is the Weber fraction or Weber constant.

This could be applied to the stimulus intensity of sound (expressed in watts/m^2), but since sound as it is perceived is already commonly converted to a base 10 log scale reflecting human hearing (i.e., dBA), this is not necessary. "In fact, the use of the factor of 10 in the definition of the decibel is to create a unit which is about the least detectable change in sound intensity" (*79*). The change in loudness required to bring about a jnd holds nearly constant at about 1.0 dBA for moderate level stimuli, regardless of frequency (*79*). Sanfilipo (*80*) found empirical support for this in his review of human amplitude sensitivity. He wrote, "the minimum discernable changes by the human ear/brain mechanism I've seen in the research . . . ranged from about 0.5 dBA to 3 dBA, depending on a number of factors." He concluded with, "I tend to use .75 dBA to 1 dBA when considering minimums."

For louder sounds above about 40 dBAs, however, research shows that the jnd can in fact drop to about ⅓ or ½ dBA (*79*) with sounds similar to those produced by rumble strips [75 or higher dBA, low-frequency sound (between 50 and 160 Hz) according to Higgins and Barbel (*81*)] having a jnd of about 0.5 to 0.6 dBA. This holds true if the ambient sound from the roadway is close in frequency to the sound of the vehicle driving over the rumble strip [a critical band of about 90 Hz for sounds below 200 Hz (*82*)]. Field measurement research discussed later indicates that this is indeed the case.

FMCSA, FHWA, and NSF Interviews

Representatives of the FMCSA and the FHWA were interviewed to determine the state of knowledge related to appropriate noise and vibration levels for rumble strips and to identify any current research projects that might be attempting to determine what those levels are. The FMCSA reported that no ongoing research on infrastructure, including rumble strips, was being conducted. None of the three FHWA contacts interviewed knew of anything ongoing at FHWA related to vibration and noise levels needed to alert drivers. Contacts at the NSF did not reveal any new information to further understand the vibration and noise levels necessary to alert drivers.

Field Data

The following sections discuss field research that directly evaluated noise levels necessary to alert drivers and the characteristics of rumble strips that could produce these levels.

Required Sound Levels

Although he did not reference the source of the information, Outcalt (*44*) provided a table showing how a typical person perceives different amounts of change in sound level (Table 75). He stated that a change of 1 dBA would be imperceptible; a change of 3 dBA would be barely noticeable; a change of 6 dBA would be clearly noticeable; a 10 dBA change would be twice as loud; and a 20 dBA change would be perceived as four times as loud. Myer and Walton (*83*) wrote that while humans are capable of detecting changes in sound as low as 1 dBA under "ideal conditions," for evaluating rumble strips, 3 dBA "is a more appropriate threshold for considering a difference to be practically significant." Walton and Myer cite the "O'Hare Noise Compatibility Commission" as the source of the 3 dBA threshold. Spring (*84*) reported that a 4 dBA increase above ambient "is adequate to be recognized as a warning device." Masayuki et al. (*85*) cited Chen (*48*) in stating, "warning drivers requires a sound [change] of more than 4 dBA." Elefteriadou et al. (*45*) qualified these statements by concluding that "rumble strips which produce 4 dBA increases or above will be readily detected by motorists who are awake if the noise level is sustained for 0.35 seconds or longer."

In 2005, Mark Rosenker, Acting Chairman of the NTSB, testified before the U.S. House of Representatives about railroad warnings, stating "if a sound is to be identified, the warning signal must be 3 to 8 decibels (dBA) above the threshold of detection; if a sound is to reach the alerting level, the warning signal must be approximately 10 decibels above the ambient noise." Similarly, Gardner et al. (*43*) also noted that through research on auditory perceptual factors influencing the ability of train horns, Lipscomb (*86*) indicated that to

Table 75. Approximate human perception of changes in sound level (Outcalt, 2001).

Change in sound level (dBA)	Change in apparent loudness
1 dBA	Imperceptible
3 dBA	Barely noticeable
6 dBA	Clearly noticeable
10 dBA	About twice – or half as loud
20 dBA	About four times – or one-fourth as loud

become aware of a sound and be alerted to the presence of that sound, the sound must typically rise 9 to 10 dBA above the sound of the environment. Green et al. (*87*), in a review of human factors literature associated with driver information systems, raised the amplitude above even that recommended by Rosenker by recommending a 15 dBA increase from ambient for "non-speech" warning sounds as a guideline, while cautioning against absolute levels above 115 dBA to avoid approaching the pain threshold. This guideline is based on a compromise from five noise studies cited in the literature (*88–92*). Green et al. (*87*) also cited research by Berson (*88*) that reported sound changes above 15 dBA produce a startle reaction.

In a 2002 study for Pennsylvania to evaluate the effect of shoulder rumble strips on bicycle comfort and safety, Zineddin et al. (*93*) examined the effect of rumble strip patterns that varied in sound level from 78 to 89 dBA at 55 mph (88 km/h). This represented increases from ambient road noise in the passenger compartment ranging from 13 to about 24 dBA. These researchers concluded that, "While the literature review uncovered research to help select rumble strip configurations capable of producing sufficient change in noise level to caution alert drivers [e.g., see Watts (*76*)], no data were found to indicate the noise level needed to arouse a fatigued, inattentive, or otherwise impaired motor vehicle operator." They recommended conducting rumble strip research using a driving simulator to test rumble strip noise and vibration "with sleep-deprived, distracted, or alcohol-impaired participants."

Rumble Strip Research

Milled Versus Rolled Rumble Strips

In a review of the literature, Spring (*84*) wrote that Perillo (*23*) reported a measurement of in-cab truck noise of 86 dBA for rolled rumble strips and 89 dBA for milled rumble strips at 40 mph (65 km/h). Spring stated that the 4 dBA increase was "a perceptible difference." Spring (*84*) also reported that under different conditions milled shoulder rumble strips can result in 12.5 times higher vibration stimuli and 3.35 times higher auditory stimuli than rolled rumble strips. In a report on rumble strip practice and needs, Turochy (*58*) reported that milled rumble strips produce 3 dBA higher sound levels than rolled rumble strips. He also reported that milled rumble strips have become the preferred standard in Pennsylvania as this type of rumble strip gives contractors greater flexibility. In a review of shoulder rumble strip design for Michigan, Morena (*21*) stated that while both milled and rolled designs "can provide some outside noise to alert a drifting driver, the milled design produces a louder noise and adds to that a vehicle vibration that most certainly increases the potential for alerting the drowsy or distracted driver."

Rumble Strip Characteristics

In a recent synthesis of centerline rumble strips, Russell and Rys (*36*) reported in-vehicle noise levels for seven test vehicles and 12 rumble strip designs at 60 mph (97 km/h). They stated that continuous 12 in. (305 mm) spacing patterns produced the highest average sound levels (80 to 94 dBA) followed by the alternating 12- and 24-in. (305- and 610-mm) spacing patterns, and that longer rumble strip patterns produced more noise. These researchers also reported on a Kansas study that surveyed driver perception of 12 and 24 in. (305 and 610 mm) spacing continuous and alternating rumble strip patterns and found that 36 percent of drivers stated that either pattern would be loud enough to get their attention. When asked about vibration, only 10 percent of their subjects thought the alternating pattern produced adequate vibration; while 36 percent thought the continuous pattern had better vibration; 34 percent thought both patterns gave adequate vibration. Spring (*84*) recommended that Missouri adopt a 5-in. (127-mm)-wide rumble strip with 12 in. (305 mm) spacing, citing the Pennsylvania bicycle-tolerable rumble strip study, which suggested that this pattern was found to be preferred by bicyclists while also providing "more than adequate noise and vibration levels for motor vehicles." Russell and Rys (*36*) reported that in part, depending on vehicle type, "continuous 12 in. (305 mm) on center spaced rumble strips" resulted in the greatest noise (from 80 and 94 dBA at 60 mph [97 km/h]).

Russell and Rys (*36*) reported that a minimum of 0.315 in. (8 mm) rumble strip depth is necessary to create a "noticeable effect on tractor-trailers" and that 0.25 in. (6 mm) resulted in no noticeable change in noise or vibration. Other recent studies have demonstrated that 0.375 in. (10 mm) depth rumble strips produce sufficient noise to alert motorists. Masayuki et al. (*85*) concluded that the deeper the groove, the greater the noise inside the test vehicle, and the slim centerline rumble strips (0.625 in. [15 mm]) generated much more sound than did the conventional centerline rumble strips. In a recent study of the safety benefits of centerline rumble strips in Japan, Hirasawa et al. (*42*) found that a length of 14 in. (356 mm), width of 6 in. (150 mm), and depth of 0.5 in. (13 mm) was optimal (producing in-vehicle sound level of 80 dBA) and that the deeper the groove, the louder the sound. This rumble strip pattern produced sounds that were at least 15 dBA louder than the ambient pavement sound. Citing Chen's (*48*) report that a minimum of 4 dBA is required to alert a driver, they concluded that their rumble strip pattern was "sufficient for warning."

Variation in In-Vehicle Sound Levels

In an evaluation of the effect of rumble strip noise on local communities, Bajdek et al. (*94*) measured the sound level produced by various vehicles driven over an assortment of rumble strip patterns. These researchers found increases of about 10 dBA to occur when drivers ran over the rumble strip and that the sound frequency was broadband, ranging from 125 to 1000 Hz, while frequencies on "standard pavement" typically range from 125 to 800 Hz. They found that speed, mass, and tire size all influence rumble strip sound amplitude and frequency. In a literature review Green et al. (*87*) found that [based on research by Potter et al., (*95*)]:

> "Interior noise [is] influenced by the state of the windows (a change of around 2 dBA at 30 mph, 5 dBA at 50 mph), use of snow or studded tires (increase of up to 8 dBA), road surface roughness (up to approximately 10 dBA), wet roads (up to 3 dBA increase), and use of the radio [which] can increase the ambient noise level on the order of 20 dBA. Aerodynamic and road/tire noise increases at a rate of about 12 dBA per doubling of vehicle speed. Engine/drivetrain noise increases at a rate of approximately 6 dBA per doubling of speed . . . Whatever the current validity of these results, interior noise levels are highly design-specific, and the acoustic environment should be determined on a case-by-case basis."

Green et al. concluded that "ambient sound levels should be tracked, and that the intensity of the auditory message should be adjusted accordingly, to be a specified amount above . . . threshold."

Summary of Key Findings

After reviewing the literature and conducting interviews with several agencies, no conclusive evidence was found concerning the minimum stimuli levels needed to be generated by shoulder or centerline rumble strips to be effective in alerting inattentive, distracted, drowsy, or fatigued drivers. Several key findings related to this issue are as follows:

- Several sources, not necessarily related to rumble strip research, indicate that humans can perceive a change in sound level intensity when the difference is as low as 1 dBA, or even lower. None of these sources suggest that a change of 1 dBA should be the minimum threshold level for the alerting properties of shoulder or centerline rumble strips.
- Several sources suggest that if a sound is to reach the alerting level, then the noise should increase approximately 3 dBA, 4 dBA, 6 dBA, or 10 dBA above the ambient noise. Another source recommends a 15 dBA increase above the ambient is necessary for non-speech warning sounds.
- At least one source reports that sound changes above 15 dBA could produce a startle reaction. Thus, although the primary objective of the literature review was to identify a minimum level of stimuli necessary to alert an inattentive, distracted, drowsy, or fatigued driver, the literature review revealed an upper threshold for design purposes.
- The state of the practice is still focusing on designing rumble strips based on the noise levels generated by the rumble strips. This is consistent with the noise study conducted as part of this research. No efforts have been made to estimate the weight of a driver's response to combinations of noise levels heard by the driver and vibration levels felt by the driver through contact points either at the seat, feet, or hands.

SECTION 9

Optimum Dimensions for Rumble Strips

The dimensions of rumble strips used in practice vary from state to state. No typical standard design for either shoulder or centerline rumble strips is used in every state. This is logical because shoulder and centerline rumble strips are being installed along numerous roadway types with a range of operating conditions (i.e., vehicular speeds), cross-sectional characteristics (e.g., lane widths, shoulder widths, clear zone widths), and potential users (e.g., motor vehicles and bicyclists). It seems reasonable to believe that the optimum dimensions for a given roadway should vary based upon these three elements (i.e., operating conditions, cross-sectional characteristics, and potential users).

For shoulder rumble strips the dimension that varies the most among states is the length. Table 6 shows a range in this dimension from 6 to 36 in. (152 to 914 mm). For milled rumble strips groove lengths are commonly between 12 and 16 in. (305 and 406 mm), and for rolled rumble strips groove lengths of 24 to 36 in. (610 to 914 mm) are common. Recently, at least one transportation agency (i.e., Arizona DOT) has adopted a policy that allows groove lengths as short as 6 in. (152 mm) for milled rumble strips. The desire to install milled rumble strips with groove lengths less than the typical 12 to 16 in. (305 to 406 mm) is:

1. To keep this dimension as narrow as possible to provide additional lateral clearance for bicyclists,
2. Due to pavement performance issues when rumble strips are installed on roadways with narrower shoulders, or
3. Simply to install rumble strips on roadways with narrow or nonexistent shoulders where rumble strips might not otherwise be installed.

The primary concern about narrowing the groove length is whether the rumble strip will still provide sufficient noise and/or vibration levels to arouse an inattentive, distracted, drowsy, or fatigued driver. Research conducted in Kansas (*36*) is the only research that has investigated this issue to any degree. Results of the research indicate that longer rumble strip lengths generally produce higher noise levels in the passenger compartment; it was suggested that one reason for this finding could be that with the shorter patterns there was a lower probability of the vehicle's tires making full contact with the pattern. The Kansas research, and most previous rumble strip research where noise data were collected in the field, collected noise levels while driving the motor vehicles over extended portions of the rumble strip patterns (i.e., parallel to the rumble strips). However, when errant vehicles encounter rumble strips, the vehicle tires cross the rumble strips at an angle so the interaction between the rumble strip pattern and the tires is different than what has typically been evaluated. This difference in the way vehicles encounter rumble strips during actual roadway departures (i.e., at angles) and the way rumble strip noise levels are typically collected in the field (i.e., parallel to the rumble strips) may or may not change the magnitude of the sound level generated in the passenger compartment for a given rumble strip. The probability that there could be a difference in the magnitude of the sound levels between the two types of encounters likely increases when the groove length is shortened because there is less opportunity for the tire to completely drop into the groove.

To determine optimum dimensions for both shoulder and centerline rumble strips for a range of operating conditions, a field experiment was conducted where noise data were collected and statistical models developed to predict noise responses within the passenger compartment of a passenger car while it traversed various rumble strip patterns. The remainder of this section is organized as follows: Field Data Acquisition Methodology, Field Data Collection, Analysis Methodology, and Analysis Results. Next, Application of the Noise Models provides examples of how agencies can apply several predictive models for developing recommended dimensions for use within their rumble strip policies. This section concludes with a Summary of Key Findings from the study.

Data Acquisition Methodology

This field experiment involved driving a mid-size passenger car over a variety of rumble strip patterns at various speeds and departure angles. Data were collected in six states using a Chevrolet Impala. The decision was made to include only passenger cars in this experiment primarily because the crash data suggest that passenger cars (and light trucks) are involved in the majority of crashes that could be remedied by shoulder and centerline rumble strips. Heavy vehicles are involved in a relatively significant portion of head-on crashes, but it is not known what portion of these crashes actually involved the heavy vehicle crossing the centerline into oncoming traffic. In summary, the field experiment was designed with the intention of developing rumble strip patterns that generate sufficient stimuli to alert drivers in passenger cars.

To collect the noise data, a portable data acquisition system was developed using a laptop personal computer (PC), a global positioning system (GPS) module, a hand held sound level meter (SLM), and a USB analog-to-digital (A-D) converter module, as illustrated in Figure 13. Interface software for the GPS and A-D modules was written in MATLAB. The laptop PC was also used for manual record keeping by the observer.

The SLM was mounted on the centerline of the vehicle facing forward at approximately the same height and same fore-aft location as the driver's ear. The GPS module was mounted on the roof of the vehicle with a magnetic base. The USB A-D module was mounted into a plastic junction box. The junction box was carried on the floor of the vehicle, and the PC was carried on the lap of the observer. Figure 14 shows a photograph of the data acquisition system.

Ten seconds of raw data were collected for each test. Raw data information is provided in Table 76. Data acquisition was initiated manually by the observer before the driver initiated the steering maneuver. Analog voltages from the SLM for sound level (A weighting) and direct microphone output were measured at 5 KHz by the USB A-D module. Global position, vehicle speed, and vehicle heading were transferred in standard NMEA 0183 text at 5 Hz using a 19,200 baud RS-232 serial interface and held in the serial buffer for interrogation after the test. Raw data for each test were immediately recorded into a standard MATLAB data file.

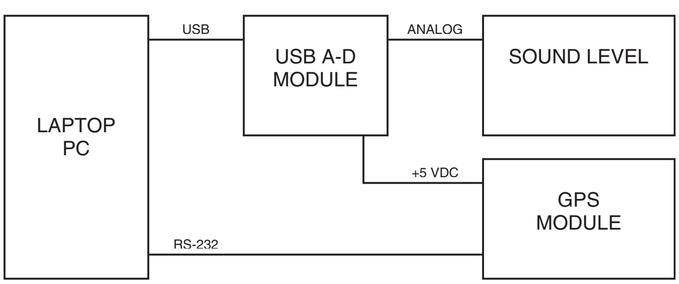


Figure 13. Block diagram of data acquisition system.

Figure 14. Photograph of data acquisition system.

Raw data were post-processed to record results for each test into a tab-delimited ASCII file as shown in Table 77. Vehicle heading at the start of the test was subtracted from all vehicle heading measurements to provide relative heading during the maneuver. Maximum relative heading was recorded as angle of departure.

Ambient sound level at the start of the test and maximum sound level while traversing the rumble strips were recorded. Ambient sound level was defined as the average over the first 0.5 seconds of the test. Duration of the sound event was measured whenever the sound level rose above the mean sound level plus 1.5 standard deviations over the entire test. A Fast Fourier Transform (FFT) of sound intensity was computed to determine the dominant frequency of the sound event. A TXT file for a single typical trial at 59 mph (95 km/h) and 4 degrees angle of departure is provided in Table 78. Sample plots of vehicle speed and relative heading are shown in Figure 15. Plots of sound level in dBA (Channel 0), raw sound intensity (Channel 1), and frequency spectrum are shown in Figure 16 for the test in Table 78 at 59 mph (95 km/h) and 4 degrees angle of departure.

Field Data Collection

The in-vehicle sound field data collection effort focused on milled rumble strips; however, a sample of rolled rumble strip patterns was also included in the experiment. All field data collection was performed using a Chevrolet Impala passenger car because it is representative of the current vehicle fleet and was readily available at all data collection locations. Data were collected in six states. Separate vehicles were used in several states. Each vehicle had low mileage with relatively new tires. Most field data collection was performed during dry, daylight

Table 76. Raw data collected by data acquisition system.

Raw data	Device	Data rate	Value
Date/time stamp	PC	once per test	date and time
Global position	GPS	5 Hz	latitude and longitude
Vehicle speed	GPS	5 Hz	miles/hour
Vehicle heading	GPS	5 Hz	degrees CW from north
Sound level (A weighting)	SLM	5 KHz	dBA (10 mV per db)
Sound intensity	SLM	5 KHz	voltage

Table 77. Sound-level data acquisition fields.

Data field	Device	Units	Note
File name	PC		
Year	PC		Recorded at start of test
Month	PC		Recorded at start of test
Day	PC		Recorded at start of test
Hour	PC		Recorded at start of test
Minute	PC		Recorded at start of test
Latitude	GPS	ddmm.mm	Recorded at start of test
Longitude	GPS	ddmm.mm	Recorded at start of test
Vehicle speed	GPS	miles/hour	Recorded at start of test
Angle of departure	GPS	degrees	Maximum difference in heading from start of test
Ambient sound level	SLM	dBA	Average over first 0.5 seconds
Maximum sound level	SLM	dBA	Maximum value during test
Duration of sound event	SLM	seconds	Time when sound level is above mean plus 1.5 standard deviations
Dominant frequency of sound event	MIC	Hz	FFT peak frequency

Table 78. Sample text file for a typical trial.

```
      File        Yr    Mo   Day    Hr   Min       Lat        Lon
pilot_east1     2006    10    12     9    18   4048.97    7754.65

   Speed    Ang_Dep     Amb_SL     Max_SL         Dur       Freq
   59.67       4.10      66.22      79.83        1.05     172.20
```

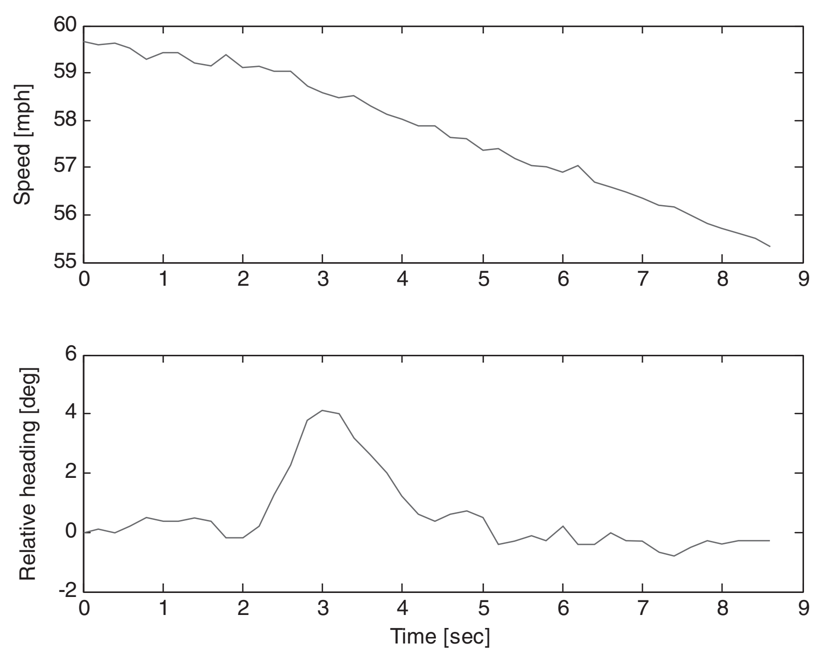


Figure 15. Typical vehicle speed and relative heading.

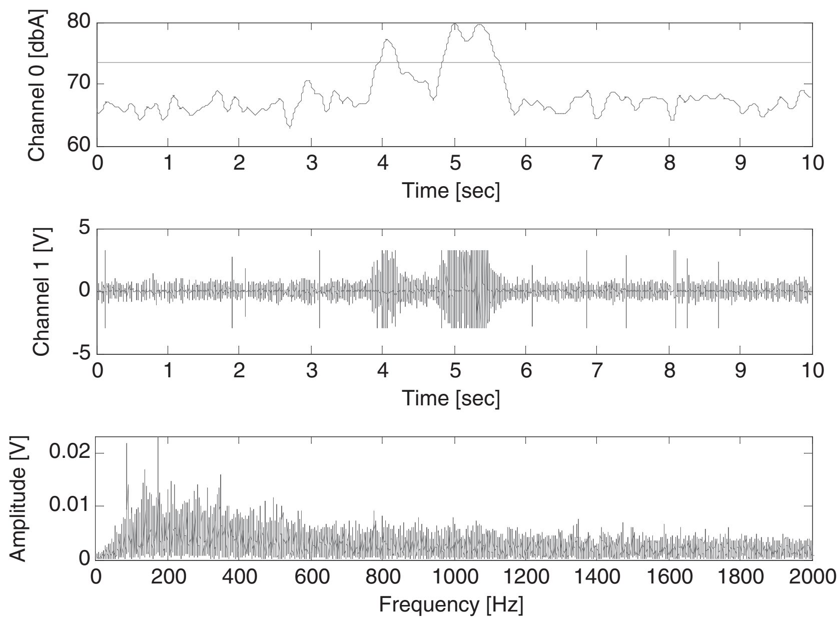


Figure 16. Typical sound level, sound intensity, and frequency spectrum.

conditions. In situations where the pavement surface was wet or where light rainfall occurred, the data collection team noted the occurrence in the data acquisition system. Two observers collected the in-vehicle noise data. One observer drove the test vehicle, while the other executed the data acquisition system described in the previous section. The following variables were collected in the field:

- Pavement surface type (asphalt or concrete);
- Travel speed;
- Roadway departure angle;
- Rumble strip dimensions (length, width, depth, and spacing); and
- Location of rumble strip pattern (shoulder or centerline).

The survey conducted in this project produced information about the dimensions of milled rumble strip patterns being used by various transportation agencies. From the survey, for milled shoulder rumble strip patterns the length dimension ranged from 6 to 18 in. (152 to 457 mm); the width dimension ranged from 5 to 8 in. (127 to 203 mm); the groove depth dimension ranged from 0.375 to 0.75 in. (10 to 19 mm); and the spacing dimension ranged from 11 to 19 in. (280 to 483 mm). For centerline rumble strip patterns the length dimension ranged from 6 to 24 in. (152 to 610 mm); the width dimension ranged from 5 to 7 in. (127 to 178 mm); the depth dimension ranged from 0.375 to 0.625 in. (10 to 16 mm); and the spacing dimension ranged from 12 to 48 in. (305 to 1,220 mm). The states included in the field data collection efforts were selected based on the desire to develop a database with a balance of rumble strip pattern locations (shoulder vs. centerline) and pattern dimensions. The states included in the sound level testing were Arizona, Colorado, Kentucky, Minnesota, Pennsylvania, and Utah. A list of data collection locations, rumble strip pattern and type, and pavement surface type are shown in Table 79.

It was anticipated that the dimensions reported in the agency survey may be different than those constructed in the field because the state standards typically include tolerances. As such, the observers sampled the dimensions in the field to verify the field dimensions matched the dimensions provided by the transportation agencies for the given locations. If the dimensions did not match those anticipated, the observers recorded the dimension in the field and updated the analysis database.

Sound level data were collected using the data acquisition system described above. To closely approximate typical driving speeds on roadways with rumble strips, the test vehicles were driven at speeds ranging from approximately 40 to 65 mph (65 to 105 km/h). Chen (*48*) collected sound level data using a 5 degree angle of departure, while Mak and Sicking (*96*) indicate that highest run-off-road encroachment angle probabilities are 7.5 and 12.5 degrees on high-speed roadways (> 45 mph [70 km/h]). The roadway departure angles collected during experimentation ranged from 1 to nearly 10 degrees. Steeper angles were not possible because either shoulder widths were not wide enough or roadside hardware were adjacent to the shoulder, thus preventing maneuvers at larger angles. In many cases, left-side encroachments over centerline rumble strips were limited to 5 degrees

Table 79. Rumble strip locations, patterns, and dimensions.

State	Route	Begin	End	Shoulder or centerline	Milled or rolled	Pavement type	Length (in.)	Width (in.)	Depth (in.)	Spacing (in.)	Number of observations
PA	220	77	83	Shoulder	Milled	Concrete	17	7.5	0.5	12	14
PA	80	165	221	Shoulder	Milled	Asphalt & Concrete	16.5–17.0	6.5–7.0	0.375	12.0–12.5	61
PA	219	41	68	Shoulder	Milled	Asphalt	16.5	6.0	0.5	11.5-12.0	41
PA	989	180	180	Centerline	Milled	Asphalt	12.0	7.0	0.5	12.0	3
PA	837	190	190	Centerline	Milled	Asphalt	12.0	7.0	0.5	12.0	3
PA	79	59	73	Shoulder	Milled	Asphalt	16.0	5.0	0.375	6.0	28
PA	51	550	550	Centerline	Milled	Asphalt	12.0	7.0	0.5	24.0	2
PA	48			Centerline	Milled	Asphalt	12.0	7.0	0.5	24.0	3
PA	288	90	90	Centerline	Milled	Asphalt	12.0	7.0	0.5	24.0	2
PA	22	11	13	Shoulder	Milled	Asphalt	16.0	5.0	0.375	6.0	7
PA	18	160	170	Centerline	Milled	Asphalt	12.0	7.0	0.5	24	6
PA	108	60	60	Centerline	Milled	Asphalt	12.0	7.0	0.5	24	3
PA	80	95	152	Shoulder	Milled	Asphalt	16.5	7.0–8.0	0.5	12	35
PA	28	6	221	Shoulder	Milled	Asphalt	16.0–16.5	5.0–7.0	0.375/0.5	6/12	43
MN	23	212	231	Centerline	Milled	Asphalt	8	8	0.5	20	18
MN	25	97	142	Centerline	Milled	Asphalt	8	8	0.5	20	30
MN	95	9	28	Centerline	Milled	Asphalt	8	8	0.5	20	20
MN	65	51	54	Shoulder	Milled	Asphalt	12	7	0.5	12	9
MN	65	55	56	Centerline	Milled	Asphalt	8	8	0.5	20	6
MN	169	216	219	Centerline	Milled	Asphalt	8	8	0.5	20	6
MN	18	16	19	Shoulder	Milled	Asphalt	12	7	0.5	12	12
CO	70	294	304	Shoulder	Milled	Concrete	24	4	0.375	4.75	35
CO	6	262	271	Centerline	Milled	Asphalt	12	5	0.375	12	5
CO	70	189	237	Shoulder	Milled	Asphalt	12	4.5	0.375	12	28
CO	70	172	179	Shoulder	Rolled	Asphalt	24	1	0.375	9	15
CO	70	163	163	Shoulder	Milled	Asphalt	12	4.5	0.375	12	3
CO	70	133	142	Shoulder	Rolled	Asphalt	24	1	0.375	9	18
CO	70	86	114	Shoulder	Milled	Asphalt	12	4.5	0.375	12	45
CO	70	79	86	Shoulder	Milled	Concrete	24	4	0.375	4.75	9
CO	70	41	78	Shoulder	Milled	Asphalt	12	4.5	0.375	12	21
UT	70	207	212	Shoulder	Milled	Asphalt	12	12	0.5	12	6
UT	70	201	203	Shoulder	Milled	Asphalt	24	8.5	0.5	9	15
UT	70	160	192	Shoulder	Milled	Asphalt	12	8	0.625	12	30
UT	6	294	298	Shoulder	Milled	Asphalt	9	5	0.5	12	9
UT	6	283	285	Shoulder	Milled	Asphalt	10	9	0.5	12	9
UT	6	274	275	Shoulder	Milled	Asphalt	8	8	0.5	12.5	8
UT	6	188	188	Shoulder	Milled	Asphalt	15	6	0.375	12	3
UT	6	179	257	Shoulder	Rolled	Asphalt	12	8	0.75	12	32
AZ	89	458	–	Shoulder	Milled	Asphalt	8	7	0.375	12	8
AZ	89	–	–	Shoulder	Milled	Asphalt	9	5.5	0.75	11	45
AZ	89	–	495	Centerline	Milled	Asphalt	6	7	0.375	12	68
AZ	–	–	–	Shoulder	Milled	Asphalt	12	7	0.375	12	5
AZ	40	318	342	Shoulder	Rolled	Asphalt	24	2	1	8	44
AZ	40	290	317	Shoulder	Milled	Asphalt	12	7	0.375	12	35
KY	31	9	24	Centerline	Milled	Asphalt	24	7	0.625	24	46
KY	9006	4	55	Centerline	Milled	Asphalt	24	7	0.5	24	102

when opposing traffic volumes were high or when sight distance was limited.

The data acquisition team manually recorded or validated the rumble strip pattern dimensions (length, width, depth, and spacing), rumble strip pattern type (milled or rolled), rumble strip location (shoulder or centerline), pavement surface type (concrete or asphalt), and pavement surface condition (dry or wet). The portable data acquisition system recorded the time (year, month, day, hour, minute), location (latitude and longitude), travel speed, angle of departure, ambient and maximum sound levels, and duration and frequency of rumble strip noise generated in the vehicle. The observers provided a unique file name for each measurement so the location (state, route number, and milepost/segment location) of the observation was recorded. There were 990 sound level measurements recorded in the field during the experiment. This included 204 measurements in Arizona, 175 measurements in Colorado, 147 measurements in Kentucky, 101 measurements in Minnesota, 251 measurements in Pennsylvania, and 112 measurements in Utah.

Analysis Approach

In previous research Khan and Bacchus (*97*) used both linear and nonlinear regression models to estimate in-vehicle noise generated when traversing various rumble strip patterns. In the present study, ordinary least squares (OLS) linear regression was used to model sound level differences. Sound level difference was defined as the difference between the maximum and ambient sound levels generated during each test. The OLS estimator assumes the following:

- The explanatory variables are nonstochastic,
- No omitted or irrelevant variables are included in the model specification,
- The disturbance has a mean value of zero and is normally distributed,
- Homoskedastic disturbances,
- No autocorrelation between disturbances,
- No perfect multicollinearity,
- Correctly specified model, and
- Zero covariance between the disturbance and explanatory variables.

Violating the assumptions of the OLS estimator can result in biased, inconsistent, or inefficient parameter estimates. As such, several diagnostic measures were applied to test the OLS assumptions. The Anderson-Darling test was used to test the normality assumption of the disturbances. This test compares the cumulative distribution of the residuals to those of a theoretically normal distribution. The null hypothesis is that the residuals follow a normal distribution. A Breusch-Pagan/Cook-Weisburg test was used to assess the residuals for heteroskedasticity. The null hypothesis (χ^2 test) is that the residuals have a constant variance. The autocorrelation assumption was tested using the Durbin-Watson statistic. The null hypothesis is that the residuals are not autocorrelated. Variance inflation factors (VIFs) were used to determine the presence of multicollinearity. VIFs are a measure of multicollinearity among the explanatory variables in a model; values exceeding 10 indicate that multicollinearity is present. Last, the Ramsey RESET test was used to assess the model for omitted variable bias. The null hypothesis (F test) is that the model has no omitted variables. When assumption violations result from the analysis, various treatments can be applied. These are discussed in the following section.

The independent variables considered in the sound level difference model are as follows:

- Vehicle speed (mph);
- Vehicle angle of departure (degrees);
- Pavement type (concrete vs. asphalt);
- Pavement condition (wet vs. dry);
- Rumble strip location (shoulder vs. centerline);
- Rumble strip type (milled vs. rolled); and
- Rumble strip length, width, depth, and spacing (in.).

The general model form used in the analyses was as follows:

$$\mathrm{SLDiff} = \beta X + \varepsilon \tag{4}$$

where
SLDiff = sound level difference (dBA),
β = regression parameter estimates for sound level difference model,
X = vector of explanatory variables for sound level difference model, and
ε = disturbance term for sound level difference model.

Using the general form shown in Equation (4), several different models were estimated. These include an aggregate model using all data collected in the experiment with the rumble strip dimensions, speed, and departure angle all in continuous form. Additionally, disaggregate models using only the milled rumble strip data were estimated.

In the analysis approach, the dependent variable used in the model specification is the sound level difference. The sound level difference was computed as the difference between the maximum sound level generated as the test vehicle traversed the rumble strip pattern minus the ambient sound generated in the passenger compartment of the test vehicle prior to encroaching the rumble strips. Separate models for the maximum and ambient sound levels were not specified because the sound level distributions obtained on the travel lane (ambient sound) and as the vehicle traversed the rumble strip pattern (maximum sound) were different. Specifically, the variability of these distributions differ; therefore, using predictions from separate ambient and maximum sound level models will either over- or underestimate the sound level difference experienced by drivers who leave the roadway and pass over a rumble strip pattern. A model of the sound level difference is based only on a single distribution.

Analysis Results

The response and explanatory variables used in the sound level difference model, and their descriptive statistics, are shown in Table 80. Nearly 44 percent of the sound level measurements were recorded on shoulder rumble strips. Approximately 8 percent of the sound level measurements were recorded on concrete pavement, while nearly 89 percent were recorded on the milled rumble strip pattern.

Modeling results are presented in Table 81. Each of these variables was statistically significant in the model at the 10 percent confidence level. A normal probability plot of

Table 80. Descriptive statistics of variables included in noise database.

Variable name	Minimum	Maximum	Mean	Standard deviation
Ambient noise level (dBA)	56.40	77.57	63.43	2.90
Maximum noise level (dBA)	67.12	90.02	79.41	4.08
Sound level difference (dBA)	2.63	26.26	15.98	4.32
Location indicator 1: shoulder rumble strips ; 0: centerline rumble strips	0	1	0.44	0.50
Pavement type indicator 1: concrete; 0: asphalt	0	1	0.08	0.27
Rumble strip type indicator 1: milled 0: rolled	0	1	0.86	0.35
Pavement condition indicator 1: wet surface 0: dry surface	0	1	0.20	0.40
Vehicle travel speed (mph)	39.5	66.6	52.2	7.5
Angle of departure (degrees)	0.6	9.6	2.8	1.9
Length of rumble strip (in.)	6	24	15.4	6.2
Width of rumble strip (in.)	1	12	6.2	1.9
Depth of rumble strip (in.)	0.375	1.0	0.5	0.2
Spacing of rumble strip (in.)	4.75	24	13.6	5.7

the residuals is shown in Figure 17. The residuals generally appear normally distributed. The Anderson-Darling test ($A^2 = 0.623$; p-value = 0.104) indicates that the null hypothesis of a normal distribution is not rejected. The Breusch-Pagan/Cook-Weisberg test for heteroskedasticity is not rejected ($\chi^2(1) = 2.63$; p-value = 0.105); therefore, the assumption of homoskedastic disturbances is met. The Durbin-Watson statistic was 1.106, which indicates positive autocorrelation. This suggests that the disturbance terms are correlated. Autocorrelation occurs for a variety of reasons, including specification bias (omitted variables or incorrect functional form), lags, or data manipulation (interpolation or extrapolation). The Ramsey RESET test was used to assess the linearity assumption of the explanatory variables in the model specification. The null hypothesis (F test) is that the model specification is linear (as opposed to nonlinear). The null hypothesis that the model is correctly specified using linear explanatory variables is not rejected (F[3, 976] = 2.43; p-value = 0.064), thus no omitted variable bias is present in the model. No data interpolation or extrapolation occurred so the likely reason for autocorrelation

Table 81. Regression model of sound level difference.

Variable	Parameter estimate	Standard error	t–statistic	P > |t|	95% confidence interval		VIF
					Lower	Upper	
Constant	8.650	1.307	6.62	0.000	6.084	11.216	N/A
Speed (mph)	0.027	0.017	1.60	0.109	–0.006	0.060	1.03
Location indicator (1: shoulder; 0: centerline)	–1.689	0.337	–5.01	0.000	–2.351	–1.028	1.79
Angle of departure (degrees)	–0.271	0.082	–3.30	0.001	–0.432	–0.110	1.53
Length (in.)	0.267	0.027	9.90	0.000	0.214	0.320	1.77
Width (in.)	0.771	0.109	7.05	0.000	0.557	0.986	2.67
Depth (in.)	4.494	0.988	4.55	0.000	2.556	6.432	1.47
Spacing (in.)	–0.394	0.035	–11.31	0.000	–0.462	–0.326	2.49
Rumble strip type indicator (1: milled; 0: rolled)	2.652	0.560	4.74	0.000	1.553	3.751	2.43
Pavement type indicator (1: concrete; 0: asphalt)	–1.391	0.534	–2.60	0.009	–2.439	–0.343	1.37
Pavement condition indicator (1: wet; 0: dry)	–2.596	0.363	–7.15	0.000	–3.309	–1.883	1.33

Number of observations: 990.
R^2: 0.179.
R_{adj}^2: 0.171.
Root MSE: 3.936.

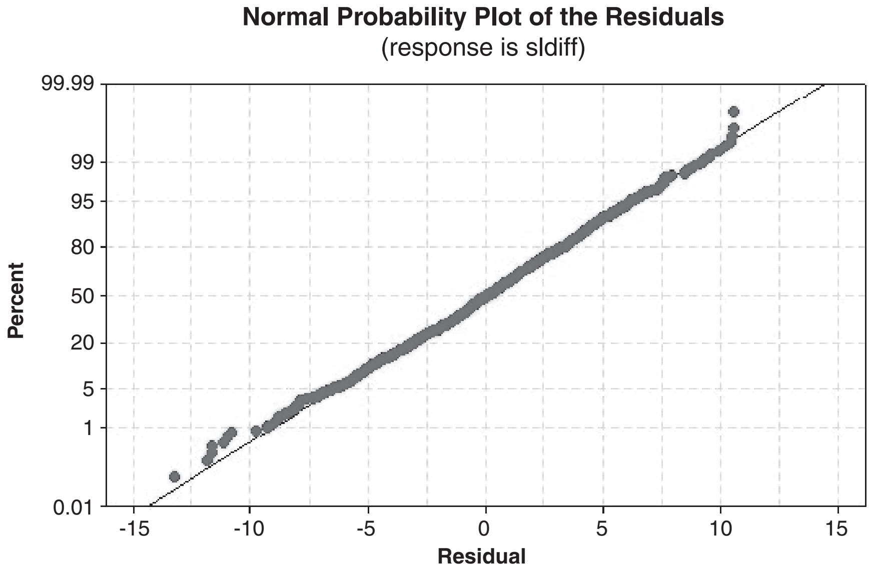


Figure 17. Normal probability plot of sound level difference residuals.

is the potential lag of the dependent variable (sound level difference). In the presence of autocorrelation, the standard errors are inefficient. To treat the problem of autocorrelation, the Newey-West method to obtain the standard errors was applied. The results of the regression estimation, corrected for autocorrelation with a single lag, are shown in Table 82.

Based on the results shown in Tables 81 and 82, the results of the model can be interpreted as follows:

- A one unit increase in travel speed (mph) increases the sound level differential by 0.027 dBA.
- Rumble strips encountered on the shoulder by the right-side tires of a passenger car are associated with lower sound level differences when compared to centerline rumble strips encountered by the left-side tires of a passenger car.
- A one unit increase in the vehicle angle of departure (degrees) is associated with a 0.271 dBA decrease in the sound level differential.
- A one unit increase in the rumble strip length (in.) is associated with a 0.267 dBA increase in the sound level difference.
- A one unit increase in the rumble strip width (in.) is associated with a 0.771 dBA increase in the sound level difference.

Table 82. Regression model of sound level difference with Newey-West standard errors.

Variable	Parameter estimate	Standard error	t–statistic	P > |t|	95% confidence interval	
					Lower	Upper
Constant	8.650	1.619	5.34	<0.001	5.474	11.827
Speed (mph)	0.027	0.018	1.48	0.140	–0.009	0.063
Location indicator (1: shoulder; 0: centerline)	–1.689	0.398	–4.25	<0.001	–2.470	–0.909
Angle of departure (degrees)	–0.271	0.076	–3.55	<0.001	–0.421	–0.121
Length (in.)	0.267	0.029	9.35	<0.001	0.211	0.323
Width (in.)	0.771	0.126	6.13	<0.001	0.525	1.018
Depth (in.)	4.494	1.328	3.38	0.001	1.887	7.100
Spacing (in.)	–0.394	0.041	–9.70	<0.001	–0.474	–0.314
Rumble strip type indicator (1: milled; 0: rolled)	2.652	0.811	3.27	0.001	1.060	4.244
Pavement surface type indicator (1: concrete; 0: asphalt)	–1.391	0.685	–2.03	0.043	–2.736	–0.046
Pavement surface condition indicator (1: wet; 0: dry)	–2.596	0.465	–5.58	<0.001	–3.509	–1.683

Number of observations: 990.
R^2: 0.179.
R_{adj}^2: 0.171.
Root MSE: 3.936.

- A one unit increase in the rumble strip depth (in.) is associated with a 4.494 dBA increase in the sound level difference.
- A one unit increase in the rumble strip spacing (in.) is associated with a 0.394 dBA decrease in the sound level difference.
- Milled rumble strips are associated with a higher sound level difference when compared to rolled rumble strips.
- A concrete pavement surface is associated with a lower sound level difference when compared to an asphalt pavement surface.
- A wet pavement surface is associated with a lower sound level difference when compared to a dry pavement surface.

The adjusted R^2 value of 0.171 indicates that the regression line does not fit the sample data very well. Because interior vehicle noise is a complex measurement, there are several possible explanations for this low value, including the following:

- Vehicle tires used on the test vehicles may have had different inflation pressures or tread wear;
- Pavement surface temperatures were different among and within experimental locations. The research team attempted to collect pavement surface temperature during field testing but could not safely stop the vehicle on many high-speed roadways during each test to consistently record this information;
- Rumble strip pattern wear differs within experimental test locations, particularly on asphalt pavement surfaces; and
- Pavement surface texture can vary considerably between test locations.

As noted in the Analysis Approach discussion above, additional models of sound level difference were estimated using linear regression. These models were estimated with two specific purposes in mind:

1. Can more of the variability of the data be explained by accounting for the use of different test vehicles in the different states, and
2. To determine statistical differences between certain rumble strip dimensions.

Only data collected on milled rumble strips were considered in developing these additional models.

Table 83 shows a model developed to account for the use of different test vehicles in different states. Table 83 shows the parameter estimates with Newey-West standard errors to correct for autocorrelation. All other assumptions of the linear regression model were met. The signs of the parameter

Table 83. Linear regression with state indicator variables.

Variable	Parameter estimate	Standard error	t-statistic	P > |t|	95% confidence interval	
					Lower	Upper
Constant	7.712	1.291	5.97	<0.001	5.178	10.246
Speed (mph)	0.057	0.016	3.58	<0.001	0.026	0.089
Location indicator (1: shoulder; 0: centerline)	–1.116	0.335	–3.34	<0.001	–1.773	–0.459
Angle of departure (degrees)	–0.275	0.079	–3.50	<0.001	–0.429	–0.121
Length (in.)	0.352	0.037	9.45	<0.001	0.279	0.425
Width (in.)	0.498	0.191	2.61	0.009	0.123	0.873
Depth (in.)	3.106	1.495	2.08	0.038	0.172	6.041
Spacing (in.)	–0.300	0.050	–5.97	<0.001	–0.398	–0.201
Pennsylvania indicator* (1: Pennsylvania; 0: otherwise)	2.197	0.513	4.28	<0.001	1.189	3.205
Minnesota indicator* (1: Minnesota; 0: otherwise)	1.165	0.752	1.55	0.122	–0.310	2.641
Arizona indicator* (1: Arizona; 0: otherwise)	4.039	0.713	5.66	<0.001	2.639	5.439
Utah indicator* (1: Utah; 0: otherwise)	–3.219	0.937	–3.43	0.001	–5.058	–1.379
Pavement type indicator (1: concrete; 0: asphalt)	–3.065	0.568	–5.40	<0.001	–4.179	–1.950

* Kentucky and Colorado are the baseline, and set to zero. State effects in the table should be interpreted using Kentucky and Colorado as a baseline. State effects with a negative sign are expected to have lower sound level differences than the baseline, while state effects with a positive sign are expected to have higher sound level differences than the baseline.

Number of observations: 850.

R^2: 0.332.

R_{adj}^2: 0.323.

Root MSE: 3.452.

estimates in Table 83 are the same as those in Tables 81 and 82. The magnitudes of the parameter estimates are also similar. The Pennsylvania, Arizona, and Utah state indicators in Table 83 are statistically significant, and the Minnesota state indicator is marginally significant. Wet pavement in Arizona and Utah may explain the large parameter estimates for these state indicators when compared to the baseline of Kentucky and Colorado (both set to zero). The vehicle type, tire tread wear, and air temperature may also be influencing sound levels in all four states. When interpreting the meaning of the state indicator variables, the intention is that states would not have to select a given state (i.e., Arizona, Colorado, Kentucky, Minnesota, Pennsylvania, or Utah) that they are somehow most similar to, but rather the state indicator variables should be viewed as separate vehicles. By including these different vehicles in the model, more of the variability in the data can be explained, so there is greater reliability in the predictions.

Efforts were also made to use indicator variables to determine the relative effects of different rumble strip dimensions on sound level difference. To create the dimension indicator variables, construction tolerances were considered. For example, if a state standard indicated a milled rumble strip pattern of 16 in. (L) × 7 in. (W) × 0.5 in. (D) × 12 in. (S) [406 mm (L) × 178 mm (W) × 13 mm (D) × 305 mm (S)], contractors may be permitted a tolerance of ± 1 in. (25 mm) for the length, width, and spacing dimensions, and a tolerance of ± 0.25 in. (6 mm) for the depth dimension. This was confirmed based on the field measurements. As such, efforts to group dimensions into bins based on tolerances were undertaken. At least 10 percent of the observations for any binned dimension category were sought. The descriptive statistics for the binned dimension data are shown in Table 84.

A linear regression model was estimated using the categorical dimension data. State indicator variables were not considered because of the multicollinearity problems created by the including both state and dimensions indicators in the same model. Several dimensions were unique to a single state; thus perfect multicollinearity (a linear regression assumption violation) resulted. All remaining regression assumptions were met using the categorical dimension data, except the autocorrelation assumption. As such, the standard errors were estimated using the Newey-West method. The regression model estimates are shown in Table 85.

Interpretation of the parameter estimates in Table 85 indicates the following:

- The trends for travel speed, rumble strip location (shoulder vs. centerline), angle of departure, pavement type, and pavement surface are consistent with findings reported in Table 82, but changes in the magnitude of the estimators do occur.
- The rumble strip length dimension indicator is highly significant and negative when compared to the baseline condition (length > 14 in. [356 mm]). This indicates that longer rumble strips are associated with a higher sound level difference than shorter patterns. Rumble strips with length dimensions less than or equal to 14 in. (356 mm) generate approximately 3.5 dBA of less sound above the ambient level than rumble strips greater than 14 in. (356 mm) in length.
- The rumble strip width dimension indicator is highly significant and positive when compared to the baseline condition (width > 6 in. [152 mm]) indicating that rumble strips with narrower widths produce greater sound level differences. However, the interaction between the width and depth dimension indicators is highly significant and negative, suggesting that width and depth are jointly associated with sound level difference. For a given milling machine, cutting heads are a given diameter so increasing the width of a rumble strip consequently increases the depth of the rumble strip as well, and vice versa.
- The depth indicator is not statistically significant in Table 85 (t-stat = 0.79) when compared to the baseline (width > 0.5 in. [13 mm]). As noted previously, however, the depth-width interaction has a negative parameter estimate.
- The rumble strip spacing indicator is highly significant and positive when compared to the baseline condition (spacing > 12 in. [305 mm]). This indicates that closely spaced rum-

Table 84. Descriptive statistics of categorical rumble strip dimension data.

Variable name	Minimum	Maximum	Mean	Standard deviation
Length 6–10 in. indicator	0	1	0.240	0347
Length 12–14 in. indicator	0	1	0.250	0.433
Length > 14 in. indicator	0	1	0.489	0.500
Width 4–6 in. indicator	0	1	0.802	0.398
Width > 6 in. indicator	0	1	0.198	0.398
Depth $\leq$ 0.5 in. indicator	0	1	0.864	0.343
Depth > 0.5 in. indicator	0	1	0.136	0.343
Spacing 4–8 in. indicator	0	1	0.135	0.260
Spacing 10–12 in. indicator	0	1	0.586	0.493
Spacing > 12 in. indicator	0	1	0.279	0.357

Table 85. Linear regression model with categorical rumble strip dimension data.

Variable	Parameter estimate	Standard error	t–statistic	P > |t|	95% confidence interval	
					Lower	Upper
Constant	14.281	1.237	11.55	<0.001	11.853	16.709
Speed (mph)	0.053	0.017	3.19	0.001	0.020	0.085
Location indicator (1: shoulder; 0: centerline)	–1.468	0.334	–4.39	<0.001	–2.124	–0.812
Angle of departure (degrees)	–0.373	0.081	–4.63	<0.001	–0.531	–0.215
Pavement type indicator (1: concrete; 0: asphalt)	–2.599	0.562	–4.63	<0.001	–3.703	–1.500
Pavement condition indicator (1: wet; 0: dry)	–2.515	0.382	–6.58	<0.001	–3.264	–1.765
Length ≤ 14 in.[a]	–3.487	0.283	–12.32	<0.001	–4.042	–2.931
Width ≤ 6 in.[b]	3.632	0.798	4.55	<0.001	2.064	5.199
Depth ≤ 0.5 in.[c]	0.615	0.780	0.79	0.431	–0.916	2.146
Spacing ≤ 12 in.[d]	3.766	0.371	10.16	<0.001	3.039	4.494
Width ≤ 6 x Depth ≤ 0.5 in interaction	–4.245	0.870	–4.88	<0.001	–5.952	–2.538

[a] Length > 14 in. is the baseline. Since the length ≤ 14 in. effect has a negative sign, rumble strip pattern lengths > 14 in. are expected to have higher sound level differences.
[b] Width > 6 in. is the baseline. Rumble strip widths > 6 in. are expected to have lower sound level differences than narrow rumble strip patterns (≤ 6 in.).
[c] Depth > 0.5 in. is the baseline. This parameter is not statistically significant.
[d] Spacing > 12 in. is the baseline. Rumble strip spacing > 12 in. are expected to have lower sound level differences than closer spaced patterns (≤ 12 in.).
Number of observations: 850.
R^2: 0.283.
R_{adj}^2: 0.274.
Root MSE: 3.573.

ble strip patterns are expected to have a higher sound level difference than patterns spaced further apart.

The decision was made to model the difference between the ambient sound level while traveling in the travel lane and the maximum sound level generated while traversing the rumble strips either on the shoulder or on the centerline. This decision was based on the fact that the sound level distributions for the ambient sound levels and the maximum sound levels were different. Several models were developed (but are not included here within the report) that predicted ambient sound levels and maximum sound levels separately. These models explained approximately 26 to 32 percent (i.e., the adjusted R^2 values were on the order of 0.26 and 0.32) of the variability of the ambient and maximum sound levels. These models provide credibility to the data collection effort indicating that the data were collected in a reasonable manner and the correct data were collected. These models also illustrated the complexity in modeling the sound level difference between the interaction of a passenger car, its tires, the pavement surface, and the rumble strip dimensions.

Application of the Noise Models

This section provides several examples of how the noise prediction models developed as part of this research can be used to establish rumble strip dimensions for different types of rumble strip applications. The examples demonstrate how to use the noise prediction models presented in Tables 82 and 83. The advantage of using either of these models is that the rumble strip dimension variables are included as continuous variables. Therefore, agencies can perform sensitivity analyses by varying the rumble strip dimensions to determine desirable or optimal dimensions for their policies. The disadvantage of using the noise prediction model from Table 83 is that an agency has to assume whether its roads are most like the states of Kentucky and Colorado (i.e., the base condition of the model) or more like roads in Pennsylvania, Minnesota, Arizona, or Utah. A simple recommendation on how agencies should assess which state their roads most closely resemble cannot be provided because there is much information that is confounded within this indicator variable such as (a) the differences in the individual cars used to collect data within that given state; (b) Arizona was the only state where data were collected during wet pavement conditions; and (c) the condition of the rumble strips in the varying states (i.e., whether the rumble strips were recently installed or had been in place for several years), etc. Because of the type of information confounded within the state indicator variables, unless an agency is from one of the four states represented in the model, it is recommended that the agency assume the base conditions when using the model from Table 83.

Three examples are presented below. The first two examples make use of the noise prediction model in Table 82. The third example makes use of the noise prediction model in Table 83.

Example No. 1: Designing Shoulder Rumble Strip Dimensions for Freeways

Suppose a state transportation agency wants to establish a policy for the design of milled shoulder rumble strips on rural and urban freeways with posted speed limits between 55 and 65 mph (88 and 105 km/h). On freeways, the shoulders can consist of either concrete or asphalt pavement. Horizontal curves on freeways are relatively flat due to the higher design speeds, so the typical angle of departures can be assumed to be relatively low. Because a wet pavement surface produces lower sound level differentials than dry pavement surfaces, a wet pavement surface will be assumed. Because the policy will be for freeways, the shoulders will be relatively wide, and in most cases bicycles will not be permitted on the roadways; thus the length dimension of the rumble strip can be determined independent of the shoulder width and bicycle considerations. Also, because bicycles are not permitted on freeways in most states, the rumble strips can be designed for the higher ranges of desirable maximum sound level difference. Because asphalt surfaces generate higher sound level differences, asphalt surfaces will be considered first in the analysis.

In this first example, the noise prediction model from Table 82 is used to establish potential rumble strip dimensions:

$$\begin{aligned} \text{SLDiff} = {} & 8.650 + 0.027\,Speed - 1.689\,Location - 0.271\,Angle \\ & + 0.267\,Length + 0.771\,Width + 4.494\,Depth \\ & - 0.394\,Spacing + 2.652\,RS\ Type \\ & - 1.391\,PVMT\ Surface - 2.596\,PVMT Condition \end{aligned} \tag{5}$$

where

Speed = vehicle speed (mph);
Location = location indicator (1 = shoulder; 0 = centerline);
Angle = angle of departure (degrees);
Length = length of rumble strip (in.);
Width = width of rumble strip (in.);
Depth = depth of rumble strip (in.);
Spacing = spacing between rumble strips (in.);
RS Type = rumble strip type indicator (1 = milled; 0 = rolled);
PVMT Surface = pavement surface type indicator (1 = concrete; 0 = asphalt); and
PVMT Condition = pavement surface condition indicator (1 = wet; 0 = dry).

It will be assumed the rumble strip dimensions will be established first for the right (outside) shoulder of the freeway. The process could be repeated for establishing desirable dimensions for the left (median) shoulder of the freeway. The following are known based upon the information given above:

- Location: Right (outside) shoulder rumble strips (Indicator = 1);
- Rumble strip type: Milled (Indicator = 1);
- Pavement type: Asphalt (Indicator = 0); and
- Pavement condition: Wet (Indicator = 1).

Inputting the variables above into the sound level difference model yields the following:

$$\begin{aligned} \text{SLDiff} = {} & 7.017 + 0.027\,Speed - 0.271\,Angle + 0.267\,Length \\ & + 0.771\,Width + 4.494\,Depth - 0.394\,Spacing \end{aligned} \tag{6}$$

The dimensions for three different rumble strip patterns, two vehicle speed levels (assuming 55 and 65 mph [88 and 105 km/h] posted speeds), and three angles of departure are shown in Table 86. Pattern 1 can be assumed to be an edgeline

Table 86. Rumble strip dimensions and parameters considered in example no. 1.

Rumble strip pattern	Rumble strip dimensions				Speed (mph)	Departure angle (degrees)	Sound level difference (dBA)
	Length (in.)	Width (in.)	Depth (in.)	Spacing (in.)			
1	6	5	0.375	12	55	1	10.70
2	12	6	0.375	12	55	1	13.09
3	16	7	0.5	12	55	1	**15.51**
1	6	5	0.375	12	55	3	10.16
2	12	6	0.375	12	55	3	12.55
3	16	7	0.5	12	55	3	14.97
1	6	5	0.375	12	55	5	**9.62**
2	12	6	0.375	12	55	5	12.58
3	16	7	0.5	12	55	5	14.43
1	6	5	0.375	12	65	1	10.97
2	12	6	0.375	12	65	1	13.93
3	16	7	0.5	12	65	1	**15.78**
1	6	5	0.375	12	65	3	10.43
2	12	6	0.375	12	65	3	13.39
3	16	7	0.5	12	65	3	**15.24**
1	6	5	0.375	12	65	5	**9.89**
2	12	6	0.375	12	65	5	12.85
3	16	7	0.5	12	65	5	14.70

rumble strip, while patterns 2 and 3 are common shoulder rumble strip patterns used in Canada and the U.S., respectively. Assume for this example that a transportation agency would like to develop rumble strip patterns that generate sound levels differences in the range of 10 to 15 dBA (i.e., 10 dBA ≤ SLDiff ≤ 15 dBA).

The last column in Table 86 shows the estimated difference in sound level generated in the passenger compartment of a passenger car by the three rumble strip patterns based on the given design parameters. The shaded rows represent designs where the rumble strip pattern, speed, and angle of departure fall outside the desired sound level difference range. When the departure angle is 1 degree, Patterns 1 and 2 are expected to generate the appropriate sound level difference for both speed ranges. When increasing the departure angle to 3 degrees, again Patterns 1 and 2 are expected to produce sound level differences in the desired range, while Pattern 3 would be expected to generate sound levels slightly below the maximum criterion for speeds of 55 mph (88 km/h) and slightly above the maximum criterion for speeds of 65 mph (105 km/h). When the departure angle is 5 degrees, rumble strip Patterns 2 and 3 are expected to produce sound levels within the desirable range at both speeds (55 and 65 mph [88 and 105 km/h]), while Pattern 1 would be expected to generate slightly less than the desired sound level. Based on this example, Pattern 2 appears to be the most appropriate pattern based on the agency's policy decision, but Patterns 1 and 3 are not far removed from meeting the desired design guidelines so it is conceivable that Patterns 1 and 3 would be acceptable for use by the transportation agency along urban and rural freeways.

Example No. 2: Designing Shoulder Rumble Strip Dimensions for Rural Two-Lane Roads

Suppose a transportation agency wants to establish a policy for the design of milled shoulder rumble strips on rural two-lane roads. In establishing such a policy, the agency will need to consider the following:

- Bicyclists;
- Narrower shoulders;
- Sharper curves;
- Intermediate and high speeds (e.g., 45 to 55 mph [70 to 88 km/h] posted speed limits); and
- Nearby residents.

Since most rural two-lane roads are constructed of asphalt pavement, asphalt pavement will be assumed for the design. However, bicyclists are assumed to use the roadway only when the pavement surface is dry so it is assumed that the pavement condition in this example is dry. In this second example, the model from Table 82 is used again to establish potential rumble strip dimensions. The base conditions for the model (i.e., location, rumble strip type, and pavement type) are the same as in the first example. The main difference is that the wet indicator variable shown in Equation (6) should be 0 rather than 1 as in the previous example. It is assumed desirable to develop rumble strip patterns that generate sound level differences in the range from 6 to 12 dBA (i.e., 6 dBA ≤ SLDiff ≤ 12 dBA). This sound level difference represents a compromise between the in-vehicle noise required to alert a drowsy or fatigued driver while attempting to provide for a reasonable level of comfort and control for bicyclists.

As a starting point for developing a rumble strip policy for rural two-lane roads, research results on recommended dimensions for bicycle-tolerable rumble strips are presented in Table 87. The results of these studies are in agreement for the dimensions that are specified (i.e., rumble strip width, depth, and spacing). Essentially, rumble strips with the following dimensions are recommended for the design of bicycle-tolerable rumble strips:

- Width: 5 in. (127 mm);
- Depth: 0.375 in. (10 mm); and
- Spacing: 11 or 12 in. (280 or 305 mm).

The dimension not addressed by the previous research is rumble strip length; on rural two-lane roads, due to bicyclists and narrower shoulder widths, rumble strip length is a dimension of particular interest in developing such a policy. Therefore, the length of the rumble strips will be varied when

Table 87. Rumble strip designs recommended to accommodate motorists and bicyclists from previous research.

State	Width	Depth	Spacing (on centers)	Comments
Pennsylvania (Elefteriadou et al., 2000)	5 in.	0.375 in.	12 in.	Nonfreeway facilities with operating speeds near 55 mph.
	5 in.	0375 in.	11 in.	Nonfreeway facilities with operating speeds near 45 mph.
California (Bucko and Khorashadi, 2001)	5 in.	0.3125 ± 0.0625 in.	12 in.	None
Colorado (Outcalt, 2001)	5 in.	0.375 ± 0.125 in.	12 in.	Recommend gap pattern of 48 ft of rumble strip followed by 12 ft of gap.

modeling several potential patterns. The rumble strip dimensions of three potential patterns and other conditions (i.e., vehicle speed and departure angle) under consideration to establish the rumble strip policy are shown in Table 88.

The last column in Table 88 shows the estimated difference in sound level generated in the passenger compartment of a passenger car by the three potential rumble strip patterns for the given parameters. The shaded rows represent designs where the rumble strip pattern, speed, and angle of departure fall outside the desired sound level difference range. For the patterns with a 16 in. (406 mm) and 12 in. (305 mm) length, the expected in-vehicle noise levels exceed the 6 to 12 dBA design range specified in the example. However, the pattern with a 6 in. (152 mm) length does produce an expected sound level difference in the design range at a speed of 45 mph (72 km/h) and departure angles of 5 and 10 degrees, and at speeds of 55 mph (88 km/h) at departure angles of 10 degrees. With this type of information, an agency could consider several options such as the following:

- Establish a single rumble strip pattern (i.e., dimensions) for all rural two-lane roads.
- Establish a set of dimensions for edgeline rumble strips on roadways where bicycle traffic is expected and an alternative set of dimensions for rumble strips installed on the shoulders where bicyclists are not expected.

Example No. 3: Designing Centerline Rumble Strip Dimensions for Rural Two-Lane Roads

Suppose a transportation agency wants to establish a policy for the design of milled centerline rumble strips on rural two-lane roads. In establishing such a policy, the agency will need to consider the following:

- Sharper curves;
- Intermediate and high speeds (e.g., 45 to 55 mph [70 to 88 km/h] posted speed limits); and
- Possibly, nearby residents.

In this example, the noise prediction model from Table 83 is used to establish potential dimensions for centerline rumble strips.

$$\begin{aligned} SLDiff = {} & 7.712 + 0.057\mathit{Speed} - 1.116\mathit{Location} - 0.275\mathit{Angle} \\ & + 0.352\mathit{Length} + 0.498\mathit{Width} + 3.106\mathit{Depth} \\ & - 0.300\mathit{Spacing} - 3.065\mathit{PVMT\ Surface} + 2.197\mathit{PA} \\ & + 1.165\mathit{MN} + 4.039\mathit{AZ} - 3.219\mathit{UT} \end{aligned} \tag{7}$$

where

PA = Pennsylvania indicator (= 1 if located in Pennsylvania; = 0 if not);
MN = Minnesota indicator (= 1 if located in Minnesota; = 0 if not);
AZ = Arizona indicator (= 1 if located in Arizona; = 0 if not); and
UT = Utah indicator (= 1 if located in Utah; = 0 if not).

Since most rural two-lane roads are constructed of asphalt pavement, an asphalt pavement is assumed for the design, but because no indicator variable for pavement condition is present in this noise prediction model, no assumption needs to be made concerning whether the rumble strips will be designed for wet or dry pavement conditions. Assuming a base condition for the state indicator variable, the following

Table 88. Rumble strip dimensions and parameters considered in example no. 2.

Rumble strip dimensions				Speed (mph)	Departure angle (degrees)	Sound level difference (dBA)
Length (in.)	Width (in.)	Depth (in.)	Spacing (in.)			
16	5	0.375	12	45	1	15.7
16	5	0.375	12	45	5	14.6
16	5	0.375	12	45	10	13.3
16	5	0.375	12	55	1	16.0
16	5	0.375	12	55	5	14.9
16	5	0.375	12	55	10	13.6
12	5	0.375	12	45	1	14.6
12	5	0.375	12	45	5	13.6
12	5	0.375	12	45	10	12.2
12	5	0.375	12	55	1	14.9
12	5	0.375	12	55	5	13.8
12	5	0.375	12	55	10	12.5
6	5	0.375	12	45	1	13.0
6	5	0.375	12	45	5	11.9
6	5	0.375	12	45	10	10.6
6	5	0.375	12	55	1	13.3
6	5	0.375	12	55	5	12.2
6	5	0.375	12	55	10	10.9

values are input into Equation 7, yielding the base model (i.e., Equation 8) for use in the sensitivity analysis for this example:

- Location: Centerline rumble strips (*Location* = 0);
- Pavement type: Asphalt (*PVMT Surface* = 0); and
- State: KY and CO (*PA, AZ, MN,* and *UT* = 0).

$$SLDiff = 4.647 + 0.057 Speed - 0.275 Angle + 0.352 Length + 0.498 Width + 3.106 Depth - 0.300 Spacing \quad (8)$$

The rumble strip dimensions of five potential patterns and other conditions (i.e., vehicle speed and departure angle) under consideration to establish the centerline rumble strip policy for a rural two-lane road are shown in Table 89. Assume that it is desirable to develop rumble strip patterns that generate sound level differences in the range from 10 to 15 dBA (i.e., 10 dBA ≤ SLDiff ≤ 15 dBA).

The last column in Table 89 shows the estimated difference in sound level generated in the passenger compartment of a passenger car by the five potential rumble strip patterns for the given parameters. The shaded rows represent designs where the rumble strip pattern, speed, and angle of departure fall outside the desired sound level difference range. All of the rumble strip patterns considered meet the desired sound level difference for at least one of the scenarios considered in Table 89. Rumble strip patterns 1, 2, and 3 appear to be the most reasonable patterns to potentially adopt for this type of policy. It is also possible that different policies could be established for varying posted speeds.

Table 89. Rumble strip dimensions and parameters considered in example no. 3.

Potential rumble strip pattern	Rumble strip dimensions under consideration				Speed (mph)	Departure angle (degrees)	Sound level difference (dBA)
	Length (in.)	Width (in.)	Depth (in.)	Spacing (in.)			
1	8	5	0.375	12	35	1	12.87
2	10	5	0.375	12	35	1	13.58
3	12	5	0.375	12	35	1	14.28
4	16	6	0.375	12	35	1	**16.19**
5	16	6	0.5	11	35	1	**16.88**
1	8	5	0.375	12	35	5	11.77
2	10	5	0.375	12	35	5	12.48
3	12	5	0.375	12	35	5	13.18
4	16	6	0.375	12	35	5	**15.09**
5	16	6	0.5	11	35	5	**15.78**
1	8	5	0.375	12	35	7	11.22
2	10	5	0.375	12	35	7	11.93
3	12	5	0.375	12	35	7	12.63
4	16	6	0.375	12	35	7	14.54
5	16	6	0.5	11	35	7	**15.23**
1	8	5	0.375	12	35	9	10.67
2	10	5	0.375	12	35	9	11.38
3	12	5	0.375	12	35	9	12.08
4	16	6	0.375	12	35	9	13.99
5	16	6	0.5	11	35	9	14.68
1	8	5	0.375	12	55	1	13.44
2	10	5	0.375	12	55	1	14.15
3	12	5	0.375	12	55	1	14.85
4	16	6	0.375	12	55	1	**16.76**
5	16	6	0.5	11	55	1	**17.45**
1	8	5	0.375	12	55	5	12.34
2	10	5	0.375	12	55	5	13.05
3	12	5	0.375	12	55	5	13.75
4	16	6	0.375	12	55	5	**15.66**
5	16	6	0.5	11	55	5	**16.35**
1	8	5	0.375	12	55	7	11.79
2	10	5	0.375	12	55	7	12.50
3	12	5	0.375	12	55	7	13.20
4	16	6	0.375	12	55	7	**15.11**
5	16	6	0.5	11	55	7	**15.80**
1	8	5	0.375	12	55	9	11.24
2	10	5	0.375	12	55	9	11.95
3	12	5	0.375	12	55	9	12.65
4	16	6	0.375	12	55	9	14.56
5	16	6	0.5	11	55	9	**15.25**

Summary of Key Findings

The present experiment was designed to collect sound level data for a variety of shoulder and centerline rumble strip applications in the United States. Variables collected during the field data collection effort included rumble strip dimensions (length, width, depth, and spacing), vehicle speed, vehicle angle of departure, rumble strip location (shoulder or centerline), pavement surface type (concrete or asphalt), rumble strip type (milled or rolled), and pavement surface condition (wet or dry). Exploratory analyses revealed that the sound level differential could be modeled using ordinary least squares regression. Initial modeling results (see Table 82) indicated that all parameter estimates had plausible signs, while the variability in the sound level difference was not well explained by the model. Subsequent models for milled rumble strips included state indicator variables. Several of the state indicator variables were statistically significant suggesting that vehicle characteristics, tire tread wear, and air temperature may all influence the sound level difference generated by rumble strips. The regression model with the state indicator variables (see Table 83) improved the goodness-of-fit of the model compared to the model without the state indicators, explaining approximately 33 percent of the variability in the sound level difference generated by the rumble strips. Subsequent efforts to model rumble strip dimensions as indicator variables did not improve the goodness-of-fit from the regression model as shown in Table 85.

The key finding from this noise study are as follows:

- The analysis found that sound level differentials generated by rumble strips could be modeled using ordinary least squares regression.
- Several prediction models were developed that included the four primary dimensions of rumble strips (i.e., length, width, depth, and spacing) as significant predictor variables of sound level differences generated by rumble strips, and all of the parameter estimates had plausible signs. These are the first predictive models developed that include all four primary rumble strip dimensions. Models from previous research by Khan and Bacchus (*97*) do not include all four primary rumble strip dimensions.
- The predictive models include other independent variables such as vehicle speed, angle of departure, pavement type, and pavement condition, which logically explain some of the variability in the sound levels generated by rumble strips above the ambient level.

SECTION 10

Rumble Strip Application and Design Criteria

This section summarizes the implications from the key research findings for design and application of shoulder and centerline rumble strips. In formulating policies regarding the design and application of shoulder and centerline rumble strips, transportation agencies should address the following six key issues:

1. On what roadways is it appropriate to install shoulder/centerline rumble strips?
2. What type of rumble strips will be used?
3. What will the dimensions be?
4. Where will the rumble strips be installed, relative to either the edgeline or to the centerline?
5. Should the rumble strip be installed in a continuous pattern or with intermittent gaps?
6. What features or areas might necessitate an interruption in the rumble strip pattern?

After rumble strips are installed, transportation agencies should also address maintenance issues. In particular, transportation agencies should consider adopting a policy on the preparation of rumble strips prior to pavement surface overlays.

Guidance is provided below on each of these issues. First, guidance is provided on these issues as they specifically relate to shoulder rumble strip policies. Second, guidance is provided on these issues as they specifically relate to centerline rumble strip policies.

Implications on Shoulder Rumble Strip Policies

Roadway Types Where it is Appropriate to Install Shoulder Rumble Strips

Shoulder rumble strips may be considered for implementation on a wide range of roadway types, including urban freeways, urban freeway on-ramps and off-ramps, urban multilane divided highways (nonfreeways), urban multilane undivided highways (nonfreeways), urban two-lane roads, rural freeways, rural freeway on-ramps and off-ramps, rural multilane divided highways (nonfreeways), rural multilane undivided highways (nonfreeways), and rural two-lane roads. When developing a policy on which roadway type (or types) it is appropriate to install shoulder rumble strips, and for help in prioritizing actual sites for the installation of shoulder rumble strips, the following criteria have been considered by one or more transportation agencies. Guidance is provided on common values and ranges of values used by transportation agencies. The values provided here are based upon common practices by agencies rather than being substantiated by research. Also, some criteria may be considered for certain roadway types, but not others.

- **Shoulder Width:** Minimum shoulder widths for rumble strip application range from 2 to 10 ft (0.6 to 3.0 m), with 4 ft (1.2 m) being the most common value. Minimum shoulder widths may differ by roadway type.
- **Lateral Clearance:** Minimum lateral clearances range from 2 to 7 ft (0.6 to 2.1 m), with 4 ft (1.2 m) and 6 ft (1.8 m) being the most common values. Some agencies may prefer to define the lateral clearance to be the distance from the outside (i.e., right) edge of the rumble strip to the outside edge of the shoulder, while others may measure the clearance to the nearest roadside object rather than the outside edge of the shoulder.
- **ADT:** Minimum ADTs for rumble strip application range from 400 to 3,000 ADT, but in most cases fall between 1,500 and 3,000 ADT.
- **Bicycles:** Agencies address bicycle considerations in several ways, including: (a) not installing rumble strips on roads with significant bicycle traffic or if the roadway is a designated bicycle route, (b) adjusting the dimensions of the rumble strips, (c) adjusting the placement of the

rumble strips, (d) adjusting the minimum shoulder width and/or lateral clearance requirements, and/or (e) providing gaps in periodic cycles. Guidance provided in the AASHTO *Guide for the Development of Bicycle Facilities* (*98*) should also be considered.

- **Pavement Type:** Some agencies only install shoulder rumble strips on asphalt surfaces. Pavement type also influences whether rolled rumble strips can be used.
- **Pavement Depth:** Minimum pavement depths range from 1 to 6 in. (25 to 152 mm).
- **Area Type:** Some agencies only install shoulder rumble strips in rural areas, primarily due to potential noise disturbance.
- **Speed Limit:** Minimum speed limits used by agencies ranged from 45 to 50 mph (72 to 80 km/h). Some agencies also adjust the rumble strip dimensions depending upon the speed limit.
- **Crash Frequencies/Rates:** Some agencies establish a threshold value, such as the statewide average for the given roadway type.

Reliable estimates for the safety effectiveness shoulder rumble strips provide useful information for highway agencies. The most reliable and comprehensive estimates to date of the safety effectiveness of shoulder rumble strips are for freeways and rural two-lane roads. For consistency with previous sources, the results from Griffith (*1*) are indicated as applying to rolled rumble strips. The combined results of this research and the Griffith study include both milled and rolled rumble strips and are therefore indicated as applying to should rumble strips in general. There is no indication of any substantive differences in safety between milled and rolled rumble strips. The safety effectiveness estimates with their associated standard errors are as follows:

Urban/Rural Freeways

- Rolled shoulder rumble strips [based on results from Griffith (*1*)]:
  - 18 percent reduction in SVROR crashes (SE = 7) and
  - 13 percent reduction in SVROR FI crashes (SE = 12).

Rural Freeways

- Shoulder rumble strips [based on combined results from this research and Griffith (*1*)]:
  - 11 percent reduction in SVROR crashes (SE = 6) and
  - 16 percent reduction in SVROR FI crashes (SE = 8).

Rural Two-Lane Roads

- Shoulder rumble strips [based on results from this research and Patel et al., (*2*)]:
  - 15 percent reduction in SVROR crashes (SE = 7) and
  - 29 percent reduction in SVROR FI crashes (SE = 9).

Estimates on the safety effectiveness of shoulder rumble strips along rural multilane divided highway (nonfreeways) are also available, but they are not considered as reliable as the estimates for freeways and rural two-lane roads. The safety estimates for rural multilane divided highway (nonfreeways) are as follows:

Rural Multilane Divided Highways (nonfreeways)

- Shoulder rumble strips [based on results from Carrasco et al., (*3*)]:
  - 22 percent reduction in SVROR crashes and
  - 51 percent reduction in SVROR FI crashes.

The estimates above are considered appropriate only for the roadway types for which they are shown. In all likelihood, the safety benefits of shoulder rumble strips vary by roadway type because the different types of roadways have varying geometric design standards (i.e., lane widths, shoulder widths, roadside, etc.), accommodate varying traffic volumes and distributions, serve different driver populations, and accommodate a range of operating speeds. It should be clearly stated that the lack of reliable estimates of the safety effectiveness of shoulder rumble strips along the other roadway types does not indicate that shoulder rumble strips are ineffective on these other roadway types. Rather, it should be understood that the safety effects of rumble strips on these roadway types are simply unknown at this time. The safety effects have not been quantified due to limited mileage of shoulder rumble strip installations along these respective roadway types.

As a final note regarding the safety effectiveness of shoulder rumble strips, shoulder rumble strips are expected to reduce SVROR crashes involving heavy vehicles on rural freeways by approximately 40 percent, but no evidence exists to suggest that shoulder rumble strips reduce SVROR involving heavy vehicles on rural two-lane roads. Therefore, if a problem of SVROR crashes involving heavy vehicles is identified along a rural freeway, then installation of shoulder rumble strips can be expected to mitigate these types of crashes. However, if a similar problem is identified along a rural two-lane road, then it is unknown how effective shoulder rumble strips will be at mitigating such a problem. Also, evidence suggests that shoulder rumble strips reduce SVROR crashes that occur during low-lighting conditions on rural two-lane roads. This may be due to the positive guidance that rumble strips provide when the delineation of the roadway is limited. Therefore, in situations where SVROR crashes during low lighting conditions are noted, shoulder rumble strips may be considered as a potential safety improvement.

Type of Rumble Strips to Use

A variety of shoulder rumble strip types are used in North America. These include milled, rolled, raised, or formed.

Based on noise and vibration research, milled rumble strips generally provide higher in-vehicle noise and vibration levels than rolled rumble strips. Also, because one of the primary advantages of milled rumble strips over other types is that they can be installed at any time on new or existing pavements, milled rumble strips are the preferred rumble strip type among most agencies. Assuming the alerting properties are sufficient, nothing necessarily prohibits the use of the other types of rumble strips. The primary concern associated with rolled rumble strips, besides the alerting properties, is that rolled rumble strips are sensitive to the pavement temperature at the time of installation. When the temperature is too low, the indentations may not reach the specified depth. When the temperature is too high, the asphalt may not be stable enough to attain the specified pattern. Also, the use of raised rumble strips is usually restricted to warmer climates due to maintenance difficulties resulting from snow removal in northern climates.

Dimensions of Shoulder Rumble Strips

For transportation agencies to begin determining the dimensions of shoulder rumble strips, agencies first must start by determining the desired alerting properties of the rumble strip pattern for the given roadway type. There is no conclusive evidence from practice or research to serve as a basis in answering this question; however, the literature provides a range of recommended values for this design criterion. To alert an inattentive, distracted, drowsy, or fatigued driver, the literature indicates that rumble strips should generate a 3 to 15 dBA increase above the ambient in-vehicle sound level. However, there is also some evidence suggesting that sudden changes in sound level above 15 dBA could startle a driver.

Considering the research methodologies of the studies that have investigated this issue and based upon the recommended values presented in the literature that may or may not be supported through research, it is recommended that rumble strips should, at minimum, be designed to generate sound levels 3 dBA above the ambient in-vehicle sound and should not generate sound levels greater than 15 dBA above the ambient in-vehicle sound. These limits of 3 and 15 dBA increases above the ambient in-vehicle sound level should be viewed as minimum and maximum design values. Rumble strips that generate less than a 3 dBA increase in the ambient sound level will likely not have the alerting properties to prove effective in reducing target crashes, and rumble strips that generate more than 15 dBA above the ambient sound level have the potential to startle drivers, which would be an undesirable result.

To take a slightly more conservative approach when designing rumble strips, it is recommended that an increase in 3 dBA above the ambient in-vehicle sound level be viewed as an absolute minimum design value and that an increase of 6 dBA above the ambient in-vehicle sound level should be viewed as the desired minimum design value. This recommendation provides for some tolerance in the desired response. At a 3 dBA increase in ambient sound, a driver will likely be able to notice the change in sound level. However, the literature does not provide sufficient detail to qualify the state of the driver, nor the driver's response. It is likely that an inattentive or distracted driver will notice a 3 dBA change in sound level, but it is not known whether drowsy or fatigued drivers will (a) notice this change in ambient sound, nor (b) respond correctly to the stimulus. It is more likely that a 6 dBA increase in the ambient sound level will alert the full range of target drivers (i.e., inattentive, distracted, drowsy, or fatigued drivers) sufficiently to enable drivers to correct their steering in an appropriate manner.

Regarding the upper end of the scale, there is conflicting information. Some literature suggests that an increase of 15 dBA above the ambient sound level is necessary to alert drivers, while other information suggests that sound changes above 15 dBA could produce a startle reaction. Therefore, an increase of 15 dBA above the ambient sound level appears to be a reasonable maximum design value, recognizing that if a rumble strip pattern generates more than a 15 dBA increase above the ambient sound level, it should not be automatically assumed that the rumble strip will cause negative impacts (e.g., an increase in crashes), but rather could increase the potential for startling drivers who encounter the rumble strips.

Having recommended three design values (i.e., minimum design value [3 dBA], desirable minimum design value [6 dBA], and maximum design value [15 dBA]) for consideration in developing a rumble strip policy, further guidance is provided that considers bicyclists needs. On roadways where bicyclists are not expected, such as on freeways, it is recommended that rumble strip patterns be designed to generate approximately 10 to 15 dBA above the ambient in-vehicle sound level, but for roadways where bicyclists may be expected, it is recommended that rumble strip patterns be designed to generate between 6 to 12 dBA above the ambient in-vehicle sound level. Another way to consider this is that for roadways where bicyclists are not expected, relatively aggressive rumble strip patterns may be used, while for roadways where bicyclists are expected, more bicycle-tolerable rumble strip patterns should be used. This also implies that different rumble strip patterns should be used for different roadway types. While the difference in the safety effectiveness of rumble strips designed using the lower and higher decibel ranges is unknown, there is no indication from safety studies and predictive modeling that this difference would be substantial.

Having specified recommended design thresholds or limits for sound level differences to be generated by rumble strips, transportation agencies have the option to conduct their own field research to identify rumble strip patterns that generate the desired thresholds, or agencies could look at previous research results to identify potential patterns. Another option that transportation agencies now have for determining the dimensions of rumble strips is to utilize the noise prediction models developed through this research. The models in Tables 82 and 83 provide the greatest flexibility and explain the greatest variation in the sound level difference generated by the rumble strips. It is recommended that one or both of these predictive models be applied to establish rumble strip patterns for application under certain operating conditions. Because of the type of information confounded within the state indicator variables in the model from Table 83, unless an agency is from one of the four states represented in the model, it is recommended that an agency assume the base conditions when using this respective prediction model. In addition, in situations where the pavement surfaces for the through travel lanes and shoulders differ, it is recommended that the coefficients for the "Concrete" indicator variable be halved (i.e., divided by 2) and the "Concrete" indicator be a value of 1.

As a starting point or for comparison purposes, two rumble strip patterns are worth noting here. First, the most common dimensions of milled shoulder rumble strips used throughout United States are:

- Length: 16 in. (406 mm);
- Width: 7 in. (178 mm);
- Depth: 0.5 to 0.625 in. (13 to 16 mm); and
- Spacing: 12 in. (305 mm).

Based upon the noise prediction models, this pattern generates a sufficient amount of noise in the upper range of the recommended design thresholds. These dimensions can be considered a relatively "aggressive" pattern and are considered appropriate for use on roadways where bicyclists are not expected (e.g., freeways). Second, there is consensus that a milled rumble strip pattern with the following dimensions provides a reasonable compromise between the needs of bicyclists and motorists (i.e., bicycle-tolerable rumble strip pattern):

- Width: 5 in. (127 mm),
- Depth: 0.375 in. (10 mm), and
- Spacing: 11 to 12 in. (280 to 305 mm).

Notice above that in specifying the dimensions of the bicycle-tolerable rumble strip patterns, the length dimension is not provided. One of the key dimensions concerning shoulder rumble strips is their length. For milled rumble strips, typical lengths of patterns are 12 and 16 in. (305 and 406 mm), but at least one state transportation agency has adopted a policy that allows lengths as short as 6 in. (152 mm) for milled rumble strips. The desire to install milled rumble strips with groove lengths less than the typical 12 to 16 in. (305 to 406 mm) is (a) to keep this dimension as narrow as possible to provide additional lateral clearance for bicyclists, (b) due to pavement performance issues when rumble strips are installed on roadways with narrow shoulders, and/or (c) simply to install rumble strips on roadways with narrow or nonexistent shoulders where rumble strips might not otherwise be installed. Based upon the unit increase above the ambient sound level per unit increase of the length dimension of the noise prediction model, there is approximately a 2.5 to 3.6 dBA difference in sound level above the ambient when comparing a rumble strip with a 6 in. (152 mm) length to a rumble strip with a typical length of 16 in. (406 mm), holding all other dimensions constant. Considering that the range of recommended design thresholds for roadways where bicyclists may be expected is 6 dBA (i.e., an increase between 6 to 12 dBA above the ambient sound level is desirable), a rumble strip with a 16 in. (406 mm) length that is expected to generate an increase above ambient sound between 9 and 12 dBA can be reduced in length to 6 in. (152 mm) and still be expected to generate a sound level difference above the desirable range of 6 dBA. Thus, it can be concluded that rumble strips designed with narrower lengths (e.g., 6 in. [152 mm]) can generate the desired sound level differences to alert inattentive, distracted, drowsy, or fatigued drivers. Example No. 2 in Section 9 clearly illustrates this. It is not necessarily recommended that all rumble strip patterns have a narrow length of 6 in. (152 mm), but in those situations where it is desirable to design a rumble strip with a narrower length for a particular reason (e.g., to provide more lateral clearance for bicyclists or for very narrow shoulders), it is likely that a rumble strip pattern can be designed as such and still generate an increase in the sound level difference sufficient to alert inattentive, distracted, drowsy, or fatigued drivers.

One question often raised when discussing the design dimensions of rumble strips is whether shoulder rumble strips should be designed specifically to consider heavy vehicles. Based upon the results of the safety evaluation of shoulder rumble strips on rural freeways, the results imply that the current dimensions of shoulder rumble strips installed along rural freeways provide sufficient levels of stimuli to alert inattentive and drowsy drivers of heavy vehicles and that it is not necessary to design rumble strip patterns that are "more aggressive" based strictly on the needs of drivers of heavy vehicles.

Finally, in an effort to minimize the adverse effects of rumble strips on nearby residents, it is recommended that rumble strip patterns designed to generate between 6 to 12 dBA above the ambient in-vehicle sound level should be applied on roadways in close proximity to residential areas, rather than rumble strips designed to generate between 10 to 15 dBA above the ambient in-vehicle sound level. Although these design criteria were not necessarily established with the intent to address issues related to noise generated outside of the vehicle, use of less aggressive patterns (i.e., patterns designed to generate between 6 to 12 dBA above the ambient in-vehicle sound level) in close proximity to residential areas seems logical in an effort to minimize the adverse effects of the rumble strips on nearby residents.

Placement of Shoulder Rumble Strips Relative to the Edgeline

Typical offset distances range from 0 to 30 in. (0 to 762 mm). Some transportation agencies prefer to install shoulder rumble strips close to the travel way on the inside portion of the shoulder or in some cases on the edgeline, while other states install rumble strips more toward the middle of the shoulder. Reasons for the varying policies include providing sufficient lateral clearance for bicyclists to ride along the shoulder without encountering the rumble strips, minimizing the number of motor vehicle encounters with the rumble strips so as not to cause excessive noise for nearby residents, and providing the capability to install rumble strips along roads with narrow or nonexistent shoulders.

Based upon the analyses designed to determine the impact that rumble strip placement (i.e., offset distance from the edgeline) has on the safety effectiveness of shoulder rumble strips, there is conclusive evidence to show that on rural freeways rumble strips placed closer to the edgeline are more effective in reducing SVROR FI crashes compared to rumble strips placed farther from the edgeline. Therefore, for rural freeways, it is recommended that shoulder rumble strips be placed as close to the edgeline as possible or even on the edgeline, taking into consideration other factors such as pavement joints to provide the maximum safety benefit from this treatment.

For other roadway types, such as rural two-lane roads, there is no conclusive evidence to indicate that offset distance impacts the safety effectiveness of shoulder rumble strips. Therefore, based strictly upon the safety benefits, there is no current basis for recommending that transportation agencies change their current policies concerning the placement of shoulder rumble strips with respect to the edgeline on these other roadway types.

On divided highways, consideration may be given to specifying different offsets for rumble strips installed on the right (outside) shoulder compared to rumble strips installed on the left (median) shoulder. For transportation agencies that adopt this policy, typically the offset for the left (median) shoulder is less than the offset for the right (outside) shoulder.

Regarding the placement issue, it is also important to note that the AASHTO *Guide for the Development of Bicycle Facilities* (*98*) states that rumble strips are not recommended where shoulders are used by bicyclists unless there is (a) a minimum 1 ft (0.3 m) offset between the travel lane and the rumble strip, (b) a 4 ft (1.2 m) lateral clearance from the rumble strip to the outside edge of the paved shoulder, or (c) 5 ft (1.5 m) to adjacent guardrail, curb, or other obstacle. If existing conditions preclude achieving the minimum desirable clearance, then AASHTO policy indicates the length of the rumble strip may be decreased or other appropriate alternative solutions should be considered.

Finally, some transportation agencies have reported concerns over the visibility and retroreflectivity of pavement markings when rumble strips are installed on the edgeline (i.e., edgeline rumble strips). These agencies note potential problems may occur under nighttime conditions especially if snow, salt, sand, or debris collect in the grooves of the rumble strips. Conflicting evidence as to whether this is an actual problem is found in the literature. However, the majority of studies suggest that visibility/retroreflectivity of pavement markings placed over rumble strips is higher compared to standard edgeline pavement markings, particularly during wet-night conditions. Thus, concerns over the visibility and retroreflectivity of pavement markings should not prohibit the use of edgeline rumble strips.

Use of a Continuous or Intermittent Pattern

Primarily to better accommodate the needs of bicyclists, consideration may be given to providing intermittent gaps in the rumble strip patterns, compared to a continuous pattern. Based upon research and current practice, it is common to provide periodic gaps in the rumble strips of 10 or 12 ft (3.0 or 3.6 m), in 40 or 60 ft (12 or 18 m) cycles. Provision of intermittent gaps enables bicyclists to maneuver from one side of the rumble strips to the other without having to encounter the indentations/grooves.

Features or Areas That Might Necessitate an Interruption in the Shoulder Rumble Strip Pattern

Within a shoulder rumble strip policy, consideration should be given to specific features or areas where the rumble strip pattern should be discontinued or interrupted to avoid adverse consequences (e.g., pavement deterioration, noise, etc.). Specific features or areas along the shoulder or roadway where it is common to discontinue or interrupt shoulder rumble strips include the following:

- Intersections, driveways, and turn lanes;
- Entrance and exit ramps;
- Structures (i.e., bridges);
- Areas where the lateral clearance drops below a specified value and/or areas where the lateral clearance is limited due to adjacent guardrail, curb, or other obstacles;
- Residential areas;
- Catch basins and drainage grates;
- Pavement joints; and
- Median crossings.

Concerning further guidance on ways to minimize the impact of shoulder rumble strips on nearby residents, consideration should be given to terminating the rumble strips 656 ft (200 m) prior to residential/urban areas. This threshold value is based upon studies that showed when rumble strips were terminated 656 ft (200 m) prior to residential or urban areas, the noise impacts proved tolerable to nearby residents.

Preparation of Shoulder Rumble Strips Prior to Overlayment of the Pavement Surface

Once shoulder rumble strips are in place, transportation agencies need to consider a policy on how they plan to prepare rumble strips prior to overlaying the shoulder surface so that rideability and/or pavement integrity are not compromised. Based upon one observational study, it is recommended to prepare areas with rumble strips prior to overlayment either by (1) milling, inlaying, and overlaying or (2) by simply milling and overlaying. Other preparation approaches such as shim and overlay or simply overlay will likely result in some degree of reflection in the area of the former rumble strips.

Implications on Centerline Rumble Strip Policies

Roadway Types Where it is Appropriate to Install Centerline Rumble Strips

Centerline rumble strips may be considered for implementation on a wide range of roadway types including urban multilane undivided highways (nonfreeways), urban two-lane roads, rural multilane undivided highways (nonfreeways), and rural two-lane roads. When developing a policy on which roadway type or types it is appropriate to install centerline rumble strips, and for help in prioritizing actual sites for the installation of centerline rumble strips, the following criteria have been considered by one or more transportation agencies:

- Lane width,
- ADT,
- Pavement depth,
- Area type,
- Speed limit, and
- Crash frequencies/rates.

Valuable information that may help agencies decide on which roadway types they should install centerline rumble strips are reliable estimates on the safety effectiveness of this treatment. The most reliable and comprehensive estimates to date of the safety effectiveness of centerline rumble strips are for those installed on urban and rural two-lane roads. The safety effectiveness estimates for centerline rumble strips with their associated standard errors are as follows:

Urban Two-Lane Roads

- Centerline rumble strips (based on results from this research):
  - 40 percent reduction in TOT target crashes (SE = 17) and
  - 64 percent reduction in FI target crashes (SE = 27).

Rural Two-Lane Roads

- Centerline rumble strips [based on combined results from this research and Persaud et al., (*4*)]:
  - 9 percent reduction in TOT crashes (SE = 2),
  - 12 percent reduction in FI crashes (SE = 3),
  - 30 percent reduction in TOT target crashes (SE = 5), and
  - 44 percent reduction in FI target crashes (based on results from this research) (SE = 6).

The expected safety benefits of centerline rumble strips are for practical purposes the same whether installed along horizontal curves or tangents. Target crashes are defined to be head-on and opposite-direction sideswipe crashes.

The estimates above are considered appropriate only for the roadway types for which they are shown. In all likelihood, the safety benefits of centerline rumble strips vary by roadway type because the different types of roadways have varying geometric design standards (i.e., lane widths, shoulder widths, roadside, etc.), accommodate varying traffic volumes and distributions, serve different driver populations, and accommodate a range of operating speeds. The lack of reliable estimates of the safety effectiveness of centerline rumble strips along the other roadway types does not indicate that centerline rumble strips are ineffective on these other roadway types. Rather, it should be understood that the safety effects are simply unknown at this time. The safety effects have not be quantified at this time due to limited mileage of centerline rumble strip installations along these respective roadway types. Also, limited mileage of dual applications of rumble strips (i.e., centerline and shoulder rumble strips installed on the same road section) along rural two-lane roads prohibited formal evaluation of the safety effectiveness of this treatment along this respective roadway type; however, because the safety effect of this treatment is unknown and not quantified does not imply that the treatment is ineffective.

Finally, concerns have been expressed about the potential of motorcyclists losing control of their motorcycles when they encounter centerline rumble strips. Based upon a recent study, conclusive evidence exists to show that centerline rumble strips add no measurable risk to motorcyclists. Therefore, there is no need to consider potential adverse effects for motorcyclists when developing a centerline rumble strip policy. Similarly, there is no need to prohibit the use of centerline rumble strips on roadways with significant motorcycle traffic.

Type of Rumble Strips to Use

Nearly all transportation agencies in North America that install centerline rumble strips use milled rumble strips. As indicated above for shoulder rumble strips, the primary advantages of milled rumble strips over other types is that they can be installed at any time on new or existing pavements.

Dimensions of Centerline Rumble Strips

The general principles of the related discussion above for shoulder rumble strips hold true for determining the dimensions of centerline rumble strips. Regarding the recommended design threshold values for centerline rumble strips, it is recommended that centerline rumble strip patterns be designed to generate approximately 10 to 15 dBA above the ambient in-vehicle sound level. Due to the placement of the rumble strips in the center of the roadway, bicyclists should very rarely encounter the rumble strips themselves, so bicyclists rarely need to be considered in design dimensions of centerline rumble strips. On the other extreme, crash data presented in Section 2, Crashes and Heavy Vehicles, suggest that heavy vehicles should potentially be considered in the design of centerline rumble strips. Designing centerline rumble strips to generate approximately 10 to 15 dBA above the ambient in-vehicle sound level should be more than sufficient to alert drivers of heavy vehicles, based upon the results of the safety evaluation of shoulder rumble strips.

The noise prediction models in Tables 82 and 83 are applicable for designing centerline rumble strips. The following are the most common dimensions of milled centerline rumble strips used throughout North America:

- Length: 12 or 16 in. (305 to 406 mm);
- Width: 7 in. (178 mm);
- Depth: 0.5 in. (13 mm); and
- Spacing: 12 in. (305 mm).

Based upon the noise prediction models, this pattern generates a sufficient amount of noise in the upper range of the recommended design thresholds.

Near residential or urban areas, consideration should be given to designing centerline rumble strip patterns that generate between 6 to 12 dBA above the ambient in-vehicle sound level to minimize the impacts on nearby residents.

Placement of Centerline Rumble Strips Relative to the Centerline Pavement Markings

The placement of centerline rumble strips can be within the pavement markings, extend into the travel lane, or on either side of the centerline pavement markings. The most common type of application is to install centerline rumble strips that protrude into the travel lane, followed by centerline rumble strips that are within the limits of the painted centerline pavement marking. Only a few transportation agencies currently install centerline rumble strips on either side of the centerline pavement marking. It should be noted that the safety estimates provided above for centerline rumble strips do not directly consider the placement of the rumble strips relative to the centerline pavement markings.

The discussion above for shoulder rumble strips related to concerns over the visibility and retroreflectivity of pavement markings when rumble strips are installed on the edgeline (i.e., edgeline rumble strips) also applies to centerline rumble strips. In summary, concerns over the visibility and retroreflectivity of pavement markings should not prohibit the use of centerline rumble strips.

Features or Areas That Might Necessitate an Interruption in the Centerline Rumble Strip Pattern

Within a centerline rumble strip policy, consideration should be given to specific features or areas where the rumble strip pattern should be discontinued or interrupted to avoid adverse consequences. The following are specific features or areas along the roadway where it is common to discontinue or interrupt centerline rumble strips:

- Intersections and driveways;
- Passing zones;
- Structures (i.e., bridges); and
- Residential areas.

Regarding the discontinuation of centerline rumble strips at passing zones, it is currently not known what percentage of transportation agencies that install centerline rumble strips permit this treatment within passing zones versus the percentage of agencies that prohibit it. The safety estimates provided above do not directly account for passing zones. Treatment sites with and without passing zones were included in the safety evaluation. Also, previous research indicates that centerline rumble strips have little or no influence on driver behavior in passing zones. Therefore, there is no conclusive evidence to recommend that centerline rumble strips should be discontinued within passing zones.

The discussion above for shoulder rumble strips related to minimizing the impacts of rumble strips on nearby residents also applies to centerline rumble strips. In summary, consideration should be given to terminating centerline rumble strips 656 ft (200 m) prior to residential/urban areas.

Preparation of Centerline Rumble Strips Prior to Overlayment of the Pavement Surface

The general principles of the related discussion above for shoulder rumble strips hold true for centerline rumble strips. In summary, it is recommended to prepare areas with rumble strips prior to overlayment either by (1) milling, inlaying, and overlaying or (2) by simply milling and overlaying. Other preparation approaches such as shim and overlay or simply overlay will likely result in some degree of reflection in the area of the former rumble strips.

SECTION 11

Conclusions and Recommendations for Future Research

This section presents the primary conclusions from this research related to the design and application of shoulder and centerline rumble strips. This section also summarizes key unresolved issues related to the design and application of shoulder and centerline rumble strips.

Conclusions

The conclusions of this research are as follows:

- Shoulder rumble strips are an effective low-cost crash mitigation measure. The most reliable and comprehensive estimates to date of the safety effectiveness of shoulder rumble strips are for freeways and rural two-lane roads. Estimates of the safety effectiveness of shoulder rumble strips for rural multilane divided highways are also available but are not considered as reliable as the estimates for freeways and rural two-lane roads. The lack of reliable estimates on the safety effectiveness of shoulder rumble strips for other roadway types does not necessarily mean that shoulder rumble strips are ineffective on these roadway types; rather, the safety effects of shoulder rumble strips on these other facility types are not known at this time.
- The best available estimates of the safety effectiveness of shoulder rumble strips are as follows:
  - Rolled shoulder rumble strips on urban/rural freeways are expected to reduce SVROR crashes by 18 percent and SVROR FI crashes by 13 percent.
  - Shoulder rumble strips on rural freeways are expected to reduce SVROR crashes by 11 percent and SVROR FI crashes by 16 percent.
  - Shoulder rumble strips on rural two-lane roads are expected to reduce SVROR crashes by 15 percent and SVROR FI crashes by 29 percent.
  - Shoulder rumble strips on rural multilane divided highways are expected to reduce SVROR crashes by 22 percent and SVROR FI crashes by 51 percent.
- Given their proven safety benefits for several roadway types, the likelihood that shoulder rumble strips are effective on other roadway types, the low cost of installation, and relatively few concerns (i.e., noise, bicyclists, pavement performance, and visibility), shoulder rumble strips are considered appropriate for installation along a range of roadway types including freeways, on- and off-ramps, multilane divided and undivided highways, and two-lane roads in both rural and urban areas.
- On rural freeways, shoulder rumble strips should be placed as close to the edgeline as possible to maximize the safety benefits of the measure, taking into consideration other factors such as pavement joints.
- Centerline rumble strips are also an effective low-cost crash mitigation measure for undivided roadways with two-way traffic. The most reliable and comprehensive estimates to date of the safety effectiveness of centerline rumble strips are for rural and urban two-lane roads. The lack of reliable estimates on the safety effectiveness of centerline rumble strips for other roadway types does not indicate that centerline rumble strips are ineffective on these roadway types; rather, the safety effects of centerline rumble strips on other facility types are not known at this time.
- The best available estimates of the safety effectiveness of centerline rumble strips are as follows:
  - Centerline rumble strips on urban two-lane roads are expected to reduce TOT target crashes by 40 percent and FI target crashes by 64 percent.
  - Centerline rumble strips on rural two-lane roads are expected to reduce TOT crashes by 9 percent, FI crashes by 12 percent, TOT target crashes by 30 percent, and FI target crashes by 44 percent.
- The safety benefits of centerline rumble strips for roadways on horizontal curves and on tangent sections are for practical purposes the same.
- Given their proven safety benefits for several roadway types, the likelihood that centerline rumble strips are effective on

other roadway types, the low cost of installation, and relatively few concerns, centerline rumble strips are considered appropriate for installation along a range of roadway types including multilane undivided highways and two-lane roads in both rural and urban areas.

- For roadways where bicyclists are not expected (e.g., freeways), shoulder rumble strip patterns should be designed to produce sound level differences in the range of 10 to 15 dBA in the passenger compartment; and on roadways where bicyclists can be expected or near residential or urban areas, shoulder rumble strip patterns should be designed to produce sound level differences in the range of 6 to 12 dBA in the passenger compartment.
- Centerline rumble strip patterns should be designed to produce sound level differences in the range of 10 to 15 dBA in the passenger compartment, except near residential or urban areas where consideration should be given to designing centerline rumble strips to produce sound level differences in the range of 6 to 12 dBA in the passenger compartment.
- Statistical models developed in this research to predict the sound level difference in the passenger compartment when traversing rumble strips can be used to design rumble strip patterns that produce the desired alerting properties. Predictive models are available that include, as independent variables, the four primary rumble strip dimensions (i.e., length, width, depth, and spacing), vehicle speed, angle of departure, pavement type (asphalt or concrete), pavement condition (wet or dry), rumble strip type (milled or rolled), and location (shoulder or centerline).
- In situations where it is desirable to provide more lateral clearance for bicyclists or for installing shoulder rumble strips on roads with very narrow shoulders, shoulder rumble strips can be designed with relatively narrow lengths (e.g., 6 in. [152 mm]) and still generate the desired sound level differences in the passenger compartment.

Recommendations for Future Research

The key unresolved issues associated with shoulder rumble strips that should be addressed in future research are as follows:

- **Better quantify the safety effectiveness of rumble strip applications on different types of roads:** The most reliable and comprehensive estimates on the safety effectiveness of shoulder rumble strips are available for freeways and rural two-lane roads. Estimates on the safety effectiveness of shoulder rumble strips along rural multilane divided highway (nonfreeways) are also available but are not considered as reliable as the estimates for freeways and rural two-lane roads. The safety effectiveness estimates for freeways, rural two-lane roads, and rural multilane divided highways are considered appropriate only for the respective roadway types.

  The safety benefits of shoulder rumble strips along urban freeways (by themselves), urban freeway on-ramps and off-ramps, urban multilane divided highways (nonfreeways), urban multilane undivided highways (nonfreeways), urban two-lane roads, rural freeway on-ramps and off-ramps, and rural multilane undivided highways (nonfreeways) have not been quantified at this time due to limited mileage of shoulder rumble strip treatments along these respective roadway types. In the future it is desirable to calculate reliable safety estimates for these roadway types. Given the current state of applications, this issue should likely not be addressed for at least another 3 to 5 years to allow for more installations along the respective roadway types.
- **Determine the optimal placement of shoulder rumble strips on rural two-lane roads:** Conclusive evidence shows that on rural freeways rumble strips placed closer to the edgeline are more effective in reducing SVROR FI crashes compared to rumble strips placed farther from the edgeline. However, for other roadway types (e.g., rural two-lane roads), there is no conclusive evidence based upon crash statistics to indicate that offset distance influences the safety effectiveness of shoulder rumble strips. Further investigations, potentially through kinematic modeling, should be made to assess the optimal placement of shoulder rumble strips along roadway types, focusing primarily on rural two-lane roads.
- **Determine the optimal longitudinal gaps in rumble strips to provide accessibility for bicyclists while maintaining the effectiveness in reducing lane departures:** It may be possible to provide accessibility for bicyclists, while still preserving the effectiveness of rumble strips for motor vehicles, by providing longitudinal gaps in rumble strips. Moeur (*99*) addressed this issue from a bicyclist's perspective. However, this research did not account for vehicle speed and trajectory. In addition, the Moeur study did not vary the length of the rumble strip patterns, and the trajectories of bicyclists as they navigate from the outside of the rumble strip along the shoulder to the inside of the rumble strip near the travel lane are a function of bicycle speed, gap length, and rumble strip groove length. Further investigation into these issues is desirable.
- **Better quantify the safety effectiveness of shoulder rumble strips in varying conditions:**
  - **Along varying roadway geometry.** Studies concerning the safety effectiveness of shoulder rumble strips have utilized crash data collected over long segments of highway, such that the study segments included both tangents and horizontal curves. No distinction has been made in these studies or in the present research between

tangent and horizontal curve sections, and there are no studies that have analyzed the effectiveness of shoulder rumble strips at horizontal curves only. Therefore, there is no definitive information about potential differences in the safety effectiveness of shoulder rumble strips between tangents and horizontal curves.

 – **Effectiveness of rumble strips installed on the inside (left) or outside (right) shoulder.** Crash data suggest that the probability of leaving the travel lane on the outside (right) of the road differs from the probability of leaving the travel lane on the inside (left) of the road. This implies that different safety benefits should be expected for shoulder rumble strips installed on the inside (left) shoulder as compared to those installed on the outside (right) shoulder (*100*). However, this effect has not been quantified. The inability to distinguish between SVROR-left and SVROR-right crashes in the electronic databases assembled during this research prohibited the evaluation of this issue.

The key unresolved issues associated with centerline rumble strips that should addressed in future research are as follows:

- **Better quantify the safety effectiveness of centerline rumble strips in varying conditions:**
  - **Along passing zones and no-passing zones:** Safety evaluations of centerline rumble strips have not distinguished between the safety benefits in passing zones and no-passing zones. Research by Miles et al. (*38*) suggests that centerline rumble strips do not significantly change driving behaviors in passing zones, but no accident analyses have been conducted to support this conclusion.
  - **Along different roadway types:** The most reliable and comprehensive estimates on the safety effectiveness of centerline rumble strips are available for urban and rural two-lane roads. The safety benefits of centerline rumble strips along urban multilane undivided highways (non-freeways) and rural multilane undivided highways (non-freeways) likely differ from the safety estimates for urban and rural two-lane roads. The safety benefits have not been quantified at this time due to limited mileage of centerline rumble strip treatments along these respective roadway types, but in the future it is desirable to calculate reliable safety estimates for these roadway types. Given the current state of applications, this issue should likely not be addressed for at least another 3 to 5 years to allow for more installations along the respective roadway types.

The key unresolved issues associated with both shoulder and centerline rumble strips that should be addressed in future research are as follows:

- **Determine the minimum level of stimuli (i.e., sound or vibration) necessary to alert a drowsy or inattentive driver:** The minimum level of stimuli necessary to alert a drowsy or inattentive driver is a key human factors issue for which there is little reliable information. Recommended design thresholds are provided in this research, but the recommendations are based on common practice and engineering judgment. Further human factors research is needed to better assess noise thresholds for design purposes and to gain a better sense of the combined properties of noise and vibration in alerting inattentive, distracted, drowsy, and/or fatigued drivers.
- **Determine optimum dimensions of shoulder/centerline rumble strips necessary for effective vehicular warning with least potential for adverse effects:** Regression models have been developed to predict the in-vehicle sound level differential generated by rumble strips based on a number of factors including rumble strip dimensions (length, width, depth, and spacing), vehicle speed, vehicle angle of departure, rumble strip location (shoulder or centerline), pavement surface type (concrete or asphalt), rumble strip type (milled or rolled), and pavement surface condition (wet or dry). The noise prediction models developed during this research are the most comprehensive developed to date for determining optimum dimensions for rumble strips; however, the goodness-of-fit of the models is relatively low. Further investigations should be undertaken to improve the goodness-of-fit of these models, expand on the types of vehicles for which the models are calibrated, and assess appropriate ranges of the variables for design purposes.
- **Determine the impact of rumble strips on pavement performance:** Pavement deterioration due to the installation of rumble strips is a concern for many transportation agencies. Very little scientific research has been conducted to address these concerns, but through observational reports most of the pavement performance concerns appear to be unwarranted. Along the same lines, only a few transportation agencies consider pavement performance issues in their current rumble strip policies. Research is needed to determine the effect of rumble strips on long-term pavement performance and to provide guidance on minimum pavement depths for rumble strip installation.
- **Determine the visibility/retroreflectivity of pavement markings installed on milled shoulder/centerline rumble strips:** Some transportation agencies have reported concerns over the visibility and retroreflectivity of pavement markings when rumble strips are installed on the edgeline or centerline (i.e., edgeline or centerline rumble strips). These agencies note that potential problems may occur under nighttime conditions especially if snow, salt, sand, or debris collect in the grooves of the rumble strips. Conflicting evidence as to whether this is an actual problem is

found in the literature. The majority of studies suggest that visibility/retroreflectivity of pavement markings placed over rumble strips is higher compared to pavement markings placed on flat pavement, particularly during wet-night conditions. It does not appear that definitive research has been performed to completely resolve this issue.

- **Assess the impact of noise produced by rumble strips on adjacent residents:** This as a common problem cited by transportation agencies, although the problem is more related to rumble strips installed in the travel lane as compared to on the shoulder or centerline. This may become more of an issue as rumble strips are being installed (or are considered for installation) more frequently in urban areas. It does not appear that definitive research has been performed to completely resolve this issue. Future research should be undertaken to develop noise prediction models based on the rumble strip pattern and type, terrain, distance to nearby residents, and the type of building construction used in nearby residential communities. A procedure for selecting mitigation measures should then be developed to reduce noise propagation to residents that will experience noise levels above a predetermined minimum level.
- **Quantify the safety effectiveness of dual application treatments:** An attempt was made during this research to quantify the safety effectiveness of dual applications of rumble strips (i.e., sites with both centerline and shoulder rumble strips installed along the same roadway segment); however, limited mileage of such sites prohibited formal evaluation of the safety effectiveness of this treatment. In the future, it is desirable to calculate reliable safety estimates for the dual treatment of both centerline and shoulder rumble strips installed along the same roadway section. Given the current state of applications, this issue should likely not be addressed for at least another 3 to 5 years to allow for more installations of this dual treatment.

SECTION 12

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ACRONYMS

A-D	analog-to-digital
ADT	Average Daily Traffic
AMF	Accident Modification Factor
CalTrans	California Department of Transportation
C-G	Comparison Group
DUI	Driving Under the Influence
EB	Empirical Bayes
FARS	Fatality Analysis Reporting System (NHTSA)
FFT	Fast Fourier Transform
FI	Fatality and Injury
GEE	General Estimating Equations
GES	General Estimates System
GLM	Generalized Linear Model
GPS	Global Positioning System
HSIS	Highway Safety Information System
HSM	Highway Safety Manual
IHSDM	Interactive Highway Safety Design Model
IIHS	Insurance Institute for Highway Safety
ISO	International Standard Organization
IRI	International Roughness Index
jnd	just noticeable difference
MnDOT	Minnesota Department of Transportation
MoDOT	Missouri Department of Transportation
MRI	Midwest Research Institute
NB	Negative Binomial
NSF	National Sleep Foundation
OLS	ordinary least squares
PCC	Portland cement concrete
PennDOT	Pennsylvania Department of Transportation
RHR	roadside hazard rating
SE	standard errors
SLM	sound level meter
SPF	safety performance measure
SVROR	single vehicle run-off-road
TMS	transportation management system
TOT	total
VIF	variance inflation factors
WSDOT	Washington State Department of Transportation

Appendix A

Detailed Literature Review

This appendix provides a detailed summary of completed research on shoulder and centerline rumble strips. The information is organized in the following manner:

- Safety impacts of shoulder rumble strips
- Safety impacts of centerline rumble strips
- Operational impacts of centerline rumble strips
- Vehicle dynamics related to vibration and noise stimuli
- Effects of rumble strips on specific types of highway users (i.e., motorists, motorcyclists, and bicyclists)
- Pavement performance issues
- Other potential adverse concerns

A.1. Safety Effects of Shoulder Rumble Strips

This section presents results from studies on the safety effectiveness of shoulder rumble strip applications.

Arizona Study

In 1973, the Arizona DOT completed a study of the safety effectiveness of several shoulder treatments installed at locations that did not necessarily show either a high accident count or an above-average number of SVROR accidents (*16*). The analysis was performed using 1970 to 1972 accident data for several shoulder treatments along Interstate Routes 8 and 10. Results of the analysis indicated that sections with shoulder grooving had the fewest SVROR crashes, with 61 percent fewer SVROR crashes than other shoulder treatments. Additional analyses, using 1973 to 1976 accident data on the same 10-mi (16.1-km) test section of I-8 and an adjacent 16-mi (25.7-km) control section, concluded that the grooved shoulder sections had 80 percent fewer SVROR crashes per mile and 80 percent fewer SVROR crashes per million vehicle-mi traveled (MVMT) than the control section with standard shoulders.

California Study

California DOT (Caltrans) initiated a study in the early 1970s to develop and evaluate rumble strip installations that would alert motorists and prevent SVROR crashes (*49*). The first phase of the research consisted of developing shoulder rumble strip patterns that would alert motorists. The second phase involved installing trial installations at four locations and conducting a before-after crash analysis.

After conducting sound, vibrational, and controllability studies on 57 rumble strip patterns, the most effective patterns, in terms of alerting the inattentive/drowsy motorist, were selected for trial installations. Rumble strips made from ribs of asphalt and aggregate, rows of raised ceramic pavement markers, or incised (i.e., milled) slots were placed along selected sections of I-5, I-15, I-80, and SR 99 (a non-Interstate freeway). Criteria for site selection were adequate geometrics, a history of potentially correctable accidents, and a long period of time with no major changes to the roadway. In addition, a minimum right shoulder width of 8 ft (2.4 m) was selected since this would allow sufficient space for construction of the rumble strips and provide a substantial hazard-free runout area for vehicles that cross the rumble strips. The total length of the test installations was 36 mi (60 km).

An analysis of accident data (one year before and one year after) at the treatment sites and control sites was performed to evaluate the safety effectiveness of the rumble strip treatments. The control sections consisted of highway segments equal in length and adjacent to each end of the test installations. These control sections were selected to check on the validity of the before-after data and to evaluate whether SVROR accidents were moved downstream past the treatment sections. The analysis investigated the impact on both total accidents and SVROR accidents. Table A-1 provides a summary of the accident data at the treatment sites. Results from this safety evaluation did not provide statistically significant proof that rumble strips are an effective means of reducing SVROR crashes.

Table A-1. Accident Summary for Shoulder Rumble Strip Treatments in California (*49*)

Location	SVROR (Right Side)			All Other			Total		
	Before	After	% Change	Before	After	% Change	Before	After	% Change
I-5 Seal Coat	21	15	–28	70	80	+14	91	94	+3
SR 99 (NB) Pavement Markers	8	7	–12	22	15	–32	30	22	–27
SR 99 (SB) Seal Coat	2	9	+350	26	12	–54	28	21	–25
I-15 Seal Coat	2	0	–100	6	3	–50	8	3	–63
I-80 Milled	5	5	0	14	10	–29	19	15	–21
Total	38	36	–5	138	120	–13	176	155	–11

In the later half of the 1970s and early part of the 1980s, Chaudoin and Nelson (*17*) conducted another study on shoulder rumble strip applications for Caltrans. To reduce the number of SVROR crashes, rolled rumble strips were installed continuously along the shoulders of 158.5 mi (255 km) of freeways in the Mojave Desert on I-15 and I-40. The rumble strips were installed during resurfacing operations. Along most of the treatment sections, the rumble strips were placed along both the right (outside) and left (median) shoulders, but on several treatment sections the rumble strips were only installed on the right (outside) shoulder. The rolled rumble strips were 3 ft (0.9 m) in length and were spaced 8 in (203 mm) apart. The depth varied according to the thickness of asphalt concrete surfacing being placed, but the preferred and average depth was 1.5 in (38 mm).

A one-year before-after study was performed to evaluate the safety effectiveness of the rolled rumble strips. Nearby comparison sections of approximate length to the treatment sections were also identified for evaluation. In the analysis, SVROR accidents were tabulated for sections where rumble strips were installed. If rumble strips were installed only along the right (outside) shoulder, then only right-side SVROR accidents were included in the analysis for the given site. Truck accidents were not included because it was believed that rumble strips would have a lesser effect on truck drivers. Similarly, motorcycle accidents were excluded from the analysis for the same reason.

The accident analysis indicated a significant decrease in SVROR accidents as a result of the rumble strip installations. On the roadway sections where the rumble strips were installed, 194 SVROR crashes occurred in the before period, versus 100 SVROR crashes in the after period. On the control sections, 272 SVROR crashes occurred in the before period, while 326 SVROR crashes were reported in the after period. Thus, SVROR crashes were reduced by 49 percent on the freeway sections where continuous shoulder rumble strips were installed, while SVROR crashes increased by 20 percent on the comparison sites. The decrease in SVROR crashes was found to be statistically significant at the 99 percent confidence level. In addition, right-shoulder rumble strips proved more effective than left-shoulder rumble strips. Right-shoulder rumble strips reduced SVROR crashes by 63 percent as compared to a reduction of 18 percent by left-shoulder rumble strips. The 18 percent reduction in median SVROR crashes was not significant at the 90 percent confidence level. A 19 percent reduction in total accidents was also attributed to the shoulder rumble strip installations. This decrease in total crashes was found to be statistically significant at the 99 percent confidence level. Finally, it was concluded that shoulder rumble strips may be effective in reducing SVROR accidents on similar monotonous routes where there is a history of this type of accident and should only be installed at locations where the application is practical and justified. The authors cautioned that this conclusion should not be construed to apply to urban freeways nor necessarily those considered rural in nature without unusual problems.

Connecticut Study

Between the years of 1996 and 2000, the Connecticut Department of Transportation (ConnDOT) installed 1,020 shoulder-mi (1,640 shoulder-km) of rumble strips (*18*). Rumble strips were installed on limited-access roadways with a minimum of a 3-ft (0.9-m) shoulder. ConnDOT exclusively installed milled rumble strips placed in a continuous pattern. The dimensions of the rumble strips are 7 in (178 mm) wide, 16 in (406 mm) long, and 0.5 in (13 mm) deep, spaced 12 in (305 mm) on center. Initially, the rumble strips were placed 6 in (152 mm) from the edge of the travel way on the outside shoulder, but after complaints of noise from residents, ConnDOT changed their policy and placed the rumble strips 12 in (305 mm) from the edge of the travel way on the outside shoulder. The rumble strip placement on the left (i.e., inside) shoulder is 6 in (152 mm) from the left edge of the travel way and has not changed.

A before-after study was conducted by Annino (*18*) to evaluate the safety effectiveness of the shoulder rumble strips in reducing single-vehicle, fixed object, run-off-the-road accidents. Three years of before-accident data were collected (1993-1995), and three years of after-accident data were collected (1996-1998), at 11 locations where rumble strips were installed. Accident data from these 11 sites were analyzed with accident data from 11 comparison segments that did not have rumble strips. Table A-2 summarizes the accident data from the 11 treatment sites and comparison sites.

Annino used a before-after with comparison sites to evaluate the safety benefits of the shoulder rumble strips. Annino concluded there was a 32 percent reduction of rumble-strip-related accidents (defined as single-vehicle: fixed-object, off-shoulder accidents).

Table A-2. Summary of Accident Data for Treatment and Comparison Sites for Shoulder Rumble Strips in Connecticut (*18*)

Section ID	Rumble or comparison section	Route	Dir	Start MP	End MP	Total before accidents	Total after accidents	Percent change (%)
1R	Rumble	8	NB	19.28	25.14	23	20	–13.04
1C	Comparison	8	NB	13.42	19.28	37	59	59.46
2R	Rumble	8	NB	42.64	50.11	36	36	0.00
2C	Comparison	8	NB	35.17	42.64	31	35	12.90
3R	Rumble	8	SB	19.28	25.14	20	18	–10.00
3C	Comparison	8	SB	13.42	19.28	20	28	40.00
4R	Rumble	9	NB	0.23	3.91	7	7	0.00
4C	Comparison	9	NB	3.91	7.59	15	16	6.66
5R	Rumble	9	NB	24.47	27.43	26	29	11.53
5C	Comparison	9	NB	27.43	30.39	16	9	–43.75
6R	Rumble	9	NB	37.49	39.93	9	4	–55.56
6C	Comparison	9	NB	35.05	37.49	15	14	-6.67
7R	Rumble	9	SB	37.49	40.71	11	9	–18.18
7C	Comparison	9	SB	34.27	37.49	25	22	–12.00
8R	Rumble	9	SB	24.47	29.10	36	35	–2.77
8C	Comparison	9	SB	19.84	24.47	17	13	–23.52
9R	Rumble	9	SB	0.23	3.91	10	13	30.00
9C	Comparison	9	SB	3.91	7.59	21	24	14.29
10R	Rumble	15	NB	50.20	59.72	58	24	–58.62
10C	Comparison	15	NB	37.62	47.14	39	36	–7.69
11R	Rumble	15	SB	50.20	59.72	34	15	–55.88
11C	Comparison	15	SB	37.62	47.14	29	38	31.03
Total	Rumble					270	210	–22.22
Total	Comparison					265	294	10.94

Florida Study

To reduce SVROR crashes along a 19-mi (31-km) section of U.S. 1 in Florida, the main highway to Key West, raised pavement markers were installed four abreast across the shoulder at a 45-degree angle (*16*). In its 1980 to 1981 annual report, the Florida DOT reported a decrease in fixed object crashes from 19.5 to 11.5 per year due to the raised rumble strip treatment. The Florida DOT also reported a decrease in ran-into-water accidents from 8 to 5.5 per year. Thus, the Florida DOT concluded the special raised rumble strip treatment achieved their goal in preventing the inattentive/drowsy motorists from leaving the shoulder.

Illinois and California Study

Griffith (*1*) examined the safety effects of continuous shoulder rumble strip applications on rural and urban freeways in Illinois and California. Before-after evaluations were conducted on projects that involved the installation of rolled rumble strips as part of a resurfacing project. In Illinois, the standard depth of rolled rumble strips is 0.75 in (19 mm) with a length of 3 ft (0.9 m) and a spacing of 8 in (203 mm). The rumble strips are installed 12 in (304 mm) from the edge of pavement. In California, shoulder rumble strips are 0.75 in (19 mm) or less in height if raised or 1 in (25 mm) or less in depth if indented and extend along the highway shoulder. The maximum length of the shoulder rumble strip did not exceed 3 ft (0.9 m).

Data were extracted from the Highway Safety Information System (HSIS) databases to perform the safety evaluation. The Illinois data included 63 projects totaling 284 mi (457 km) that were completed between 1990 and 1993. The California data included 28 projects totaling 122 mi (197 km) that were completed between 1998 and 1993. Griffith analyzed the data using matched-pair comparisons (i.e., one-to-one matching between treatment sites) and comparison groups (i.e., one-to-many matching between treatment sites).

In general, Griffith concluded continuous shoulder rumble strips provide a safety benefit to motorists on freeways. Because larger sample sizes were obtained from Illinois, more weight was given to the Illinois findings, so based on the Illinois data, Griffith estimated the average safety effectiveness of continuous shoulder rumble strips to be:

- On all freeways, an 18.3 percent reduction in total SVROR crashes with a standard deviation of 6.8 percent.
- On all freeways, a 13 percent reduction in injury SVROR crashes with a standard deviation of 11.7 percent.
- On rural freeways, a 21 percent reduction in total SVROR crashes with a standard deviation of 10.2 percent.

Griffith also evaluated two types of potential adverse effects related to the safety of continuous shoulder rumble strips. One potential adverse effect pertains to the possibility that some motorists may overreact to the stimulation generated by the rumble strips resulting in loss of control of their motor vehicles. The second potential adverse effect is crash migration, which occurs when a motorist is temporarily saved from a crash at a treated site but crashes downstream of the treated area or in another location on the network. Griffith found these potential adverse effects to be insignificant.

Kentucky Study

Kirk (*101*) conducted at study of continuous shoulder rumble strips in Kentucky with the primary intention to answer the following questions:

- Do continuous shoulder rumble strips reduce crash frequency on rural two-lane roads with little or no shoulder?
- When limited pavement width is available, should shoulder width be increased to provide continuous shoulder rumble strips or should lane width be maximized?

A total of 162 unique sections were identified for crash analysis, including 109 sections with rumble strips and 53 sections without rumble strips. Three years of crash data were analyzed.

The crash data were analyzed using regression analysis. Based upon this analysis, the following conclusions were made:

- Rural two-lane roads with continuous shoulder rumble strips have a statistically significant lower total crash rate than roads without continuous shoulder rumble strips.
- Rural two-lane roads with continuous shoulder rumble strips have a statistically significant lower crash rate resulting from inattention/drowsiness than roads without continuous shoulder rumble strips.
- Rural two-lane roads exhibit a statistically significant decrease in SVROR crash rates as lane width increases.
- Crash rates on rural two-lane roads are generally lower when shoulder width is maximized and lane width is minimized.

Maine Study

Maine DOT began installing continuous shoulder rumble strips along rural freeways between 1994 and 1995 (*20*). Prior to these installations, Gårder and Alexander (*102*) assessed the safety effectiveness of continuous shoulder rumble strips for Maine DOT based upon previous studies and estimated a 50 percent reduction in sleep related accidents due to the installation of shoulder rumble strips. Approximately, 37 mi (59 km) of rumble strips were installed on the Interstate system in Maine. The dimensions of the rumble strips were as follows:

Construction—milled
Length—16 in (406 m)
Width—7 in (178 mm)
Depth—0.5 to 0.75 in (13 to 19 mm)
Spacing—12 in (305 mm) on centers

A preliminary analysis of accident data was performed (*20*). The analysis included accident data from 1991 to 1994. Accident reports from 1995 were not available for the evaluation. Table A-3 provides a summary of the accident data. Based upon the limited data, it was not possible to draw any conclusions on the safety effects of continuous shoulder rumble strips installed along selected sections of Maine's Interstate highways.

Table A-3. Accident Counts Before and After Installation of Shoulder Rumble Strips in Maine (*20*)

Analysis period	Treatment sections	Comparison sections
Before Period (44 months)	53 accidents	56 accidents
After Period (3 months)	3 accidents	3 accidents

Michigan Study

Morena (*21*) evaluated the safety effectiveness of different shoulder rumble strip types/designs in reducing SVROR accidents. Morena compared the safety of roads with milled, rolled, and formed (intermittent) rumble strips. Milled shoulder rumble strips in Michigan are 7 in (178 mm) wide, 16 in (406 mm) long, and 0.5 in (13 mm) deep; they are placed 12 in (305 mm) from the edgeline on the left shoulder and 12 in (305 mm) or 24 in (610 mm) from the edgeline on the right shoulder. No design criteria were given for Michigan's rolled or formed concrete intermittent rumble strips.

The safety analysis included accident data from 984 mi (1,584 km) of roadway with rumble strips installed from 1996-2001. From these 984 mi (1,584 km) of roadway, over 3,000 accident reports were reviewed to determine whether they should be considered SVROR accidents. A total of 1,887 of the 3,000 accidents were classified as SVROR. Morena reasoned that SVROR accidents were the accidents types most likely to be preventable by shoulder rumble strips and include drowsy or distracted drivers. The safety performance of the 984 mi (1,584 km) of roadway with rumble strips was compared to the safety performance of the 454 mi (730 km) of roadway without rumble strips.

Morena found an almost equal number of SVROR accidents and similar severity distributions on each side of the roadway. The severity of SVROR accidents was extremely high with 17 percent of the accidents resulting in a fatal or incapacitating injury. Morena also reported a noticeable decline in SVROR accidents with the increase of ADT.

Morena found that roads with milled rumble strips had a 38 to 39 percent reduction in SVROR accidents in an ADT range of 5,000-60,000 vpd. Both formed intermittent and rolled rumble strips reduced SVROR accidents by 25 percent.

Minnesota Studies

Carrasco et al. (*3*) examined the safety effect of shoulder rumble strips constructed on rural multilane highways in Minnesota. Highway Safety Information System (HSIS) data from Minnesota were used in the evaluation along with additional data provided by the Minnesota Department of Transportation (MnDOT). The dimensions of the rumble strips installed along the rural multilane highways in Minnesota were as follows:

Construction:	milled
Pattern:	continuous
Length:	24 in (610 mm)
Width:	2 to 4 in (51 to 102 mm)
Depth:	0.375 to 0.625 in (10 to 16 mm)
Spacing:	8 to 12 in (203 to 305 mm) on centers
Lateral Offset:	6 and 12 in (152 and 305 mm) from outside edge of travel lane

Data from 23 treatment sites were included in the before-after evaluation. The section lengths ranged from 2.7 to 12.9 mi (15.9 to 20.8 km), encompassing a total of 163 mi (262 km) of highway. The shoulder rumble strips were constructed on the divided multilane highways between 1991 and 1998. The rumble strips were installed on the inside and outside shoulders for both directions of travel. The speed limits of the treatment sites ranged from 55 to 70 mph (89 to 113 km/h). Data from 11 comparison sites were also collected. The section lengths of the comparison sites ranged from 4.45 to 11.5 mi (7.16 to 18.5 km), encompassing a total of 83 mi (134 km) of highway.

Carrasco et al. analyzed the data using both a naïve before-after study approach and a before-after analysis with comparison sites. The results of the naïve before-after analysis indicated the average reduction in total crashes and injuries at the treatment sites were 16 and 17 percent, respectively. The naïve before-after analysis also found a 10- and 22 percent reduction in total and injury SVROR crashes, respectively. Based upon the analysis with comparison sites, total crashes and injuries were reduced by 21 and 26 percent, respectively. Total and injury SVROR crashes were reduced by 22 and 51 percent, respectively.

Similar to the Carrasco et al. (*3*) study, Patel et al. (*2*) conducted research on the safety effects of shoulder rumble strips in Minnesota utilizing available HSIS data. However, the focus of this evaluation was on estimating the reduction in SVROR crashes along rural two-lane roads.

All sites had lane widths of 12 ft (3.7 m) and right shoulders that varied in width from 1-2 ft (0.3-0.6 m) to 12 ft (3.7 m). An initial pool of 36 sites in Minnesota were reduced to 23, representing 183 mi (294 km) of roadway, after eliminating sites where additional geometric changes might have occurred at the same time the rumble strips were installed. After an effort was made to remove non-conforming sites from the study, safety performance functions (SPFs) were developed for all crashes and injury crashes.

The effect of installing shoulder rumble strips was estimated to be a 13 percent reduction for all SVROR crashes and an 18 percent reduction for injury SVROR crashes. This effect was found to be statistically insignificant at the 95th percentile confidence level; Patel et al. postulated that this was due to the relatively small sample size and restated their confidence in the positive effect of shoulder rumble strips in this highway class. Patel et al. recommended, but was unsuccessful at finding any correlation between rumble strip effectiveness and horizontal curvature, night-time crashes, shoulder clear-zone width, or clear-zone nature (i.e., side slopes).

Montana Study

Marvin and Clark (*22*) conducted a study to evaluate the safety effectiveness of shoulder rumble strips in preventing single vehicle off-road and rollover crashes (under wet or dry pavement conditions only) on Interstate and primary highways in Montana. The rumble strips in this study were all consistent with Montana's 1996 design polices for rumble strips:

Concrete:

Construction—formed continuous corrugation
Length—12 to 16 in (300 to 400 mm)
Radius—1 in (25 mm)
Depth—1 in (25 mm)
Spacing—4.5 in (114 mm) on centers
Lateral Offset—6 in (150 mm) outside edgeline

Asphalt:

Construction—milled
Length—12 to 16 in (300 to 400 mm)
Radius—12 in (300 mm)
Depth—0.5 to 0.75 in (13 to 19 mm)
Spacing—4.5 in (114 mm) on centers
Lateral Offset—6 in (150 mm) outside edgeline

The study investigated 393 mi (632 km) of Interstate (35 percent of Montana's total Interstate system) and 213 mi (343 km) of primary roadway (4 percent of Montana's total primary routes). Accident data from three years before the rumble strips were installed were compared with accident data for three years after the installation. In most cases, the study periods were 1992-1994 (before) and 1997-1999 (after). The analysis also considered data from comparison sections. Several conclusions drawn from this evaluation are as follows:

- In the case of both Interstate and primary highways, rumble strips appear to lessen the number of crashes occurring during hours of darkness. It follows that through times of compromised visibility, the ability of rumble strips to offer warning that appeals to senses other than sight would decrease the probability of being involved in a SVROR accident.
- On Interstate roadways, rumble strips may have contributed to reducing the number of crashes experienced by drivers under the age of 21 and older drivers over the age of 50. No significant benefits were evident regarding primary roadways concerning age. The differences from Interstate highways likely stem from the fact that primary routes often have narrower shoulders than Interstates.
- Limited data suggest that motorcycles may be impacted by rumble strip installations on Interstates.
- No conclusions were drawn concerning rumble strips and bicycles because there were no records of bicycle accidents on any of the study segments.
- Roadway widths were investigated for primary highways due to their high variability on such roads throughout Montana. Crash rates before and after rumble strip installation did not show any appreciable dependence upon roadway widths, however, behaviors regarding severity were found to be counterintuitive without explanation.
- Statistical analyses indicated that the reduction of Interstate off-road crash rates attributable to shoulder rumble strips was 14 percent with a corresponding reduction of 23.5 percent in severity rates. In conjunction, the benefit/cost ratio for construction of shoulder rumble strips on Interstate highways was 19.5. However, the safety benefits of shoulder rumble strips on primary highways was uncertain.
- In general, rumble strips seem to be moderately successful in reducing the occurrence of various situation crashes, most notably those caused by drowsy or inattentive driving. As they pertain to the roadway system, the effect of shoulder rumble strips on crash experience was not statistically significant at the confidence level investigated. In fact, while Interstate and primary system analyses shows some benefit for off-road crash rate and severity in certain situations, rumble strip performance for rollover crashes showed that severity may well have increased through rumble strip deployment or other undefined factors. No specific rationale for determining the reason behind this increase is evident.

Nevada Study

Nambisan et al. (*103*) conducted an evaluation of the effectiveness of continuous shoulder rumbles in reducing SVROR crashes in Nevada. A total of 370 roadway segments were analyzed. The segments consisted of interstates, U.S. routes, and state routes. Crash data from 1995 to 2003 were analyzed. The analysis was based on before-after comparisons of SVROR crash frequencies and crashes rates. It was concluded from the analysis that continuous shoulder rumble strips on roads in Nevada were effective in reducing the frequency of SVROR crashes and the corresponding crash rates. The analyses did not include information related to traffic volumes or vehicle miles of travel.

New York Study

In New York, continuous shoulder rumble strips have been installed along Interstate highways and parkways maintained by the New York State Department of Transportation (NYSDOT) and along the New York State Thruway which is owned and operated by the New York State Thruway Authority (NYSTA) (*23*). In 1993, NYSDOT installed only 91 shoulder-mi (148 shoulder-km) of continuous rumble strips, as compared to 1,725 shoulder-mi (2,777 shoulder-km) in 1995 and 3,150 shoulder-mi (5,017 shoulder-km) in 1998. Continuous shoulder rumble strips were installed on 1,945 shoulder-mi (3,131 shoulder-km) of the New York State Thruway by 1996. Both agencies, NYSDOT and NYSTA, collected before and after data to evaluate the safety effectiveness of the continuous shoulder rumble strips installed within the state. A sample of the data collected by NYSTA is presented in Table A-4, summarizing the number of SVROR crashes and the vehicle-miles traveled during the before and after study periods. The crashes represented in Table A-4 are due to the following causes:

- Alcohol involvement
- Driver inattention
- Driver inexperience
- Drugs (illegal)
- Fell asleep
- Illness
- Passenger distraction
- Prescription medication
- Fatigue, drowsiness
- Glare

Both agencies have noted a reduction in SVROR crashes of at least 65 to 70 percent based, apparently, upon a naïve before-after approach.

Table A-4. Before-After Comparison for Shoulder Rumble Strips Along the New York State Thruway (*23*)

Year	Total SVROR crashes	Total injuries	Total fatalities	Vehicle-miles traveled (millions)
Before and During Rumble Strip Installation				
1991	557	358	17	6,744
1992	566	407	17	7,612
1993	588	328	8	7,792
After Rumble Strip Installation Completed (Percent Reduction from 1991)				
1996	161 (74)	113 (72)	4 (75)	8,512
1997	74 (88)	54 (87)	1 (95)	8,692

Pennsylvania Study

In 1984, 48 percent of the crashes along the Pennsylvania Turnpike were SVROR crashes (*104*). The percentage of SVROR crashes continued to increase over the next two years to 51 percent in 1985 and 57 percent in 1986. During this same time period, the Pennsylvania Turnpike Commission was developing the Sonic Nap Alert Pattern or SNAP, a narrow rumble strip to be located continuously along the right shoulder, just outside of the edgeline of the pavement. After testing five different patterns, a standard rumble strip pattern was selected:

Construction—milled
Length—16 in (406 mm)
Width—7 in (178 mm)
Depth—0.5 (13 mm)
Spacing—12 in (305 mm) on centers

Based upon an initial experience at a single site approximately 7 mi (11 km) in length, by May 1992 rumble strips were installed along five more sections of the Turnpike totaling 31 mi (50 km). A safety evaluation in 1993 confirmed the effectiveness of SNAP. The Turnpike experienced a 70 percent reduction in SVROR crashes over substantial time periods. As a result of their experiences, the Turnpike Commission initiated a program to have over 80 percent of the turnpike system protected with SNAP by the end of 1994.

In a follow-up study, Hickey (*24*) reviewed the initial results presented by Wood (*104*) and further accounted for traffic exposure and a decline in all accidents during the years considered. Furthermore, Hickey excluded from the analysis several single-vehicle accident types considered non susceptible to SNAP such as weather (snow, ice, slippery, wet, and spun out), blow out, flat, mechanical defect, improper towing, forced movement, evading object, animal, work zone, blackout, and inside vehicle event. Thus, Hickey revised the initial reported accident reduction attributable to SNAP to a 65 percent reduction in SVROR rates. Hickey also expanded the study to consider all the sections of the turnpike where SNAP were installed, and based upon data from 1990 to 1995 Hickey found a 60 percent reduction in SVROR crashes over 53 sections of the turnpike totaling 348 mi (560 km).

Tennessee Study

The Tennessee Department of Transportation (TDOT) (*25*) has been installing milled shoulder rumble strips on all of its Interstate resurfacing projects since 1996. In 2001, TDOT began a statewide project to install shoulder rumble strips along the approximately 315 mi (507 km) of Tennessee's Interstate system where rumble strips had not yet been installed. TDOT reported a 31 percent reduction in SVROR crashes on the portions of the Interstate system that did not previously have rumble strips.

Texas Study

The effect of edgeline rumble strips on erratic driving behaviors was evaluated by Miles et al. (*105*) at the request of TxDOT. Using a before-after video analysis of sites where edgeline rumble strips were installed, Miles et al. attempted to document events in which the driver's reaction to entering the shoulder was effected in such a way as to cause an unsafe situation. The erratic behaviors in question included (but were not limited to) hard braking, swerving, rapid alignment or lane shifting, correcting the trajectory in the wrong direction or losing control of the vehicle. After reviewing 120 hours of video for the before and after period (cumulative) at sights along a rural highway, Miles et al. were unable to find any events that were considered erratic. They did, however, find a reduction in passenger vehicles encroaching upon the shoulder of approximately 35 percent. Thus, it was concluded that while the installation of edgeline rumble strips did increase the number of corrective actions by drivers to remain in-lane, it did not create an unsafe environment.

Utah Study

The Utah DOT compared the accident rate experience along Interstate highways with and without rumble strips (*26*). In Utah, rolled rumble strips were installed along interstates with asphalt shoulder pavements, and formed rumble strips were installed along interstates with concrete shoulder pavements. The dimensions of the rumble strips were as follows:

Asphalt:
- Construction—rolled
- Length—2 ft (0.6 m)
- Width—1.5 in (38 mm)
- Depth—1 in (25 mm)
- Spacing—8 to 9 in (203 to 229 mm) on centers
- Lateral Offset—12 in (305 mm) from outside edgeline

Concrete:
Construction—formed skip pattern
Length—6 ft (1.8 m) for 10 ft (3.0 m) shoulders
4 ft (1.2 m) for 6 ft (1.8 m) shoulders
3 ft (0.9 m) for 4 ft (1.2 m) shoulders
Width—4.5 in (114 mm)
Depth—0.75 in (19 mm)
Spacing—4.5 in (114 mm) on centers
Lateral Offset—6 in (152 mm) to 2 ft (0.6 m) from outside edgeline
Skip Pattern—6 ft (1.8 m) rumble strips and 4 ft (1.2 m) clear space or
6 ft (1.8 m) rumble strip patterns on 10 ft (3.0 m) centers

The analysis included 41 segments (30 asphalt and 11 concrete pavements) with rumble strips totaling 186 mi (299 km), and 35 segments without rumble strips totaling 110 mi (177 km). Among the segments with rumble strips, there were 111 mi (179 km) of asphalt pavement and 75 mi (121 km) of concrete pavement. Accident data for the years 1990 through 1992 were used in the evaluation.

Cheng et al. compared the accidents rates of Intestate segments with and without rumble strips. Both overall accident rates and SVROR type accident rates were considered in the analysis. The results showed overall crash rates were 33.4 percent higher on the control sections as compared to the sections where rumble strips were installed. Similarly, SVROR crash rates were 26.9 percent higher on the sections without rumble strips. Statistical tests conducted during the analysis could not verify the significance level of the difference in the accident rates.

Cheng et al. also compared the accident rates of rumble strip on asphalt shoulders and rumble strips on concrete shoulders. The analysis revealed the overall accident rate for concrete pavement was 16.9 percent higher than that for asphalt pavement. Similarly, the accident rate for SVROR crashes on concrete pavement was 23.8 percent higher than that for asphalt pavement. Statistical tests could not verify the significance level of difference in the accident rates. The study also showed that rumble strips were effective in reducing crash severity.

In general, Cheng et al. concluded the following:

- Freeways without shoulder rumble strips experience a higher rate of accidents over those highways with shoulder rumble strips.
- Highway segments with rumble strips on asphalt shoulders (continuous and near travel lane design) have lower accident rates than highway segments with rumble strips on concrete shoulders (discontinuous and offset from travel lane design).
- The discontinuous design proved to be less effective in alerting drivers to potentially dangerous driving patterns.

- Rumble strips are effective in lowering accident severity, and furthermore, the continuous design proved to be even more effective over the discontinuous design.

Based on the results of the safety evaluation, Cheng et al. recommended the following points when considering installation of rumble strips along highway shoulders:

1. Shoulder rumble strips should be installed on highway and freeway shoulders.
2. Rumble strips should be as wide as possible.
3. Highway segments with high SVROR accident rates, such as rural areas should receive highest priorities.
4. Detours during road construction should be considered when determining the method of installation. Generally, milled rumble strips will be an effective method during any phase of construction.
5. The continuous design is preferred over the discontinuous design.
6. Rumble strips should be placed as close to the travel lanes as possible. Such placement not only provides advance warning to drivers but also provides a buffer zone between traffic and bicyclists on the shoulder.

Virginia Study

Chen et al. (*27*) performed a three-year before-after safety evaluation of continuous shoulder rumble strips installed along rural freeways in Virginia. Crash data were obtained from the Highway Traffic Records Inventory System (HTRIS) database maintained by Virginia DOT. Crash data from June 1994 through October 2000 were used in the analysis. The safety evaluation was based on a before-after analysis with comparison sites using data from 9 treated sites representing 285 mi (459 km) of roadway, and 9 comparison sites of similar length. Table A-5 summarizes the accident data and analysis results. The detailed statistical analysis indicated an overall reduction rate in SVROR crashes on Virginia's rural highway was 51.5 percent.

Washington Study

The Washington State DOT installed shoulder rumble strips at six locations between 1986 and 1990 [unpublished; cited in Harwood (*15*)]. Three types of rumble strips were installed at the various locations. Raised pavement markers were installed on the shoulder at one location; raised 12-in (305-mm) wide rumble strips were installed at a second location; and rolled rumble strips were installed at four other locations. A safety evaluation for five of the six locations revealed a statistically significant reduction in crash frequency at only one of the five locations. However, when considering the five sites collectively, the overall crash frequency decreased by 18 percent from before to after rumble strip installation. The report does not indicate whether this overall reduction in accident experience was statistically significant.

Table A-5. Accident Summary of SVROR Crashes and Statistical Significance Before and After Installation of Shoulder Rumble Strips in Virginia (*27*)

	Treated Sites		Comparison Sites			
Segment	Before	After	Before	After	Percent change	Statistically significant (95%)
1	65	46	69	73	–49.50	Yes
2	157	89	170	149	–54.60	Yes
3	52	37	47	62	–85.40	Yes
4	52	31	49	54	–84.80	Yes
5	41	25	55	35	–4.40	No
6	33	48	77	99	11.60	No
7	64	67	66	93	–34.60	Yes
8	48	45	59	103	–86.00	Yes
9	79	70	72	50	21.60	No
All	591	485	654	718	–51.50	Yes

Multistate Study

Ligon et al. (*16*) conducted a before-after safety evaluation of shoulder texture treatments on rural freeways based on data from 11 states (Arizona, California, Florida, Georgia, Mississippi, Nevada, North Carolina, South Carolina, South Dakota, Utah, and Wisconsin). The various shoulder texture treatments installed in the 11 states included:

Concrete Shoulder Treatments:
- Concrete corrugated panels

Bituminous Shoulder Treatments:
- Bituminous single groove
- Bituminous indented strip
- Bituminous surface treatment

Miscellaneous Textured Shoulder Treatments:
- Raised Shoulder Treatments
  - Jiggle bars
  - Raised circular pavement markers
  - Bituminous ribbed panels
- Indented Shoulder Treatments
  - Bituminous corrugated panels
  - Cold planing

The analysis included comparing accident rates at treatment sites and control sites. The control sites were chosen to be as similar as possible as the treatment sites except that the shoulders had nontextured surfaces. In almost all cases, the comparison sites were highway sections on the same Interstate route, either adjacent to or near the treatment section. Tables A-6 and A-7 provide a summary of the accident data at the treatment sites and control sites. About two-thirds of the sites had accident data for two years and one-third of the sites had accident data for one year.

Table A-6. SVROR Accidents (right and left) Before and After Textured Shoulder Treatments in 11 States (treatment sections) (*16*)

Test Section										
				Number of accidents		ADT		Accident rate (per 10^6 veh-mi)		
Site No.	Texture type	Number of years	Test length (mi)	Before	After	Before	After	Before	After	Signif. change
1	BIS	1	14.7	9	9	2,715	2,915	0.309	0.288	N
2[a]	BSG	1	12.5	10	7	2,315	2,640	0.473	0.291	N
3[a,b]	BSG	2	18.5	38	36	4,425	7,750	0.318	0.172	Y
4[a,b]	BSG	2	9.7	30	36	4,175	4,750	0.507	0.535	N
52	BST	2	15.3	59	46	3,750	4,075	0.706	0.507	N
6	BIS	1	17.3	26	14	10,200	10,600	0.202	0.105	Y
7	BIS	1	9.2	16	7	10,400	10,150	0.229	0.103	Y
8	BIS	1	20.7	20	16	7,750	7,400	0.171	0.143	N
9	CCP	1	13.0	NA[d]	1	10,473	10,000	NA[4]	0.011	NA[d]
10	CCP	2	14.2	NA[d]	9	2,252	2,150	NA[4]	0.202	NA[d]
11	CCP	2	23.8	NA[d]	8	6,834	6,525	NA[4]	0.035	NA[d]
12	CCP	2	22.2	NA[d]	14	6,038	5,765	NA[4]	0.075	NA[d]
13[b]	BST	2	9.7	1	3	2,620	3,100	0.025	0.069	N
14	CCP	2	6.7	7	6	2,820	3,050	0.254	0.201	N
15	BIS	2	16.6	46	43	3,140	3,585	0.604	0.495	N
16	BIS	2	26.2	56	63	2,345	2,415	0.624	0.682	N
17[c]	BST	2	13.5	34	25	9,125	7,625	0.189	0.166	N
18	BST	2	7.9	24	9	8,375	9,525	0.248	0.082	Y
19	CCP	2	12.0	NA[d]	7	2,128	2,420	NA[4]	0.165	NA[d]
20	CCP	2	10.0	13	25	3,630	4,240	0.245	0.404	N
21	CCP	2	23.0	NA[d]	9	3,724	4,350	NA[4]	0.062	NA[d]

[a] Texture on right shoulder only.
[b] Test section had textured shoulders during both before and after periods.
[c] Test section before was textured and after was smooth shoulder. “After” data is for textured condition.
[d] “Before” accident data not available with new construction sites.

N—Not significant at 0.05 level
Y—Significant at 0.05 level

BIS—Bituminous indented strip
BSG—Bituminous single groove
BST—Bituminous surface treatment
CCP—Concrete corrugated panel

Table A-7. SVROR Accidents (right and left) Before and After Textured Shoulder Treatments in 11 States (comparison sections) (16)

Test Section										
				Number of accidents		ADT		Accident rate (per 10^6 veh-mi)		
Site No.	Texture type	Number of years	Test length (mi)	Before	After	Before	After	Acc. rate before	Acc. rate after	Signif. change
1	BIS	1	20.0	12	8	3,450	3,500	0.238	0.157	N
2[a]	BSG	1	20.0	9	13	3,400	3,450	0.181	0.258	N
3[a,b]	BSG	2	20.0	26	22	4,200	4,625	0.212	0.163	N
4[a,b]	BSG	2	20.0	26	22	4,200	4,625	0.212	0.163	N
5[b]	BST	2	20.0	26	22	4,200	4,625	0.212	0.163	N
6	BIS	1	37.9	46	49	7,350	7,150	0.226	0.248	N
7	BIS	1	37.9	39	61	7,350	7,150	0.192	0.308	Y
8	BIS	1	37.9	45	61	7,350	7,150	0.221	0.308	N
9	CCP	1	13.0	7	16	9,600	11,500	0.077	0.147	N
10	CCP	2	22.9	5	7	4,550	4,570	0.033	0.046	N
11	CCP	2	24.5	10	17	4,880	5,675	0.057	0.064	N
12	CCP	2	21.4	3	9	8,715	9,600	0.011	0.029	N
13[b]	BST	2	7.0	1	2	2,815	2,945	0.035	0.067	N
14	CCP	2	7.0	1	2	2,815	2,945	0.035	0.067	N
15	BIS	2	10.0	18	15	3,000	3,390	0.411	0.303	N
16	BIS	2	11.5	13	9	2,215	2,290	0.350	0.235	N
17[c]	BST	2	18.7	79	59	10,525	6,750	0.275	0.247	N
18	BST	2	18.7	60	75	8,500	9,850	0.259	0.279	N
19	CCP	2	12.0	13	7	2,550	2,670	0.291	0.150	N
20	CCP	2	10.0	18	22	3,600	4,230	0.342	0.356	N
21	CCP	2	14.0	10	4	4,315	4,985	0.113	0.039	N

[a] Texture on right shoulder only.
[b] Test section had textured shoulders during both before and after periods.
[c] Test section before was textured and after was smooth shoulder. "After" data are for textured condition.

N—Not significant at 0.05 level
Y—Significant at 0.05 level

BIS—Bituminous indented strip
BSG—Bituminous single groove
BST—Bituminous surface treatment
CCP—Concrete corrugated panel

The following conclusions were drawn from a detailed analysis of the accident data:

- There is insufficient evidence to indicate any significant differences in accident reduction when comparing:
  - Types of textured shoulder treatments
  - High ADT vs. low ADT sites
  - Day vs. night reduction in accidents
  - Normal vs. other driver conditions
  - Wide vs. narrow shoulder textured treatments
  - Spaced vs. continuous shoulder textured treatments

- Least squares regression analysis of accident rates before texturing compared to accident rates after texturing at the test sites showed a significant 9 percent reduction in SVROR accidents.
- Chi-squared tests of before-after accident data at treatment sites and control sites indicated in a significant reduction in accidents at sites with textured treatments. Treatment sites exhibited a 19.8 percent decrease in SVROR accidents compared to a 9.3 percent increase at the comparison sites.

A.2. Safety Effects of Centerline Rumble Strips

This section presents results from studies on the safety effectiveness of centerline rumble strip applications.

California Study

A state route in California had a high number of fatal crashes that generated concerns from the local community and elected officials (*29*). In 1995 the location experienced six fatal crashes resulting in 14 deaths while historic data showed 2.7 fatal crashes per year for the previous nine years. Motivated by a high number of fatal crashes, the California DOT (Caltrans) conducted a demonstration project on a 23-mi (37-km) two-lane road with three passing lane sections in California. The project attempted to improve the visibility of the centerline markings and thereby reduce fatal head on crashes. The demonstration program consisted of installing the following treatments on the test section:

- Profiled thermoplastic centerline markings
- Milled rumble strips on the centerline to replace the double yellow strips
- Raised yellow retroreflective pavement markers along the rumble strips spaced 28 in (711 mm) apart
- Shoulder rumble strips

Crash data for 34 months before the change and 25 months after the change were analyzed. All crash types were included in the analysis. The results showed there were 4.5 crashes per month in the before period; the crash frequency was decreased to 1.9 crashes per month after applying the aforementioned treatments. This included a 90 percent reduction in fatal crashes (10 fatal crashes before versus 1 fatal crash after). The study concluded that the centerline treatment used in the project was effective in reducing head on fatal crashes.

Colorado Study

A 17-mi (27-km) section of a winding, two-lane mountain highway in Colorado with centerline rumble strips was evaluated for potential safety effects by comparing 44 months of crash histories both before and after the installation of centerline rumble strips (*30*). The resulting crash data and associated percent change are shown in Table A-8. The overall study found benefits of installing centerline rumble strips from reductions in head on and side-swipe collisions in spite of increases in traffic volume after the installation. Outcalt also noted that centerline rumble strips might increase the danger to motorcyclists and bicyclists.

Table A-8. Before-After Crash Analysis Summary for Installation of Centerline Rumble Strips in Colorado (*30*)

Crash type	Average number of crashes per year		
	Before period	After period	Percent change
Head-on	18	14	
Head-on collisions/million vehicles	2.91	1.92	–34%
Sideswipe opposite direction	24	18	
Sideswipe collisions/million vehicles	3.88	2.46	–36.5%
Average ADT	4,628	5,463	+18%

Delaware Study

A simple before-after study was performed to assess the effectiveness of centerline rumble strips on US Route 301 in Delaware (*31*). Average yearly accident data for three years prior to installation of the rumble strips were compared to eight years of data after installation. The results of the crash study are shown in Table A-9 and indicate that centerline rumble strips are a very effective method of reducing head on crashes. A benefit-cost ratio of 110 to 1 was also reported. The Delaware study reported the following advantages of installing centerline rumble strips:

- Reduces the number of head on collisions owing to driver in-attention, error, and fatigue
- Installation costs are low
- No noticeable degradation to pavement
- Requires little or no maintenance
- Installation is not a function of pavement age
- Novelty effects and consequent decrease in performance are not expected

The disadvantages of CRS were as follows:

- Noise effects

- Could transfer head on collisions to locations without centerline rumble strips

Table A-9. Before-After Crash Analysis Summary for Installation of Centerline Rumble Strips in Delaware (*31*)

Crash type	Average number of crashes per year		
	Before period	After period	Percent change
Head-on	2	0.1	–95%
Drove left of center	2	0.8	–60%
Property damage only	6.3	7.1	+13%
Injury	4.7	4.9	+4%
Fatal	2	0	N/A
Total	13	12	–8%
Average daily traffic	16,500	22,472	+4% yearly

Massachusetts Study

Noyce and Elango (*32*) conducted a before-after crash analysis with comparison sites to evaluate the effectiveness of centerline rumble strips in Massachusetts. The data used for the analysis included target crash types such as head on, opposite direction angle, opposite direction sideswipe, and run-off-the-road crashes with centerline encounters. One of the three two-lane rural highways treated with centerline rumble strips experienced a slight decrease in the targeted crash types, while the other two sites experienced an increase in the targeted crash frequency. None of the results, however, were statistically significant. As such, there was no statistical evidence that centerline rumble strips decrease the frequency of targeted crash types for three two-lane rural highways in Massachusetts.

Minnesota Study

Briese (*33*) conducted a cross-sectional analysis to determine the safety effectiveness of centerline rumble strips on two-lane rural highways. Data from two-lane rural highways in Minnesota were used for the analysis. The analysis included data from 109 mi (175 km) of treatment sites and 215 mi (346 km) of nontreatment sites. Based upon total crashes, Briese found:

- 73 percent lower crash rate of fatal and severe injury crashes on sections with centerline rumble
- 42 percent lower crash rate on sections with centerline rumble strips
- 37 percent lower severity rate on sections with centerline rumble strips
- 19 percent lower crash density on sections with centerline rumble strips

When analyzing target crashes, defined to be head on, opposite direction sideswipe, and SVROR-to-the-left crashes, Briese found:

- 13 percent higher crash rate of fatal and severe injury crashes on sections with centerline rumble
- 43 percent lower crash rate on sections with centerline rumble strips
- 37 percent lower severity rate on sections with centerline rumble strips
- 20 percent lower crash density on sections with centerline rumble strips

The analyses of both total crashes and target crashes produced very similar results except for the analyses based on fatal and severe injury crashes. Briese indicated that he had very little confidence in the analysis of target crashes based upon fatal and severe injury crashes because the number of crashes was so low. Briese stated that the analysis of target crashes based upon fatal and severe injury crashes should not be considered evidence that centerline rumble strips are not effective.

Missouri Study

Unpublished results of a study conducted by the traffic safety section of the Missouri Department of Transportation (*34*) found a general reduction in crossover crashes after the installation of centerline rumble strips along State Route MO 21. The analysis included 2 years of before data and 2 years of after data. Table A-10 displays crash data during the before and after periods by severity level, collision type and light condition. No statistical analysis was performed on the data.

Table A-10. Before-After Crash Analysis Summary for Centerline Rumble Strips Installation Along MO 21 (*34*)

	Before: 2001 to 2003	After: 2003 to 2005	Percent change
Severity Level			
Fatal crashes	1	0	–100
Disabling injury crashes	5	1	–80
Minor injury crashes	2	0	–100
Property damage only	2	3	+50
Total	10	4	–60
Collision Type			
Head-on	2	0	–100
Out of control	7	2	–71
Sideswipe	1	2	+100
Light Condition			
Daylight	6	3	–50
Dark	4	1	–75

Nebraska Study

Unpublished results of a Nebraska Department of Roads (*35*) study showed a reduction in cross-center-line crashes of 64 percent along two-lane rural roads. The positive effect was found using before and after data for three years around the installation date of 28 mi (45 km) of centerline rumble strips. A statistically significant decrease in the fatal and injury crash rate of 44 percent was accompanied by a 90 percent decrease in property damage only crashes.

Oregon Study

The Oregon Department of Transportation installed and evaluated the safety effects of noncontinuous centerline rumble strips on crossover crashes at two rural highway locations (*36*). One of the sites was an 8.7-mi (14.0-km) long, four-lane highway with a posted speed limit of 55 mph (88 km/h). The average daily traffic (ADT) ranged from 12,000 to 14,000 vehicles per day along the segment with centerline rumble strips installed on a 4-ft (1.2-m) median channelizing device. The other section was an 8.4 mi (13.5 km) rural two-lane road with periodic, alternating passing zones. The posted speed limit was 55 mph (88 km/h), and the ADT was 18,000 veh/day with centerline rumble strips installed intermittently within the evaluation section. The two sections were divided into segments resulting in six sites for the safety analysis. Crossover crashes were the measure evaluated at each study site. Simple before-after and Yoked comparison analyses were used to perform the safety assessment. The simple before-after method showed a 13 to 100 percent reduction in five of the six sites within the two study sections. Overall, there was a 69.5 percent reduction in crossover crashes after the installation of centerline rumble strips. The summary of simple before-after analysis results are presented in Table A-11. The matched-pair method, which involves one-to-one matching of treatment sites to comparison sites, showed a 79.6 percent reduction in fatal crashes as a result of crossover collisions at the 95 percent confidence level.

Table A-11. Simple Before-After Analysis Summary for Installation of Centerline Rumble Strips in Oregon (*36*)

	Before		After		Statistical analysis		
Site	Years	Target crashes	Years	Target crashes	Adjusted crashes	% reduction	Z -statistic
1	6.1	33	2.7	4	9.2	–72.0	–3.42
2	6.1	2	2.7	1	2.3	15.4	0.15
3	7.4	5	1.4	0	0.0	–100.0	–
4	7.4	6	1.4	1	5.2	–13.0	–0.23
5	7.4	8	1.4	0	0.0	–100.0	–
6	7.4	1	1.4	0	0.0	–100.0	–
Total		55	N/A	6	16.8	–69.5	–4.26

Texas Study

The effect of centerline rumble strips on erratic driving behaviors was evaluated by Miles et al. (*105*) at the request of TxDOT. Using a before-after video analysis of sites where centerline rumble strips were installed, Miles et al. documented events in which drivers' reactions to consciously crossing the centerline were effected in such a way as to cause an unsafe situation (e.g., during passing maneuvers). The erratic behaviors in question included (but were not limited to) hard braking, swerving, rapid alignment or lane shifting, correcting the trajectory in the wrong direction or losing control of the vehicle. After reviewing 479 passing maneuvers during 50 hours of video (18 before, 32 after) at sites along a rural highway, Miles et al. were unable to find any events that were considered erratic. It was concluded that centerline rumble strips do not create an unsafe environment, nor did they contribute to any irregular behaviors by drivers.

Multistate Study

Persaud et al. (*4*) conducted a before-after study of the safety effectiveness of centerline rumble strips on two-lane rural highways using data from seven states, including California, Colorado, Delaware, Maryland, Minnesota, Oregon, and Washington. The study included 98 treatment sites totaling 210 mi (338 km) in length. Table A-12 provides a summary of the treatment data for each state. The EB methodology was used in the analysis. After the installation of centerline rumble strips, total frontal/opposite direction sideswipe crashes were reduced by 21 percent, while injury crashes caused by frontal/opposite direction sideswipe collisions were reduced by 25 percent. For all crash types, the frequency was reduced by 14 percent and injury crash frequency was reduced by 15 percent after treating road sections with centerline rumble strips. These respective percent reductions were statistically significant at the 95 percent confidence interval. Persaud et al. also investigated the difference in crashes between daytime and nighttime hours. Although the percent reduction was somewhat greater at night than during the day (19 versus 9 percent), this difference was not significant at the 95 percent confidence level.

Table A-12. Summary of Before and After Data for Installation of Centerline Rumble Strips in Seven States (*4*)

State	Miles	Sites	Before period				After period			
			Mile-years	Avg AADT	Crash count		Mile-years	Avg AADT	Crash count	
					Total	Injury			Total	Injury
California	47.8	29	206.5	9,235	679	257	112.5	10,430	351	144
Colorado	16.9	10	118.4	5,000	551	262	84.6	6,154	415	187
Delaware	2.9	1	8.4	16,500	34	16	21.3	21,685	82	38
Maryland	30.4	11	91.4	11,680	156	55	42.5	12,991	55	14
Minnesota	66.2	24	508.6	9,305	751	156	158.6	10,315	275	41
Oregon	3.1	2	22.8	11,400	31	20	4.6	11,150	6	3
Washington	43.5	21	166.5	7,290	308	116	173.3	7,963	297	109
Total	210.8	98	1,122.6	8,829	2,510	882	597.3	9,668	1,481	536

Study in an Unspecified Location

Fitzpatrick et al. (*29*) also described two other studies that used centerline rumble strips as safety treatments in unspecified locations. One treatment consisted of 15 mi (24 km) of centerline rumble strips installed along a principal arterial that connected an Interstate highway to a rural community. Selection of this treatment site was biased as the centerline rumble strips were installed at a location with a crash frequency and severity rate above the statewide average for similar roadway types. The other segment was 10 mi (16 km) and connected a major northwestern city to a nearby suburban city and served as a high volume commuter route. The commonality among these two sites was that they were both considered high crash locations. Many improvements were made to these sites including installation of centerline rumble strips, guardrail, raised pavement markers on horizontal curves, traffic signalization and channelization, inclusion of right-turn or bypass lanes, and exclusive left-turn lanes.

After the improvements were made to each location, a before-after crash analysis was conducted. The analysis indicated a reduction in various crash types. However, the study did not attribute the reductions to centerline rumble strips. This is because one of the sites did not show a statistically significant reduction, while the other site showed only a statistically significant reduction in read-end crashes which were not considered to have a direct relationship to centerline rumble strips. Because several treatments were applied at the same instance at both sites, drawing conclusions about the effects of centerline rumble strips was not possible.

A.3. Operational Effects of Centerline Rumble Strips

While the safety effectiveness of centerline rumble strips is fairly well documented, the effect on traffic operational characteristics has not been extensively researched. This section describes the findings from several recent research studies relating traffic operation performance changes attributed to centerline rumble strip installation.

Minnesota Study

Briese (*33*) conducted a before-after study to determine the effect that centerline rumble strips have on (1) travel speed on horizontal curve and tangent sections, (2) lateral placement of vehicles on tangent sections, and (3) centerline encroachment on horizontal curves. Data from two-lane rural highways in Minnesota were used for the analysis. The results indicate that centerline rumble strips have no impact on travel speed. Similarly, it was determined that the presence of centerline rumble strips do not impact the lateral placement of vehicles. Finally, it was determined that centerline rumble strips have a large effect on centerline encroachments and crossings along horizontal curves. Reductions in encroachments ranged from 40 to 76 percent.

Pennsylvania Study

Porter et al. (*37*) conducted a before-after study with comparison sites to determine the effect that rumble strips have on lateral vehicle placement and vehicle speed. Data from two-lane rural highways in Pennsylvania were used for the analysis. The results indicate that there is a statistically significant difference in the mean lateral placement when comparing the before and after periods at centerline rumble strip treatment sites. The mean lateral vehicle shift ranged from 3.0 to 5.5 in (76 to 140 mm) away from the roadway centerline for 11- and 12-ft (3.3- and 3.6 m) lanes, respectively. There was a very small change in the mean lateral placement at comparison sites, but it was not statistically significant. Therefore, it is reasonable to conclude that the change in vehicle location was due to the presence of the centerline rumble strips. In addition, no statistically significant relationship between vehicle speed and the placement of centerline rumble strips was found.

Texas Study

Miles et al. (*38*) investigated how centerline rumble strips affect driver behavior in Texas. The specific measures of effectiveness that were used to quantify changes in driver behavior were:

1. Number and type of erratic driving movements during the initial stage of a passing maneuver.
2. Gap distance between the front end of a passing vehicle and the rear end of a vehicle being passed, prior to completing a passing maneuver.
3. Centerline crossing time during the initial stage of a passing maneuver.
4. Passing opportunity.
5. Percentage of traffic conducting passes along rural two-lane roads marked for passing.

These measures were collected along a 15-mi (24-km) section of rural two-lane road on US 67 in Comanche County, Texas. Field data were videotaped from a data recording vehicle that was driven at 5-, 10-, and 15-mph (8-, 16-, and 24-km/h) increments below the posted daytime speed limit of 70 mph (113 km/h) to induce passing maneuvers. Analysis of the videotapes revealed the following:

- Installation of centerline rumble strips did not induce erratic movements.
- Installation of centerline rumble strips did not change driver behavior with respect to encroaching on the centerline prior to initiating a passing maneuver.
- Passing drivers initiated their passes closer to a vehicle that they were passing after the installation of centerline rumble strips. This difference may be a

combination of the variation in the weather and the installation of the centerline rumble strips.

- Driver behavior with respect to centerline crossing time while initiating a passing maneuver changed with drivers taking more time to cross the centerline after the installation of centerline rumble strips. This difference may be a combination of the differences in the weather, the part of the week that the data were collected, and the installation of the centerline rumble strips.
- Passing opportunity was observed by measuring how long a passing vehicle was queued immediately behind a passed vehicle while in passing zones, no-passing zones, and when opposing vehicles were present. After installation of centerline rumble strips, drivers appear to be waiting longer before passing a vehicle traveling at 55 mph (88 km/h).
- Centerline rumble strips do not appear to affect (i.e., decrease or increase) the number of passes made by drivers.

Miles et al. also investigated how centerline rumble strips affect lateral positioning of vehicles within the travel lane. Field data were collected at eight locations using a camera trailer. Tape markers were placed on the pavement at 6-in (152-mm) intervals from centerline markings to determine lateral positioning of vehicles. The project sites, their geometric configurations, and the centerline rumble strip pattern are summarized in Table A-13. Miles et al. found that at all eight data collection locations, vehicular placement changed. The majority of drivers in the after period (i.e., after installation of centerline rumble strips) moved away from the centerline. Overall, Miles et al. concluded that:

- No erratic movements were recorded either before or after the installation of centerline rumble strips.
- None of the changes in the various measures of effectiveness were considered to be increases or decreases of a magnitude that merited a practical change in driving characteristics.
- None of the changes in the various measures of effectiveness were considered to either affect the driving environment adversely or to induce unsafe driving practices.

Table A-13. Centerline Rumble Strip Lateral Position Project Site Characteristics in Texas (*38*)

Roadway	Alignment	No. of lanes	Shoulders	Centerline rumble strip design
FM 195	Curve 1	2	Yes	Yellow, 4 ft (1.2 m) spacing, on each side of centerline marking[a]
FM 195	Curve 2	2	Yes	Yellow, 4 ft (1.2 m) spacing, on each side of centerline marking[a]
FM 969	Tangent	2	No	Black, 4 ft (1.2 m) spacing, staggered inside centerline marking
FM 969	Curve	2	No	Yellow, 4 ft (1.2 m) spacing, on each side of centerline marking
FM 1431	Tangent	4	No	Yellow, 4 ft (1.2 m) spacing, on each side of centerline marking
FM 1431	Curve	4	No	Yellow, 4 ft (1.2 m) spacing, on each side of centerline marking
FM 2222	Tangent	4	No	Yellow, 4 ft (1.2 m) spacing, on each side of centerline marking
FM 2222	Curve	4	No	Yellow, 4 ft (1.2 m) spacing, on each side of centerline marking

[a] This site also included white pavement buttons spaced at 4 ft (1.2 m) spacing adjacent to the outside of the edgeline, and are therefore raised edgeline rumble strips.

Finland Studies

Räsänen (*39*) conducted a before-after observational study to evaluate the effectiveness of centerline rumble strips in a horizontal curve section on a rural two-lane undivided highway facility in Finland. The main objective of this research was to study the changes in lane keeping as a result of centerline rumble strips on horizontal curves. Field observations were made on a curve during four different conditions:

1. Worn-out painted centerlines
2. Freshly painted centerlines without centerline rumble strips
3. Resurfaced and freshly painted centerline with centerline rumble strips
4. One-year after installing centerline rumble strips

The field observations consisted of measuring the number of encroachments, vehicle lateral positions, and vehicle speeds traveling in both directions of travel for various traffic situations. The traffic situations included free flow conditions, flow conditions less than five seconds headway, and flow conditions during the presence of on-coming traffic. The results of the field experiment indicated that the number of centerline encroachments along the curve decreased when the centerline was freshly painted than compared to the worn-out painted condition. However, there was no difference in the centerline encroachments after centerline rumble strips were installed when compared with the freshly painted condition. This suggested that the reason for reduction in centerline encroachments are due to enhanced visibility by the freshly applied pavement marking and not necessarily because of centerline rumble strips.

The means and standard deviations of lateral positions were compared among all the four conditions. The results indicated that there was a decrease in the lateral position (i.e., the drivers moved closer to the edgeline) after the installation of centerline rumble strips. This suggests that the drivers are providing more attention while negotiating the curve when centerline rumble strips are installed. Comparisons of speed on the curve did not indicate any apparent differences among the different conditions.

Overall, Räsänen concluded that the effects of centerline rumble strips and freshly painted centerlines on encroachments, lateral position, and vehicle speeds were not major differences. However, it was postulated that centerline rumble strips could improve driver behavior consistency more effectively than painted lines on horizontal curves. This is because noise and vibration levels produced by the rumble strips are expected not to degrade as quickly as the visibility or retroreflectivity of painted lines. The study concluded that the presence of centerline rumble strips on curves has the potential to enhance safety by preventing unintentional and intentional centerline encroachments and by improving driver attention on horizontal curves during both free flow and oncoming traffic situations.

Touvinen and Enberg (*40*) investigated the operation effects of centerline rumble strips on two lane highways in Finland. The operational areas that were being examined were: mean travel speeds, spot speeds, number of passes, amount of platooning, and lateral placement. The centerline rumble strips at the study site were rolled in asphalt; however, a recent review in Finland has recommended the future use of milled rumble strips. Using, what appears to be, a naïve before-after analysis, there was no statistically significant change one month and one year after the treatment installation in any of the key areas under investigation. After looking at the data and its applications from several angles, it was concluded that the installation of centerline rumble strips had no significant impact on driver behavior; at least for flow rates comparable to those observed during the study of 500 veh/hr. A driver survey accompanied the statistical analysis and revealed that 86 percent of drivers did not feel that centerline rumble strips affected their driving behavior, a result that was corroborated by the data.

Japan Study

Hirasawa et al. (*42*) investigated how centerline rumble strips influenced driving behavior in Japan relative to other treatments. Driving speeds and lateral positionings were compared along different sections of roads with median strips, center poles, chatter bars, rumble strips, and double-yellow centerlines (Figure A-1). The differences in average driving speed measured in each section were within 1.2 mph (2 km/h) so Hirasawa et al. concluded the safety measures including the rumble strips did not impact driving speeds. When measuring the lateral position of a vehicle in the lane, the location of the left front wheel relative to the outer edge of the shoulder was recorded using a video camera. Table A-14 shows the lateral positions of large vehicles along the various treatment sections. In the section with a double-yellow centerline, very few vehicles traveled on the shoulder. In the section where center poles separated the lanes, many vehicles distanced themselves from the center poles, and some even drove on the shoulder. In the chatter bar and rumble strip sections, the vehicles distanced themselves from these treatments, but not as far as on the center pole section. Small vehicles showed the same behavior as large vehicles. Thus, Hirasawa et al. regarded the rumble strips as being effective in reducing head on collisions because they kept vehicles at a proper distance from the centerline.

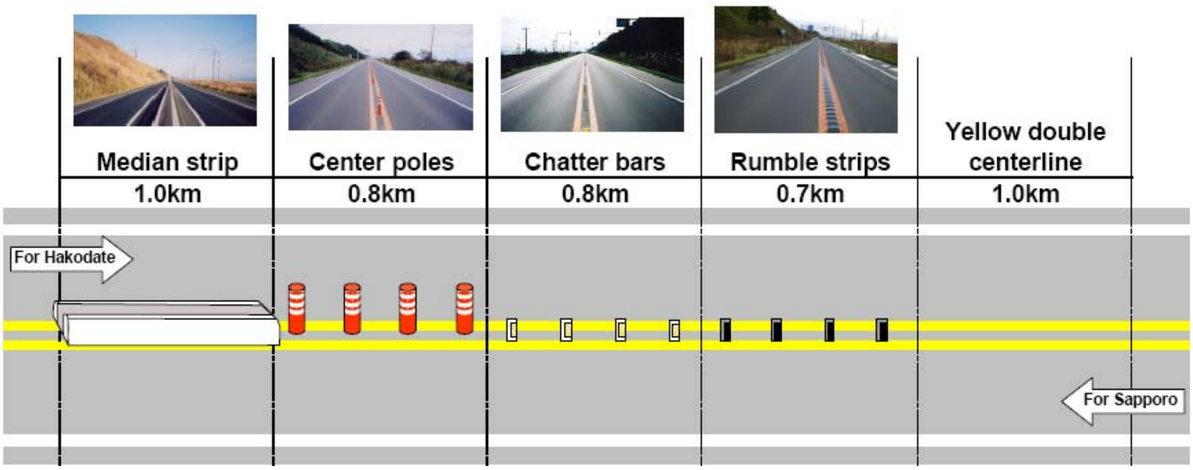


Figure A-1. Installation of Safety Treatments Against Head on Collisions on the Yakumo Section of National Route 5 in Japan (*42*)

Table A-14. Lateral Position of Large Vehicles Relative to the Outer Edge of Shoulder at a Site in Japan (*42*)

Treatment	Average distance to outer edge of shoulder
Median strip	26 in (671 mm)
Center pole	7 in (173 mm)
Chatter bar	14 in (349 mm)
Rumble strip	14 in (360 mm)
Yellow double centerline	23 in (576 mm)

Simulation Studies

Noyce and Elango (*32*) used a passenger car driving simulator to determine how drivers react when encountering centerline rumble strips. Although the analysis showed drivers take more time to return to their intended travel lane when encountering centerline rumble strips than compared to two-lane roadway centerline encroachment without rumble strips, the results were not statistically significant. It was also shown that drivers take longer time to return to their travel lane when centerline rumble strips are encountered as compared to centerline encroachments when no rumble strips are present. Again, the results were not statistically significant. Differences between the time to return to the intended travel lane were compared for roadway sections with and without centerline rumble strips. The findings show a statistically significant difference in mean time to return to the travel lane on roadway sections that are curved. Thus, this result indicates that roadway geometry has an influence on the time needed to return to the travel lane when centerline rumble strips are present. Lastly, it was shown that 20 to 40 percent of drivers initially steer left when encountering centerline rumble strips on two-lane roads. This is the opposite maneuver expected and should be considered an inappropriate corrective maneuver.

Harder et al. (*41*) also conducted a study to examine the effects of centerline treatments on driving performance using a driving simulator. Lateral position and speed were used as measures of driver performance. The following six centerline treatments were investigated:

1. The control condition: 12-ft (3.6-m) lanes and 4-in (102-mm) centerline dashes (current US standard)
2. 14-ft (4.3-m) lanes with 4-in (102-mm) centerline dashes
3. 14-ft (4.3-m) lanes with both longitudinal rumble strips and 4-in (102-mm) dashes marking the centerline
4. 12-ft (3.6-m) lanes separated by a 4-ft (1.2-m) central buffer area bounded by 4-in (102-mm) dashes
5. 12-ft (3.6-m) lanes separated by a 4-ft (1.2-m) central buffer area bounded by longitudinal rumble strips. In addition, there were 4-in (102-mm) centerline dashes
6. 12-ft (3.6-m) lanes separated by a 4-ft (1.2-m) central buffer area bounded by 8-in (203-mm) dashes

Human participants drove these six test trials and in each trial, the participant faced several different driving situations, including:

- Cruising with no traffic in the opposing lane
- Cruising with traffic in the opposing lane
- Following behavior, when the driver had to adjust to the speed of the car that it was following
- Attempts to overtake a car in the same travel lane (i.e., passing maneuver)

Harder et al. found that all the centerline treatments were effective when compared to the control condition based on driver performance. Participants drove significantly further away from the centerline for Conditions 2 and 3 when compared to Conditions 1, 4, 5, and 6. However, driver performance did not change when comparing Conditions 2 and 3. Other findings from the research include:

- Use of 12-ft (3.6-m) lanes with a 4-ft (1.2-m) center buffer area resulted in a lateral vehicle position shift away from the centerline when compared to the use of 14-ft (4.3-m) lanes.
- Subjects tended to shy away from the centerline during the presence of oncoming traffic when compared to the condition of cruising with no oncoming traffic.

- Widening of the markings from 4 to 8 in (102 to 203 mm) had similar driver performance effects.

Overall, Harder et al. concluded that if any of the centerline treatments are to be implemented, it can be expected that drivers would position their vehicle further away from the centerline than they would with the control centerline marking configuration. Thus, it is expected that the alternative centerline treatments studied would reduce the likelihood of a crash with on-coming traffic. Particularly, Harder et al. supported the use of a 14-ft (4.3-m) lane with 4-in (102-mm) skip lines or a 14-ft (4.3-m) lane with 4-in (102-mm) skip lines with centerline rumble strips.

A.4. Vehicle Dynamics Related to Vibration and Noise Stimuli

The noise and vibration created by rumble strips is the key feature in their use. Unlike most other visual based traffic controls, rumble strips use noise and vibration to create a response from the driver. In an effort to determine optimum rumble strip dimensions, numerous studies have been conducted to determine the amount of vibration and noise generated by vehicles as they traverse different types and patterns of rumble strips. This section summarizes studies in which the vibration levels, as measured at a particular location or locations on a vehicle, were measured as the vehicle was traversing a known rumble strip pattern. Similarly, this section summarizes studies where the noise levels were measured inside the vehicle passenger compartment.

Since the mid 1990s the Virginia Department of Transportation (VDOT) has been conducting research on continuous shoulder rumble strips (27). One of the primary issues that VDOT has researched is clarifying the optimal continuous shoulder rumble strip pattern based on measured and tactile levels as well as ease of construction and quality. Chen et al. (*27*) indicate that the overall performance quality of rumble strips can be determined using the following relationship:

$$P = f\,(a_d - a_r;\ t_d - t_r)$$

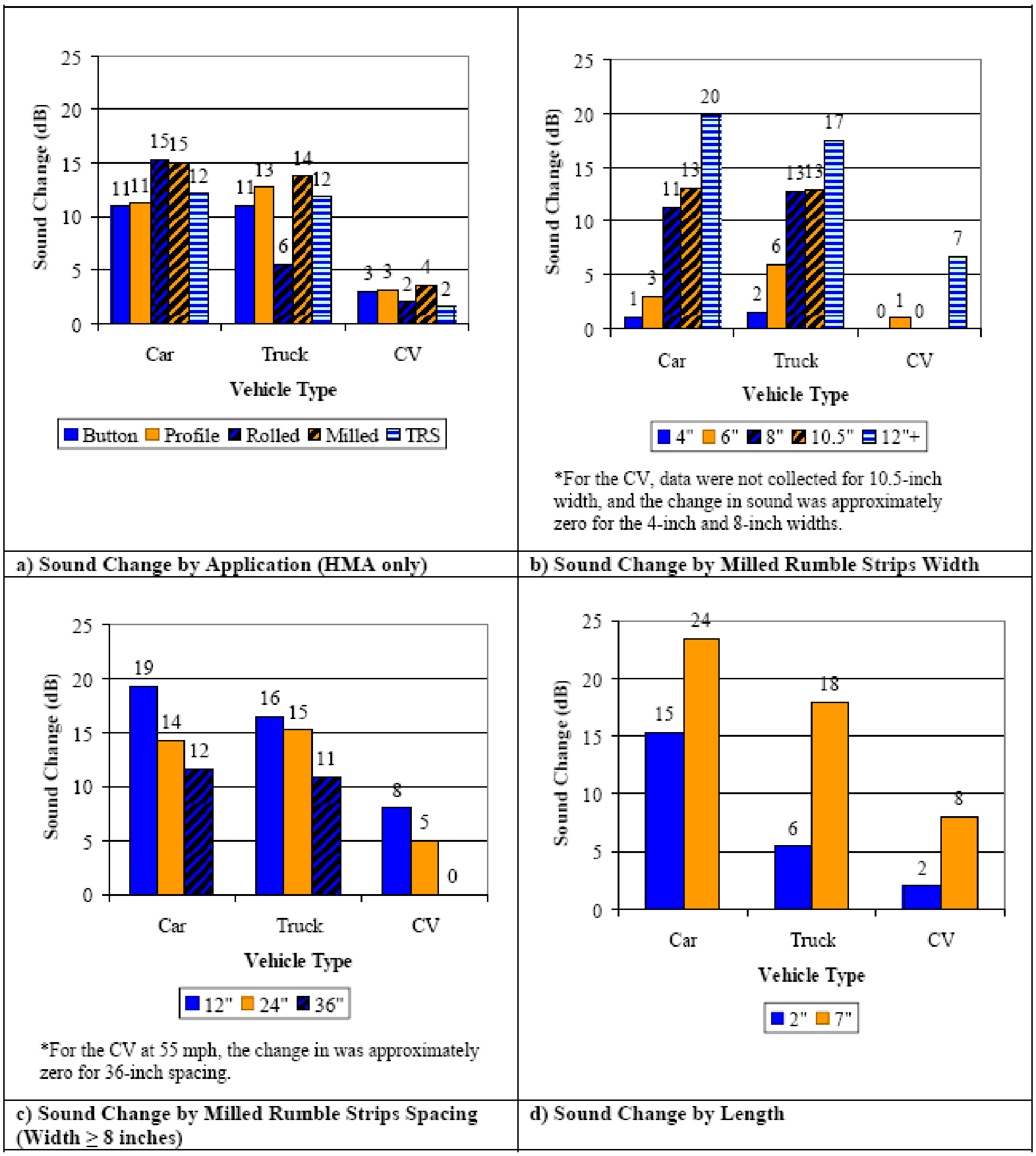
where:

where:	P	=	effectiveness of rumble strip
	a_d	=	mean audible index of travel way
	a_r	=	mean audible index of rumble strips
	t_d	=	mean tactile index of travel way
	t_r	=	mean tactile index of rumble strips

To determine the optimal rumble strip pattern, it is necessary to find the difference between a_d and a_r and t_d and t_r. Thus, the optimal rumble strip pattern is a function of the difference in the mean values of both audible and tactile indexes, not the absolute values of each.

Miles and Finley Study

Finley and Miles (*106,107*) aimed their study at evaluating the factors related to noise generation that impact the effectiveness of rumble strips. Both passenger car and commercial truck variations were driven on milled, rolled and raised rumble strips at speeds of 55 and 70 mph. Among all of the factors investigated, including vehicle speed, vehicle type, surface type and rumble strip dimensions, the geometric dimensions of the rumble strips proved to be the most striking factor at alerting the driver by means of auditory signals. Figure A-2 shows the most effective rumble strip layouts are those that maximize the vehicle's tire displacement into the rumble strip.



a) Sound Change by Application (HMA only)

b) Sound Change by Milled Rumble Strips Width

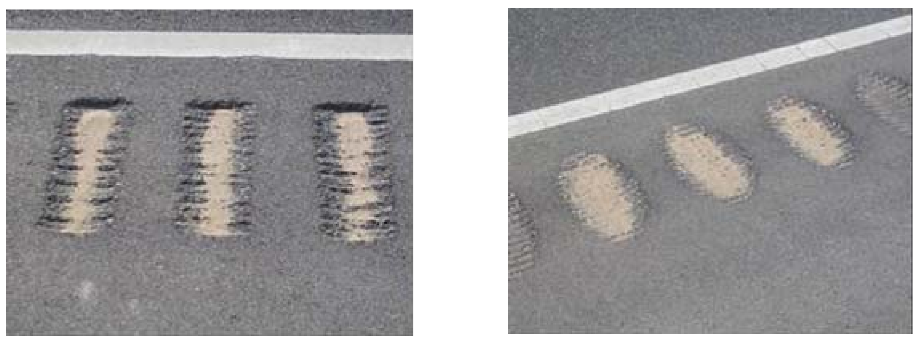
c) Sound Change by Milled Rumble Strips Spacing (Width ≥ 8 inches)

d) Sound Change by Length

Figure A-2. Effect of Rumble Strip Design (*106,107*)

Gardner et al. Study

Researchers in Kansas conducted a study on the design of a new rumble strip pattern for centerline rumble strips (*43*). A new "football" shaped rumble strip pattern was installed along a Kansas highway, and several tests were conducted to evaluate the new football shaped rumble strip versus the typical rectangular rumble strip. Figure A-3 illustrates the difference between the two rumble strip patterns. The comparison consisted of water and debris collection, interior sound and vibration production, the opinions of bicyclists, and the opinions of residents in areas where the rumble strips were installed.



Rectangular Pattern   Football Pattern

Figure A-3. Rectangular Rumble Strip Compared to "Football" Shaped Rumble Strip (*43*)

As part of the sound and vibration testing, noise and vibration produced from vehicle crossover of the rectangular rumble strips were compared to the noise and vibration produced from vehicle crossover of the football shaped rumble strips. Interior noise and steering wheel vibration were measured and compared. As part of the noise testing, six vehicles were included:

- 1996 International 4900 DT466 Dump Truck
- 1999 Chevrolet 2500 Diesel Pickup Truck
- 2000 Ford Ranger XLT 2WD Pickup Truck
- 2002 Dodge Caravan
- 1996 Ford Taurus LX
- 2005 Lexus RX 300 Sport Utility Vehicle

Table A-15 shows the difference in noise levels compared to a base noise level in the travel lane for each type of rumble strip pattern and vehicle type. Gardner et al. note that a rumble strip must generate at least 9 to 10 dBA above the ambient noise level to alert a driver. Based upon this assumption, Gardner et al. concluded that each type of rumble strip pattern produced a recognizable amount of noise when crossover, and the football shaped rumble strips produced at least as much noise as the rectangular shaped rumble strips.

Table A-15. Differences in Noise Levels for Each Type of Rumble Strips and the Base Level (dBA) on K-96 (*43*)

Vehicle type	Rectangular rumble strips vs. base	Football rumble strips vs. base	Football rumble strips vs. rectangular rumble strips
1996 International 4900 DT466 Dump Truck	23.1	31.4	8.3
1999 Chevrolet 2500 Diesel Pickup Truck	7.7	7.7	0.0
2000 Ford Ranger XLT 2WD Pickup Truck	9.3	13.7	4.4
2002 Dodge Caravan	7.8	8.5	0.7
1996 Ford Taurus LX	12.3	16.2	3.9
2005 Lexus RX 300 Sport Utility Vehicle	16.2	15.9	–0.3

As part of vibration testing, the same six vehicle were used as those in the noise study. Table A-16 shows the average resultant acceleration, f(x,y,z), for the base, football shaped rumble strips, and rectangular shaped rumble strips. Based upon an analysis of the data, Gardner et al. concluded that both types of rumble strips produce a significant tactile response; however, there is no statistical difference between the mean values of vibration for five of the six tested vehicles.

Table A-16. Average f(x,y,z) for Vibration Trails (g) on K-96 (*43*)

Vehicle type	Base	Football Rumble Strips[a]	Rectangular Rumble Strips[a]
1996 International 4900 DT466 Dump Truck	1.027	1.074 (4.5 %)	1.084 (5.5 %)
1999 Chevrolet 2500 Diesel Pickup Truck	1.020	1.036 (1.6 %)	1.049 (2.8 %)
2000 Ford Ranger XLT 2WD Pickup Truck	1.003	1.089 (8.6 %)	1.027 (2.4 %)
2002 Dodge Caravan	1.015	1.053 (3.7 %	1.081 (6.5 %)
1996 Ford Taurus LX	1.001	1.043 (4.2 %)	1.021 (2.0 %)
2005 Lexus RX 300 Sport Utility Vehicle	1.012	1.115 (10.2%	1.128 (11.5 %)

[a] The percent difference from the base condition is given in parentheses.

Hirasawa et al. Study

In Japan, Hirasawa et al. (*42*) collected vibration and sound levels generated in a passenger car while traversing three rumble strip patterns (Table A-17). The rumble strip patterns were installed at the Tomakomai Winter Test Track. The test vehicle was a station wagon. The test vehicle was driven at speeds of 25, 37, 50, and 62 mph (40, 60, 80, and 100 km/h) over each of the rumble strip patterns. Figure A-4 shows the setup for measuring the sound and vibration levels. Figures A-5 and A-6 show the average sound and vibration levels. The sound generated by all three rumble strip patterns was at least

15 dBA greater than the ambient sound generated by the pavement surface without rumble strips. According to Figure A-5, sound levels increase with groove depth. The vibration generated by each rumble strip pattern exceeded that on smooth pavement by 7 dB. The smallest vibration was measured at 37 mph (60 km/h). This was attributed to the vehicle characteristics, such as suspension performance. At each of the other speeds, the measured vibration for each groove depth exceeded that generated on the smooth pavement by 10 dB.

Table A-17. Dimensions of Rumble Strips Installed at Tomakomai Winter Test Track in Japan (*42*)

Dimension	Pattern 1	Pattern 2	Pattern 3
Length	14 in (350 mm)	14 in (350 mm)	14 in (350 mm)
Width	5 in (127 mm)	6 in (147 mm)	6.5 in (163 mm)
Depth	0.32 in (9 mm)	0.5 in (12 mm)	0.625 in (15 mm)
Spacing	12 in (302 mm)	12 in (302 mm)	12 in (302 mm)

Figure A-4. Setup for Measuring Sound (left) and Vibration (right) (*42*)

Hirasawa et al. also collected sound and vibration data from a vehicle traversing rumble strips on snow-covered roads. Figure A-7 shows the road surface condition on National Route 274 at the time of the testing, and the sound and vibration data measured inside the test vehicle. The road surface was slushy, and the centerline was not visible. Without rumble strips, the sound was 60 to 65 dB; with rumble strips the sound was 75 to 80 dB. The ambient vibration was 90 to 95 dB when not running on the rumble strips compared to 95 to 105 dB when running on the rumble strips. Hirasawa et al. concluded that the rumble strips gave sufficient warning (sound and vibration) of lane deviation on slushy winter roads, even when the centerline was not visible.

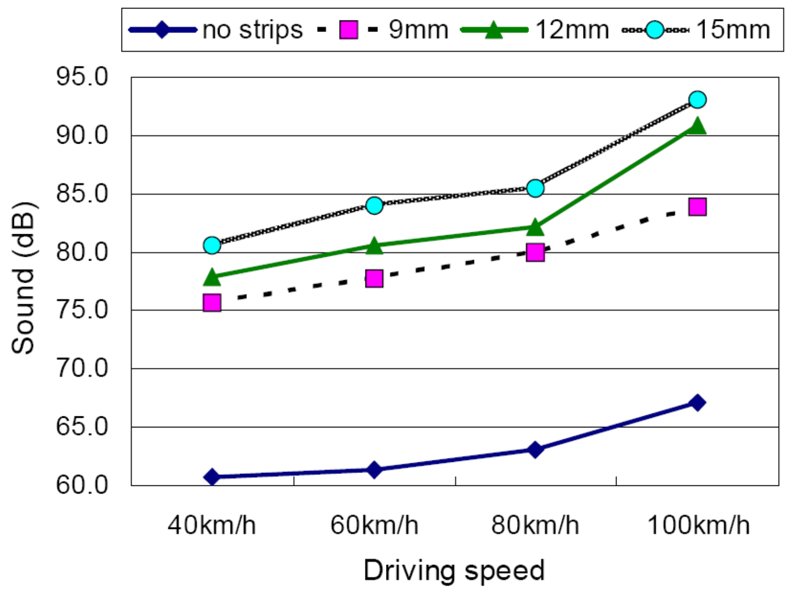


Figure A-5. Sound Versus Driving Speed (*42*)

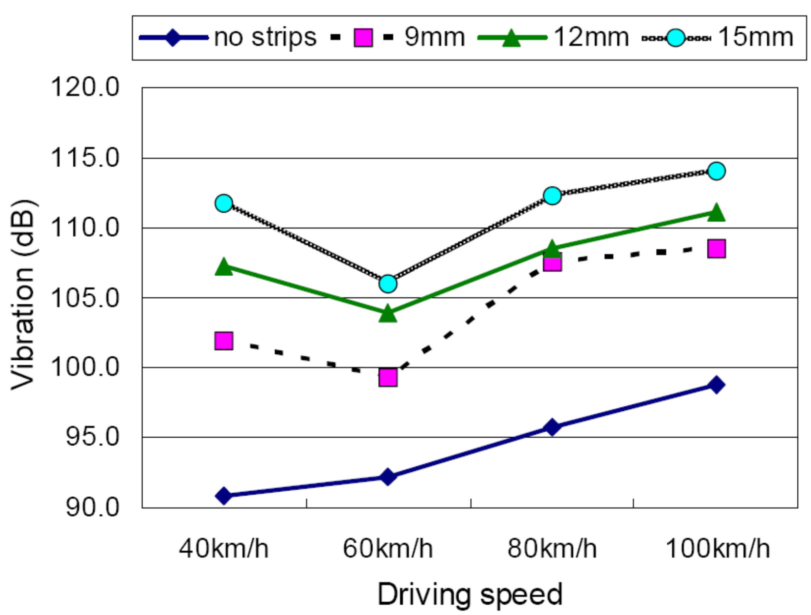


Figure A-6. Vibration Versus Driving Speed (*42*)

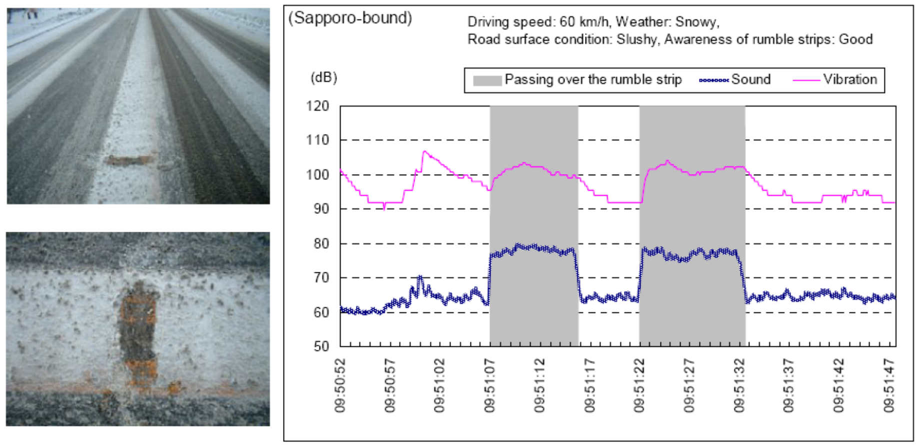


Figure A-7. Sound and Vibration Measured on National Route 274 During Winter Conditions (*42*)

Bucko and Khorashadi Study

Bucko and Khorashadi (*14*) tested a variety of rumble strip and edge stripe treatments to determine which applications are the most appropriate for bicyclists and still provide sufficient audible and vibratory sensation to alert automobile drivers. One of the primary objectives of this research was to collect and evaluate sound and vibration data from various vehicles being driven over different rumble strip patterns. The testing was conducted at the Caltrans Dynamic Test Facility in West Sacramento, California. Table A-18 summarizes the rumble strips patterns installed and tested at the Caltrans test facility. Six motor vehicles were used to collect sound and vibration data:

- Light Passenger Vehicles
  - Chevrolet Lumina (1992)
  - Dodge Spirit (1993)
  - Dodge Ram 150 Pick-up Truck (1997)
- Commercial Style Trucks
  - International 10-Wheel Tractor (without trailer) (1999)
  - Autocar 10-Yard Dump Truck (1991)
  - GMC Topkick Single Unit Van (1996)

Table A-18. Rumble Strip Patterns Tested by Caltrans (*14*)

Pattern number	Rumble strip type	Groove length in (mm)	Groove width in (mm)	Groove spacing in (mm)	Groove depth in (mm)	Comments
1	Rolled	24 in (600 mm)	2 in (50 mm)	8 in (200 mm)	1 in (25 mm)	
2	Milled	16 in (406 mm)	5 in (123 mm)	12 in (305 mm)	0.25 in (6 mm)	
3	Milled	16 in (406 mm)	6 in (151 mm)	12 in (305 mm)	0.32 in (9 mm)	
4	Milled	16 in (406 mm)	7 in (174 mm)	12 in (305 mm)	0.5 in (13 mm)	
5	Milled	16 in (406 mm)	7.5 in (194 mm)	12 in (305 mm)	0.625 in (16 mm)	
6	Chip Seal	N/A	N/A	N/A	N/A	Installed using a tar epoxy and chip seal grade aggregate
7	Raised pavement marker	N/A	N/A	12 in (305 mm)	N/A	Installed using Caltrans standard Botts Dot pavement markers on 12 in (305 mm) centers
8	Raised pavement marker	N/A	N/A			One run of raised pavement markers was installed using Caltrans standard Botts Dot pavement markers on 12-in (305-mm) centers. A second run was placed 6 in (152 mm) to the right of section one and skewed 6 in (152 mm) for two skewed runs of pavement markers.
9	Carsonite bars	24 in (600 mm)	N/A	24 in (600 mm)	N/A	Carsonite bars placed 2 ft (0.6 m) on center and 2 ft (0.6 m) in width.
10	Raised and inverted thermoplastic stripe	N/A	N/A	N/A	N/A	
11	Raised thermoplastic stripe	N/A	N/A	N/A	N/A	

The light passenger test vehicles were driven over the rumble strip patterns 1 through 5 at speeds of 50 and 62 mph (80 and 100 km/h), while the commercial style test vehicles were tested at 50 mph (80 km/h) only. The instrumented tests were conducted by driving each test vehicles right side tires onto and following a straight path over the series of rumble strip patterns. The steering wheel was instrumented with accelerometers to measure the vibration generated by the rumble strips (Figure A-8). The four accelerometers were positioned as such because in addition to providing direct values from each accelerometer, additional motion parameters could be calculated. Sound levels were also collected at ear level close to the center of the vehicle front passenger seat.

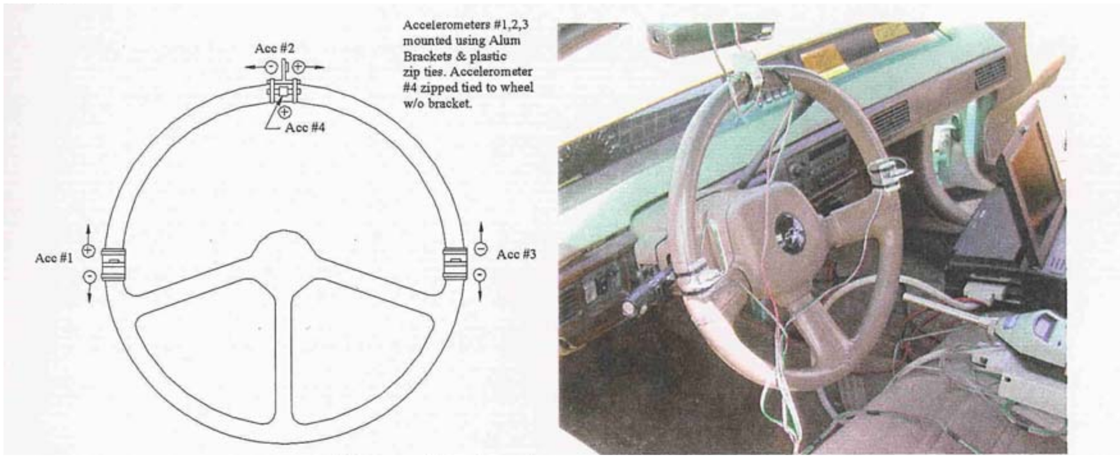


Figure A-8. Measuring the Acceleration of the Steering Wheel (*14*)

Results of the vibration and noise tests are presented in Tables A-19 and A-20. Table A-19 shows the average vibration measurements for the light passenger vehicles and commercial vehicles. The average vibration values are the "resultant" vibrations (i.e., above the background level) calculated from the 4 accelerometers mounted on the steering wheel. Table A-20 shows the average noise measurements for the light passenger vehicles and commercial vehicles. The average noise values are the "resultant" levels above the background noise. The vibration and sound testing yielded the following results:

- Vibration on light vehicles:
  - The vibration for rumble strip 1 (rolled) was greater than milled rumble strip 2 and less than rumble strips 3, 4, and 5 (all milled).
  - Vibration for rumble strips 3, 4, and 5 appeared to be linear in ascending order. Rumble strip 2 produced substantially less vibration than the other milled strips and consequently was not linear when compared to them.
- Noise in light vehicles:
  - In relationship to the instrumented vibration tests, the noise tests followed the same trend.
  - The noise created by rumble strip 1 (rolled) was greater than milled rumble strip 2 and less than rumble strips 3, 4, and 5 (all milled).
  - Noise levels for rumble strips 3, 4, and 5 appeared to be linear in ascending order. Rumble strip 2 produced substantially less noise than the other milled rumble strips and consequently was not linear when compared to them.
- Vibration on commercial vehicles:
  - When compared to the averages of the 50 mph (80 km/h) instrumented tests of light vehicles, the vibration averages of the commercial vehicles were less, but followed the same general trends.
  - For two of the trucks, vibration levels for rumble strip 1 (rolled) were greater than for rumble strips 2, 3, 4, and 5 (all milled). Significantly less

vibration was produced in the dump truck on rumble strip 1 than on the other strips.
  - Vibration for rumble strips 2, 3, 4, and 5 appeared to be linear in ascending order.

- Noise in commercial vehicles:
  - When compared to the averages of the 50 mph (80 km/h) instrumented tests of light vehicles, the noise averages of the commercial vehicles were less, but followed the same general trends.
  - The average noise created by rumble strip 1 (rolled) was greater than for rumble strips 2 and 3 and less than rumble strips 4 and 5.
  - Noise averages for rumble strips 2, 3, 4, and 5 appeared to be linear in ascending order.

Table A-19. Average Vibration Measurements of Light Passenger Vehicles and Commercial Vehicles (*14*)

	Rumble strip configuration				
	1	2	3	4	5
	Resultant accelerations (g) of light passenger vehicles				
50 mph (80 km/h)	0.253	0.115	0.379	0.432	0.542
62 mph (100 km/h)	0.306	0.135	0.437	0.469	0.591
Average	0.280	0.125	0.408	0.450	0.567
	Resultant accelerations (g) of commercial vehicles				
Average	0.342	0.150	0.226	0.246	0.286

Table A-20. Average Noise Measurements of Light Passenger Vehicles and Commercial Vehicles (*14*)

	Rumble strip configuration				
	1	2	3	4	5
	Resultant noise levels (dBA) of light passenger vehicles				
50 mph (80 km/h)	14.4	11.8	18.2	19.7	21.4
62 mph (100 km/h)	12.6	10.2	15.2	16.9	18.5
Average	13.5	11.0	16.7	18.3	19.9
	Resultant noise levels (dBA) of commercial vehicles				
Average	4.72	1.88	3.62	4.61	4.62

Outcalt Study

A Colorado DOT by Outcalt (*44*) compared various rumble strip configurations to find a rumble strip pattern that is less disruptive to bicyclists than the standard rumble strip but still provides a safety factor to help prevent accidents caused by motorists running off the road. Twelve milled rumble strip configurations were tested along with a rolled concrete pattern. Table A-21 lists the dimensions of the rumble strip patterns included in the evaluation.

Table A-21. Rumble Strip Dimensions Tested in Colorado (*44*)

Pattern number	Rumble strip type	Groove width (in)	Flat width (in)	Rumble strip/gap (ft)	Average depth (in)	Target depth (in)	Max. measured (in)	Min. measured (in)
1	Milled	2	10	Continuous	0.44	0.5	0.58	0.36
1A	Milled	2	10	12/6	0.44	0.5	0.58	0.36
2	Milled	2	5	Continuous	0.44	0.5	0.46	0.43
2A	Milled	2	5	12/6	0.44	0.5	0.46	0.43
3	Milled	2	5	12/6	0.29	0.375	0.38	0.20
4	Milled	2	3	Continuous	0.39	0.5	0.48	0.33
4A	Milled	2	3	12/6	0.39	0.5	0.48	0.33
5	Milled	7.5	4.5	48/6	0.58	0.75	0.71	0.50
6	Milled	6.5	5.5	Continuous	0.49	0.5	0.59	0.35
7	Milled	6.0	6.0	Continuous	0.46	0.375	0.53	0.42
8	Milled	5.5	6.5	Continuous	0.41	0.25	0.47	0.37
9	Milled	5.0	7.0	Continuous	0.28	0.125	0.40	0.22
10	Rolled	2.375	1.625	Continuous	0.75	0.5–1.0	–	–

The investigation included both bicycle and motor vehicle testing. As part of the bicycle testing, bicycle vibration levels were collected. Table A-22 shows the frequency and amplitude of the vibrations measured on the test bike. The vibration maximum level is expressed in decibels (dB) (re: 1 m/s^2). Table A-22 shows the frequency at which the highest level of vibration occurred. In many cases there where peak values at more than one frequency. For those cases, the highest peak is listed. It was noted that the frequency of the maximum vibration level did not necessarily increase with an increase in speed.

Four vehicles were used in the motor vehicle testing. Sound levels generated by the rumble strip patterns were compared to the sound levels generated inside the vehicles on smooth pavement. The four test vehicles included:

- 1994 Oldsmobile Cutlass station wagon
- 1999 Dodge full sized pickup truck
- 2000 GMC minivan
- Unloaded tandem axle dump truck

Table A-22. Measured Vibration Levels on a Test Bicycle (*44*)

Pattern number	Bicycle speed							
	5 mph		10 mph		15 mph		20 mph	
	Max (dB)	Freq. (Hz)	Max (dB)	Freq. (Hz)	Max (dB)	Freq. (Hz)	Max (dB)	Freq. (Hz)
1, 1A	8	31.5	21	25	21	20	23	25
2, 2A	11	12.5	18	20	27	31.5	26	40
3,4,4A	10	12.5	25	31.5	34	40	21	63
5	12	20	28	12.5	35	20	N/A	N/A
6	13	25	25	12.5, 25	33	20	35	25
7	11	31.5	26	25	32	20	33	25
8	10	25	24	25	31	16	33	25
9	6	31.5	21	25	26	20	31	25
10	8	31.5	18	40	15	63	12	20

The sound level in the passenger compartment was measured using an A-weighted scale (i.e., dBA). Motor vehicle tests were conducted at 55 and 65 mph (80 and 105 km/h). Figures A-9 and A-10 show the sound levels generated above the ambient noise for the respective rumble strip patterns and motor vehicles. The sound data showed that the sound levels generated by the various rumble strip configurations were different in the various test vehicles. There was considerable variation in which rumble strip was loudest in each vehicle. Also, the loudest at 55 mph (80 km/h) was not necessarily the loudest in the same vehicle at 65 mph (105 km/h). In general, rumble strips patterns 5 through 9 had the highest sound levels.

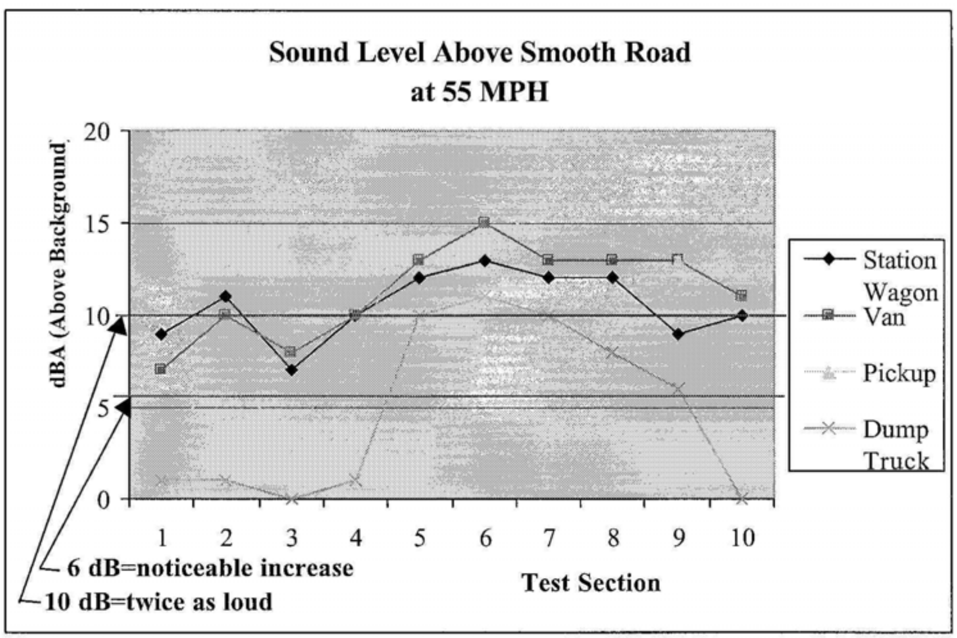


Figure A-9. Increase in the Sound Level Inside the Vehicles at 55 mph (80 km/h) (*44*)

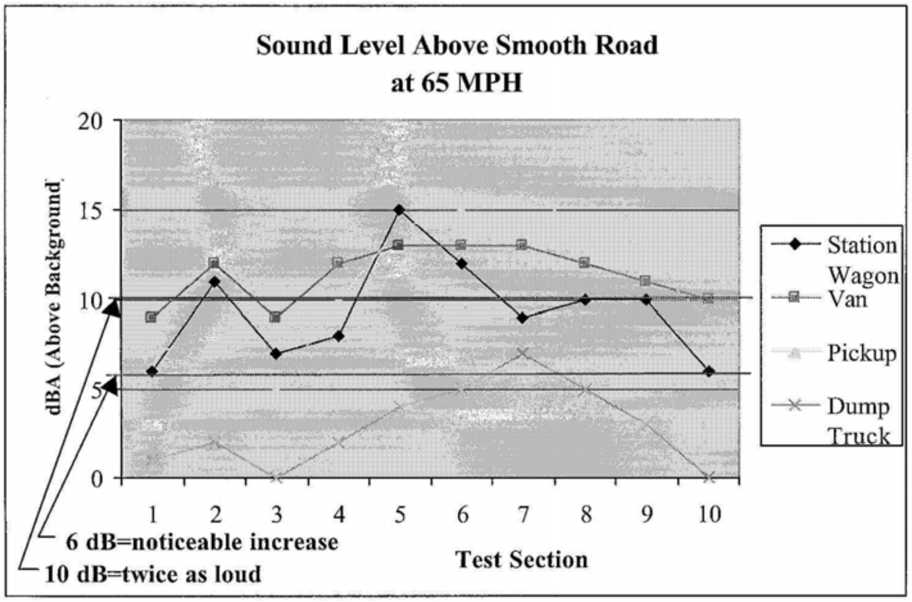


Figure A-10. Increase in the Sound Level Inside the Vehicles at 65 mph (105 km/h) (*44*)

Motor vehicle vibration levels were also collected using the GMC minivan. Vibration data were collected at two locations. One accelerometer was mounted on the floor of the van just behind the driver's seat at the spot where the floor was welded to the vehicle frame. The second accelerometer was mounted to the steering wheel. Vibrations were measured perpendicular to the plane of the steering wheel and perpendicular to the floor of the van. Vibration measurements were taken at 55 and 65 mph (80 and 105 km/h). Background measurements were taken in the travel lane at each speed to provide a comparison to the vibration measurements while traversing the rumble strips. Table A-23 presents the vibration levels in decibels and the frequency at which it occurred for each rumble strip pattern. Patterns 5 through 10 had the highest vibration levels.

Table A-23. Measured Vibrations and Frequencies of Motor Vehicle Tests (*44*)

Pattern number	Accelerometer Mounted to Floor				Accelerometer Mounted to Steering Wheel			
	55 mph		65 mph		55 mph		65 mph	
	Max (dB)[a]	Freq. (Hz)	Max (dB)	Freq. (Hz)	Max (dB)	Freq. (Hz)	Max (dB)	Freq. (Hz)
1	–6	80	–9	100	5	80	–5	40
1A	–9	80	–11	200	5	80	–5	100
2	–8	125	–6	160	0	80	–6	40 & 160
2A	–9	125	–8	160	–3	125	–4	160
3	–10	125	–9	160	–5	125	–6	160
4	–9	200	–1	250	–6	80	–[b]	–[b]
4A	–17	25	–4	250	–4	80	–[b]	–[b]
5	6	80	3	100	11	80	7	100
6	8	80	3	100	8	80	2	100
7	8	80	3	100	9	80	3	100
8	5	80	2	100	5	80 & 160	5	100
9	–2	160	–1	100	2	80 & 160	7	100
10	3	630	8	630	1	63	1	63

[a] dB, re: 1 m/s^2.
[b] Data at or below background acceleration (as measured on smooth pavement alongside rumble strips).

Torbic Study

Vehicle ride models provide guiding principles to control the vibration of vehicles for better passenger comfort. By applying the same principles to bicycles that have been developed for passenger cars and other transport vehicles, Torbic (*54*) evaluated the vibrational ride characteristics of bicycles. This served to identify how bicycles may be improved to provide better ride quality for bicyclists when they encounter rumble strips.

Torbic utilized a system of equations to solve for the oscillation centers of several types of bicycles. The location of the oscillation centers has practical significance to ride behavior. Depending upon where the oscillation centers are located, it can be determined whether the bicycles exhibit good or poor vibrational characteristics. For good ride quality of a vehicle, it is desirable that the oscillation centers be located near the front and rear axles. As the oscillation centers move further from axles, this results in poorer ride quality.

Using data from fifteen bicyclists, Torbic calculated the oscillation centers for three bicycles. In general the oscillation centers do not vary as a function of the characteristics of the bicycle or its rider. For each bicycle, the bounce oscillation center was located approximately 6.5 ft (2 m) to the left of the center of gravity, and the pitch oscillation center was located approximately 2.6 ft (0.08 m) to the right of the center of gravity. Based upon the locations of these oscillations centers, Torbic concluded each bicycle exhibited poor vibrational characteristics and that bicycles without active suspension exhibit poor vibrational characteristics.

As part of the same research, Torbic examined the conditions that cause bicyclists to experience the highest levels of discomfort and control problems while traversing milled rumble strips. Torbic concluded that whole-body vibration of bicyclists increases with unit increases in groove depth and tire pressure, and whole-body vibration decreases with unit increases in groove spacing. In addition, a bicyclist experiences the highest levels of whole-body vibration while traversing rumble strip configurations at a speed of approximately 12 mph (20 km/h).

Russell et al. Study

In an attempt to find an appropriate pattern for centerline rumble strips, field tests of 12 rumble strip patterns were conducted in Kansas (*46*). The rumble strips patterns were as follows:

Pattern 1: Continuous 12 in (305 mm) on center / 16 in (406 mm) in length

Pattern 2: Continuous 24 in (610 mm) on center / 16 in (406 mm) in length

Pattern 3: Alternating 12 and 24 in (305 and 610 mm) on center / 16 in (406 mm) in length

Pattern 4: Continuous 12 in (305 mm) on center / 12 in (305 mm) in length

Pattern 5: Continuous 24 in (610 mm) on center / 12 in (305 mm) in length

Pattern 6: Alternating 12 and 24 in (305 and 610 mm) on center / 12 in (305 mm) in length

Pattern 7: Continuous 12 in (305 mm) on center / 8 in (203 mm) in length

Pattern 8: Continuous 24 in (610 mm) on center / 8 in (203 mm) in length

Pattern 9: Alternating 12 and 24 in (305 and 610 mm) on center / 8 in (203 mm) in length

Pattern 10: Continuous 12 in (305 mm) on center / 5 in (127 mm) in length

Pattern 11: Continuous 24 in (610 mm) on center / 5 in (127 mm) in length

Pattern 12: Alternating 12 and 24 in (305 and 610 mm) on center / 5 in (127 mm) in length

The cutting spindle of the milling machine used to install the rumble strip patterns had a 12-in (305-mm) milling radius and the depth of the cut was 0.5 in (13 mm) on all patterns. Seven vehicles were included in the field testing: 2 dump trucks, 1 pick-up truck, 1 full size car, 1 compact car, 1 minivan, and 1 sport utility vehicle. Interior noise level and steering wheel vibration levels associated with the centerline rumble strip patterns at vehicle speeds of 60 mph (97 km/h) were measured for each combination of pattern and vehicle type. Table A-24 shows the average decibel level inside the passenger compartment of the respective vehicles for each of the rumble strip patterns. The results of the noise level analysis indicated that the continuous 12-in (305-mm) patterns produced higher noise levels at 60 mph (97 km/h) followed by the alternating 12- and 24-in (305- and 610-mm) and continuous 24-in (610-mm) patterns. Thus, it was theorized that patterns with higher densities produce higher average decibel levels. As for trends in decibel levels owing to rumble strip length, it appeared that the longer rumble strips generally produced higher average decibel levels, but there was no consistency among the longer lengths. This could be the result of the vehicle tires not remaining in full contact with the shorter rumble strip patterns. This was reasoned because with the shorter patterns there was a greater likelihood that the vehicles left tires did not remain in full contact with the patterns. The results of the steering wheel vibrations indicated that the alternating 12- and 24-in (305- and 610-mm) patterns produced the highest vibration levels followed by continuous 12-in (305-mm) and continuous 24-in (610-mm) patterns. Based on these preliminary results, continuous 12-in (305-mm) and alternating 12- and 24-in (305- and 610-mm) patterns were selected for further research in an existing highway setting.

Table A-24. Decibel Level at Driver's Position—60 mph (97 km/h) (*46*)

Vehicle	Pattern Tested											
	1	2	3	4	5	6	7	8	9	10	11	12
1996 IH 4900 DT 466 Dump Truck (GW = 75,000)	91.23	92.16	92.94	94.12	92.23	93.35	93.41	91.47	92.84	92.24	–	–
	0.316	0.685	0.373	0.429	0.494	0.346	0.546	0.482	0.490	0.852	–	–
1995 Ford L8000 Dump Truck (GW = 48,000)	91.34	90.73	91.07	92.73	90.48	91.43	92.01	90.03	90.54	92.31	88.21	–
	0.915	0.263	0.587	0.465	0.440	0.592	0.456	0.433	0.283	0.950	0.445	–
1991 Chevrolet 2500 Pick-Up Truck	83.50	82.86	83.77	87.47	82.68	84.18	88.77	81.44	84.11	85.29	–	–
	1.194	0.845	0.452	0.796	0.572	0.896	1.242	0.614	0.753	1.117	–	–
1993 Pontiac Bonneville Full-Size Passenger Car	82.89	80.01	83.48	84.24	79.61	84.65	83.59	79.46	83.75	83.32	79.01	82.86
	0.568	0.312	0.179	0.274	0.150	0.374	0.970	0.371	0.459	0.786	0.703	1.053
1994 Ford Escort Wagon Compact Passenger Car	87.34	86.22	87.76	89.97	86.57	87.44	89.74	87.75	88.62	88.42	85.60	–
	0.711	0.351	0.508	0.430	0.083	0.238	0.483	0.465	0.083	0.990	0.390	–
1995 Ford Aerostar Minivan	88.33	85.89	85.59	87.77	84.97	86.12	89.49	82.83	84.09	87.83	80.62	82.56
	1.146	0.904	0.612	0.600	0.530	0.668	0.692	0.851	0.604	0.437	1.083	1.255
1997 Jeep Cherokee Sport Utility Vehicle (SUV)	85.63	81.24	83.80	88.65	80.48	84.22	86.76	79.87	82.82	–	–	–
	0.676	0.821	0.544	0.338	0.419	1.014	0.683	0.725	0.563	–	–	–
Grand Mean	87.18	85.59	86.92	89.28	85.29	87.34	89.11	84.69	86.68	88.24	83.36	82.71

Notes: For each vehicle, the first row of numbers is the mean and the second row is the standard deviation.
(–) Indicates the test results were inconclusive.

Bahar et al. Study

Complaints about noise from rumble strip contact prompted the province of Alberta (CA) to commission a noise study on rumble strips to identify the optimum dimensions for rumble strips in terms of alerting drivers, as well as the noise impacts of rumble strips on the surrounding area (*57*). The testing involved continuous and intermittent milled rumble strips of varying depths, from 0.8 to 0.32 in (2 to 8 mm), and varying lengths, from 12 to 20 in (300 to 500 mm). The tests were conducted using three vehicles (i.e., tractor trailer, passenger vehicle, and motorcycle). In general, it was found that sound levels increase with rumble strip depth.

Elefteriadou et al. Study

Elefteriadou et al. (*45*) conducted a study for the Pennsylvania DOT (PennDOT) with the primary objective to develop new rumble strip configurations that decrease the level of vibration experienced by bicyclists when traversing the rumble strips. At the same time, an adequate amount of stimuli, both auditory and tactile, must be maintained to alert an inattentive/drowsy motorist. To achieve this objective, Elefteriadou et al. utilized a simulation model to evaluate how numerous rumble strip configurations impact the dynamics (i.e., the vertical acceleration and pitch angular acceleration) of a bicycle and its rider. By comparing the vertical and pitch angular acceleration of the bicycle/rider system traversing different simulated rumble strip configurations, the simulated configurations could be ranked as having the greatest or least potential to be "bicycle-tolerable." Those configurations that had the greatest potential of being "bicycle-tolerable" and could also be constructed were selected for installation at the Pennsylvania Transportation Institute (PTI) test track for further evaluation (see Table A-25).

Table A-25. Rumble Strip Configurations Installed at PTI's Test Track for Further Evaluation (*45*)

Test pattern	Groove width in (mm)	Flat portion between cuts in (mm)	Depth in (mm)
1[a]	7 in (178 mm)	5 in (127 mm)	0.5 in (13 mm)
2	5 in (127 mm)	7 in (178 mm)	0.5 in (13 mm)
3	5 in (127 mm)	7 in (178 mm)	0.375 in (10 mm)
4	5 in (127 mm)	6 in (152 mm)	0.5 in (13 mm)
5	5 in (127 mm)	6 in (152 mm)	0.375 in (10 mm)
6	5 in(127 mm)	7 in (178 mm)	0.25 in (6.3 mm)

[a] PennDOT's current standard.

The test track experiments involved testing several bicycles and a motor vehicle. To measure the effects of the different configurations on bicyclists, volunteer participants rode different types of bicycles over the rumble strip configurations at different speeds and different angles. Table A-26 presents the rankings of the test configurations based upon the vertical acceleration levels measured on mountain, road, and hybrid bicycles across all speed ranges. Similarly, Table A-27 presents the rankings from the tandem bicycle across all speed ranges. Table A-28 presents the rankings of the test configurations based upon the pitch angular acceleration levels measured on mountain, road, and hybrid bicycles across all speed ranges, and finally Table A-29 presents the rankings from the tandem bicycle across all speed ranges.

Table A-26. Ranking of Test Configurations Based on Vertical Acceleration (mountain, road, and hybrid bicycles) (*45*)

	Rank	Test pattern	Average RMS—vertical acceleration ft/s^2 (m/s^2)
Best	1	6	37.123 (11.315)
	2	3	43.228 (13.176)
	3	2	55.613 (16.951)
	4	5	63.396 (19.323)
	5	1	71.880 (21.909)
Worst	6	4	71.988 (21.942)

Table A-27. Ranking of Test Configurations Based on Vertical Acceleration (tandem bicycle) (*45*)

	Rank	Test pattern	Average RMS—vertical acceleration ft/s^2 (m/s^2)
Best	1	6	29.327 (8.939)
	2	3	34.003 (10.364)
	3	2	40.850 (12.451)
	4	1	55.131 (16.804)
	5	5	58.940 (17.965)
Worst	6	4	62.605 (19.082)

Table A-28. Ranking of Test Configurations Based on Pitch Angular Acceleration (road, mountain, and hybrid bicycles) (*45*)

	Rank	Test pattern	Average RMS—Pitch angular acceleration rad/s^2
Best	1	6	13.288
	2	3	15.809
	3	5	18.994
	4	2	21.230
	5	4	21.711
Worst	6	1	30.593

Table A-29. Ranking of Test Configurations Based on Pitch Angular Acceleration (tandem bicycle) (*45*)

	Rank	Test pattern	Average RMS—Pitch angular acceleration rad/s^2
Best	1	6	10.912
	2	3	13.171
	3	5	15.407
	4	2	16.404
	5	4	17.829
Worst	6	1	22.006

Elefteriadou et al. also measured the lateral stability of bicycles by measuring the ability of bicyclists to ride along a designated path along the rumble strip. Lower percentages of time spent deviating from the designated path indicate better control while traversing the rumble strip configuration. Higher percentages of time spent deviating from the designated path indicate greater loss of control. Table A-30 presents the rankings of the test configurations based on this objective control measure.

Table A-30. Ranking of Test Configurations Based on Objective Control (all bicycles) (*45*)

			Percentage of Time Off the Line	
	Rank	Test pattern	Average	Difference (Pattern—Base)
		Smooth	0.0814	
Best	1	3	0.1228	0.0414
	2	6	0.126	0.0446
	3	4	0.1644	0.0830
	4	5	0.1922	0.1108
	5	2	0.1956	0.1142
Worst	6	1	0.2535	0.1721

To assess the effectiveness of the various rumble strip configurations on alerting inattentive/drowsy motorists, measurements were taken of the auditory and vibrational stimuli generated by the rumble strip configurations. A 1998 Plymouth Grand Voyager was used to collect the motor vehicle data. Three objective measures were collected during the motor vehicle testing at PTI's test track:

- vertical acceleration of the body frame
- pitch angular acceleration of the body frame
- maximum sound level in the passenger compartment

Based upon preliminary results of the vibration data, only the maximum sound level in the passenger compartment of the minivan was used to assess the relative effect of the six rumble strip patterns on the dynamics of the minivan. Table A-31 presents the rankings of the test configurations based upon the noise level testing for the motor vehicle. One set of rankings is provided based upon the low speed testing at 45 mph (72 km/h), and a second set of rankings is provided based upon the high speed testing at 55 mph (88 km/h).

Table A-31. Ranking of Test Configurations Based on Noise Level Testing (*45*)

	Rank	Test pattern	Speed mph (km/h)	Avg. max. sound level dBA	Difference (pattern—smooth)
Best	1	4	45 (72)	83.6	15.2
	2	1	45 (72)	80.0	11.6
	3	5	45 (72)	79.3	10.9
	4	2	45 (72)	78.4	10.0
	5	3	45 (72)	75.2	6.8
Worst	6	6	45 (72)	74.7	6.3
		Smooth	45 (72)	68.4	
Best	1	1	55 (88)	88.9	23.7
	2	2	55 (88)	83.7	18.5
	3	3	55 (88)	81.3	16.1
	4	4	55 (88)	81.2	16.0
	5	5	55 (88)	79.1	13.9
Worst	6	6	55 (88)	78.2	13.0
		Smooth	55 (88)	65.2	

Chen Study

Chen (*48*) studied the vibrational and noise stimuli generated by rumble strips on motor vehicles. As part of the study, Chen conducted a theoretical analysis of the tire drop to evaluate the effectiveness of rumble strips. For rumble strips to be effective, Chen determined that the width of the strip should be large enough for the tire to drop into the groove so as to generate vibration and noise. The tire drop is dependent on the tire static and dynamic deflection, which is a function of the load and inflation pressure, the speed of the motor vehicle, and the width of the rumble strip. As part of the field testing, Chen conducted pavement roughness and sound level tests on three different types of rumble strips: continuous rolled rumble strips on asphalt shoulders, continuous milled rumble strips on asphalt shoulders, and intermittent corrugated rumble strips on concrete shoulders. Data were collected at 112 locations on Interstates 85 and 295 in Virginia under the following conditions:

- Testing speed: 55 and 65 mph (88 and 105 km/h)
- Angle of departure: 5°
- Road conditions: dry and clean

From the pavement roughness data, Chen concluded that the milled rumble strips performed better than the rolled or corrugated strips. Roughness levels measured by the International Roughness Index (IRI) were 12.6 times greater for the milled rumble strips than the rolled rumble strips. The roughness levels for the milled rumble strips were also 7.2 times greater than the corrugated rumble strips. Chen also noted rolled rumble strips have very little effect (i.e., change in vibration) on trucks.

As part of the sound level testing, Chen compared the difference in sound levels between driving in the travel lane and driving over the different rumble strips. The sound levels were measured while driving at 65 mph (105 km/h). The tests showed milled rumble strips generated the largest sound excesses. The sound excesses for each type of rumble strip were as follows:

- 2.5 dBA difference between rolled rumble strips and travel lane
- 7.0 dBA difference between corrugated rumble strips and travel lane
- 10.87 dBA difference between milled rumble strips and travel lane

In a follow-up to the research that was conducted in 1994, Chen et al. (*27*) compared sound data collected from Virginia highways with regression models developed by Khan and Bacchus (*97*) that predict sound levels generated by rumble strips. The regression models developed by Khan and Bacchus are as follows:

$$\text{Nonlinear: dBA} = e^{3.412}C^{0.074}V^{0.172}$$

$$\text{Linear: dBA} = 53.636 + 0.585C + 3.28E + 0.161V$$

where: dBA = sound level in passenger car (in decibels)
C = width of rumble strip (cm)
E = depth of rumble strip (cm)
V = speed of test vehicle (km/h)

Chen et al. (2003) concluded the field data from Virginia highways fit the models developed by Khan and Bacchus very well. The comparison reached a correlation factor of 96 percent.

Pennsylvania Turnpike Study

The Pennsylvania Turnpike Commission conducted tests to evaluate the level of sound generated by various milled rumble strip patterns (Figure A-11) (*24,104*). Tests were conducted with both a passenger car and a truck. During the testing, the motor vehicles were driven over the different designs, and the sound level was recorded inside the motor vehicles to compare their effectiveness. Several speeds were tested: 40, 50, 60, and 65 mph (truck only) (64, 80, 97, and 105 km/h). Tables A-32 and A-33 present the results of the sound measurements. Tables A-32 and A-33 do not show the mean noise level inside the sedan or truck while being driven in the travel lane. The average level of noise inside a car being driven in the travel lane was 73 dBA at 55 mph (88 km/h), and the average level of noise in the truck was around 79 dBA. Considering first the tests with the sedan, pattern 5 gave the highest dBA readings for any of the speeds. In the case of the truck tests, only pattern 5 gave a noise level higher than the background noise in the passenger compartment. Pattern 5 had the deepest and the widest groove.

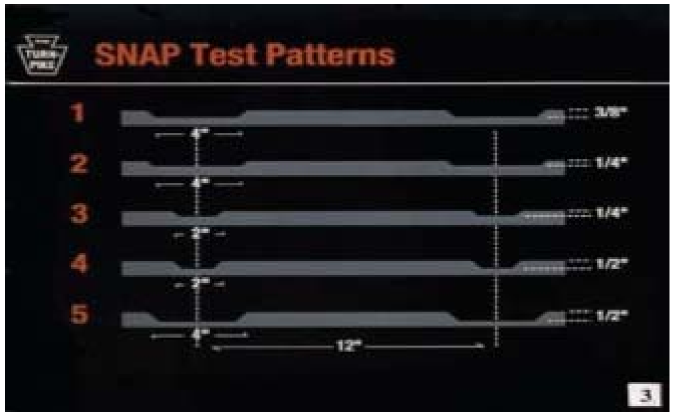


Figure A-11. SNAP Test Patterns (*104*)

Table A-32. Noise Test Results for a Passenger Car Traversing Various Rumble Strip Patterns (*104*)

Sedan speed	Mean noise level (dBA) 40 mph (64 km/h)	50 mph (80 km/h)	60 mph (97 km/h)
Pattern 1	74	77	80
Pattern 2	70	75	76
Pattern 3	68	74	74
Pattern 4	71	73	74
Pattern 5	75	78	80

Table A-33. Noise Test Results for a Truck Traversing Various Rumble Strip Patterns (*104*)

Truck speed	Mean noise level (dBA) 40 mph (64 km/h)	50 mph (80 km/h)	60 mph (97 km/h)	65 mph (105 km/h)
Pattern 1	–	–	–	–
Pattern 2	–	–	–	–
Pattern 3	–	–	–	–
Pattern 4	–	–	–	–
Pattern 5	–	82	82	86

Note: Not recordable, 79 dBA in the truck cab.

Chaudoin and Nelson Study

In their study of rumble strips on Interstates 15 and 40, Chaudoin and Nelson (*17*) investigated the influence of groove shape and spacing on noise. Noise measurements were gathered from three different shapes of rumble strips: v-shape, rectangular, and rounded. According to the evaluation, the v-shaped groove gave a good sound effect, and the rounded shape gave a very good sound effect. There were no results concerning the noise generated by the rectangular groove.

Chaudoin and Nelson also studied the effects of four groove spacings: 4 in (102 mm), 8 in (203 mm), variable, and 16 in (406 mm). The 4-in (102-mm) spacing gave a high-pitched sound effect. The 8-in (203-mm) spacing provided a good sound effect with a lower pitch than the 4-in (102-mm) spacing. The variable spacing provided a sound that was more of a flat tire sound than a tone. The 16-in (406-mm) spacing did not provide adequate sound to be heard.

Tye Study

Tye (*49*) evaluated raised and milled rumble strips by instrumenting a test car and driving over various configurations of rumble strips to collect data on sound, vibration, and handling. The test vehicle was instrumented with a tri-axial accelerometer mounted on the front floor over the transmission to measure the vertical, transverse, and longitudinal vibration components. The controllability of the motor vehicle was reasoned to be related to the front-wheel bounce so the magnitude of the wheel bounce was measured by a rectilinear potentiometer mounted behind the right front wheel.

Using the instrumented test vehicle, Tye collected sound, vibration, and handling data for numerous rumble strip designs. Raised rumble strip patterns were tested using plywood rib rumble strips. The plywood rumble strip patterns tested had a thickness between 0.25 and 0.75 in (6 and 19 mm) and had a rib width ranging from 3 to 8 in (76 to 203 mm), in 1-in (25-mm) increments. The spacing was varied from 3 to 6 in (76 to 152 mm), also in 1-in (25-mm) increments. A total of 57 raised rumble strip patterns were tested at speeds ranging from 30 to 70 mph (48 to 113 km/h). In summary, these tests revealed:

- **Sound level:** Rumble strip ribs 0.25-in (6-mm) thick were marginally effective, in producing a sound level that averaged 7 dBA above the background level on bare pavement. The 0.5-in (13-mm) high rumble strips produced a sound level that averaged 9 dBA above the background level, while the 0.75-in (19-mm) high strips produced an 11 dBA increase.

  For each rumble strip pattern, the sound level generally increased to the highest levels at the fastest speeds, 60 and 70 mph (97 and 113 km/h); however, the background sound level from the bare pavement increased with speed as well. The difference between the sound levels was greatest in the 30- to 40-mph (48-

to 64-km/h) range than at higher speeds for more than 80 percent of the plywood rib rumble strip patterns tested. This difference was lowest at the 60- to 70-mph (97- to 113-km/h) range for over 95 percent of the patterns.

Varying the width of the rumble strip ribs did not produce significantly higher or lower sound levels for any given spacing of ribs.

Rumble strips spacings of 3, 4, and 5 ft (0.91, 1.22, and 1.52 m) produced significantly different sound levels. Sound levels decreased with the 6 ft (1.83 m) and greater rib spacing.

- **Right front wheel movement:** The data showed a somewhat erratic pattern of right front wheel movement. There was a tendency for the movement to decrease with increasing speed and to increase with increasing rib spacing. Many of the test patterns caused little or no difference from the background level of wheel movement on normal pavement.
- **Vertical acceleration:** The 0.75-in (19-mm) thick rumble strip ribs produced a higher than average increase in vertical acceleration over the background level. The 0.5-in (13-mm) thick pattern, with 7-in (178-mm) wide ribs were the next best. The 0.5-in (13-mm) thick patterns, by 3- or 5-in (76- or 127-mm) wide ribs, produced vertical accelerations that were 1/3 lower in amplitude than those 0.5-in (13-mm) high by 7-in (178-mm) wide. The 0.25-in (6-mm) thick rumble strip ribs produced an even lower average level of vertical acceleration. In general, thicker rumble strips generated greater vertical acceleration.
- **Lateral acceleration:** Regardless of rib thickness or width, the greatest increase in amplitude of lateral acceleration was produced by ribs spaced on 5-ft (1.5-m) centers. The ribs spaced on 8-ft (2.4-m) centers produced the lowest average increase in amplitude over the background level.

The instrumented vehicle was also driven over a series of milled rumble strips. The grooves varied from 0.5 to 0.75 in (6 to 19 mm) in depth. The width of the grooves was either 3, 5, or 7 in (76, 127, or 178 mm). All of the grooves were spaced 5 ft (1.5 m) apart, and the sides of the grooves were vertical. The milled rumble strips, in general, produced lower average differences in sound, wheel movement, and vertical and lateral acceleration from background levels than the raised plywood rumble strips. The 7-in (178-mm) wide grooves produced slightly greater average increases in sound and vibration over the background level.

Tests with the instrumented vehicle were also made on a series of rumble strips composed of rows of ceramic pavement markers. The markers were 4 in (102 mm) in diameter and approximately 0.75 in (19 mm) in height. All of the pavement marker rumble strips except one used variable row spacing. The pavement marker rumble strips as a group produced sound and vibration levels that were less effective than the 0.25-in (6-mm) high plywood rumble strips.

Franke Study

Franke (*108*) studied the optimum spacing of shoulder rumble strips on the Interstate relative to speed. The optimum spacing was determined from vibrational measurements of a car. Heights of 0.5 in (13 mm) and 0.375 in (10 mm) were evaluated, but time limitations for the study did not allow evaluation of various rumble strip widths. Various spacings were tested: 1.25, 2, 2.5, 3.25, 3.75, 5, 7.5, 10, 10.5, and 15 ft (0.38, 0.61, 0.76, 0.99, 1.14, 1.52, 2.29, 3.05, 3.20, and 4.57 m). The test car was driven at the following speeds: 20, 30, 40, 50, 60, and 70 mph (32, 48, 64, 80, 97, and 113 km/h). Conclusions from the study were as follows:

- A spacing of 2 ft (0.61 m) or less created a large amount of wheel hop and/or did not allow the tires to descend between the rumble strips, which created a situation where the vibration level increased when the speed decreased.
- A 5 ft (1.52 m) spacing seemed to be the best suited for use on the shoulder of roadways.
- Rumble strips should not be of a height or depth greater than 0.5 in (13 mm).

A.5. Effects of Rumble Strips on Specific Types of Highway Users

This section describes the effects that rumble strips have on specific types of highway users (i.e., drivers of passenger cars, drivers of trucks, motorcyclists, bicyclists, and pedestrians), primarily from a human factors perspective. In most cases, the intended effect of shoulder and centerline rumble strips is to alert inattentive or drowsy drivers of motor vehicles that their vehicles have departed from the travel lane. However, shoulder and/or centerline rumble strips may also cause unintended behaviors or may negatively impact certain types of highway users such as motorcyclists and bicyclists. This section focuses primarily on those studies in which participants subjectively rated the impact of rumble strips. To the extent possible, this section also focuses on the correlation between the alerting properties of the rumble strips (i.e., vibration and sound levels) and the reactions or behaviors of highway users to these stimuli.

Drivers of Passenger Cars

Rumble strips are intended to warn motorists that their vehicles have partially or completely left the travel lane and that they must correct their steering to return back within their intended travel lane. Rumble strips provide this warning through audible and tactile stimuli. As motor vehicle tires pass over rumble strips, the dynamic interaction between the vehicle tires and the pavement surface cause noise to be generated within the passenger compartment and cause vibration of the vehicle floor, seat, and steering wheel. The noise provides an audible warning to the motorist, while the vibration provides a tactile warning. Rumble strips are intended to provide a sufficient amount of both audible and tactile stimuli to effectively alert drivers, while minimizing any adverse effects such as startling drivers to a degree that drivers overreact or over steer when trying to return to their travel lane or by causing too much vibration which could negatively impact vehicle handling capabilities.

Recently, Anund et al. (*77*) conducted a driving simulator experiment to investigate the effects of rumble strips on fatigued drivers. The driving simulator was an advanced moving based passenger car simulator (Figure A-12). Four patterns of rumble strips (Table A-34) were simulated and placed at two locations along the shoulder (i.e., near the edgeline and near the outside edge of the shoulder) and along the centerline. Data from 40 regular shift workers driving during morning hours after a full night shift were used in the analysis. Both driving behavior and physiological data were recorded. The primary measures of interested included:

Figure A-12. Moving Base Driving Simulator at VTI (*74*)

- Maximum lateral position
- Time from lane departure to "steady state"
- Velocity at "steady state"
- Time since last lane departure
- The number of steering wheel corrections per minute
- Time to correct action

Table A-34. Patterns of Simulated Rumble Strips at VTI (*77*)

Pattern	Length	Width	Depth	Spacing
Pennsylvania	20 in (500 mm)	7 in (170 mm)	0.5 in (12 mm)	12 in (300 mm)
Swedish	20 in (500 mm)	12 in (300 mm)	0.75 in (20 mm)	21 in (530 mm)
Malilla	14 in (350 mm)	6 in (150 mm)	0.375 in (10 mm)	48 in (1200 mm)
Finnish	7 in (175 mm)	0.75 in (20 mm)	0.625 in (15 mm)	12 in (300 mm)

The primary findings of interest from this study are as follows:

- For departures to the right (i.e., shoulder rumble strips), the maximum excess lane departure (i.e., how far beyond the rumble strip the vehicle traveled after encountering the rumble strip) was greater when the rumble strips were placed along the outside portion of the shoulder than when placed close to the edgeline.
- For departures to the right (i.e., shoulder rumble strips), there were no significant differences in other measured driver behaviors (i.e., time from lane departure to "steady state," velocity at "steady state," time since last lane departure, number of steering wheel corrections per minute, and time to correct action).
- For departures to the left (i.e., centerline rumble strips), the results showed that the time gaps between lane departures were shortest for the Finnish rumble strips and the longest for the Swedish rumble strips. There were no other significant differences in the other measured driving behaviors.
- Through a subjective questionnaire, the drivers rated the effectiveness of different levels of sound and vibration which contributed most to the alerting properties of the rumble strips. The majority of the drives indicated that both sound and vibration contributed to their impression from the rumble strip. Figure A-13 illustrates in more detail the drivers' opinions on the effectiveness of different levels of sound and vibration.

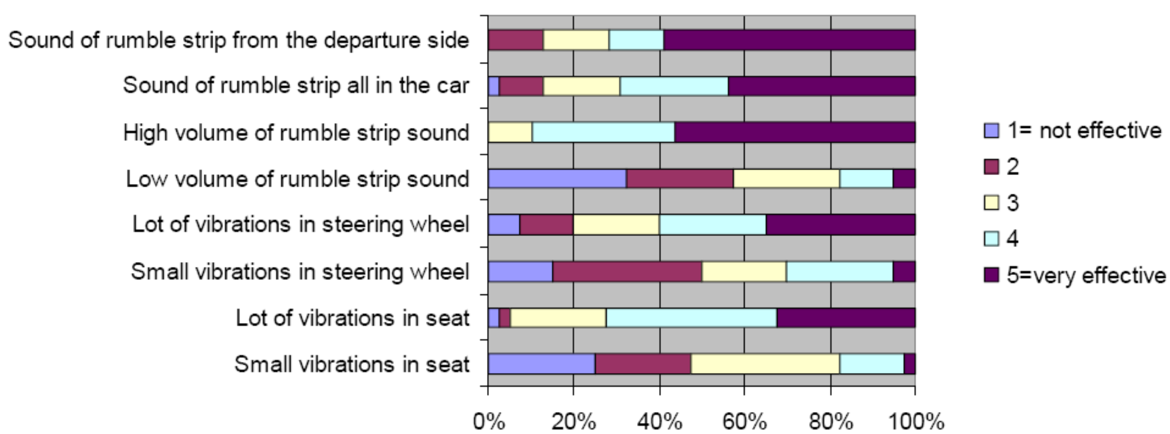


Figure A-13. Drivers' Opinions of the Effectiveness of Different Levels of Sound and Vibrations (*77*)

Given that the behavior data did not show any great differences between the types of rumble strips, Anund et al. concluded that the more aggressive rumble strips (i.e., Swedish and Pennsylvania style patterns) should be used. Anund et al. reasoned this because the subjects preferred them and they did not see any danger of being scared and thereby causing accidents. Anund et al. also cited that this investigation only included passenger cars and reasoned that heavy vehicles should benefit even more from the more aggressive designs. Concerning the placement of the rumble strips, Anund et al.

recommended placing the rumble strips close to the edgeline which provides a wider recovery area along the shoulder. The support for this conclusion was that drivers preferred this solution and most of them did not think that the road width was too narrow as a result of this placement. Further, there are other benefits of this placement as well, especially as it relates to bicyclists.

Hirasawa et al. (*42*) also conducted subjective testing at the Tomakomai Winter Test Track. The vehicles tested during the subjective experiments included passenger cars, motorcycles, and bicycles. Sixty-two participants participated in the test track experiments. At the driving/riding experiment, each participant filled out a questionnaire rating the safety of the three test patterns (Table A-17). Figure A-14 shows the results of the safety questionnaire. The results are combined for all road users. The participants' negative evaluation of the rumble strips increases with the depth of the grooves. More participants answered that they felt danger when riding on the deep grooves than on the shallow grooves.

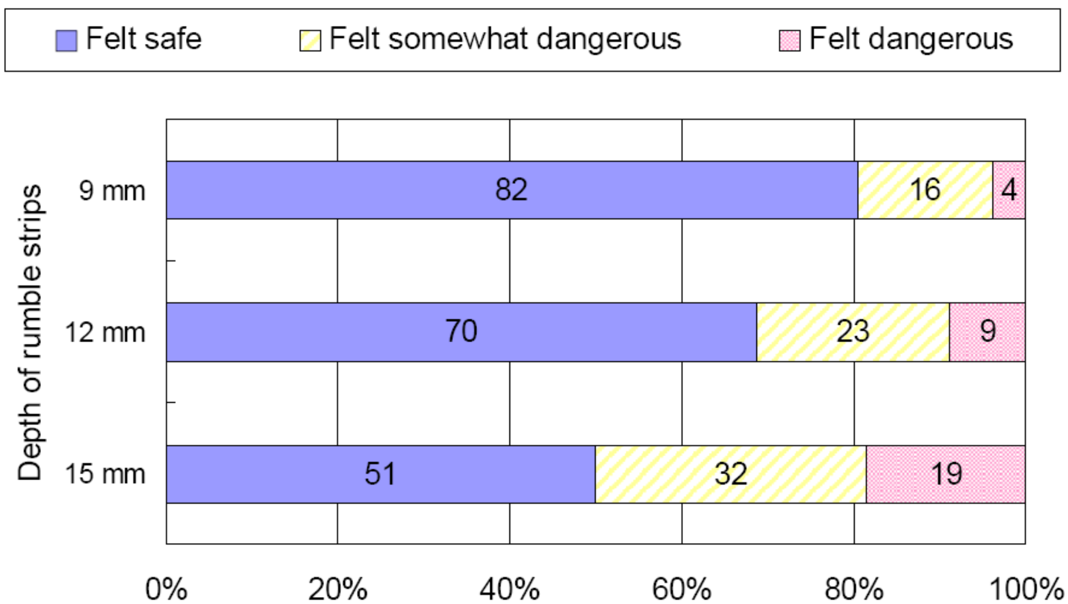


Figure A-14. Subjective Ratings of Safety (*42*)

When Outcalt (*44*) conducted his research in Colorado, he assumed that if rumble strips generated noise levels 6 dBA above the ambient noise level during normal operations (i.e., while driving the in travel lane), that this change in noise level would be a "clearly noticeable change" and would be sufficient to alert an inattentive/drowsy driver. Outcalt based his assumption on how a typical person perceives different amounts of change in sound level. Outcalt never investigated or verified this assumption as part of this research. Table A-35 suggests the approximate human perception of changes in sound level.

Table A-35. Approximate Human Perception of Changes in Sound Level (*44*)

Change in sound level (dBA)	Change in apparent loudness
1 dBA	Imperceptible
3 dBA	Barely noticeable
6 dBA	Clearly noticeable
10 dBA	About twice—or half as loud
20 dBA	About four times—or one-fourth as loud

As part of the investigation conducted by Bucko and Khorashadi (*14*) in California, two drivers provided a subjective assessment of the experimental rumble strips patterns. Based upon the subjective opinions of the two evaluators who tested several light passenger vehicles at speeds of 50 and 62 mph (80 and 100 km/h), Bucko and Khorashadi (2001) concluded the following [**NOTE:** The vibration levels provided in parentheses for the rumble strip patterns are the average resultant accelerations from both speed levels (Table A-19). Similarly, the sound levels provided in parentheses for the rumble strip patterns are the average resultant noise levels from both speed levels (Table A-20)]:

- The vibration for rumble strips 1 (0.280 g) and 2 (0.125 g) was relatively similar to each other at 50 and 62 mph (80 and 100 km/h).
- Rumble strips 3 (0.408 g), 4 (0.450 g), and 5 (0.567 g) produced a higher degree of vibration than rumble strips 1 (0.280 g) and 2 (0.125 g) at 50 and 62 mph (80 and 100 km/h).
- The degree of vibration increased in ascending order with rumble strip 1 having the lowest vibration and rumble strip 5 having the highest vibration.
- The noise generated by rumble strips 1 (13.5 dBA) and 2 (11.0 dBA) were relatively similar to each other at 50 and 62 mph (80 and 100 km/h) and were considered to have a low to moderate alerting value when compared to rumble strips 3 (16.7 dBA), 4 (18.3 dBA), and 5 (19.9 dBA) which were considered to have a high alerting property.
- Vibrations felt through the steering wheel are negligible in their alerting properties compared to the noise level produced in the passenger compartment.
- Although several rumble strip configurations required an additional amount of hand grip strength, none of the rumble strips caused any fishtailing or loss of control of light passenger vehicles.

Watts (*76*) investigated the alerting properties of the rumble strips using a driving simulator. A stereo tape player was connected to the driving simulator, and noise pulses were triggered each time the motorist would drift from the lane. The motorist was asked to evaluate the noise patterns on a scale from one to seven, from not noticeable to very noticeable. The motorists were also asked to answer multiple choice questionnaires related to the type of noise they heard and what generated the noise. Watts concluded that rumble strips that produce 4 dBA increases or above would be readily detected by motorists if the noise level was sustained for 350 ms or longer. However if the noise increase was only 2 dBA, a pulse length of at least 900 ms would probably be required. Also, a pattern of noise consisting of a regular series of 500 ms pulses separated by 500 ms would be suitable for alerting motorists. The noise increase in the pulses over the ambient levels should be at least 4 dBA.

As part of the motor vehicle tests conducted by Tye (*49*), a subjective evaluation of the rumble strips patterns was performed by two California highway patrol officers and two traffic engineers. Their combined opinion was that the 0.25-in (6-mm) high plywood rumble strips did not provide adequate vibration. The 0.5-in (13-mm) high rumble strips were considered to have adequate alerting properties, and the 0.75-in (19-mm) high rumble strips were considered to have adequate to good properties. There were good correlations between the sound levels measured by the instrumentation and the loudness experienced by the evaluators. Similarly, there was a good correlation between the vertical vibration data and the shaking felt by the evaluators. However, the evaluators' subjective opinions of motor vehicle controllability did not correlate well with the instrument data for front wheel bounce. This was understandable because the motorists' sensation of control was related to the wheel spinning and fishtailing. The front wheel bounce data would probably bear a better relationship to vehicle control if the motorists were turning while traversing the rumble strips. All test runs, however, were made with the motor vehicle on a straight path through the rumble strip pattern.

O'Hanlon and Kelly (*50*) conducted an experiment to empirically evaluate the effectiveness of different shoulder treatments for arousing fatigued drivers who allow their vehicle to drift from the travel way onto the shoulder. Physiological data from drivers were recorded from an instrumented vehicle in which 51 young male drivers collectively drove for 11,841 minutes on four test circuits covering 3,976 mi (6,400 km). Three shoulder treatments were installed along the test circuits:

- Rib treatment which consisted of parallel raised strips of rock aggregate set in bituminous binder
- Marker treatment which consisted of parallel arrays of raised circular pavement markers
- Groove treatment which consisted of parallel slots cut into the shoulder surface

In total the test subjects drove onto the shoulder on 229 different occasions, and these excursions resulted in 112 separate impacts with the various shoulder treatments. The subjects were monitored as to heart rate, electrocardiogram, electroencephalogram, skin conductance, and overall performance. O'Hanlon and Kelley did not measure the vibration levels experienced by the drivers so they did not investigate the correlation between vibration levels and measured physiological measures. Several relevant conclusions from this investigation are as follows:

- Relative to SVROR incidents which do not involve impacts with the respective shoulder treatments, those involving impacts tended to forestall the occurrence of subsequent SVROR incidents. However, the elapsed driving time preceding the first SVROR incident is generally much longer than the time elapsed before the next incident, regardless of whether or not the first incident involved an impact with a shoulder treatment.

- Sizable percentages of drivers experiencing SVROR incidents, which do and do not involve impacts with shoulder treatments, run off the road again within the next five minutes (in this study, 18.5% and 28.6%, respectively).
- The rib shoulder treatment evoked the greatest immediate increase in arousal when struck during the course of SVROR incidents.
- The marker shoulder treatment was less effective in evoking arousal than the rib treatment, although probably not to any significant degree.
- The groove shoulder treatment was ineffective in arousing the driver. In other words, the SVROR incidents involving this groove treatment evoked no greater arousal than those without impacts.
- The persistence of arousal following impacts with every type of shoulder treatment was very brief. Little, if any, measurable residual of the immediate arousal reaction was present five minutes after any type of SVROR incident.
- No hazardous behavioral overreaction occurred following the impacts with the shoulder treatments in this study.
- Drivers tend to inadvertently drift to and beyond their lane boundaries with increasing frequency as a function of time on the road. Under some circumstances, drivers will allow their lane drifting frequencies to reach dangerously high levels.
- Lane drift frequency is sensitive to as yet undefined road and traffic factors which vary between different highways and between dissimilar segments of the same highway.
- Drivers drift more frequently from their lane to the right than to the left.
- Driver arousal falls as a function of time on the road in correspondence with a deterioration in continuous road tracking performance.
- In this study, the average angle of departure followed during SVROR incidents was approximately 3 degrees.

Relevant recommendations made by O'Hanlon and Kelly (*50*) include:

- The use of rib or marker shoulder treatments along highways having relatively high incidents of SVROR accidents. Further, they recommended that the treatment be placed along a considerable length of the target highway because evidence suggests that "spot" applications of 10 to 20 mi (16.1 to 32.2 km) would be ineffective in reducing the overall SVROR accident frequency on the target highway.
- Place the treatments on the shoulder as close as possible to the travel way.
- Install signing along the target highway to inform motorists of the presence of the treatment and of the significance of inadvertent impacts with the treatment.

- Heightened visual contrast between the travel way and the shoulder may reduce the tendency for drivers to drift onto the shoulder.

In Michigan a recent community survey was conducted on the safety of rumble strips along with focus group interviews (*109*). The survey results showed a positive reaction to the presence of rumble strips by the majority of survey respondents. The major findings are as follows:

- Roughly 84 percent of respondents either “strongly” or “somewhat” agree that rumble strips warn them when they are distracted, while 77 percent feel safer because of their presence.
- 71 percent of respondents indicated that an added benefit of the rumble strips was improving the visibility of the road edge at night.
- During focus group interviews, drivers felt that the best placement of rumble strips is 8 to 14 in (203 to 350 mm) from the edgeline.

As part of their centerline rumble strip research, Russell and Rys (*36*) conducted a survey to determine the driver’s perceived effectiveness of several rumble strip patterns and the presence of centerline rumble strips. The most telling results of the survey were that 38 percent of respondents indicated that they would prefer a continuous pattern of centerline rumble strips over an alternating pattern and 96 percent felt that centerline rumble strip applications would reduce accidents.

Drivers of Heavy Vehicles (i.e., Trucks)

With heavy vehicles, the most relevant issue is whether a sufficient amount of stimuli is generated within the passenger compartment to alert a truck driver. Only one study was found that investigated the subjective reaction of truck drivers while traversing rumble strips. Based upon the subjective opinions of two evaluators who tested several commercial vehicles at speeds of 50 and 62 mph (80 and 100 km/h), Bucko and Khorashadi (*14*) concluded the following:

- The vibration for rumble strips 1 (0.342 g) and 2 (0.150 g) was judged to be minimal and have a low to negligible alerting value.
- Rumble strips 3 (0.226 g), 4 (0.246 g), and 5 (0.286 g) produced a higher degree of vibration than rumble strips 1 (0.342 g) and 2 (0.150 g). However, in commercial vehicles vibrations are dampened considerably because of the size and weight of the vehicles. Thus, the alerting properties of the vibration levels are essentially insignificant.
- The noise generated for rumble strips 1 (4.72 dBA) and 2 (1.88 dBA) were considered to have a low alerting value when compared to noise generated by rumble strips 3 (3.62 dBA), 4 (4.61 dBA), and 5 (4.62 dBA) which were considered to have a moderate alerting value.

- The noise in the passenger compartment of a commercial vehicle, generated from rumble strips, has a greater effect in alerting a driver than the vibration produced by the same rumble strips.
- The noise in the passenger compartment of a commercial vehicle, generated from rumble strips, has low-to-moderate alerting properties.
- None of the rumble strips caused any fishtailing or loss of control of commercial vehicles.

Motorcyclists

The primary concern of motorcyclists about rumble strips relates to controllability. Only a few studies of rumble strips have included motorcycles in field experiments. The most detailed study of the interaction between motorcycles and rumble strips was performed by Miller (*53*). Miller investigated motorcycle rider behavior on roads with centerline rumble strips. The research involved a review of motorcycle crash records, an observational study of motorcyclists on roads with centerline rumble strips, and a closed course field study where 32 motorcyclists traversed rumble strips. Miller concluded that centerline rumble strips add no measurable risk to motorcyclists.

In the research conducted by Bucko and Khorashadi (*44*), a limited number of field tests with motorcycles were completed by several members of the California Highway Patrol (CHP). Four members of the CHP, all considered to be advanced motorcyclists, subjectively rated all of the rumble strip treatments installed at the Dynamic Test Facility while traveling at 50 and 65 mph (80 and 105 km/h) on either a BMW R1100RTP or Harley Davidson FX motorcycle from their fleet. Although the results were statistically insignificant, Bucko and Khorashadi (*14*) noted that the results of the tests were quite positive. None of the treatments was found to have significant deficiencies from a safety point of view. In fact, all treatments were rated very high. The only concerns noted from the CHP participants were that the raised pavement markers and Carsonite Bars were slick when wet.

The CHP also participated in earlier rumble strip research conducted in California by Tye (*49*). Based upon testing that involved driving a fully equipped CHP Harley-Davidson motorcycle over plywood rumble strips at speeds of 30, 50, and 60 mph (48, 80, and 97 km/h), Tye reported that control of the motorcycle was not affected by any of the rumble strips. Tye speculated that the wheelbase of the motorcycle was such that the motorcycle was affected by only one rib at a time.

Kansas and Massachusetts also report testing motorcycles on rumble strips (*63*). While the composition of the Kansas test group was unknown, the Massachusetts test group was comprised of the police motorcycle squad. In both studies the test groups reported noticing the rumble strips, but none of the motorcyclists reported experiencing control problems.

Bicyclists

Bicyclists and bicycle groups have expressed concerns about both shoulder and centerline rumble strips. Their main concerns are that a bicyclist may lose control while riding over the rumble strips and that bicyclists experience discomfort while traversing rumble strips. Several studies have investigated the subjective reactions of bicyclists as they experienced a variety of rumble strip patterns.

Gardner et al. (*43*) conducted a survey of bicyclists to assess their like or dislike of the football shaped rumble strips compared to rectangular shaped rumble strips. The survey was distributed to a Wichita based bicycle group, and twenty-three responses were obtained. The survey revealed that the bicyclists preferred the football shaped rumble strips over the rectangular shaped rumble strips.

Torbic (*54*) examined the fundamental relationships between rumble strip dimensions, bicyclists' perceptions of ride comfort, and the controllability of a bicycle and investigated the causes of discomfort as well as controllability problems that bicyclists experience while traversing rumble strips. The primary objectives of this research were:

- To investigate the relationship between whole-body vibration generated by milled rumble strips and bicyclists' perceptions of comfort
- To investigate the relationship between whole-body vibration generated by milled rumble strips and the controllability of a bicycle
- To identify the conditions that cause bicyclists to experience the highest levels of discomfort and control problems while traversing milled rumble strips

Torbic used data gathered during the PennDOT *Bicycle-Tolerable Shoulder Rumble Strips* project (*45*) and supplemented it with additional data to evaluate the ride quality of bicycles. In this research, Torbic developed a methodology for quantifying whole-body vibration of bicyclists. The methodology was based upon guidelines in International Standard (ISO) 2631 (*55*) for quantifying whole-body vibration to assess human response. Whole-body vibrations were calculated by combining vertical and pitch angular accelerations into one measure to assess the combined effect on comfort and controllability. Then, the relationships between whole-body vibration and bicyclists' perceptions of comfort and the controllability of bicycles were assessed. Based upon the analysis results, Torbic concluded that the relationship between whole-body vibration and a bicyclist's perception of comfort is linear; as vibration increases comfort decreases. The analysis also indicated there is no clear relationship between whole-body vibration and the controllability of a bicycle.

As part of the bicycle testing portion of their study, Bucko and Khorashadi (*14*) collected subjective data from bicycle riders of all ages and experience levels while riding over eleven different rumble strip patterns (Table A-18). Participants traversed the eleven rumble strip patterns at varying speeds, angles, in groups, and as a single rider. Participants could select to ride one of the 18 bicycles available for the testing or could use their own bicycle during the tests. After traversing the rumble strip patterns, the participants stopped and subjectively rated the comfort and control level of the rumble strips. Fifty-five bicyclists participated in the subjective testing. Figure A-15 shows the mean subjective comfort ratings for the eleven treatments. In Figure A-15, higher values of mean response represent a higher level of comfort, while lower values of mean response represent a lower level of comfort. Figure A-16 shows the mean subjective control ratings for the eleven treatments. In Figure A-16, higher values of mean response represent a higher level of control, while lower values of mean response represent a lower level of control.

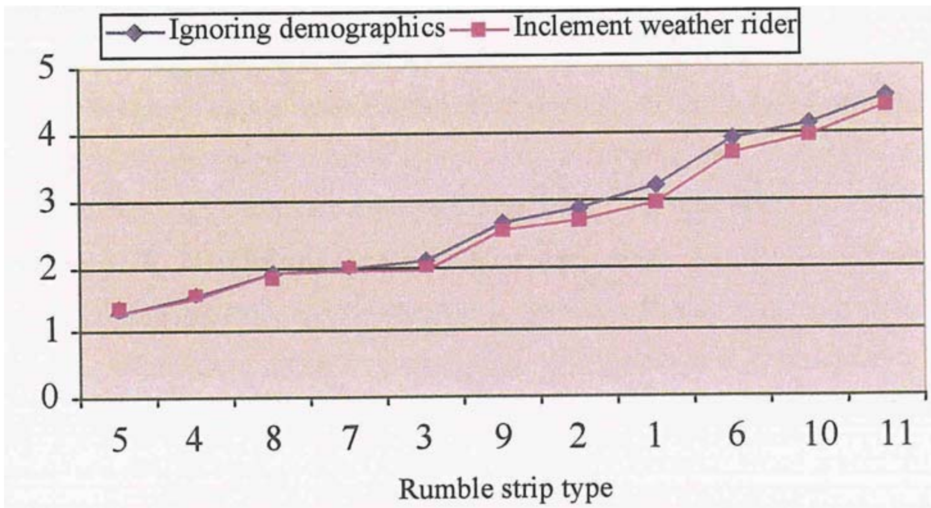


Figure A-15. Bicyclist Subjective Comfort Ratings Averaged Across Various Factors (*14*)

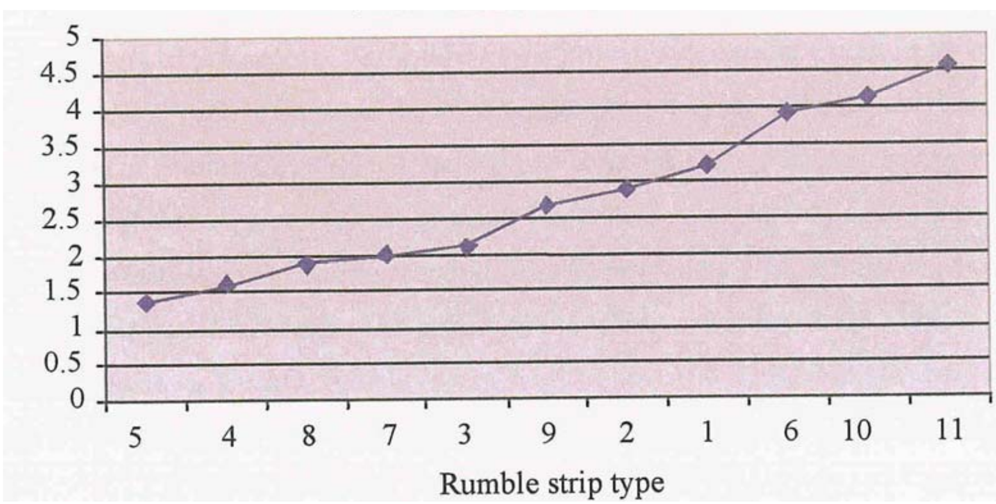


Figure A-16. Bicyclist Subjective Control Ratings Averaged Across Various Factors (*14*)

As part of the bicycle testing conducted in Colorado, 29 bicyclists participated in subjective testing to rate the comfort and controllability of bicycles while traversing 10 rumble strip patterns (Table A-21). Road bikes with narrow, high pressure tires were used in the testing as well as mountain bikes with fat, low pressure tires. Each bicyclist traversed the test patterns at 5, 10, 15, and 20 mph (8, 17, 24, and 32 km/h). Each bicyclist rated the pattern for both comfort and controllability on a scale from 1 (No Effect) to 5 (Severely Uncomfortable/Uncontrollable). Some of the bicyclists were unable or unwilling to rid some of the test sections at higher speeds because their bicycles became uncontrollable. Those sections were recorded as a 5 (Severely Uncomfortable/ Uncontrollable) for that speed. Figure A-17 and Table A-36 show the average ratings from all riders for all speeds for each rumble strip pattern. As Figure A-17 and Table A-36 illustrate, the 0.75 in (19 mm) deep rumble strip pattern (Section 5) is the most objectionable to bicyclists and the concrete strip (Section 10) is the most favorable. Outcalt notes that the trends in Figure A-17 and Table A-36 are similar to the trends in sound levels in the motor vehicles, indicating that rougher rumble strips to bicyclists are louder rumble strips with more vibration felt in a motor vehicle.

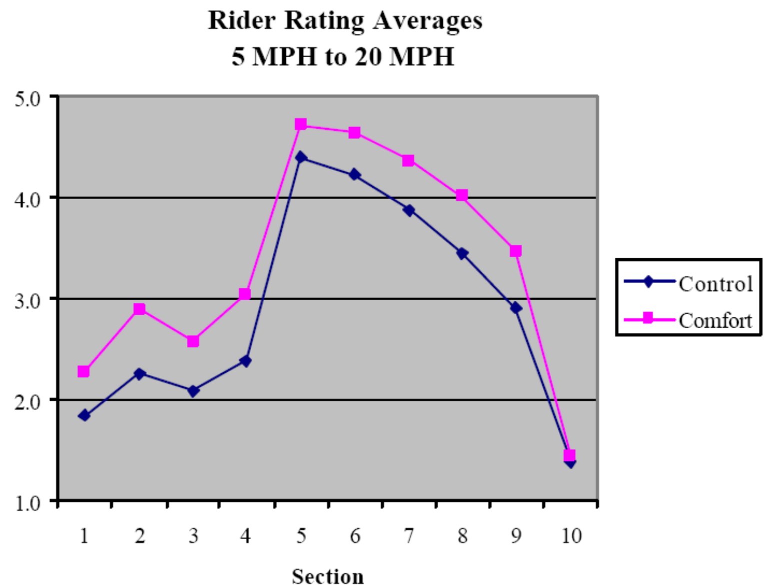


Figure A-17. Average Comfort and Control Ratings of Bicyclists [scale: 1 (no effect) to 5 (severely uncomfortable/uncontrollable)] (*44*)

Table A-36. Average Comfort and Control Ratings of Bicyclists (*44*)

Section	Average control rating	Average comfort rating
1	1.8	2.3
2	2.3	2.9
3	2.1	2.6
4	2.4	3.0
5	4.4	4.7
6	4.2	4.6
7	3.9	4.3
8	3.4	4.0
9	2.9	3.5
10	1.4	1.4

Scale: 1 (No Effect) to 5 (Severely Uncomfortable/Uncontrollable).

As part of the bicycle tests conducted by Elefteriadou et al. (*45*), 25 volunteer riders subjectively rated the comfort and controllability of bicycles while traversing the 6 rumble strip patterns (Table A-25) over an extended distance of approximately 45 ft (14 m). The bicyclists traversed the rumble strip patterns at various speeds and after each trial, the bicyclists were asked to fill-out a questionnaire rating the comfort level of different body parts while traversing the rumble strip configurations. In addition, the bicyclists were asked to rate the overall control level while traversing the configurations. Table A-27 presents the average ranking (based on a 25-point scale) of the comfort level for the different body parts, the overall comfort level, and the overall control level across all test patterns, all bicycle types, and all speed ranges. The table indicates the body parts that are most affected while traversing rumble strips. Lower values indicate greater discomfort, while higher values indicate better comfort. Based on the subjective results, the ordered list below ranks the body parts most affected while traversing rumble strips:

- Wrists, fingers, and elbows (most uncomfortable)
- Seat area
- Shoulders and neck
- Back
- Knees, ankles, and feet (most comfortable)

Table A-37. Overall Average Subjective Ranking of Comfort and Control Levels for Bicyclists (*45*)

	Wrists, fingers, and elbows	Shoulders and neck	Back	Seat area	Knees, ankles, and feet	Overall comfort	Overall control
Average Value	11.26	12.90	13.47	12.02	13.57	11.64	11.30

Comfort scale: very uncomfortable (0) and very comfortable (25).
Control scale: uncontrollable (0) and no effect on handling (25).

Tables A-38, A-39, and A-40 present the rankings of the test configurations based on the subjective wrist comfort level, overall comfort level, and overall control level, respectively. The average values combine the ratings across all bicycle types and all speeds. From the perceptions of the participants, test configurations 6, 3, and 5 in that order consistently ranked the best from the standpoint of comfort and control. Test pattern 1 was consistently perceived as the worst test pattern from the standpoint of comfort and control.

Young (*110*) conducted a test with a road bicycle on a section of U.S. 191 in Teton County, Wyoming, that had milled “Pennsylvania Turnpike” style rumble strips. A test rider rode over or across the rumble strips at speeds of less than 5 mph (8 km/h), 10 mph (16 km/h), 20 mph (32 km/h), and 30 mph (48 km/h). In general, at speeds greater than 5 mph (8 km/k), the test rider found it dangerous riding over or across the rumble strips.

Gårder (*111*) conducted tests to verify bicyclist concerns about maneuverability problems associated with rumble strips. Gårder, together with 20 students and staff at the

University of Maine, rode over two different configurations of milled rumble strips on several types of bicycles. Gårder found that, "Not a single rider reported any tendency to lose control at any speed or any angle even when not holding on to the handle bars. But every rider reported that riding on the rumble strips was annoying." Thus, these tests did not support bicyclists' fears that shoulder rumble strips would cause them to lose control of their bicycles.

Table A-38. Ranking of Test Configurations Based on Subjective Wrist Comfort Level (all bicycles) (*45*)

	Rank	Test pattern	Average wrist comfort level[a]
Best	1	6	14.3
	2	3	13.7
	3	5	11.9
	4	4	10.5
	5	2	10.1
Worst	6	1	7.1

[a] Comfort scale: very uncomfortable (0) and very comfortable (25).

Table A-39. Ranking of Test Configurations Based on Subjective Overall Comfort Level (all bicycles) (*45*)

	Rank	Test pattern	Average overall comfort level[a]
Best	1	6	14.8
	2	3	14.5
	3	5	12.1
	4	2	11.0
	5	4	10.0
Worst	6	1	7.3

[a] Comfort scale: very uncomfortable (0) and very comfortable (25).

Table A-40. Ranking of Test Configurations Based on Subjective Overall Control Level (all bicycles) (*45*)

	Rank	Test pattern	Average overall control level[a]
Best	1	6	14.3
	2	3	13.4
	3	5	11.5
	4	2	10.8
	5	4	9.5
Worst	6	1	7.4

[a] Control scale: uncontrollable (0) and no effect on handling (25)

Pedestrians

Very few pedestrians encounter rumble strips so for the most part rumble strips do not affect pedestrians. Shoulders are not usually appropriate as pedestrian facilities (*112*), particularly on facilities where vehicular traffic speeds are high, which is often the type of facility where rumble strips are installed. At intersections, rumble strips are discontinued so pedestrians do not encounter rumble strips while crossing at intersections. Several studies (*113,114*) have looked at the vibration levels experienced by wheelchair users while traversing obstacles similar to rumble strips, but this is viewed as a relatively low priority issue so the results of these studies are not summarized here.

A.6. Pavement Performance Issues

Several pavement performance concerns associated with shoulder and centerline rumble strips have been identified. Very little scientific based research has been conducted to address these concerns, but through observational reports most of the pavement performance concerns appear to be unwarranted.

Several maintenance concerns associated with shoulder and centerline rumble strips have been reported. Maintenance crews reported concerns that heavy traffic would cause shoulder pavements with rumble strips to deteriorate faster and that the freeze-thaw cycle of water collecting in the grooves would crack the pavement (*115*). Although the literature review revealed no published, controlled studies regarding the impact of rumble strips (primarily milled rumble strips) on pavement integrity, FHWA reports that these concerns have proven to be unfounded. Rumble strips have little effect on the rate of deterioration of new pavements. Older shoulder pavements tend to degrade more quickly, but tests in several states indicate that these rumble strips continue to perform their intended function. There are also no apparent problems with installation or faster deterioration of rumble strips on open-graded pavement surfaces. Most transportation agencies do advice against installing shoulder rumble strips on pavements that are rated as deformed or show high degrees of deformation and/or cracking.

Inclement weather also appears to have an insignificant impact on the durability of shoulder rumble strips. Field tests refute concerns about the effects of the freeze-thaw cycle as water collects in the grooves. In fact, field tests show that vibration and the action of wheels passing over the rumble strips knock debris, ice, and water out of the grooves. Snow plow drivers have also noted that they have come to depend on shoulder rumble strips to help them find the edge of the travel lane during heavy snow and other low visibility situations.

Shoulder rumble strips may also present a challenge to maintenance and rehabilitation crews when lane closures require traffic to be diverted to the shoulder. For long-term rehabilitation projects involving asphalt shoulders, most agencies simply mill a trench around the rumble strips and fill the trench with asphalt. Once construction is complete, the shoulder can be resurfaced and new rumble strips installed along the new asphalt overlay.

Similar to the experience with shoulder rumble strips, several agencies have expressed concerns about pavement deterioration associated with the installation of centerline rumble strips (*56*). However, none of these concerns have been validated.

The pavement performance issue that has received the most detailed investigation deals with preparation of rumble strips prior to overlayment of the shoulder surface so that rideability and/or pavement integrity are not compromised. New Hampshire DOT (NHDOT) conducted a study to develop a specification defining materials, sequences, and/or options to perform this operation successfully.

In summer 2005 NHDOT prepared four test sections to evaluate how the preparation of rumble strips prior to overlayment of the shoulder surface impacts the rideability and/or pavement integrity of the shoulder. Four test sections, each 500 ft (152 m) in length, were prepared along I-89 in slightly different manners to compare the differences in preparation practices. The four preparation scenarios were performed prior to placing a 1.5 in (38 mm) bituminous overlay (*116*):

Scenario A (Shim and Overlay):
- Tacked and shimmed entire 10 ft (3.0 m) width of shoulder section
- Used 0.5 in (13 mm) shim coat with 1.5 in (38 mm) overlay
- 10 ton roller used to shim, both 10 ton and 30 ton rollers used on overlay

Scenario B (Just Overlay):
- No special treatment of rumble strip, just tack and 1.5 in (38 mm) overlay
- Compressed 1.5 in (38 mm) overly with roller

Scenario C (Mill, Inlay, and Overlay):
- Ground out 20 in (508 mm) wide rumble strip first, 0.5 in (13 mm) deep
- Tack coated ground out rumble strip portion of shoulder
- Filled inlay with asphalt
- Compressed rumble strip inlay with 10 ton back roller. Compacted to same level as existing pavement.
- Tack coated over inlay and rest of area to be overlayed.
- Overlayed entire shoulder with 1.5 in (38 mm) overlay

Scenario D (Mill and Overlay):
- Ground out rumble strip 0.5 in (13 mm) deep
- Tack coated over inlay and rest of area to be overlayed.
- Overlayed shoulder with 1.5 in (38 mm) overlay, except near rumble strip inlay which required 2 in (51 mm) of material

The resurfacing operations were performed at night. The following observations were made immediately following the preparation and resurfacing activities:

- Scenarios A, C, and D seemed to be about the same resulting product with A having the rumble strip show through slightly, while C and D did not show through at all.
- Scenario B resulted in the rumble strips clearly showing through the pavement, made more visible due to nighttime lighting.

The following observations were reported during an inspection approximately 3 weeks after the overlay operations (*117*):

Scenario A (Shim and Overlay):
- Showed no indication of rumble strip reflection

Scenario B (Just Overlay):
- Showed occasional longitudinal cracks along the edge of the rumble strip, indicating movement of the mix by the roller through the affected rumble. The rumble strip reflected through the overlay along the entire length of the test section.
- Additionally, a parallel line of "reflected" rumble strips was observed in this test section. It is hypothesized that the vibratory roller drum bounces due to the alternating mix thickness in the rumble strip resulted in the indentation of the surface alongside of the original rumble strips.

Scenario C (Mill, Inlay, and Overlay):
- Showed no reflection of the milling, which would have displayed as a rut

Scenario D (Mill and Overlay):
- Showed no sign of the former rumble strip

The following observations were reported during an inspection in April 2006, following the first winter after the overlay activities (*118,119*):

Scenario A (Shim and Overlay):
- Mild depressions are now visible due mainly to the abrasion of the snowplows over the rumble strip area. The rumble strips are also felt when driven over.

Scenario B (Just Overlay):
- Continues to show a pronounced rumble strip reflection, enhanced by the abrasion of the rumble strips.
- Not additional deterioration was noted.

Scenario C (Mill, Inlay, and Overlay):

- Showed no reflection of the milled area
- The outline of the former rumble strip area is vaguely visible on the shoulder surface.

Scenario D (Mill and Overlay):

- Showed no sign of reflection in the area of the former rumble strips

A third inspection of the test sections was performed in June 2007, after the second winter of the overlay activities (*118,119*). No noticeable changes were observed since the last inspection in April 2006. This suggests that the rumble strip reflection is complete, having occurred within the first year after the overlay.

A.7. Other Potential Adverse Concerns

This section presents other potential issues or concerns associated with shoulder and/or centerline rumble strips that have not been discussed in Sections A.1 through A.5. A brief discussion of the following issues/concerns is presented.

Impact of Noise on Nearby Residents

A common problem cited by transportation agencies concerning the use of rumble strips is noise that disturbs nearby residents (*15*). However, noise is generated relatively infrequently by rumble strips placed on the shoulders and on the centerlines of undivided highways. For shoulder and centerline rumble strips, noise is generated only by errant motor vehicles, not by every motor vehicle.

Although the noise produced by shoulder and centerline rumble strips is intermittent, transportation agencies continue to receive complaints from nearby residents. For example, when shoulder rumble strips were installed along a limited-access road in Connecticut, several noise complaints were received from residents in the near vicinity (*18*). As a result, the Connecticut DOT modified the offset for rumble strips in the right shoulder from 6 to 12 in (152 to 305 mm). The reason for this change was to decrease the incidence of vehicles falsely traversing the rumble strips. As a result of this offset modification, noise complaints eventually decreased. Concerning noise produced from centerline rumble strips, the Alberta Transportation Authority has received complaints about noise where the ambient noise level is very low (*56*). Some residents claim to be able to hear the noise generated from the centerline rumble strips from up to 1.2 mi (2 km) away. On the other hand, Gardner et al. (*43*) conducted a survey of residents along a Section of US Highway 40 where football shaped centerline rumble strips were installed. All of the respondents to the survey (n = 32) lived within 600 ft (183 m) of US Highway 40. The survey showed that 78 percent (n=25) of the respondents could hear noise from the rumble strips while in their homes, but only 16 percent (n=4) indicated that the noise is loud enough to cause a concern or distraction. Gardner et al. concluded that the majority of the residents are satisfied with the centerline rumble strips along US Highway 40 because there is more potential for driver safety than the effects of external noise produced from coming in contact with the rumble strips.

Noise concerns are one area where evaluations of noise generated from transverse rumble strips may be applicable to this research associated with shoulder and centerline rumble strips. Gupta (*120*) evaluated the effectiveness of several rumble strip designs on speed reduction in the travel lane. As part of the evaluation, noise levels associated with the rumble strip designs were measured. Noise data were gathered from four different rumble strip designs for both cars and trucks. The sound levels generated by the rumble strips were measured approximately 10 ft (3 m) from the pavement edge. Gupta determined that the rumble strips created an increase in noise level of 6 to 8 dBA. The amount of noise created by rumble strips is related to various factors such as vehicle speed, vehicle types, tire tread, pavement surface, and rumble strip dimensions.

Higgins and Barbel (*81*) conducted a study to determine the noise levels in the surrounding neighborhood generated from transverse rumble strips. Higgins and Barbel concluded that transverse rumble strips produced a low frequency noise that can increase the noise levels by up to 6 or 7 dBA over the noise levels produced by traffic on normal pavement.

These values were confirmed in a Texas study (*106,107*) aimed at measuring the exterior noise created by various configurations of rumble strips. Both passenger car and commercial truck variations were recorded on milled, rolled, and raised rumble strips at a distance of 50 ft (15 m) from the travel way. The average base exterior noise was measured for the passenger car at speeds of 55 and 70 mph (88 and 113 km/h) and the commercial vehicle at 55 mph (88 km/h); the respective sound levels were found to be 76, 79 and 83 dBA. The average exterior noise for the same passenger vehicles traveling over the range of rumble strip configurations was 82, 87, and 88 dBA, respectively. Finley and Miles noted, from these results, that the noise generated by the average passenger car traveling over the average rumble strip configuration is still lower than the noise impact of a commercial vehicle on a smooth surface. It also appears that the greatest noise increase (10 to 19 dBA) for milled rumble strips from the base condition came when the length was maximized (16 in [406 mm]) and the spacing was minimized (12 in [305 mm]).

In a study of various milled rumble strip patterns conducted in Alberta (*56*), the following points were found:

- A change in speed from 50 to 75 mph (80 to 120 km/h) has little effect on the outside sound level when the vehicle is traveling in the normal driving lane (e.g., from 75 dBA to 82 dBA); however, when driving on rumble strips, the sound level is greatly affected (e.g., from 88 dBA to 102 dBA).
- The sound level outside the vehicle increases linearly with vehicle speed.
- The majority of sound created by rumble strips dissipates at approximately 328 ft (100 m).

- For heavy vehicles (i.e., trucks), a minimum rumble strip depth of 0.32 in (8 mm) is required to produce an increase in sound within the cab.

Studies show that rumble strips that are terminated 656 ft (200 m) prior to residential or urban areas produce tolerable noise impacts on nearby residents (*57*). At a distance of 1,640 ft (500 m), the noise generated from rumble strips is negligible.

Several transportation agencies have experimented with numerous alternatives to mitigate the noise generated by rumble strips installed near residential areas. One alternative is to construct noise barriers. Some have also moved the shoulder rumble strips further away from the edge of the travel lane. This measure, however, provides less time and distance for errant motorists to recover control of their vehicles.

Other Bicycle Issues

Most of the studies that investigate the impact of rumble strips on bicyclists focus on the comfort and control problems that bicyclist may (or may not) experience while traversing rumble strips. In other words, most studies have been concerned whether the vibrations experienced by bicyclists when they encounter rumble strips cause discomfort to bicyclists or loss of control of bicycles. However, bicyclists have several other concerns associated with rumble strips.

One concern with shoulder rumble strips is that they may encourage bicyclists to ride in the travel lane in situations where bicyclists would rather ride on the shoulder (*15*). Even though rumble strips are typically installed on only about half of the paved shoulder, the remaining area between the outer edge of the rumble strip and the outside edge of the shoulder is often littered with debris. This discourages bicyclists from utilizing that area. Therefore, bicyclists may prefer to ride in the travel lane. A possible solution to this dilemma is to move the rumble strip further from the travel lane to provide bicyclists with adequate room to ride between the travel lane and the rumble strip. This, however, decreases the recovery area available to errant motor vehicles. Another possibility is to make the rumble strips narrower. Yet, another possibility is to provide a gap in the rumble strip pattern to allow bicyclists to cross back and forth from the paved shoulder to the travel lane without having to encounter rumble strips. Moeur (*99*) conducted a study in Arizona to determine the optimum length of gaps in continuous shoulder rumble strips to accommodate bicyclists. As part of the field experiment, bicyclists traversed through gaps in rumble strips ranging from 10 to 20 ft (3.0 to 6.1 m) at various speeds. Based upon the bicyclists behaviors, Moeur recommended that rumble strips on all noncontrolled access highways include periodic gaps of 12 ft (3.7 m) in length, and that these gaps be placed at periodic intervals at a recommended spacing of 40 ft (12.2 m) or 60 ft (18.3 m).

A general concern with centerline rumble strips is that motorists may not provide sufficient clearance distance between the bicyclist and the motor vehicle when passing a bicyclist on a section of roadway with centerline rumble strips (*56*). In other words, the centerline rumble strips may force motorists away from the centerline closer to bicyclists riding near the outside edge of the travel lane, leaving less distance between bicyclists and motor vehicle during the actual passing maneuver. Another concern is that when motorists encounter centerline rumble strips during the passing maneuver, the noise generated by the rumble strips may startle bicyclists which could result in an undesirable maneuver by the bicyclist.

Maintenance Concerns

Weather does cause problems with raised rumble strips. Snow plow blades passing over the rumble strips tend to scrape them off the pavement surface, which is why raised rumble strips are usually restricted to areas that do not contend with snow removal. When raised rumble strips get scraped from the pavement surface, a secondary concern is that the material could become a projectile.

Visibility/Retroreflectivity of Centerline and Edgeline Pavement Markings

Some transportation agencies have reported concerns over the visibility and retroreflectivity of centerline pavement markings installed on centerline rumble strips (*32,36*). This could potentially be a problem under nighttime conditions especially if snow, salt, sand, or debris collect in the grooves of the rumble strips. Visibility of pavement markings can also be an issue when rumble strips are installed along the edgeline.

Conflicting evidence as to whether this is an actual problem is provided in the literature. For example, Colorado reports that during winter the grooves in the strip tend to collect some of the sand that is applied during snow removal (*30*). The sand does not completely fill the grooves; however, it does obscure some of the paint strip at the bottom of the grooves. Saskatchewan reports a loss of retroreflectivity of the centerline markings during wet conditions (*56*). A focus group in Minnesota reported that some participants felt that the painted centerline markings were less visible at night, particularly under wet conditions. Conversely, Alberta indicates that they have not experienced any difficulties or adverse wear of pavement markings after the installation of centerline rumble strips (*56*). In fact, Alberta reports that the pavement markings in the grooves of rumble strips may actually experience less wear and tear from snowplows and other vehicles because the paint is somewhat protected from the surface. In Texas, pavement markings applied over rumble strips were found to maintain their visibility during rainy nighttime conditions. Although as indicated above Saskatchewan reports a loss of retroreflectivity of the centerline markings during wet conditions, Saskatchewan also reports no reduction in nighttime visibility of markings painted on top of rumble strips. In fact, one location was selected for installation of centerline rumble strips based upon a frequent lack of visibility due to fog, and centerline rumble strips were found to enhance the centerline delineation at this site.

In a 2003 survey transportation agencies were asked whether centerline rumble strips reduce nighttime retroreflectivity of the material (*36*). Fourteen of the 24 respondents answered that there was not any reduction in nighttime visibility. Four respondents answered yes, and six other respondents indicated unknown. Russell and Rys (*36*) also indicated that all the answers to the survey were based upon subjective evaluations (i.e., no data were mentioned).

The objective of a study conducted by Filcek et al. (*121*) in Michigan was to discover alternative methods of increasing the durability, retroreflectivity, and wet-night retroreflectivity of pavement markings subjected to winter maintenance activity, utilizing standard Michigan DOT (MDOT) pavement marking materials. The study consisted of a side-by-side comparison of standard MDOT edgelines and standard MDOT waterborne paint and glass beads placed on milled shoulder rumble strips. The results of the study yielded the following conclusions:

- Milled rumble strip edgeline pavement markings are more resilient to winter maintenance activities than standard pavement markings.
- Retroreflectivity measurements for dry and wet-night conditions are significantly higher for milled rumble strip edgeline markings as compared to standard edgeline markings.

Filcek et al. also reported about a study in Mississippi that indicated wet-night retroreflectivity benefits of pavement markings being placed on a profiled surface.

The North Dakota DOT conducted a study to determine if placing pavement markings on a rumble strip would improve the marking's wet-night retroreflectivity (*122*). North Dakota noted that the position of the markings, on the rumble strip, does not appear to greatly affect the day-time appearance of the marking. The application of marking paint on fog seal material may cause some durability problems, but so far it has only caused some limited problems in one area with unusually thick fog seal material. Wet-night retroreflectivity readings appear to show that "rumble strips" provide higher retroreflectivity readings than nearby flat markings.

Results from a study in Texas (*123*) indicate that rumble stripes do provide at least twice the wet-night retroreflectivity compared to their equal but flat thermoplastic counterpart. Partial results are presented in Table A-41.

Table A-41. Retrorefectivity Measurements by Rainfall Rate for Pavement Markings (*123*)

Material, bead, color	Measured retroreflectivity (mcd/m^2/lux) for indicated rainfall rate in inches per hour												
	Dry	Recovery	0.28	0.87	1.2	2.0	4.0	6.0	8.0	9.5	11.5	14.0	Flood
Thermo, Type II, W	524	96	71	39	31	25	19	22	23	22	22	27	21
Thermo Rumble, Type II, W	503	185	144	129	99	101	70	64	64	57	61	58	49

A study comparing the service life, life-cycle costs, and wet-night visibility of edgeline rumble stripes and standard thermoplastic edge markings was conducted by the Alabama Department of Transportation (*124*). Data were collected over a three year period using a mobile retroreflectometer at locations where each of the treatments had been installed. The results were then extrapolated over time to determine the long term effectiveness of both types of edgeline markings. While the standard markings had initial retroreflective values approximately 25 percent higher than the rumble stripe counterparts, dry retroreflective decay curves indicated that the rumble stripes lost their visibility at a slower rate. It was postulated that this was due to less traffic driving on the marking due to the rumble effect on the vehicle. Service life values were established and are presented in Table A-42 that display a marked improvement for rumble stripes over a range of ADT values and retroreflective thresholds. Because of the inability to collect sufficient data for wet-night visibility of standard pavement markings, the retroreflectivity of the rumble stripes were incomparable; however, the Lindly and Narci concluded that the values would have been lower for flat pavement markings than for rumble stripes.

Table A-42. Estimated Service Lives in Terms of Age of Markings (*124*)

ADT per lane	Average service life in months							
	Threshold = 100 mcd/m^2/lux				Threshold = 150 mcd/m^2/lux			
	FTM		Rumble stripe		FTM		Rumble stripe	
	Average	95% C.I.	Average	95% C.I.	Average	95% C.I.	Average	95% C.I.
2,500	60+	60+	60+	60+	60+	45-60	60+	45-60
5,000	46	33-60	60+	60+	34	23-51	48	27-60+
7,500	31	22-48	60	42-60+	22	15-34	32	18-54
10,000	23	16-36	45	32-60+	17	11-26	24	14-40

Appendix B

Survey Questionnaire

National Cooperative Highway Research Program
Project 17-32

"Guidance for the Design and Application of Shoulder and Centerline Rumble Strips"

The following survey on shoulder and centerline rumble strips is being conducted as part of the National Cooperative Highway Research Program (NCHRP), which is sponsored by the American Association of State Highway and Transportation Officials (AASHTO) in cooperation with the Federal Highway Administration (FHWA). Your responses to the following questions concerning your agency's policies and practices regarding the design and application of shoulder and centerline rumble strips would be greatly appreciated.

SURVEY QUESTIONNAIRE
*(Please return by **September 23, 2005**)*

SHOULDER RUMBLE STRIP POLICIES AND PRACTICES:

1. Does your agency have a written policy or set of guidelines concerning the installation/application of shoulder rumble strips? .... ☐Yes ☐ No

   If YES, please attach a copy of your guidelines with your response or provide a web address.
   Web Address to
Guidelines:____
   If NO, does your agency use shoulder rumble strips? .... ☐Yes ☐No

2. On what types of roadways does your agency install shoulder rumble strips? (Select all that apply)

   ☐ Urban freeway mainline roadways
   ☐ Urban freeway on-ramps and off-ramps
   ☐ Urban multilane divided highways (nonfreeways)
   ☐ Urban multilane undivided highways (nonfreeways)
   ☐ Urban two-lane roads
   ☐ Rural freeway mainline roadways
   ☐ Rural freeway on-ramps and off-ramps
   ☐ Rural multilane divided highways (nonfreeways)
   ☐ Rural multilane undivided highways (nonfreeways)
   ☐ Rural two-lane roads
   ☐ Other: ____

3. On roadways with medians, does your agency install shoulder rumble strips on both the right (outside) and left (median) shoulder?.. ☐Yes ☐No

   If YES, does your policy differ between rumble strips installed on the right (outside) versus the left (median) shoulder? .... ☐Yes ☐No

If your policy differs, what are the primary differences?

____

____

____

____

4. Does your policy concerning shoulder rumble strips differ depending upon the type of shoulder surface? ... ☐Yes ☐No

   If YES, please elaborate: ____

   ____

5. How close to the edgeline does your agency install shoulder rumble strips? ____________________

   If the lateral placement from the edgeline is variable, what specific features are considered in determining the lateral placement of the shoulder rumble strips? ______________________________

   ____

   ____

6. At what specific features or areas along the shoulder/roadway (e.g., ramps or catch basins) are shoulder rumble strips discontinued to avoid adverse consequences (e.g., pavement deterioration, noise, etc)?

   ____

   ____

   ____

7. What features directly affect installation requirements within your agency's shoulder rumble strip policy or guidelines? (Select all that apply)

   - ☐ Roadway type
   - ☐ Shoulder width
   - ☐ Lateral clearance
   - ☐ Traffic volume
   - ☐ Bicycles
   - ☐ Shoulder pavement type
   - ☐ Shoulder pavement depth
   - ☐ Area type (i.e., urban vs. rural)
   - ☐ Speed limit
   - ☐ Crash frequency/rate
   - ☐ Other: ____
   - ☐ Other: ____

8. Does your agency have a minimum shoulder width requirement for the installation of shoulder rumble strips? ... ☐Yes ☐No

   If YES, please elaborate: ____

   ____

9. Does your agency have a minimum lateral clearance requirement for the installation of shoulder rumble strips?

.... ☐Yes ☐No

If YES, please elaborate: ____

____

10. Does your agency have a minimum traffic volume requirement for the installation of shoulder rumble strips?

.... ☐Yes ☐No

If YES, please elaborate: ____

____

11. Does your agency have a minimum pavement depth requirement for the installation of shoulder rumble strips?

.... ☐Yes ☐No

If YES, please elaborate: ____

____

12. Does your agency have a minimum speed limit requirement for the installation of shoulder rumble strips?

.... ☐Yes ☐
No

If YES, please elaborate: ____

____

13. Does your agency have a minimum crash frequency/rate requirement for the installation of shoulder rumble strips? .... ☐Yes ☐No

If YES, please elaborate: ____

____

14. Does your agency's policy change depending upon whether shoulder rumble strips will be installed along a designated bicycle route? .... ☐Yes ☐No

If YES, please elaborate: ____

____

____

____

____

15. Does your agency's policy provide a gap in the shoulder rumble strip pattern to allow bicyclists to maneuver from the travel lane to the shoulder and back without traversing the rumble strips? .... ☐Yes ☐No

If YES, please describe the gap pattern and whether it varies with the type of facility: ____________________

16. Most agencies that use shoulder rumble strips install them continuously along extended sections of roadway. Does your agency, in some cases, install shoulder rumble strips along specific shorter sections of roadway (e.g., specific horizontal curves)?
.... ☐Yes ☐No

If YES, please elaborate: ____________________

17. Has your agency installed milled, rolled, or formed rumble strips directly on the edgeline of the traveled way?
.... ☐Yes ☐No

18. Has your agency installed textured pavement edgeline markings (e.g., thermoplastic) to stimulate the driver with audible or tactile sensations (i.e., rumble stripes)?
.... ☐Yes ☐No

If YES, please elaborate: ____________________

19. Has your agency's policy/practice of installing shoulder rumble strips changed recently (i.e., within the last 3 to 5 years)? .... ☐Yes ☐No

If YES, how has it changed? ____________________

If YES, why was it changed? ____________________

20. Do you anticipate that your agency's policy/practice of installing shoulder rumble strips will change in the next year or so (i.e., are changes planned or are modifications currently being drafted)? ...... ☐Yes ☐No

If YES, please explain what type of modifications will be made or are anticipated? ____________________

If YES, what is the basis or justification for the planned changes? ____________________

CENTERLINE RUMBLE STRIP POLICIES AND PRACTICES:

21. Does your agency have a written policy or set of guidelines for the installation/application of centerline rumble strips on undivided roads? .... ☐Yes ☐No

    If YES, please attach a copy of your guidelines with your response or provide a web address.
    Web Address to Guidelines:____

    If NO, does your agency use centerline rumble strips? .... ☐Yes ☐No

22. Concerning the lateral placement of centerline rumble strips, check the type(s) of applications that have been installed by your agency?

Centerline rumble strips within pavement markings ☐

Centerline rumble strips extend into travel lane ☐

Centerline rumble strips on either side of pavement markings ☐

23. On what type of roadways does your agency install centerline rumble strips? (Select all that apply)

    ☐ Urban multilane undivided highways (nonfreeways)
    ☐ Urban two-lane roads
    ☐ Rural multilane undivided highways (nonfreeways)
    ☐ Rural two-lane roads
    ☐ Other: ____

24. Does your agency have a minimum lane width requirement for the installation of centerline rumble strips?

    .... ☐Yes ☐No

    If YES, please elaborate: ____

    ____

25. Does your agency have a minimum traffic volume guideline for the installation of centerline rumble strips? .... ☐Yes ☐No

If YES, please elaborate: ____

____

26. Does your agency have a minimum speed limit guideline for the installation of centerline rumble strips? .... ☐Yes ☐No

If YES, please elaborate: ____

____

27. Does your agency have a minimum crash frequency/rate guideline for the installation of centerline rumble strips? .... ☐Yes ☐No

If YES, please elaborate: ____

____

28. Has your agency installed both centerline rumble strips and shoulder rumble strips along the same roadway? .... ☐Yes ☐No

If YES, approximately how many miles of this dual application have been installed? ______________________

GENERAL QUESTIONS

29. Has your agency installed midlane rumble strips (i.e., rumble strips installed in the center of the travel lane)? .... ☐Yes ☐No

If NO, what is the possibility that your agency would consider installing midlane rumble strips on an experimental basis?

☐ Highly unlikely
☐ Willing to consider
☐ High likelihood

30. Does your agency have statewide or district level data in electronic format that contains information concerning the application of shoulder and/or centerline rumble strips (e.g., implementation dates, design information, etc.)? .... ☐Yes ☐No

31. Does your agency install rumble strips…

☐ Only as part of larger projects?
☐ As a stand-alone safety improvement?
☐ Both situations

32. Does your agency have data on bicycle only crashes or non-crash injuries related to rumble strip encounters? .... ☐Yes ☐No

33. We are currently setting priorities for the research in NCHRP Project 17-32. Your opinion would be appreciated. Please rank the priority for research to address gaps in knowledge associated with SHOULDER rumble strips? In column two of the table, please rank each research need on a 1 (Low Priority) to 5 (High Priority) scale. Please identify additional research needs in the empty rows at the bottom of the table. In column three, please check if your agency has already performed related research. In column four, please check if your agency might be willing to participate in future research or has available data to address the issue.

NOTE: When assigning the priority, please do not assign high priority (i.e., 5) to more than three topics.

Future Research Needs Related to **Shoulder** Rumble Strips	Priority*	Check if your agency has already performed related research	Check if your agency might be willing to participate in future research or has available data to address the issue
Determine optimum dimensions (e.g., length, width, depth, spacing)			
Determine minimum level of stimuli (i.e., sound or vibration) necessary to alert a drowsy or inattentive driver			
Determine optimum lateral placement from the edgeline			
Determine minimum shoulder width			
Better quantify safety effectiveness:			
• Along different types of roads (e.g. freeways, 2-lane highways, multilane highways, etc.)			
• Along roadways with varying speeds or ADT			
• Under varying conditions (e.g., wet vs. dry, light vs. dark, etc.)			
• Along varying roadway geometry			
• Along varying roadside conditions (e.g., 10 ft clear zone vs. 20 ft clear zone vs. 30 ft clear zone)			
• Differences in rumble strips installed along the right (outside) vs. left (median) shoulder			
Determine optimum longitudinal gaps in rumble strips to provide accessibility for bicyclists			
Improve physical design of rumble strips with respect to "rideability" for bicyclists and motorcyclists			
Determine impact of noise produced by rumble strips on adjacent residents			
Determine effect on pavement performance			
Determine effect on maintenance activities			
Others (please specify):			

*Priority Ranking Scale:
1 – Low priority 2 – Low-medium priority 3 – Medium priority4 – Medium-high priority 5 – High priority

34. Please rank the priority for research to address gaps in knowledge associated with CENTERLINE rumble strips? In column two of the table, please rank each research need on a 1 (Low Priority) to 5 (High Priority) scale. Please identify additional research needs in the empty rows at the bottom of the table. In column three, please check if your agency has already performed related research. In column four, please check if your agency might be willing to participate in future research or has available data to address the issue.

NOTE: When assigning the priority, please do not assign high priority (i.e., 5) to more than three topics.

Future Research Needs Related to **Centerline** Rumble Strips	Priority*	Check if your agency has already performed related research	Check if your agency might be willing to participate in future research or has available data to address the issue
Determine optimum dimensions (e.g., length, width, depth, spacing)			
Determine optimum placement with respect to the centerline pavement markings (related to Question 22)			
Operational impacts on vehicular traffic (i.e., vehicle speeds and lateral placement)			
Assess advantages/disadvantages of installing centerline rumble strips in passing zones			
Better quantify safety effectiveness:			
• Along different types of roads (e.g. 2-lane highways, multilane highways, etc.)			
• Along roadways with varying speeds and ADTs			
• Under varying conditions (e.g., wet vs. dry, light vs. dark, etc.)			
• Along varying roadway geometry			
• Installed in combination with shoulder rumble strips (related to Question 28)			
Improve physical design of rumble strips with respect to "rideability" for bicyclists and motorcyclists			
Determine impact of noise produced by rumble strips on adjacent residents			
Determine effect on visibility of pavement markings			
Determine effect on pavement performance			
Determine effect on maintenance activities			
Others (please specify):			

*Priority Ranking Scale:
1 – Low priority 2 – Low-medium priority 3 – Medium priority4 – Medium-high priority 5 – High priority

35. May we have the name of an engineer in your agency that we may contact to clarify any aspect of your response or to obtain additional information?

Contact: ______________________ Title: ______________________

Agency: ______________________

Address: ______________________

____

Telephone #: ______________________ Fax #: ______________________

e-mail address: ______________________

Please return the completed survey by **September 23, 2005**, to:

Darren J. Torbic, Ph.D.
Senior Traffic Engineer
Midwest Research Institute
2362 Raven Hollow Rd
State College, PA 16801
814-237-8831
dtorbic@mriresearch.org

Appendix C

Detailed Summary of Survey Results

This appendix provides a detailed summary of the survey responses received from 27 U.S. state transportation agencies and 4 Canadian provincial transportation agencies. Responses to categorical questions are summarized by showing both the percentage of the responses and the frequency/number of responses shown in parentheses. For those questions that asked agencies to further explain an issue, the explanations are provided in bullet form.

Survey Results: Shoulder Rumble Strip Policies and Practices

1. *Does your agency have a written policy concerning the installation/application of shoulder rumble strips?*

   YES: 80.6% (25)
   NO: 19.4% (6)

   If no, does your agency use shoulder rumble strips?

   YES: 16.1% (5)
   NO: 3.2% (1)

   Total agencies using shoulder rumble strips:

   96.8% (30)

   States/Provinces that have their policy information available on the internet:
   Arizona, Iowa, Indiana, Minnesota, North Carolina, North Dakota, Nevada, Oregon, Pennsylvania, Texas, Utah, Virginia, Washington, British Columbia.

2. *On what types of roadways does your agency install shoulder rumble strips?*

Urban freeways:	54.8%	(17)
Urban freeway on-ramps and off-ramps:	9.7%	(3)
Urban multilane divided highways (nonfreeways):	32.3%	(10)
Urban multilane undivided highways (nonfreeways):	22.6%	(7)
Urban two-lane roads:	12.9%	(4)
Rural freeways:	96.8%	(30)
Rural freeway on-ramps and off-ramps:	22.6%	(7)
Rural multilane divided highways (nonfreeways):	77.4%	(24)
Rural multilane undivided highways (nonfreeways):	71.0%	(22)
Rural two-lane roads:	71.0%	(22)
Other:	3.2%	(1)

3. *On roadways with medians, does your agency install shoulder rumble strips on both the right (outside) and left (median) shoulder?*

   YES: 93.5% (29)
   NO: 6.5% (2)

If yes, does your policy differ between rumble strips installed on the right (outside) versus the left (median) shoulder?

YES: 35.5% (11)
NO: 51.6% (16)

If your policy differs, what are the primary differences?

- For instance, the right strips are located 2 ft from the edge of the traveled lane, but the left strips are located 1 ft from edge of travel lane. For multilane divided, the right strips are intermittent (40-ft milled strip with a 10-ft gap), but the left stripes are continuously milled.
- We use a 4-in offset from the high speed lane (left edge lane), and a 12-in offset from the low speed lane (right edge lane).
- Where left (median) shoulder is narrower than outside (4 ft vs. 10 ft), strips are milled 6 in from pavement edge vs. 30 in.
- We require wider shoulders on the right to install rumble strips in response to the bike community.
- As a general rule we do not install shoulder rumble strips on both sides of the road, however, in the case of a two-lane road being converted to one direction of a divided highway there can end up being rumble strips on both shoulders.
- On a freeway, the strips are continuous on both shoulders of each roadway. On a nonfreeway, the strips are intermittent on the right or outside, and continuous on the left or inside.
- For multi-lane roadways (Interstate), rumble strips are continuous on the inside (left median) shoulder strips and have gaps on the right shoulder.
- Median rumble strips are continuous vs. outside rumble strips are intermittent on non-Interstate/freeways.
- The offset on the left (median) shoulder is 6 in, and the offset on the right (outside) shoulder is 1 ft.
- Periodic Gaps (10-ft gap, 40-ft cycle) in right shoulder, continuous in left shoulder.

4. *Does your policy concerning shoulder rumble strips differ depending upon the type of shoulder surface?*

YES: 38.7% (12)
NO: 54.8% (17)

If yes, please elaborate:

- Rumble strips are only used on PCC and asphalt surfaced shoulders. They are not used on sealed shoulders.
- Only concerning rumble strip construction.
- Rumble strips are not allowed on pavement joints (concrete pavements).
- Standards for placement on concrete shoulders differ slightly from placement on asphalt shoulders.

- We only use them on asphalt shoulders.
- Only in that they shall be installed on shoulders with a projected service life of less than three years.
- On asphalt it may require a flush coat.
- Although we did this in a few locations in the past, our current policy says do not install rumble strips in cement concrete pavement.
- Although our policy states that shoulder rumble strips can be constructed on either asphalt or concrete shoulders, our agency is not milling in rumble strips into concrete. On two freeway contracts in 2004 involving construction of new concrete pavement, since our agency overbuilds the outside driving lane by 1.6 ft into the shoulder (i.e., shoulder is 1.6 ft concrete and 8.2 ft asphalt), the rumble strips have been shifted outward 2 ft from the travel way into the asphalt. There were concerns about rumble strips potentially causing micro-cracking in the concrete which could affect pavement durability. There is also concern about installing rumble strips in open friction coarse (OFC) pavement, as noted in our policy.
- In some cases the shoulder texture is rough and acts as a rumble strip without installing any. Usually this roughness is from a fillet that is formed as part of milling and filling the driving lanes on pavement surface rehabilitation projects.

5. *How close to the edgeline does your agency install shoulder rumble strips?*

Responses range from flush against the edgeline (i.e., 0 in) to 30 in from the edgeline.

If the lateral placement from the edgeline is variable, what specific features are considered in determining the lateral placement of the shoulder rumble strips?

- Some districts place them farther than 6 in to keep the wheels of the snow plow off of the rumble strip when plowing the shoulder.
- The standard offset from the paint line is 4 in, except when 0 in is used in order to get at least 4 ft shoulder width free of the strip for bicyclists.
- Where left (median) shoulder is narrower than outside (4 ft vs. 10 ft), strips are milled 6 in from pavement edge vs. 30 in.
- Whether the shoulder is on the right/shoulder or left/median side.
- Total width of outside paved shoulder determines lateral placement. Lateral set-back is 8 in with shoulder widths of 4 ft to less then 6.5 ft. Shoulder widths equal to or greater then 6.5 ft have 1-ft lateral clearance.
- Offset can vary slightly if necessary to avoid deteriorated pavement at lane/shoulder interface.

6. *At what specific features or areas along the shoulder/roadway (e.g., ramps or catch basins) are rumble strips discontinued to avoid adverse consequences (e.g., pavement deterioration, noise, etc)?*

- Rumble strips along main lines are interrupted at entrance and exit ramps.
- Discontinued at ramps, in suburban/urban areas, and where clear shoulder width drops below 3.5 ft.

- At turn and auxiliary lanes road approaches, residences, 250 ft before intersections, and anywhere else as directed by the project engineer.
- For catch basins, the rumble strips must be placed 2 ft from the basin or else the rumble strips must be discontinued. The rumble strips should be placed at least a foot from longitudinal paving joints. Also, the rumble strips are discontinued at the beginning of the tapers for off-ramps, continued in between the off and on ramp and then discontinued for the on-ramp, and then continued at the end of the taper of the on-ramp.
- Ramps, intersections, bicycle considerations, structures and approach slabs.
- Guardrail adjacent to shoulder, public road approach, driveway.
- We gap entrances, mail box turnouts, and median crossings.
- Shoulder rumble strips are omitted between the radius points for side road approaches, entrances and median crossovers. Shoulder rumble strips should be omitted on bridges and on ramps for diamond, single point, partial cloverleaf and similar types of interchanges, but may be considered on longer ramps for directional or other large interchanges.
- Ramp terminals, intersections, loop terminals, catch basins, and bridges.
- Exit/entrance ramps, turning lanes, intersections, approaches/private drives, and scenic/historical marker turnouts. Shoulder rumble strips are not installed within urban areas, where there is curb and gutter, where the posted speed limit is 45 mph or less, across bridge approaches /decks, or adjacent to guardrail if the clear path between shoulder rumble strip and guardrail is <5 ft.
- Bridge decks; where the distance between the fog line and obstructions such as barrier or guardrail is 4 ft or less; in snow zones, climbing areas, or rolling mountainous terrain; in sections with horizontal curvature except where the data indicates a significant single vehicle run off the road problem; in the area between 300 ft before the exit ramp and 330 ft after the last entrance as measured from the point where the fog stripe departs and rejoins the mainline.
- SRS are discontinued at the following locations: Intersections, accesses, ramp terminals, where the outside shoulder is less than 5 ft, on bridge decks, at drainage gates when the shoulder width is less than 6 ft.
- Shoulder rumble strips are interrupted at intersections with side roads and farm accesses.

7. *What features directly affect installation requirements within your agency's shoulder rumble strip policy or guidelines?*

Roadway Type:	74.2 %	(23)
Shoulder Width:	80.6%	(25)
Lateral Clearance:	41.9%	(13)
ADT:	29.4%	(6)
Bicycles:	54.8%	(17)
Pavement Type:	35.5%	(11)
Pavement Depth:	25.8%	(8)
Area Type (i.e., urban vs. rural):	58.1%	(18)
Speed Limit:	16.1%	(5)
Crash frequency/rate:	35.5%	(11)
Other:	(5; listed)	

- Single vehicle off-road to the right crash frequency.
- Condition of existing shoulder.
- Scheduled upgrades for the facility.
- For concrete pavements, at discretion of Traffic Engineer as to continuous rumble strip or structural rumble strip every panel (about 15 ft)
- The presence of run off the road accident patterns.

8. *Does your agency have a minimum shoulder width requirement for the installation of shoulder rumble strips?*

   YES: 61.3% (19)
   NO: 35.5% (11)

   If YES, please elaborate:

   Response answers ranged from 2 ft to 6 ft.

9. *Does your agency have a minimum lateral clearance requirement for the installation of shoulder rumble strips?*

   YES: 45.2% (14)
   NO: 51.6% (16)

10. *Does your agency have a minimum traffic volume requirement for the installation of shoulder rumble strips?*

   YES: 16.1% (5)
   NO: 83.9% (26)

   If YES, please elaborate:

   - Rumble strips are installed when AADT is greater than 1800 veh/day.
   - For state corridor highways with shoulder widths of 4 ft or greater and the ADT is 2000 veh/day or greater, rumble strips should be installed. However, even if this criteria is not met they may be installed based on crash history.
   - Our paved shoulder policy states an ADT of 3000 veh/day before we pave shoulders so that is the de facto number for rumble strips.
   - Two-lane rural greater then 50 mph and ADT of 400 veh/day should have rumble strips.

11. *Does your agency have a minimum pavement depth requirement for the installation of shoulder rumble strips?*

   YES: 25.8% (8)
   NO: 74.2% (23)

12. *Does your agency have a minimum speed limit requirement for the installation of shoulder rumble strips?*

YES: 12.9% (4)
NO: 83.9% (26)

If YES, please elaborate:

Minimum speeds ranged from 45 to 50 mph.

13. *Does your agency have a minimum crash frequency/rate requirement for the installation of shoulder rumble strips?*

YES: 6.5% (2)
NO: 90.3% (28)

If YES, please elaborate:

- In locations with higher numbers of run-off-road crashes, minimum shoulder width requirements can be waived if justified by a study.
- Type of accident and frequency is compared to statewide average.
- For undivided highways we specify 0.6 crashes per mi or 34 crashes per 100 million VMT; however, we state that these number are not to be used as absolute values. We provide the values to establish a "baseline" for high accident experience. The numbers come from a system-wide analysis of run off the road crashes.

14. *Does your agency's policy change depending upon whether shoulder rumble strips will be installed along a designated bicycle route?*

YES: 38.7% (12)
NO: 58.1% (18)

If YES, please elaborate:

- Our policy states rumble strips can be omitted on highways "with significant bicycle traffic."
- Shoulder rumble strips have not been installed in areas of high bicycle use, but not specifically because of a bicycle route designation.
- Strips are not placed along a designated bicycle route.
- The rumble strips don't change but the shoulder policy does. Our stand is a 4 ft paved shoulder with 6-ft granular shoulder outside of that. On a designated bicycle route that changes to 6-ft paved but the rumble strip placement and pattern remain the same.
- Shoulder widths of 4 ft (1.2 m) or less with rumble strips will not adequately accommodate bicycles. Therefore, rumble strips should not be placed on these roadway sections unless the District Traffic Engineer has documented a serious ROR accident problem and little or no bicycle traffic is expected. Districts shall contact the State Bicycle Coordinator to determine the amount of bicycle traffic on a roadway.
- This is on a case by case basis but typically if there is significant bicycle traffic, milled rumble strips would not be installed on shoulders less than 8 ft wide.

- Modifications are made to the standard RS that better accommodate bicycle transportation on designated bicycle routes or facilities where the engineer has determined that significant bicycle travel exists for at least several months of the year. Essentially the revised guides provide 6-ft center to center gaps and a continuous 34-ft milled rumble on a 40-ft cycle.
- Strips are installed on limited access highways where bicycles are not allowed.
- Pattern selection changes depending on bicycle usage. Our policy includes consultation with the Washington Bicycle and Pedestrian Advisory Committee.
- Shoulder rumble strips should not be installed on highways with partially paved shoulders (2-ft asphalt width) that are designated as bicycle routes or have substantial volumes of bicycle traffic.
- Shoulder rumble strips are usually installed on a continuous basis. On designated bicycle routes we will provide an intermittent 13-ft gap between rumble strips.

15. *Does your agency's policy provide a gap in the shoulder rumble strip pattern to allow bicyclists to maneuver from the travel lane to the shoulder and back without traversing the rumble strips?*

YES:	35.5%	(11)
NO:	54.8%	(17)

If YES, please describe the gap pattern and whether it varies with the type of facility:

- Right shoulder on noncontrolled-access highways—10-ft gap on 40-ft cycle roughly even with roadway striping.
- 28-ft ground-in rumble strips and 12-ft gap typical unless interstate/freeway which is continuous.
- In areas where bicycle traffic is anticipated to cross-over rumble strips the installation of a 6-ft to 12-ft gap in the strips is recommended.
- 48 ft of rumble strips, 12 ft of gap.
- Gap provided only when justified. Gap pattern does not vary with facility type.
- For multilane divided highways, multilane undivided highways and 2 lane highways (paved shoulders equal or greater than 6 ft) there a 40-ft milled strips with 10-ft gaps on the right shoulder.
- We have three different patterns that allow a balance to reflect shoulder width, truck usage, and bicycle usage. We have two 12-in wide patterns, one with a 12-ft gap and 48-ft of continuous rumble strip, one with 12-ft gap and 28 ft of continuous rumble strip. We have a 16-in wide pattern with a 16-ft gap and 48-ft of continuous rumble strip.
- The gap is 12-ft followed by a 50 ft of strip. Note that we may be reviewing the length of the gap in the near future.
- Gap pattern is four meters of rumble strip followed by four meters of pavement. It does not vary with facility type.

16. *Most agencies that use shoulder rumble strips install them continuously along extended sections of roadway. Does your agency, in some cases, install shoulder rumble strips along specific shorter sections of roadway (e.g., specific horizontal curves)?*

YES: 29.0% (9)
NO: 71.0% (22)

If YES, please elaborate:

- Where a pattern of run-off-the-road accidents are present.
- If there is a significant number of single-vehicle run-off-the-road accidents rumble strips are considered for installation in these areas.
- Horizontal curves.
- If crash history would indicate this strategy is appropriate.
- Shorter sections can be utilized at the discretion of the engineer. This is also done in some instances where centerline RS are used in curve sections.
- Although rare, we do occasionally apply shoulder rumble strips to reduce cutting the corner by driving on the shoulder. In one instance we had drivers approaching an intersection on the inside of a curve, by driving on the shoulder. This created conflict when drivers waiting at the side street crowded the stop bar. In another instance, we had a mountainous road with a rock cut along the shoulder. There were occurrences where drivers on the shoulder were encountering rocks that had fallen on the shoulder.
- Our agency installs rumble strips at two-lane to four-lane transitions, bridge approaches, and on the top of curves at high accident areas.

17. *Has your agency installed milled, rolled, or formed rumble strips directly on the edgeline of the traveled way?*

YES: 48.4% (15)
NO: 51.6% (16)

18. *Has your agency installed textured pavement edgeline markings (e.g., thermoplastic) to stimulate the driver with audible or tactile sensations (i.e., rumble stripes)*?

YES: 29.0% (9)
NO: 71.0% (22)

If YES, please elaborate:

- These have been utilized on a limited basis in the past, but use is being phased out. These markings (Pavement Profile Markings) are very expensive, and there are maintenance issues associated with their use.
- We use profiled thermoplastic pavement markings on some roadways. No criteria design choice or preference.
- We installed Vibraline edgelines (thermal plastic) along the 3 mi of SR 900.
- These are effective to alert drivers, but we don’t think that these are a substitute to SRS. They may not be loud enough to stimulate a driver who is on the verge to dosing.

19. *Has your agency’s policy/practice of installing shoulder rumble strips changed recently (i.e., within the last 3 to 5 years)?*

YES: 48.4% (15)
NO: 51.6% (16)

If YES, how has it changed?

- Developed policy to install intermittent rumble strips and shoulder width less then 6-ft width.
- Most major installations of rumble strips along long roadway sections has occurred within the last 5 years.
- We install milled strips only. We have discontinued use of rolled or formed strips.
- We used to roll them in and now we mill.
- Milled strips on interstate and parkways (freeways).
- Policy was revised October 2004 to allow more wide spread and flexible utilization of continuous rumble strips.
- In January 2005, the RIDOT guidelines for shoulder rumble strips were first established. Before this, rumble strips were simply installed on a case-by-case basis.
- We introduced the intermittent gaps, modified the discontinuations at intersection and obstacles and reduced the shy distance to the paint line to 0 in in some cases and reduced the SRS length from 16 in to 12 in.
- If yes, why has it changed?
- Accommodate bicyclist and to address narrow shoulders respectively.
- Recognition that rumble strips are a cost effective means of reducing single vehicle run-off-the-road accidents.
- Rolled or formed strips may only on newly placed pavement. Milled strips may be placed on any pavement, regardless of age. We have also determined that rolled strips are quieter, therefore less effective, than milled strips.
- Better info available about performance. Also, we are paving more shoulders now where before they were granular.
- Providing high standards to these roadways.
- To allow more wide spread use of rumble strips as an effective countermeasure for lane departure type crashes, and to improve positive guidance.
- It was determined desirable to formally establish RIDOT's guidelines.
- Mainly to accommodate the bicycling community requests.

20. *Do you anticipate that your agency's policy/practice of installing shoulder rumble strips will change in the next year or so (i.e., are changes planned or are modifications currently being drafted)?*

YES: 29.0% (9)
NO: 71.0% (22)

If YES, please explain what type of modifications will be made or are anticipated?

- Development of a policy for the installation of rumble strips. No policy currently exists. Also, issues related to noise impacts will be investigated.
- We are in the process of developing a policy for non-Interstate roadways.
- Our new design philosophy will be looking at all standards and their cost vs. safety.
- Current typical details and specifications are DRAFT only.
- We may allow more uses on 2 lane undivided roadways with shoulders.
- May review the length of the intermittent gap between the strips.
- Consideration is being given to modifying the variable depth standard to a constant 0.5 in depth and painting wider edgelines through them to improve retro-reflectivity. Trial expected to start later this fall.

If YES, what is the basis or justification for the planned changes?

- There have been several roadways with safety problems where shoulder rumble strips would be beneficial, but not installed due to noise concerns.
- We desire to have typical details and specifications to achieve consistency in installations.
- Results from TTI research.
- We want to make sure that these gaps are sufficiently long to allow cyclists to weave across while at the same time ensure that drivers who wander across the SRS will be properly alerted by the vibrations.
- Improved edgeline retro-reflectivity under wet conditions.

Survey Results: Centerline Rumble Strip Policies and Practices

21. *Does your agency have a written policy or set of guidelines for the installation/application of centerline rumble strips on undivided roads?*

YES:	29.0%	(9)
NO:	71.0%	(22)

If NO, does your agency use centerline rumble strips?

YES:	45.2%	(14)
NO:	25.8%	(8)
Total agencies using centerline rumble strips:	74.2%	(23)

22. *Concerning the lateral placement of centerline rumble strips, check the type(s) of applications that have been installed by your agency?*

Centerline rumble strips within pavement markings: 38.7% (12)

Centerline rumble strips extend into travel lane: 48.4% (15)

Centerline rumble strips on either side of pavement markings: 6.5% (2)

23. *On what type of roadways does your agency install centerline rumble strips? (Select all that apply)*

Urban multilane undivided highways (nonfreeways):	9.7%	(3)
Urban two-lane roads:	6.5%	(2)
Rural multilane undivided highways (nonfreeways):	38.7%	(12)
Rural two-lane roads:	71.0%	(22)
Other:	6.5%	(2)

24. *Does your agency have a minimum lane width requirement for the installation of centerline rumble strips?*

YES: 9.7% (3)
NO: 71.0% (22)

If YES, please elaborate:

- We specify 12 ft as the minimum width (combined lane and shoulder) for centerline rumble strips. This is to reduce potential for drivers to shift to the right to keep off the rumble strip and then drop a tire off the road. (Could lead to run-off-the-road or over-correction and crossing centerline.)

- For application of CRS on lanes widths less than 11 ft, an engineering review is required.

25. *Does your agency have a minimum traffic volume guideline for the installation of centerline rumble strips?*

YES:	3.2%	(1)
NO:	77.4%	(24)

26. *Does your agency have a minimum speed limit guideline for the installation of centerline rumble strips?*

YES:	3.2%	(1)
NO	74.2%	(23)

If YES, please elaborate:

- 50 mph

27. *Does your agency have a minimum crash frequency/rate guideline for the installation of centerline rumble strips?*

YES:	12.9%	(4)
NO:	67.7%	(21)

If YES, please elaborate:

- To date NDOT has installed centerline rumble strips on a limited number of test sections where there is a significant problem with crossover type crashes.
- Critical Rate Factor > 1.0.

28. *Has your agency installed both centerline rumble strips and shoulder rumble strips along the same roadway?*

YES:	35.5%	(11)
NO:	38.7%	(12)

If YES, approximately how many miles of this dual application have been installed?

- Responses range from 5 to 50 mi.

Survey Results: General Issues

29. *Has your agency installed midlane rumble strips (i.e., rumble strips installed in the center of the travel lane)?*

YES:	0.0%	(0)
NO:	100.0%	(29)

If NO, what is the possibility that your agency would consider installing midlane rumble strips on an experimental basis?

Highly unlikely:	61.5%	(16)
Willing to consider:	34.6%	(9)
High likelihood:	3.8%	(1)

Note: Three states actually responded "YES" to this question, but after several follow-up telephone conversations, it was determined that either the state respondent misunderstood the question or simply provided an incorrect response.

30. *Does your agency have statewide or district level data in electronic format that contains information concerning the application of shoulder and/or centerline rumble strips (e.g., implementation dates, design information, etc.)?*

YES:	29.0%	(9)
NO:	58.1%	(18)

31. *Does your agency install rumble strips...*

Only as part of larger projects?	6.5%	(2)
As a stand-alone safety improvement?	6.5%	(2)
Both situations?	83.9%	(26)

32. *Does your agency have data on bicycle only crashes or non-crash injuries related to rumble strip encounters?*

YES:	0%	(0)
NO:	100%	(31)

APPENDIX D

Roadside Hazard Rating Category Descriptions

The following is an excerpt from *Prediction of the Expected Safety Performance of Rural Two-Lane Highways* (*67*), describing the distinguishing characteristics of the 7 roadside hazard rating categories. The final set of photos comes from the FHWA IHSDM website.

The accident prediction algorithm uses a roadside hazard rating system developed by Zegeer et al. (*66*) to characterize the accident potential for roadside designs found on two-lane roads. Roadside hazard is ranked on a seven-point categorical scale from 1 (best) to 7 (worst). The seven categories of roadside hazard rating are defined as follows:

Rating = 1
- Wide clear zones greater than or equal to 9 m (30 ft) from the pavement edgeline.
- Sideslope flatter than 1:4.
- Recoverable.

Rating = 2
- Clear zone between 6 and 7.5 m (20 and 25 ft) from pavement edgeline.
- Sideslope about 1:4.
- Recoverable.

Rating = 3
- Clear zone about 3 m (10 ft) from pavement edgeline.
- Sideslope about 1:3 or 1:4.
- Rough roadside surface.
- Marginally recoverable.

Rating = 4
- Clear zone between 1.5 and 3 m (5 to 10 ft) from pavement edgeline.
- Sideslope about 1:3 or 1:4.
- May have guardrail (1.5 to 2 m [5 to 6.5 ft] from pavement edgeline).
- May have exposed trees, poles, or other objects (about 3 m or 10 ft from pavement edgeline).
- Marginally forgiving, but increased chance of a reportable roadside collision.

Rating = 5
- Clear zone between 1.5 and 3 m (5 to 10 ft) from pavement edgeline.
- Sideslope about 1:3.
- May have guardrail (0 to 1.5 m [0 to 5 ft] from pavement edgeline).
- May have rigid obstacles or embankment within 2 to 3 m (6.5 to 10 ft) of pavement edgeline.
- Virtually nonrecoverable.

Rating = 6
- Clear zone less than or equal to 1.5 m (5 ft).
- Sideslope about 1:2.
- No guardrail.
- Exposed rigid obstacles within 0 to 2 m (0 to 6.5 ft) of the pavement edgeline.
- Non-recoverable.

Rating = 7
- Clear zone less than or equal to 1.5 m (5 ft).
- Sideslope 1:2 or steeper.
- Cliff or vertical rock cut.
- No guardrail.
- Nonrecoverable with high likelihood of severe injuries from roadside collision.

Figures D-1 through D-7 present photographs illustrating the seven roadside hazard rating categories.

Figure D-1. Typical roadway with roadside hazard rating equal to 1.

Figure D-2. Typical roadway with roadside hazard rating equal to 2.

Figure D-3. Typical roadway with roadside hazard rating equal to 3.

Figure D-4. Typical roadway with roadside hazard rating equal to 4.

Figure D-5. Typical roadway with roadside hazard rating equal to 5.

Figure D-6. Typical roadway with roadside hazard rating equal to 6.

Figure D-7. Typical roadway with roadside hazard rating equal to 7.





Road Side Hazard Rating 1





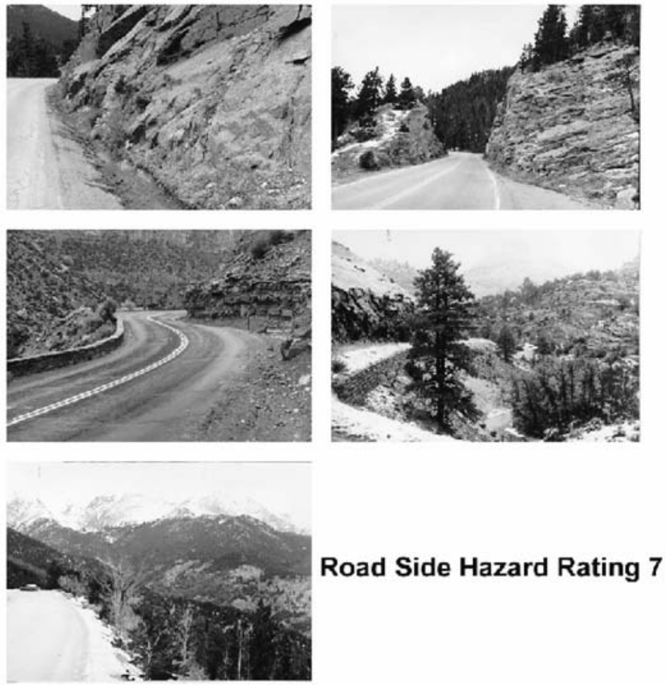
Road Side Hazard Rating 2

Road Side Hazard Rating 3

Road Side Hazard Rating 4

Road Side Hazard Rating 5

Road Side Hazard Rating 6



Road Side Hazard Rating 7

APPENDIX E

SPF Results for TOT, FI, SVROR, and SVROR FI Crashes on Selected Roadways Without Shoulder Rumble Strips

This appendix presents the SPF results developed based on all nontreatment sites (i.e., sites without shoulder rumble strips: BA-No RS and CS-No RS) in the four roadway categories for the four crash types of interest (Tables E-1 to E-4). These SPFs were developed using negative binomial regression analysis. Each line in each table provides the regression coefficients and their precision estimates for a given SPF. For example, using Table E-1 for urban freeways in Pennsylvania:

$$\begin{aligned}\text{Expected total crashes/mi/yr} &= \exp\left(-8.17 + 0.83 \ln \text{ADT} + 0.10\ \text{RHR}_{\text{Out}} + 0.19\ \text{RHR}_{\text{IN}}\right) \\ &= e^{-8.17} \times \text{ADT}^{0.83} \times e^{0.10\ \text{RHR\_Out}} \times e^{0.10\ \text{RHR\_In}}\end{aligned}$$

An empty cell in a table indicates the corresponding regression coefficient was not statistically significant at the 0.15 level or the coefficient's sign was not of the expected direction. Note that inside RHR does not apply to rural two-lane roads.

It should be noted that the analyses for SVROR crashes includes SVROR crashes to the right and to the left. No effort is made to distinguish crashes by side of the road; however, by including RHR for both the outside and inside shoulders/roadsides of divided highways, the analyses account for the differences between ROR crashes to the right and left. Also, for states that treat both sides of a divided highway as separate sites (i.e., Missouri and Pennsylvania), the RHR variables in the models represent the values for a single side of the divided highway. When both sides of a divided highway are treated as a single site (i.e., Minnesota sites), the RHR variables in the model represent average values for both directions of travel. Similarly, the RHR variable in the model for rural two-lane roads represents the average RHR for both sides of the roadway. Thus, the analysis accounts for SVROR right and SVROR left crashes, without necessarily distinguishing between the two crash types.

Table E-1. SPF results for TOT crashes based on all nontreatment sites.

Roadway type	State	Number of sites	Intercept		lnADT			Outside RHR			Inside RHR			Overdispersion		R^2_{LR}
			Estimate	SE[a]	Estimate	SE	p–value[b]	Estimate	SE	p–value	Estimate	SE	p–value	Estimate	SE	
Urban freeways	PA	90	–8.17	1.07	0.83	0.11	<.0001	0.10	0.05	0.051	0.19	0.05	0.0001	0.10	0.03	0.70
Rural freeways	MO	35	–11.69	2.79	1.31	0.28	<.0001							0.16	0.05	0.37
	PA	34	–0.15	2.59	0.08	0.27	0.782[c]							0.10	0.06	0.002
Rural multilane divided highways (nonfreeways)	MN	33	–8.10	1.36	0.87	0.15	<.0001	0.23	0.08	0.005				0.11	0.04	0.62
	MO	26	–12.84	4.42	1.50	0.47	0.002							0.64	0.19	0.25
	PA	13	–13.01	6.58	1.48	0.69	0.033							0.28	0.15	0.26
Rural two–lane roads	MN	56	–4.75	0.58	0.44	0.08	<.0001	0.33	0.07	<.0001				0.21	0.06	0.60
	MO	37	–5.95	2.68	0.51	0.25	0.039	0.61	0.34	0.075				1.49	0.39	0.15
	PA	110	–4.99	0.91	0.62	0.11	<.0001							0.31	0.06	0.23

[a] SE: standard error of estimate.
[b] p-value: significance level.
[c] ADT not significant at 0.15 significance level.

Table E-2. SPF results for FI crashes based on all nontreatment sites.

Roadway type	State	Number of sites	Intercept		lnADT			Outside RHR			Inside RHR			Overdispersion		R^2_{LR}
			Estimate	SE[a]	Estimate	SE	p–value[b]	Estimate	SE	p–value	Estimate	SE	p–value	Estimate	SE	
Urban freeways	PA	90	–8.42	1.32	0.77	0.13	<.0001	0.11	0.06	0.079	0.22	0.06	0.0001	0.12	0.04	0.61
Rural freeways	MO	35	–13.37	3.20	1.36	0.32	<.0001							0.12	0.05	0.36
	PA	34	–4.54	3.38	0.45	0.35	0.199[c]							0.10	0.09	0.05
Rural multilane divided highways (nonfreeways)	MN	33	–8.00	1.74	0.75	0.19	<.0001	0.20	0.11	0.064				0.15	0.06	0.44
	MO	26	–18.77	4.73	2.01	0.51	<.0001							0.46	0.20	0.35
	PA	13	–13.12	7.75	1.42	0.82	0.082							0.33	0.20	0.19
Rural two–lane roads	MN	56	–5.71	0.65	0.43	0.09	<.0001	0.33	0.07	<.0001				0.08	0.05	0.59
	MO	37	–7.03	2.65	0.44	0.25	0.078	0.77	0.32	0.018				1.24	0.36	0.18
	PA	110	–6.05	1.08	0.68	0.13	<.0001							0.38	0.09	0.20

[a] SE: standard error of estimate.
[b] p–value: significance level.
[c] ADT not significant at 0.15 significance level.

Table E-3. SPF results for SVROR crashes based on all nontreatment sites.

Roadway type	State	Number of sites	Intercept		lnADT			Outside RHR			Inside RHR			Overdispersion		R^2_{LR}
			Estimate	SE[a]	Estimate	SE	p–value[b]	Estimate	SE	p–value	Estimate	SE	p–value	Estimate	SE	
Urban freeways	PA	90	–6.22	1.23	0.60	0.12	<.0001	0.11	0.06	0.083	0.12	0.06	0.030	0.10	0.03	0.46
Rural freeways	MO	35	–10.23	3.71	1.09	0.37	0.003							0.26	0.08	0.19
	PA[c]	34	0.22	0.10										0.16	0.09	nc
Rural multilane divided highways (nonfreeways)	MN	33	–9.81	1.82	0.99	0.19	<.0001							0.17	0.07	0.44
	MO	26	–16.28	4.81	1.76	0.52	0.001							0.53	0.19	0.29
	PA	13	–20.34	7.42	2.21	0.78	0.005							0.19	0.14	0.37
Rural two–lane roads	MN	56	–3.62	0.74	0.07	0.10	0.475[d]	0.49	0.09	<.0001				0.21	0.10	0.40
	MO	37	–5.68	2.77	0.25	0.26	0.331[d]	0.82	0.35	0.019				1.40	0.39	0.16
	PA	110	–3.05	1.11	0.34	0.13	0.012							0.48	0.10	0.05

[a] SE: standard error of estimate.
[b] p-value: significance level.
[c] Means model; R^2_{LR} not calculated.
[d] ADT not significant at 0.15 significance level.

Table E-4. SPF results for SVROR FI crashes based on all nontreatment sites.

Roadway type	State	Number of sites	Intercept		lnADT			Outside RHR			Inside RHR			Overdispersion		R^2_{LR}
			Estimate	SE[a]	Estimate	SE	p–value[b]	Estimate	SE	p–value	Estimate	SE	p–value	Estimate	SE	
Urban freeways	PA	90	–6.88	1.36	0.62	0.13	<.0001	0.11	0.08	0.130				0.12	0.05	0.25
Rural freeways	MO	35	–10.33	4.04	1.01	0.40	0.012							0.21	0.09	0.15
	PA[c]	34	–0.52	0.11										0.14	0.12	nc
Rural multilane divided highways (nonfreeways)	MN	33	–8.61	2.26	0.79	0.24	0.001							0.23	0.10	0.25
	MO	26	–17.50	5.08	1.82	0.54	0.001							0.44	0.20	0.28
	PA	13	–20.03	9.38	2.11	0.99	0.032							0.33	0.22	0.26
Rural two–lane roads	MN	56	–3.73	1.06	0.15	0.14	0.258[d]							0.58	0.24	0.02
	MO	37	–6.00	2.61	0.13	0.26	0.611[d]	0.93	0.31	0.003				1.10	0.39	0.21
	PA	110	–3.58	1.25	0.32	0.15	0.034							0.49	0.13	0.04

[a] SE: standard error of estimate.
[b] p-value: significance level.
[c] Means model; R^2_{LR} not calculated.
[d] ADT not significant at 0.15 significance level.

APPENDIX F

GLM Analysis Results for Safety Effectiveness of Shoulder Rumble Strips

This appendix presents the generalized linear model (GLM) results to investigate the effect of treatment with shoulder rumble strips on the four crash types of interest:

- TOT crashes
- FI crashes
- SVROR crashes
- SVROR FI crashes

Two groups of tables are presented in this appendix:

- Tables F-1 through F-4: GLM results based on all site types (i.e., all nontreatment and treatment sites in the study)
- Tables F-5 through F-8: GLM results based on all before-after sites and nontreatment cross-sectional sites (i.e., same sites as in Tables G-1 through G-4 but without treatment cross-sectional sites). These results should be most comparable to the SPF results since both approaches use the same types of sites.

The statistics shown for each crash type, roadway type, and state (individually or combined) are:

- Intercept: estimate and standard error
- ADT (on natural log scale): estimate, standard error, and p-value (i.e., significance level)
- Outside RHR: estimate, standard error, and p-value
- Rumble strip effect: estimate, standard error, and p-value. Rumble strip statistics are bolded whenever the effect is statistically significant at the 0.10 level
- Overdispersion parameter: estimate and standard error

Each regression model is represented by the following equation:

$$\text{Expected crashes/mi/yr} = \exp\left(a + b\ln ADT + cRHR_{Out} + dI_{RS}\right)$$

where a (i.e., intercept), b, c, and d are the coefficients whose estimates are shown in Tables F-1 through F-8. The coefficient d only applies to treatment sites since I_{RS} is a 0,1 variable where 0 indicates absence and 1 presence of shoulder rumble strips. For states that treat both sides of a divided highway as separate sites (i.e., Missouri and Pennsylvania), the RHR variables in the models represent the values for a single side of the divided highway. When both sides of a divided highway are treated as a single site (i.e., Minnesota sites), the RHR variables in the model represent average values for both directions of travel. Similarly, the RHR variable in the model for rural two-lane roads represents the average RHR for both sides of the roadway.

Tables F-1 through F-8 are the companion tables to Tables 29 through 36. Number of sites and number of site-years for each model are provided in those tables. To obtain the percent change due to rumble strip treatment shown in Tables 29 through 36, use the rumble strip coefficient, d, shown in Tables F-1 through F-8 and calculate:

$$\text{Percent change} = 100\left[\exp(d) - 1\right]$$

Lower and upper 95-percent confidence intervals for the percent change are calculated in a similar fashion based on lower and upper 95-percent confidence intervals of the estimates in Tables F-1 through F-8 (confidence limits calculated but not shown in these tables).

Table F-1. GLM estimates for TOT crashes based on all site types.

Roadway type	State	Intercept		lnADT			Outside RHR			Rumble strips[a]			Overdispersion	
		Estimate	SE	Estimate	SE	p-value	Estimate	SE	p-value	Estimate	SE	p-value	Estimate	SE
Urban freeways	PA	–9.53	1.04	1.00	0.10	<.0001	0.15	0.10	0.111	–0.04	0.06	0.496	0.22	0.03
Rural freeways	Combined	–9.22	1.46	1.04	0.15	<.0001				0.01	0.07	0.890	0.23	0.03
	MO	–6.55	2.11	0.79	0.21	0.000				0.08	0.07	0.227	0.19	0.03
	PA	–4.27	1.85	0.50	0.19	0.008				0.08	0.11	0.480	0.21	0.05
Rural multilane divided highways (nonfreeways)	Combined	–5.90	1.10	0.64	0.12	<.0001	0.26	0.06	<.0001	**0.18**	**0.08**	**0.021**	0.24	0.03
	MN	–8.03	1.07	0.88	0.12	<.0001	0.15	0.06	0.010	**0.15**	**0.08**	**0.053**	0.11	0.02
	MO	–6.53	2.96	0.81	0.31	0.009				**0.25**	**0.11**	**0.027**	0.42	0.08
	PA	–0.97	4.23	0.20	0.46	0.653				–0.21	0.24	0.374	0.23	0.12
Rural two-lane roads	Combined	–6.27	0.87	0.66	0.10	<.0001	0.26	0.04	<.0001	–0.15	0.11	0.178	0.54	0.04
	MN	–5.72	1.11	0.56	0.14	<.0001	0.31	0.05	<.0001	–0.04	0.07	0.594	0.27	0.04
	MO	–4.71	2.01	0.64	0.23	0.006				–0.18	0.88	0.836	0.99	0.11
	PA	–4.55	0.80	0.57	0.10	<.0001				–0.28	0.19	0.145	0.36	0.06

[a] Statistics are bolded when $p \le 0.10$.

Table F-2. GLM estimates for FI crashes based on all site types.

Roadway type	State	Intercept		lnADT			Outside RHR			Rumble strips[a]			Overdispersion	
		Estimate	SE	Estimate	SE	p-value	Estimate	SE	p-value	Estimate	SE	p-value	Estimate	SE
Urban freeways	PA	–11.19	1.27	1.08	0.12	<.0001	0.20	0.12	0.086	–0.10	0.08	0.222	0.28	0.05
Rural freeways	Combined	–10.55	1.26	1.08	0.13	<.0001				–0.08	0.07	0.284	0.10	0.03
	MO	–9.95	1.67	1.02	0.17	<.0001				–0.03	0.09	0.758	0.12	0.04
	PA	–10.16	2.32	1.04	0.24	<.0001				–0.12	0.12	0.316	0.06	0.07
Rural multilane divided highways (nonfreeways)	Combined	–7.71	1.24	0.72	0.13	<.0001	0.23	0.07	0.001	0.01	0.11	0.956	0.22	0.04
	MN	–9.18	1.27	0.90	0.14	<.0001	0.11	0.07	0.131	0.07	0.09	0.474	0.09	0.04
	MO	–14.93	3.71	1.59	0.40	<.0001				0.05	0.20	0.799	0.38	0.12
	PA	0.28	0.24							**–0.54**	**0.27**	**0.045**	0.40	0.22
Rural two-lane roads	Combined	–7.16	0.77	0.65	0.09	<.0001	0.31	0.05	<.0001	**–0.32**	**0.12**	**0.006**	0.50	0.06
	MN	–6.45	1.10	0.53	0.14	0.0002	0.31	0.06	<.0001	–0.14	0.10	0.155	0.24	0.08
	MO	–8.37	1.95	0.61	0.25	0.013	0.71	0.19	0.0002	–0.51	0.75	0.501	0.51	0.11
	PA	–5.44	0.86	0.61	0.10	<.0001				–0.18	0.22	0.415	0.37	0.08

[a] Statistics are bolded when $p \le 0.10$.

Table F-3. GLM estimates for SVROR crashes based on all site types.

Roadway type	State	Intercept		lnADT			Outside RHR			Rumble strips[a]			Overdispersion	
		Estimate	SE	Estimate	SE	p-value	Estimate	SE	p-value	Estimate	SE	p-value	Estimate	SE
Urban freeways	PA	–6.79	0.90	0.72	0.09	<.0001				–0.04	0.08	0.625	0.19	0.04
Rural freeways	Combined	–5.94	1.57	0.65	0.16	<.0001				–0.10	0.07	0.175	0.25	0.04
	MO	–5.41	2.31	0.61	0.23	0.009				–0.07	0.07	0.357	0.23	0.04
	PA	–3.42	2.40	0.29	0.25	0.256	0.26	0.14	0.057	–0.02	0.13	0.875	0.26	0.07
Rural multilane divided highways (nonfreeways)	Combined	–7.11	1.08	0.62	0.11	<.0001	0.39	0.08	<.0001	**0.35**	**0.12**	**0.004**	0.39	0.05
	MN	–8.74	1.21	0.83	0.13	<.0001	0.17	0.08	0.035	**0.33**	**0.12**	**0.006**	0.24	0.05
	MO	–12.64	2.98	1.26	0.32	<.0001	0.34	0.22	0.128	**0.53**	**0.16**	**0.001**	0.45	0.12
	PA	–0.59	6.16	0.12	0.65	0.855				–0.27	0.17	0.117	0.17	0.14
Rural two-lane roads	Combined	–5.24	0.83	0.37	0.10	0.0002	0.42	0.05	<.0001	**–0.35**	**0.17**	**0.037**	0.72	0.07
	MN	–3.82	0.83	0.10	0.10	0.353	0.50	0.08	<.0001	0.18	0.13	0.180	0.51	0.13
	MO	–0.33	0.18							–0.09	0.79	0.906	1.23	0.18
	PA	–2.64	0.89	0.28	0.11	0.008				**–0.60**	**0.22**	**0.008**	0.49	0.09

[a] Statistics are bolded when $p \leq 0.10$.

Table F-4. GLM estimates for SVROR FI crashes based on all site types.

Roadway type	State	Intercept		lnADT			Outside RHR			Rumble strips[a]			Overdispersion	
		Estimate	SE	Estimate	SE	p-value	Estimate	SE	p-value	Estimate	SE	p-value	Estimate	SE
Urban freeways	PA	–6.92	1.15	0.67	0.11	<.0001				0.02	0.10	0.862	0.20	0.07
Rural freeways	Combined	–8.53	1.48	0.76	0.15	<.0001	0.22	0.11	0.042	**–0.15**	**0.08**	**0.078**	0.19	0.06
	MO	–6.75	1.85	0.65	0.19	0.001				–0.13	0.10	0.173	0.20	0.07
	PA	–9.99	2.78	0.89	0.29	0.002	0.29	0.16	0.076	–0.14	0.16	0.383	0.17	0.10
Rural multilane divided highways (nonfreeways)	Combined	–7.19	1.48	0.58	0.16	0.0004	0.32	0.10	0.001	0.05	0.14	0.738	0.45	0.09
	MN	–9.50	1.49	0.88	0.15	<.0001				0.12	0.14	0.398	0.22	0.08
	MO	–15.15	3.96	1.56	0.42	0.000				0.17	0.21	0.422	0.59	0.20
	PA	–0.07	0.28							–0.40	0.28	0.156	0.58	0.32
Rural two-lane roads	Combined	–5.46	0.77	0.32	0.10	0.001	0.41	0.06	<.0001	**–0.47**	**0.16**	**0.004**	0.85	0.13
	MN	–4.50	1.19	0.26	0.15	0.084				0.04	0.17	0.840	1.16	0.33
	MO	–8.46	2.18	0.40	0.24	0.094	0.95	0.15	<.0001	–0.90	1.38	0.515	0.19	0.14
	PA	–2.96	0.94	0.25	0.12	0.035				**–0.47**	**0.24**	**0.054**	0.57	0.14

[a] Statistics are bolded when $p \leq 0.10$.

Table F-5. GLM estimates for TOT crashes based on before and after sites and nontreatment cross-sectional sites.

Roadway type	State	Intercept		lnADT			Outside RHR			Rumble strips[a]			Overdispersion	
		Estimate	SE	Estimate	SE	p-value	Estimate	SE	p-value	Estimate	SE	p-value	Estimate	SE
Urban freeways	PA	–9.30	1.23	1.03	0.12	<.0001				–0.05	0.06	0.372	0.22	0.03
Rural freeways	Combined	–8.83	1.75	1.01	0.18	<.0001				0.07	0.07	0.363	0.21	0.03
	MO	–5.38	2.63	0.68	0.26	0.010				0.11	0.07	0.113	0.19	0.03
	PA	–1.03	2.32	0.17	0.24	0.492				0.06	0.15	0.677	0.14	0.05
Rural multilane divided highways (nonfreeways)	Combined	–5.46	1.30	0.60	0.14	<.0001	0.24	0.08	0.003	**0.25**	**0.08**	**0.004**	0.29	0.03
	MN	–7.44	1.46	0.82	0.17	<.0001	0.14	0.08	0.086	0.15	0.12	0.185	0.12	0.03
	MO	–6.59	3.18	0.82	0.34	0.014				**0.24**	**0.11**	**0.028**	0.42	0.08
	PA	–1.11	4.54	0.22	0.49	0.656				–0.30	0.31	0.337	0.26	0.13
Rural two-lane roads	Combined	–5.96	0.87	0.64	0.10	<.0001	0.23	0.04	<.0001	–0.06	0.14	0.680	0.59	0.04
	MN	–5.16	1.09	0.49	0.13	0.000	0.34	0.05	<.0001	**0.16**	**0.09**	**0.058**	0.31	0.06
	MO	–4.79	2.05	0.65	0.24	0.007				–0.17	0.93	0.858	0.99	0.12
	PA	–4.55	0.80	0.57	0.10	<.0001				–0.28	0.19	0.145	0.36	0.06

[a] Statistics are bolded when p ≤ 0.10.

Table F-6. GLM estimates for FI crashes based on before and after sites and nontreatment cross-sectional sites.

Roadway type	State	Intercept		lnADT			Outside RHR			Rumble strips[a]			Overdispersion	
		Estimate	SE	Estimate	SE	p-value	Estimate	SE	p-value	Estimate	SE	p-value	Estimate	SE
Urban freeways	PA	–10.24	1.50	1.05	0.14	<.0001				**–0.23**	**0.10**	**0.019**	0.29	0.05
Rural freeways	Combined	–9.51	1.58	0.97	0.16	<.0001				–0.04	0.09	0.631	0.12	0.04
	MO	–9.70	2.26	0.99	0.23	<.0001				–0.01	0.10	0.888	0.13	0.04
	PA	–5.19	3.37	0.52	0.35	0.134				–0.09	0.15	0.555	0.08	0.08
Rural multilane divided highways (nonfreeways)	Combined	–7.49	1.52	0.70	0.17	<.0001	0.23	0.09	0.007	0.05	0.17	0.766	0.29	0.06
	MN	–8.70	1.48	0.87	0.15	<.0001				–0.20	0.18	0.278	0.08	0.05
	MO	–15.91	3.83	1.70	0.41	<.0001				0.02	0.21	0.929	0.38	0.12
	PA	–1.02	9.61	0.14	1.03	0.893				**–0.58**	**0.29**	**0.045**	0.41	0.22
Rural two-lane roads	Combined	–6.86	0.75	0.63	0.09	<.0001	0.28	0.05	<.0001	–0.16	0.13	0.244	0.54	0.06
	MN	–5.99	1.06	0.47	0.13	0.000	0.31	0.06	<.0001	0.07	0.15	0.648	0.28	0.10
	MO	–8.46	1.91	0.63	0.24	0.010	0.70	0.19	0.000	–0.44	0.76	0.567	0.50	0.11
	PA	–5.44	0.86	0.61	0.10	<.0001				–0.18	0.22	0.415	0.37	0.08

[a] Statistics are bolded when p ≤ 0.10.

Table F-7. GLM estimates for SVROR crashes based on before and after sites and nontreatment cross-sectional sites.

Roadway type	State	Intercept		lnADT			Outside RHR			Rumble strips[a]			Overdispersion	
		Estimate	SE	Estimate	SE	p-value	Estimate	SE	p-value	Estimate	SE	p-value	Estimate	SE
Urban freeways	PA	–7.26	1.11	0.77	0.11	<.0001				–0.10	0.11	0.339	0.19	0.05
Rural freeways	Combined	–5.16	2.02	0.58	0.21	0.005				–0.10	0.08	0.214	0.26	0.04
	MO	–5.15	3.12	0.58	0.31	0.063				–0.06	0.08	0.453	0.26	0.05
	PA	0.18	0.08							–0.14	0.18	0.450	0.16	0.08
Rural multilane divided highways (nonfreeways)	Combined	–7.12	1.25	0.64	0.13	<.0001	0.33	0.09	0.0003	**0.51**	**0.14**	**0.0002**	0.42	0.06
	MN	–8.58	1.41	0.86	0.14	<.0001				**0.30**	**0.10**	**0.002**	0.20	0.06
	MO	–13.09	3.08	1.31	0.34	<.0001	0.33	0.22	0.137	**0.51**	**0.16**	**0.002**	0.46	0.12
	PA	–0.46	6.31	0.11	0.67	0.874				–0.26	0.17	0.141	0.18	0.14
Rural two-lane roads	Combined	–5.23	0.83	0.38	0.10	0.0002	0.41	0.05	<.0001	–0.30	0.22	0.177	0.73	0.08
	MN	–3.60	0.85	0.06	0.11	0.578	0.52	0.08	<.0001	0.11	0.18	0.523	0.46	0.16
	MO	–0.32	0.18							–0.06	0.79	0.940	1.21	0.17
	PA	–2.64	0.89	0.28	0.11	0.008				**–0.60**	**0.22**	**0.008**	0.49	0.09

[a] Statistics are bolded when $p \leq 0.10$.

Table F-8. GLM estimates for SVROR FI crashes based on before and after sites and nontreatment cross-sectional sites.

Roadway type	State	Intercept		lnADT			Outside RHR			Rumble strips[a]			Overdispersion	
		Estimate	SE	Estimate	SE	p-value	Estimate	SE	p-value	Estimate	SE	p-value	Estimate	SE
Urban freeways	PA	–6.95	1.39	0.67	0.13	<.0001				–0.10	0.13	0.43	0.18	0.08
Rural freeways	Combined	–6.61	1.89	0.63	0.19	0.001				**–0.19**	**0.10**	**0.05**	0.21	0.07
	MO	–8.20	2.37	0.79	0.24	0.001				–0.15	0.11	0.18	0.22	0.08
	PA	–1.86	3.25	0.14	0.34	0.680				–0.25	0.20	0.21	0.17	0.13
Rural multilane divided highways (nonfreeways)	Combined	–7.07	1.79	0.57	0.20	0.004	0.30	0.12	0.014	0.14	0.20	0.50	0.52	0.11
	MN	–8.15	1.71	0.74	0.18	<.0001				–0.16	0.19	0.40	0.16	0.09
	MO	–16.48	3.99	1.70	0.43	<.0001				0.11	0.21	0.60	0.60	0.21
	PA	–0.04	0.29							–0.24	0.20	0.23	0.59	0.32
Rural two-lane roads	Combined	–5.39	0.80	0.31	0.10	0.003	0.41	0.06	<.0001	**–0.50**	**0.20**	**0.01**	0.86	0.14
	MN	–3.83	1.22	0.17	0.16	0.286				–0.26	0.25	0.30	1.26	0.47
	MO	–8.49	2.16	0.41	0.24	0.087	0.94	0.15	<.0001	–0.84	1.43	0.56	0.19	0.14
	PA	–2.96	0.94	0.25	0.12	0.035				**–0.47**	**0.24**	**0.05**	0.57	0.14

[a] Statistics are bolded when $p \leq 0.10$.

APPENDIX G

GLM Analysis Results for Effect of Shoulder Rumble Strip Offset and Recovery Area on Safety

This appendix presents the companion tables to the four cross-sectional generalized linear model (GLM) analyses investigating the effect of shoulder rumble strip offset.

- Table G-1 presents the GLM results to investigate the effect of shoulder rumble strip placement (edgeline vs. non-edgeline) on SVROR FI crashes based on all site types; it is the companion table to Table 42.
- Table G-2 presents the GLM results to investigate the overall effect of shoulder rumble strip placement on SVROR FI crashes across all sites in all states; it is the companion table to Table 43.
- Table G-3 presents the GLM results to investigate the effect of shoulder rumble strip offset (at three levels) on SVROR FI crashes based on all site types; it is the companion table to Table 44.
- Table G-4 presents the GLM results to investigate the combined effect of shoulder rumble strip offset and recovery area on SVROR FI crashes based on all site types; it is the companion table to Table 45.

Number of sites, number of site-years, offset, and offset × recovery area statistics for each model are provided in the corresponding Tables 42 through 45.

Table G-1: The statistics shown for each roadway type and state (combined or single) include:

- Intercept: estimate and standard error
- ADT (on natural log scale): estimate, standard error, and p-value (i.e., significance level)
- Outside RHR: estimate, standard error, and p-value
- Overdispersion parameter: estimate and standard error

Each regression model is represented by the following equation:

$$\text{Expected total crashes/mi/yr} = \exp\left(a + b \times \ln\text{ADT} + c \times \text{RHR}_{\text{Out}} + d \times \text{RS Placement}\right)$$

where a (i.e., intercept), b, and c are the coefficients whose estimates are shown in Table G-1. The companion coefficients for rumble strip placement, d, at two levels (edgeline vs. non-edgeline) as compared to no RS, are shown in Table 42.

Table G-2: The statistics shown for all sites and states combined include the estimate for:

- Intercept
- ADT (on natural log scale)
- Outside RHR
- Overdispersion parameter

The single regression model is represented by the following equation:

$$\text{Expected total crashes/mi/yr} = \exp\left\{\left(a + b \times \ln\text{ADT} + c \times \text{RHR}_{\text{Out}} + d \times \text{RS Placement}\right) \times I_{\text{Roadway type} \times \text{State}}\right\}$$

where a (i.e., intercept), b, and c are the coefficients whose estimates are shown in Table G-2. The variable $I_{\text{Roadway type} \times \text{State}}$ is an indicator variable with value 1 for a particular roadway type × state combination in the table, and zero otherwise. The companion coefficients for rumble strip placement, d, at two levels (edgeline vs. non-edgeline) as compared to no RS, are shown in Table 43.

Table G-3: The statistics shown for each roadway type and state (combined or single) include:

- Intercept: estimate and standard error
- ADT (on natural log scale): estimate, standard error, and p-value (i.e., significance level)
- Outside RHR: estimate, standard error, and p-value
- Overdispersion parameter: estimate and standard error

Each regression model is represented by the following equation:

$$\text{Expected total crashes/mi/yr} = \exp\left(a + b \times \ln\text{ADT} + c \times \text{RHR}_{\text{Out}} + d \times \text{Offset}\right)$$

Table G-1. GLM estimates for SVROR FI crashes based on all sites—rumble strip placement analysis.

Roadway type	State	Intercept		lnADT			Outside RHR			Overdispersion	
		Estimate	SE	Estimate	SE	p–value	Estimate	SE	p–value	Estimate	SE
Urban freeways	PA	–6.92	1.15	0.67	0.11	<.0001				0.20	0.07
Rural freeways	Combined	–8.76	1.46	0.79	0.15	<.0001	0.21	0.11	0.0622	0.19	0.06
	MO	–7.02	1.79	0.67	0.18	0.0002				0.20	0.07
	PA[a]										
Rural multilane divided highways (nonfreeways)	Combined	–7.25	1.47	0.59	0.16	0.0003	0.30	0.10	0.0024	0.44	0.09
	MN	–9.73	1.47	0.90	0.15	<.0001				0.20	0.07
	MO	–15.06	3.93	1.55	0.42	0.0002				0.58	0.20
	PA	–0.05	0.28							0.57	0.32
Rural two–lane roads	Combined	–5.46	0.77	0.31	0.10	0.0014	0.41	0.06	<.0001	0.84	0.13
	MN	–4.49	1.20	0.25	0.15	0.09				1.15	0.33
	MO[a]										
	PA[a]										
Rural two-lane roads[b]	Combined	–5.38	0.79	0.31	0.10	0.003	0.41	0.06	<.0001	0.86	0.14
	MN	–3.83	1.20	0.17	0.15	0.28				1.21	0.46

[a] LM algorithm did not converge.

[b] Excludes 53 Minnesota nontreatment cross-sectional sites.

Table G-2. GLM estimates for SVROR FI crashes based on all sites—overall rumble strip placement analysis.

Roadway type	State	Intercept (or state effect)	lnADT	Outside RHR	Overdispersion
Urban freeways	PA	–3.70	0.62	0.07	0.29
Rural freeways	MO	–4.29	0.66	0.12	
	PA	–6.82	0.87	0.27	
Rural multilane divided highways (nonfreeways)	MN	–6.00	0.82	0.07	
	MO	–11.11	1.42	0.13	
	PA	–2.14	0.38	0.39	
Rural two–lane roads	MN	–0.93	0.06	0.43	
	MO	–6.01	0.45	0.98	
	PA	–3.01	0.25	–0.0008	

where a (i.e., intercept), b, and c are the coefficients whose estimates are shown in Table G-3. The companion coefficients of offset distance, d, at three levels as compared to no RS, are shown in Table 44.

Table G-4: The statistics shown for each roadway type and state (combined or single) include:

- Intercept: estimate and standard error
- ADT (on natural log scale): estimate, standard error, and p-value (i.e., significance level)
- Outside RHR: estimate, standard error, and p-value
- Overdispersion parameter: estimate and standard error

Each regression model is represented by the following equation:

$$\text{Expected total crashes/mi/yr} = \exp\left(a + b \times \ln\text{ADT} + c \times \text{RHR}_{\text{Out}} + d \times \text{Offset} \times \text{RA}\right)$$

where a (i.e., intercept), b, and c are the coefficients whose estimates are shown in Table G-4. The companion coefficients, d, for the combination offset × recovery area, at five levels as compared to no RS with narrow shoulders, are shown in Table 45.

Tables G-1 through G-4: For states that treat both sides of a divided highway as separate sites (i.e., Missouri and Pennsylvania), the RHR variables in the models represent the values for a single side of the divided highway. When both sides of a divided highway are treated as a single site (i.e., Minnesota sites), the RHR variables in the model represent average values for both directions of travel. Similarly, the RHR variable in the models for rural two-lane roads represents the average RHR for both sides of the roadway.

No GLM results are shown in those cases where the algorithm did not converge. Empty cells in those cases where the GLM algorithm did converge indicate that the corresponding coefficient estimate is not statistically significant at the 0.15 level or that the coefficient's sign is not in the expected direction.

Table G-3. GLM estimates for SVROR FI crashes based on all sites—offset analysis.

Roadway type	State	Intercept		lnADT			Outside RHR			Overdispersion	
		Estimate	SE	Estimate	SE	p-value	Estimate	SE	p-value	Estimate	SE
Urban freeways	PA	–6.92	1.15	0.67	0.11	< .0001				0.20	0.07
Rural freeways	Combined	–8.73	1.51	0.78	0.16	< .0001	0.21	0.12	0.068	0.19	0.06
	MO	–6.74	1.77	0.65	0.18	0.0004				0.20	0.07
	PA[a]										
Rural multilane divided highways (nonfreeways)	Combined	–7.36	1.56	0.60	0.17	0.001	0.29	0.10	0.003	0.43	0.09
	MN	–8.90	1.47	0.82	0.15	< .0001				0.19	0.07
	MO	–15.06	3.93	1.55	0.42	0.0002				0.58	0.20
	PA[a]										
Rural two-lane roads	Combined	–5.48	0.77	0.31	0.10	0.001	0.42	0.06	<.0001	0.84	0.13
	MN	–4.32	1.20	0.23	0.15	0.123				1.13	0.33
	MO[a]										
	PA[a]										

[a] GLM algorithm did not converge.

Table G-4. GLM estimates for SVROR FI crashes based on all sites—combined rumble strip offset and recovery area.

Roadway type	State	Intercept		lnADT			Outside RHR			Overdispersion	
		Estimate	SE	Estimate	SE	p–value	Estimate	SE	p–value	Estimate	SE
Urban freeways	PA	–5.85	1.21	0.60	0.11	<.0001				0.18	0.07
Rural freeways	Combined	–0.54								0.26	0.07
	MO	–7.02	1.79	0.67	0.18	0.0002				0.20	0.07
	PA	–0.54								0.24	0.11
Rural multilane divided highways (nonfreeways)	Combined	–6.59	1.49	0.60	0.16	0.0003	0.29	0.10	0.004	0.43	0.09
	MN	–9.73	1.47	0.90	0.15	<.0001				0.20	0.07
	MO	–15.11	3.91	1.55	0.42	0.0002				0.58	0.20
	PA	0.81	0.00							0.48	0.30
Rural two–lane roads	Combined	–5.45	0.78	0.34	0.11	0.0021	0.39	0.07	<.0001	0.81	0.12
	MN	–4.50	1.33	0.25	0.19	0.1774				1.14	0.33
	MO	–0.65								0.75	0.23
	PA	–0.89								0.59	0.15

APPENDIX H

SPF Results for TOT, FI, and SSOD Crashes on Selected Roadways Without Centerline Rumble Strips

This appendix presents the SPF results developed for two-lane roads based on all nontreatment sites (i.e., sites without centerline rumble strips: BA-No RS). The same SPFs apply to roads classified as urban and rural and to tangent and curved roadways. Each line in each table provides the regression coefficients and their precision estimates for a given SPF where one was estimated. For example, using Table H-1 for two-lane roads in Pennsylvania:

$$\text{Expected total crashes/mi/yr} = \exp(-5.59 + 0.58 \ln \text{ADT} + 0.10\ \text{RHR} + 0.30\ \text{SPD} + 0.02\ \text{WIDTH})$$
$$= e^{-5.59} \times \text{ADT}^{0.55} \times e^{0.10\,\text{RHR}} \times e^{0.30\,\text{SPD}} \times e^{0.02\,\text{WIDTH}} \quad (1)$$

where:

SPD = 0 if the posted speed limit is ≥ 55; otherwise 1
WIDTH = roadway width (ft)

An empty cell in a row where an SPF was estimated indicates the corresponding regression coefficient was not statistically significant at the 0.15 level or the coefficient's sign was not of the expected direction.

For some analyses, the sample size was not sufficient to estimate an SPF directly from data. An approximation was employed in which a factor was applied to the SPF for total crashes in Table H-1. This factor is the ratio of the sum of all relevant crashes at the NT sites to the sum of all (total) crashes. The dispersion parameter is not adjusted, i.e., the one for total crashes applies for all crash type subsets for which SPFs are so approximated.

Table H-1. SPF results for TOT crashes on two-lane rural roads based on all nontreatment sites.

State	Number of sites	Intercept		lnADT			RHR			SPD			WIDTH			Dispersion		R^2_{LR}
		Estimate	SE[a]	Estimate	SE	p–value[b]	Estimate	SE	p–value	Estimate	SE	p–value	Estimate	SE	p–value	Estimate	SE	
MN	244	-7.31	0.88	0.81	0.09	<.0001	0.22	0.09	0.022							0.74	0.16	30.25%
WA	228	-7.46	1.20	0.95	0.13	<.0001										0.57	0.12	46.37%
PA	603	-5.59	0.42	0.58	0.04	<.0001	0.10	0.04	0.005	0.30	0.06	<.0001	0.02	0.005	0.0007	0.29	0.03	91.31%

[a] SE: standard error of estimate.
[b] p–value: significance level.

Table H-2. SPF results for FI crashes on two-lane rural roads based on all nontreatment sites.

State	Number of sites	Intercept		lnADT			RHR			SPD			WIDTH			Dispersion		R^2_{LR}
		Estimate	SE[a]	Estimate	SE	p–value[b]	Estimate	SE	p–value	Estimate	SE	p–value	Estimate	SE	p–value	Estimate	SE	
MN	244	A factor of 0.41 is applied to the SPF for total crashes in Table H-1																
WA	228	A factor of 0.44 is applied to the SPF for total crashes in Table H-1																
PA	603	-5.55	0.47	0.55	0.06	<.0001				0.31	0.07	<.0001	0.02	0.006	0.0005	0.36	0.04	86.91%

[a] SE: standard error of estimate.
[b] p–value: significance level.

Table H-3. SPF results for SSOD crashes based on all nontreatment sites.

State	Number of sites	Intercept		lnADT			RHR			SPD			WIDTH			Dispersion		R^2_{LR}
		Estimate	SE[a]	Estimate	SE	p–value[b]	Estimate	SE	p–value	Estimate	SE	p–value	Estimate	SE	p–value	Estimate	SE	
MN	244	A factor of 0.12 is applied to the SPF for total crashes in Table H-1																
WA	228	A factor of 0.05 is applied to the SPF for total crashes in Table H-1																
PA	603	-7.78	0.95	0.73	0.11	<.0001				0.26	0.13	0.044	-0.02	0.01	0.10	0.60	0.03	39.36%

[a] SE: standard error of estimate.
[b] p–value: significance level.

Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation