State of the Practice for Shoulder and Center Line Rumble Strip Implementation on Non-Freeway Facilities

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Turner-Fairbank Highway Research Center
6300 Georgetown Pike
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FOREWORD

The overall goal of the Federal Highway Administration's Roadway Departure Program is to improve the safety of the Nation's highways through the reduction of roadway departure crashes. Roadway departures continue to account for more than half of U.S. roadway fatalities annually and nearly 40 percent of serious injuries, making such crashes a significant safety concern.

The primary purpose of this research is to provide agencies with a framework for making decisions on how to implement rumble strips. This report includes a literature review detailing research related to rumble strip design, noise and vibration testing methods and findings, impacts on bicyclists and motorcyclists, pavement condition impacts, pavement marking visibility, operational effectiveness, and safety effectiveness. The report also provides a review of current department policies and standard drawings for rumble strip implementation strategies, systematic installation criteria, currently used rumble strip dimensions, high-crash corridor installation practices, and special considerations and rumble strip modifications. This document is intended for safety engineers, highway designers, planners, and practitioners at State and local agencies involved with rumble strip decisionmaking.

Monique Evans
Director, Office of Safety
Research and Development

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16. Abstract

Center line rumble strips (CLRSs) and shoulder rumble strips (SRSs) are proven countermeasures for reducing roadway departure crashes, including head-on and run-off-road crashes. The objectives of this project were twofold. The first objective was to develop a rumble strip decision support guide to inform agencies on CLRS and SRS installation. The second objective was to document the current state of the practice for CLRS and SRS installation, conduct a gap analysis, and provide a framework for future research related to further implementation of rumble strips. This research includes a literature review detailing research related to rumble strip design, noise and vibration testing methods and findings, impacts on bicyclists and motorcyclists, pavement condition impacts, pavement marking visibility, operational effectiveness, and safety effectiveness. The project also reviewed current department policies and standard drawings for rumble strip implementation strategies, systematic installation criteria, currently used rumble strip dimensions, high-crash corridor installation practices, and special considerations and rumble strip modifications. This report details the development of the decision support guide and includes a gap analysis and action plan for future rumble strip research. Future research can help agencies identify the optimal rumble strip design for installations.

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APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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LIST OF ABBREVIATIONS

AADT	annual average daily traffic
AASHTO	American Association of State Highway and Transportation Officials
ADOT	Arizona Department of Transportation
ADT	average daily traffic
AHTD	Arkansas State Highway and Transportation Department
ALDOT	Alabama Department of Transportation
B/C	benefit/cost
Caltrans	California Department of Transportation
CLRS	center line rumble strip
CMF	crash modification factor
CRF	crash reduction factor
ConnDOT	Connecticut Department of Transportation
EB	empirical Bayes
EFL	Eastern Federal Lands
ELRS	edge line rumble strip
FHWA	Federal Highway Administration
HDOT	Hawaii Department of Transportation
HMA	hot-mix asphalt
HSM	*Highway Safety Manual*
LaDOTD	Louisiana Department of Transportation and Development
MaineDOT	Maine Department of Transportation
MDOT	Michigan Department of Transportation
MDT	Montana Department of Transportation
MnDOT	Minnesota Department of Transportation
MoDOT	Missouri Department of Transportation
NCDOT	North Carolina Department of Transportation
NCHRP	National Cooperative Highway Research Program
NDOR	Nebraska Department of Roads
NDOT	Nevada Department of Transportation
NHDOT	New Hampshire Department of Transportation
NYSDOT	New York State Department of Transportation
OGFC	open-graded friction course
PDO	property damage only
PennDOT	Pennsylvania Department of Transportation
RIDOT	Rhode Island Department of Transportation
ROR	run-off-road
SCDOT	South Carolina Department of Transportation
SPF	safety performance function
SRS	shoulder rumble strip
SVROR	single-vehicle run-off-road
TDOT	Tennessee Department of Transportation
TxDOT	Texas Department of Transportation
VDOT	Virginia Department of Transportation

VTrans	Vermont Agency of Transportation
WSDOT	Washington State Department of Transportation

EXECUTIVE SUMMARY

Center line rumble strips (CLRSs), shoulder rumble strips (SRSs), and edge line rumble strips (ELRSs) are proven safety countermeasures intended to alert drivers when they leave the roadway across the center line or edge line through the generation of noise and vibration. Previous research has quantified the noise level generated by rumble strips and safety benefits on non-freeway facilities. Additionally, researchers have identified trade-offs for rumble strips, including inconvenience for bicyclists and motorcyclists, excessive noise for nearby residents, and potential for pavement life or pavement marking degradation.(1) These trade-offs have made it difficult for some State transportation departments to identify appropriate situations for implementing rumble strips on non-freeway facilities as well as identify an appropriate rumble strip design given a set of constraints.

This project had two main objectives. The first objective was to identify the state of knowledge and practice among State transportation departments for the use and design of CLRSs and SRSs, identify any information gaps, and develop a research plan to address those gaps. This document fulfills that objective. The second objective was to develop a decision support guide to inform agencies on CLRS and SRS installation. This objective was fulfilled with the preparation of *Decision Support Guide for the Installation of Shoulder and Center Line Rumble Strips on Non-Freeways*, which can be found on the Federal Highway Administration (FHWA) Rumble Strips Web site.(1)

The project team developed the guide and final report based on a literature review, current practices review, and follow-up interviews with six departments. The literature review focused on the following areas:

- Rumble strip design.
- Noise and vibration testing methods and findings (inside and outside the vehicle).
- Impacts on bicyclists and motorcyclists.
- Pavement condition impacts.
- Pavement marking visibility.
- Operational effectiveness.
- Safety effectiveness.
- Expert system development.

The literature review showed that there has been ample research quantifying the safety effectiveness of CLRSs and SRSs on crash frequency and severity, but they do not account for reduced dimensions that are becoming more common to address bicycle accommodations and noise issues. Rumble strip effects on bicyclists and noise issues have been reviewed independently of each other and independently of safety effects; currently, there is no research identifying a relationship between sound level and safety. Additionally, few research studies made recommendations for one practice of rumble strip design over another.

The current practices review focused on departmental policies and standard drawings, and the project team conducted follow-up interviews with the Connecticut Department of Transportation, Louisiana Department of Transportation and Development, Minnesota Department of

Transportation, Montana Department of Transportation, and Texas Department of Transportation, as well as FHWA's Eastern Federal Lands. The results of the follow-up interviews are provided in appendix B and were used to supplement information found in the policies and standard drawings in the current practices review. The purpose of the current practices review was to identify currently used design dimensions for CLRSs and SRSs as well as rumble strip implementation strategies, selection criteria, special considerations, and modifications.

The current practices review identified that rumble strip implementation strategies include systemic, high-crash corridor, systematic approaches, and combinations of each. Using the systemic safety approach, departments implement rumble strips on corridors based on risk features that are correlated with higher severity focus crash types (e.g., fatal and incapacitating injuries on the fatal, incapacitating injury, nonincapacitating injury, possible injury, and no injury scale). In this approach, corridor crash history is not considered for identifying rumble strip treatment locations. Rather, crash data analyses are used to identify risk factors associated with fatal and severe injury run-off-road (ROR) crashes, fatal and severe injury head-on crashes, or other focus crashes. While the systemic approach to safety focuses on identifying locations for rumble strip installation based on risk, the systematic approach focuses on installing rumble strips system-wide (often while completing other construction activities) with exceptions for installation that are based on policy. Alternatively, departments have traditionally used crash frequency (e.g., locations with a higher number or higher than expected number of crashes) or crash rate to justify additional corridors for installing rumble strips on an as-needed basis. This approach may also be referred to as a "case-by-case" approach because installation must be considered for each corridor based on multiple factors, and the decision to install or not is made independently in each instance based on these factors. Most department policies do not address systemic installation and instead focus on systematic installation strategies and provide exclusion criteria for rumble strip implementation. Systematic installation strategies often consider average daily traffic, pavement condition, posted speed limit, lane width, shoulder width, total pavement width, and pavement maintenance. The results of the current practices review guided the development of the decision support guide (i.e., the overview of current practices and model decisionmaking framework).[1]

Additionally, through the current practices review, the authors identified that while departments have their own standard designs for rumble strips, they do allow some flexibility, especially with sites that have a history of ROR crashes and bicyclist concerns. Most departments specify that high-crash locations can be identified through crash data and will choose to install rumble strips at these locations even if the systematic criteria are not met. However, it is important to show the effectiveness of the rumble strip design because the installation may impact the usability of the roadway for bicyclists or may burden nearby residents with increased noise or perceived noise activity. Many departments struggle with these considerations, and these considerations led to the recommendation for developing a rumble strip decision-support guide.[1]

The purpose of the rumble strip decision support guide is to inform departments on CLRS and SRS installation on non-freeway facilities.[1] The draft guide was reviewed by a panel of State transportation departments and FHWA representatives. The guide describes methods for identifying appropriate locations for installation, assessing the potential crash reductions and benefit/cost ratio, and developing performance metrics for safety. As part of this research, the project team used processes from agencies that have had success with installing rumble strips to develop a model decisionmaking framework, which is a four-step process that leads decisionmakers to determine whether to install a standard rumble strip, modified rumble strip, alternative treatment, or no treatment. The framework considers whether the segment meets the department's criteria for systematic installation or is justified by crash history if pavement condition, bicyclists, or noise are concerns.

A gap analysis was conducted based on the literature review and current practices review. The gap analysis identified that departments struggle with the optimal design and location of rumble strips given the geometry and context of the roadway. Additionally, departments struggle with identifying when noise issues will be a concern and what the optimal sound level should be. To date, no research studies have explored the impacts of rumble strips on pedestrian or bicyclist safety (i.e., no crash modification factors have been developed). Most assessments of pavement condition are anecdotal, and there is little quantitative research identifying the impacts of rumble strips on pavements or longitudinal joints. Finally, few safety studies have reported the dimensions of rumble strips included in the research, making it difficult to identify the safety effectiveness of different designs, particularly narrower and shallower rumble strips.

The project team developed an action plan based on the results of the gap analysis, which serves as a list of objectives for future research grouped under overarching goals. The goals, in no particular order, include the following:

- Establish safety effects of rumble strips.
- Identify performance measures for noise trade-off analysis.
- Identify performance measures for bicyclists for trade-off analysis.
- Establish effects of pavement condition and depth on deterioration.
- Develop an optimization tool based on the previous four goals and existing rumble strip implementation policies.
- Identify impacts of current and future in-vehicle technologies on rumble strip needs.
- Identify the impacts of rumble strips on driver behavior.

CHAPTER 1. INTRODUCTION

BACKGROUND

Rumble strips are a proven safety countermeasure intended to alert drivers when they leave the roadway across the edge line or center line through the generation of noise and vibration. Center line rumble strips (CLRSs) are used on undivided highways to reduce head-on, opposite-direction sideswipe crashes and roadway departure crashes to the left, while shoulder rumble strips (SRSs) and edge line rumble strips or stripes (ELRSs) are used to reduce roadway departure crashes to the right. Rumble strip benefits have been consistently quantified; there are more than 500 crash modification factors (CMFs) in the *Crash Modification Factors Clearinghouse*.(2) While many of the CMFs have been focused on freeway applications, this large number of CMFs indicates that there is no one design application appropriate for all circumstances. Additionally, there are many varieties and patterns of rumble strips that vary in applicability due to weather constraints, geometric constraints of the cross section, and consideration of trade-offs for other roadway users and non-users (e.g., nearby residences).

Rumble strips provide additional benefits for motorists beyond alerting roadway departure through noise and vibration, including the potential to increase nighttime visibility through combined application of rumble strips and pavement markings (e.g., rumble stripes).(3–5) However, researchers have identified trade-offs for rumble strip applications with proven crash reduction potential, including inconvenience for bicyclists and motorcyclists, excess noise for nearby residents, and potential for pavement life and pavement marking degradation.(1) Additionally, there are concerns for the operational impact to vehicle placement within the travel lane for the installation of CLRSs or SRSs. For example, CLRSs implemented on a narrow travel way may result in drivers shifting their vehicles closer to the outside edge of the roadway, which may lead to increased roadway departures to the right. These trade-offs have made it difficult for some departments to identify appropriate situations for implementing rumble strips on rural two-lane highways and difficult to identify an appropriate rumble strip design given a set of constraints.

PROJECT OBJECTIVE

The objectives of this project were twofold. The first objective was to identify the state of knowledge and practice among the States for the use and design of CLRS and SRS, identify any information gaps, and develop a research plan to address those gaps. This report fulfills this objective.

The second objective was to develop a decision support guide to inform agencies on CLRS and SRS installation. This objective was fulfilled with the preparation of *Decision Support Guide for the Installation of Shoulder and Center Line Rumble Strips on Non-Freeways*, which can be found on the Federal Highway Administration (FHWA) Rumble Strips Web site.(1) The guide describes methods for identifying appropriate locations for installation, assessing the potential crash reductions and benefit/cost (B/C) ratio, and developing performance metrics for safety. Additionally, the guide discusses special considerations for rumble strip installations, identifies variability in current practices, and provides a decisionmaking framework for installing rumble strips.

DESCRIPTION OF RUMBLE STRIPS

Rumble Strip Definitions

This section introduces important concepts and characteristics of rumble strips. Rumble strips are characterized by their placement, type, and dimensions. Each of these characteristics are described in greater detail in the following subsections.

Placement of Rumble Strips

Rumble strip placements include center line (i.e., CLRS), shoulder (i.e., SRS), or combined (CLRS + SRS).[1] SRSs can be further recognized by their offset from the edge line pavement marking. If an SRS is applied in conjunction with the pavement marking, then it is characterized as an ELRS. ELRSs are sometimes referred to as "rumble stripes." If an SRS is located outside the pavement marking, then it is simply referred to as an "SRS." Throughout this report, SRSs and ELRSs are collectively referred to as "SRSs" unless specifically talking about ELRSs. Figure 1 shows an installation of a combined CLRSs and SRSs.

Figure 1. Photo. Combination of milled of CLRSs and SRSs.

Transverse rumble strips are placed within a lane to warn drivers of upcoming unexpected changes, such as traffic signals, changes in alignment, or the need to change lanes. This report does not focus on the application of transverse rumble strips and will not discuss the topic further.

Types of Rumble Strips

Currently, there are two main types of rumble strips used on rural, non-freeway facilities: milled and raised. Milled rumble strips, which are most prevalent, are milled into the roadway surface using a rotary milling machine. They function by allowing the tires to drop into the groove, which creates both sound and vibration. The sound level is a function of the dimensions of the milled rumble strip, which are explained in the next section. Figure 1 provides an example of milled rumble strips.

Recently, some departments have also began studying and specifying dimensions for milled sinusoidal rumble strips, which are intended to reduce the external noise produced while providing sufficient noise and vibration to alert the driver of roadway departure.(6) This type of rumble strip is milled into the pavement surface using a sinusoidal pattern rather than individual grooves. Figure 2 shows a profile comparison of sinusoidal rumble strips (labeled as "California" and "Pennsylvania") in comparison to a typical milled installation (labeled as "Minnesota").(6) The depth is similar between the strips and the spacing (distance from center of peak to center of peak) is the same for the California and Minnesota designs.

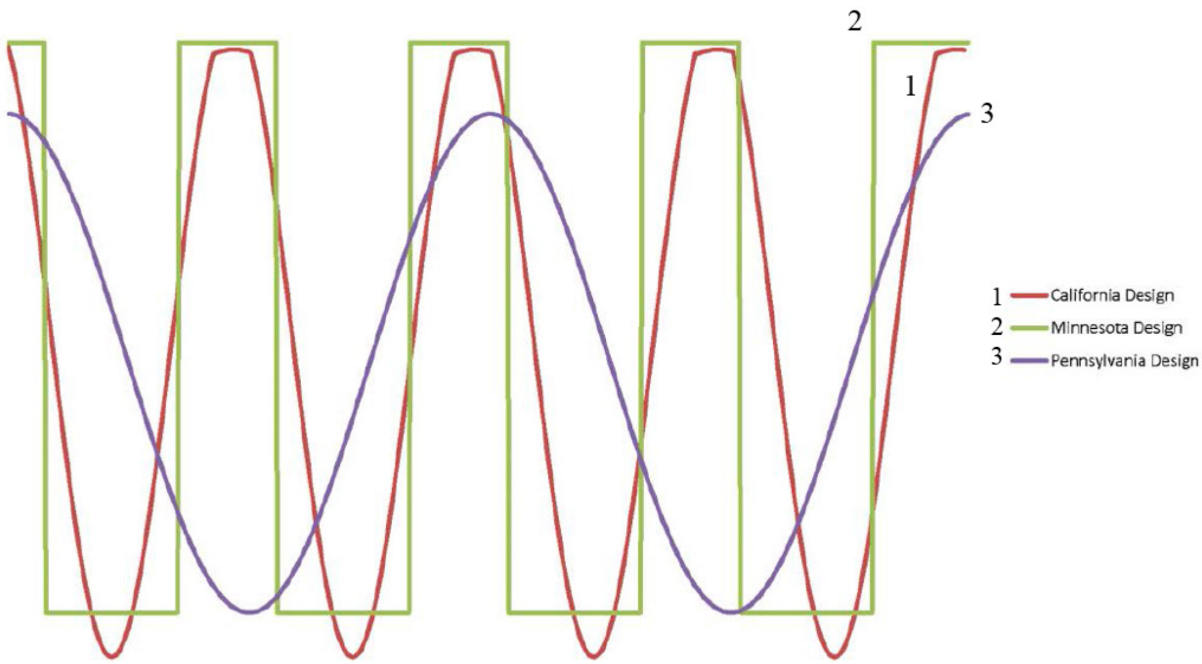


Figure 2. Illustration. Profile view of milled rumble strips.(6)

Although research suggests that milled rumble strips are the most effective application type, raised rumble strips (or rumble stripes) have been applied in States with warmer climates or where milled rumble strips cannot be installed. Raised rumble strips include side-by-side raised pavement markers, rumble bars, or plastic inserts within thermoplastic pavement markings. Profiled thermoplastic pavement markings have been developed to help with nighttime wet pavement visibility and may have some very limited rumble characteristics. Figure 3 provides an example of profiled thermoplastic pavement markings in Washington. Locations without snowplowing activities may use profiled thermoplastic pavement markings or other raised rumble strips; however, milled rumble strips are preferred. Raised rumble strips may be considered in areas where milled rumble strips are not practical, such as bridge decks or on thin surface courses (e.g., chip seals).

Figure 3. Photo. Example of profiled thermoplastic pavement marking.

Rumble Strip Dimensions

Figure 4 provides a graphical representation of rumble strip dimensions, which are explained as follows:[7]

- **Offset (A)**: Distance from the pavement marking (delineating the edge of the traveled way) to the inside edge of the rumble strip.
- **Length (B)**: Dimension of the strip that is perpendicular to the travel directions of the roadway. This is often referred to as the "transverse width" of the rumble strip.
- **Width (C)**: Dimension of the strip that is parallel to the travel direction of the roadway.
- **Depth (D)**: The maximum distance from the surface of the roadway to the bottom of the rumble strip.

- **Spacing (E)**: The distance between adjacent rumble strips. It is most often measured from the center of the strip to the center of the adjacent strip.

- **Gap (F)**: The distance from the edge of the rumble strip to the edge of the rumble strip when there is a break in the pattern. Gaps are commonly used to allow bicycles to cross the rumble strip pattern, to allow passing vehicles to cross CLRSs, and to allow turning movements at intersections and driveways.

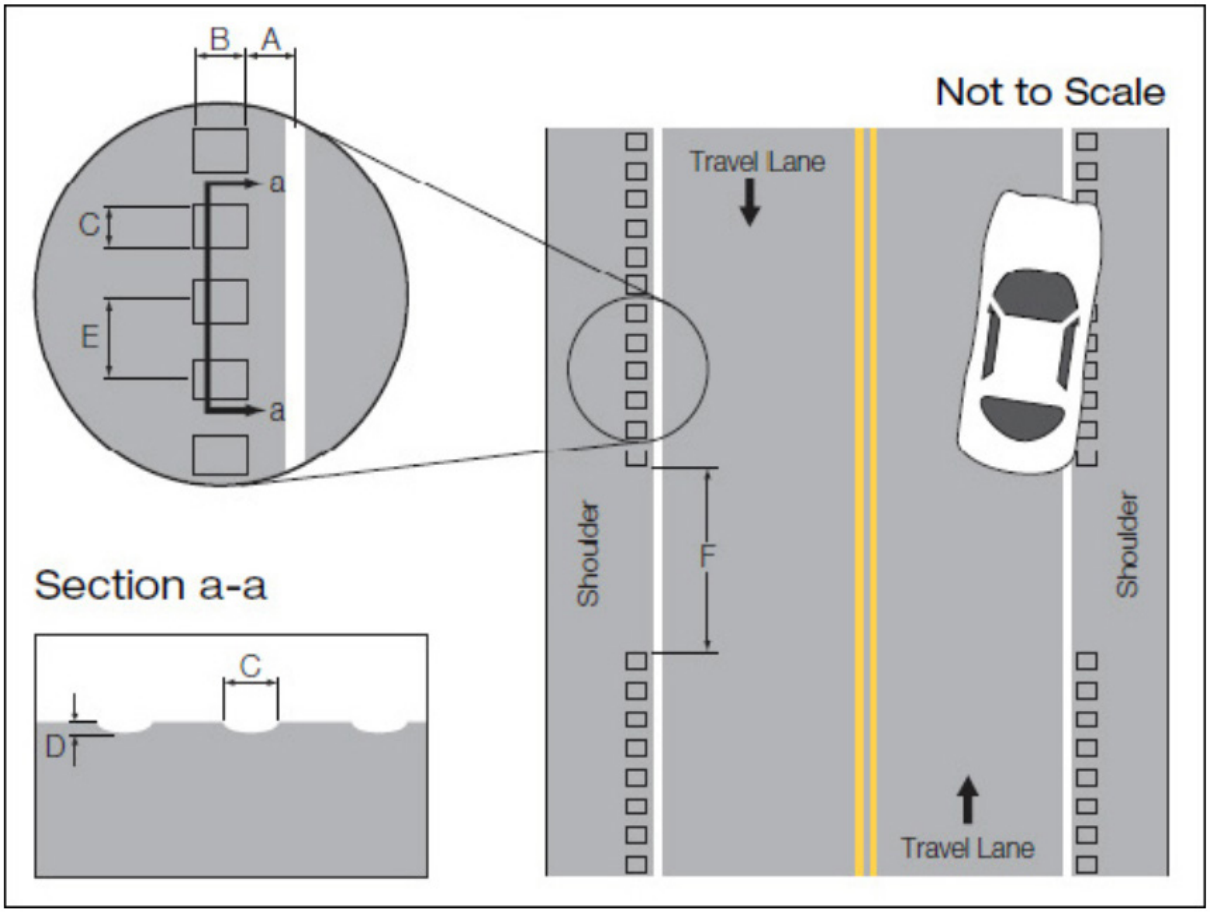


Figure 4. Illustration. Overview of rumble strip dimensions.[7]

REPORT ORGANIZATION

Beyond this introduction, this report is organized as follows:

- **Chapter 2. Literature Review**: This chapter provides a review of rumble strip research focused on rural two-lane highways and includes research from other facility types that can be applied to two-lane highways. The literature review informed the development of the guide and informed the gap analysis and action plan development.

- **Chapter 3. Current Practices Review**: This chapter synthesizes rumble strip design and implementation criteria for all State departments (and FHWA's Eastern Federal Lands (EFL)) with published policies and/or standard drawings and summarizes the results of department follow-up interviews. The review focuses on department policies related to rural two-lane highways but also includes policies from other facility types that are applied to two-lane highways or used when a specific policy for rural two-lane highways could not be found. The current practices review informed the development of the guide and informed the gap analysis and action plan development.

- **Chapter 4. Guide Development**: This chapter provides an overview of the decision support guide development. The model decisionmaking framework, webinar review comments, and overview of the final rumble strip decision guide are provided.

- **Chapter 5. Gap Analysis and Action Plan**: This chapter provides a list of gaps identified in this research and includes gaps from National Cooperative Highway Research Program (NCHRP) Report 641, *Guidance for the Design and Application of Shoulder and Centerline Rumble Strips*, and NCHRP Synthesis 490, *Practice of Rumble Strips and Rumble Stripes*, that are still applicable.(8,9) This chapter also provides a set of goals and objectives to fill those gaps through future research.

- **Appendix A. Interview Questions:** This appendix includes the verbatim list of questions provided to the five State transportation departments and FHWA's EFL in advance of follow-up interviews.

- **Appendix B. Follow-Up Phone Interviews:** This appendix includes notes taken from follow-up interviews with departments and FHWA's EFL. Additionally, this appendix includes verbatim department responses to the questionnaire provided in appendix A.

CHAPTER 2. LITERATURE REVIEW

PURPOSE OF LITERATURE REVIEW

This literature review explored the benefits and trade-offs of rumble strips. The objective was to identify and synthesize pertinent research related to rumble strip design, application, and effectiveness. The literature review enabled a gap analysis to determine information that should be explored further in department interviews or addressed in future research. The results of this literature review informed and guided the development of the rumble strip decision support guide.(1)

This literature review focused on research related to rural two-lane highways and includes research from other facility types that can be applied to two-lane highways. This chapter is organized as follows:

- **Rumble Strip Design**: Summarizes the results of recent nationwide surveys regarding dimensions and installation of SRSs and CLRSs.
- **Noise and Vibration—Testing Methods and Findings**: Summarizes research studies that have measured rumble strip noise internal and external to the vehicle.
- **Accommodation of Bicyclists and Other Users**: Summarizes research related to the accommodation of other roadway users, specifically bicyclists and motorcyclists.
- **Pavement Condition Impacts**: Summarizes research related to the impacts of rumble strips on pavements and longitudinal joints.
- **Pavement Marking Visibility**: Summarizes research related to the impacts of rumble strips on pavement marking visibility.
- **Operational Effectiveness**: Summarizes research related to the impacts of rumble strips on vehicle operating speed, lateral vehicle position, and passing maneuvers.
- **Safety Effectiveness**: Summarizes research related to the impacts of rumble strips on crash frequency and crash severity for target crashes.
- **Expert System Development**: Describes the methodology for an expert system recently developed for Wyoming.
- **Conclusions**: Summarizes the researchers' findings and conclusions.

RUMBLE STRIP DESIGN

In 2009, Torbic et al. conducted a nationwide survey regarding dimensions and installation of SRSs and CLRSs.(8) They collected responses from 27 U.S. State transportation departments and 4 Canadian provincial transportation departments. The survey revealed that rumble strip policies incorporated a wide range of criteria that impact installation of SRSs and CLRSs. Twenty-six transportation departments specified a minimum shoulder width requirement for SRSs, ranging from 2 to 10 ft, with 4 ft being the most common value. Sixteen transportation departments specified a minimum lateral clearance requirement for SRSs, ranging from 2 to 7 ft, with 4 and 6 ft being the most common values. In this case, the lateral clearance was the distance from the outside edge of the rumble strip to the outside edge of the shoulder. Minimum required pavement depth ranged from 1 to 6 inches; however, it was not reported if this was for the final surface layer only. The minimum average daily traffic (ADT) for SRS application ranged from 400 to 3,000 ADT but, in most cases, ranged between 1,500 and 3,000 ADT. Typical offset distances from the edge line ranged from 0 to 30 inches. For divided highways with SRSs on both the inside and outside shoulders, the offset for the inside shoulder was typically less than the offset for the outside shoulder. The survey also identified the most commonly reported dimensions for milled SRSs and CLRSs, as shown in table 1.

Table 1. Typical dimension of rumble strips adapted from Torbic et al.[(8)]

Rumble Strip Type	Length (inches)	Width (inches)	Depth (inches)	Spacing (inches)
Milled SRS	16	7	0.5 to 0.625	12
Milled CLRS	12 or 16	7	0.5	12

A more recent survey by Smadi and Hawkins collected responses from 41 State transportation departments regarding design and installation practices.[(9)] Their survey found that for rural two-lane highways, 71 percent of departments installed CLRSs, 85 percent of departments installed SRSs, and 5 percent of departments did not install rumble strips. The survey results indicated that shoulder width, speed limit, pavement location, and factors such as bicyclist presence were common influencing factors for SRS installation. Common factors for CLRS installation included lane width, speed limit, pavement condition, and factors such as presence of homes or noise.

The most common offset for SRSs from the edge line was 6 inches (12 of 41 departments); however, 7 departments indicated using an offset of 0 inch (i.e., ELRSs). The most commonly specified rumble strip length for SRSs was 16 inches (followed closely by 12 inches). Additionally, the most common width was 7 inches, the most common spacing was 12 inches, and the most common depth was 0.5 inch. This indicates little change between the survey by Torbic et al. and the survey conducted for the research by Smadi and Hawkins. The most commonly specified dimensions for CLRS included the following:

- Length of 12 inches.
- Width of 7 inches.
- Spacing of 12 inches.
- Depth of 0.375 inches.

These results indicated that the most commonly specified depth for CLRS was been reduced from 0.5 to 0.375 inch.

NOISE AND VIBRATION—TESTING METHODS AND FINDINGS

Inside Vehicle

To alert the drivers of travel roadway departure, the rumble strips must provide an audible level of noise that is noticeably greater than the ambient background noise. Ambient background noise inside a vehicle varies by vehicle for a number of reasons, including pavement surface, tires, suspension, and travel speed. Previous research has shown that the trained human ear can detect a 2-dB change in normal environmental noise. The average person can perceive a 3-dB noise level change, and a 5-dB change is readily perceptible.(10) Therefore, rumble strips should provide a minimum 3- to 5-dB change in noise level over the noise inside the vehicle.

Bucko and Khorashadi collected in-vehicle noise and vibration data using equipped test vehicles (both passenger cars and commercial-style trucks).(11) The following five rumble strips of different dimensions were examined:

- **Strip 1**: Rolled rumble strips with 24-inch length, 2-inch width, 1-inch depth, and 7.9-inch center-to-center spacing.
- **Strip 2**: Milled rumble strips with 16-inch length, 4.8-inch width, 0.25-inch depth, and 12-inch center-to-center spacing.
- **Strip 3**: Milled rumble strips with 16-inch length, 5.9-inch width, 0.35-inch depth, and 12-inch center-to-center spacing.
- **Strip 4**: Milled rumble strips with 16-inch length, 6.9-inch width, 0.50-inch depth, and 12-inch center-to-center spacing.
- **Strip 5**: Milled rumble strips with 16-inch length, 7.6-inch width, 0.63-inch depth, and 12-inch center-to-center spacing.

The equipped data acquisition system consisted of four piezoresistive accelerometers, a sound level meter, and a laptop. During testing, the sound level meter was held at ear level close to the center of the vehicle front passenger seat. An instrumentation engineer sat in the front passenger seat, operated the recording instruments, and collected sound level and vibration data. The light vehicles were driven over the rumble strips at 50 and 62 mi/h, and the commercial vehicles were driven at 50 mi/h. Background noise and vibration levels were extracted from the test data both before and after contact with the rumble strips. The results revealed that strip 1 generated higher levels of noise and vibration than strip 2 but less than strips 3–5. The levels of noise and vibration generated by strips 3–5 were in ascending order. Both passenger cars and commercial trucks followed the same trend.

Torbic et al. developed noise prediction models based on rumble strip dimensions.(8) Noise data were collected in six States (Arizona, Colorado, Kentucky, Minnesota, Pennsylvania, and Utah) using a passenger car operating at speeds ranging from 40 to 65 mi/h. A portable data acquisition system was developed to collect in-vehicle noise data. The system consisted of a laptop, a Global Positioning System, a hand-held sound level meter, and a Universal Serial Bus analog-to-digital converter module. The linear regression model revealed that length, width, and depth have significantly positive association with sound level difference (i.e., an increase in dimension is associated with greater sound level difference). Spacing was associated with a significant decrease in sound level difference. When using categorical dimension data, the authors found that the rumble strip length dimension indicator was significant and negative compared to the baseline condition (14 inches), which indicated that rumble strips with lengths of more than 14 inches were expected to have higher sound level differences than those equal to or less than 14 inches.(8) Rumble strips with widths greater than 6 inches were expected to have less sound level difference compared to narrower rumble strips (width less than or equal to 6 inches). Rumble strips spaced more than 12 inches apart were expected to generate lower levels of noise compared to closer spaced patterns (spacing less than or equal to 12 inches). The depth indicator was not statistically significant.

Miles and Finley collected in-vehicle sound using equipped vehicles.(12) Three different types of vehicles were used, including a sedan, a half-ton truck, and a commercial vehicle. A sound level meter was strapped inside the vehicle to the right of the driver's seat with the sensor placed at shoulder level. In each test vehicle, one driver and one data collector were present. Researchers collected sound data for the ambient (baseline) and the rumble strips conditions under dry and daytime conditions. Additionally, the researchers recorded sound not associated with rumble strips with respect to time, including sound due to the presence of another vehicle near the test vehicle and uneven pavement surfaces. These data were used to remove any anomalies in the data associated with such events.

The authors quantified the change in sound associated with rumble strip dimensions and assessed the impact of speed, vehicle type, and pavement type on sound level. Based on previous research in a driving simulator, a 4-dB or greater change in sound level was considered to be sufficient to alert drivers who were awake.(13) The authors found that speed had little impact on the change in sound level but was associated with higher ambient sound. Therefore, they recommended that speed should be considered for requiring more aggressive (i.e., larger dimension) rumble strip designs. The change in sound was more noticeable in the sedan and half-ton truck than the commercial vehicle. A 4-dB change was apparent approximately 90 percent of the time in the sedan and half-ton truck but only 23 percent of the time in the commercial vehicle. The authors recommended that vehicle type be considered when designing the rumble strip pattern. This is consistent with Torbic et al., who recommended 12- to 16-inch rumble strips for heavy trucks and patterns half that length for passenger cars.(8)

Milled rumble strip sound change was affected by the design of the application, but the most aggressive patterns resulted in the largest change in sound. Rumble strips 6 inches long or greater provided at least a 4-dB sound level change for the sedan and half-ton truck, while 12 inches was required to produce the same levels for commercial vehicles. Spacing had less impact on sound change, but spacing of 24 inches or less was sufficient for commercial vehicles, while all spacing tested was sufficient for the sedan and half-ton truck.

Elefteriadou et al. examined in-vehicle sound while developing "bicycle-friendly" rumble strip configurations to determine the effects of differing patterns on motorists.(14) A sound meter was installed next to a motorist's head in a minivan, which was driven at 45, 55, and 65 mi/h. For the milled rumble strip with 16-inch length, 7-inch width, 12-inch spacing, and 0.5-inch depth, the sound level difference was 14 to 16 dB from the sound level in the travel lane.

The researchers evaluated the noise level of the following six rumble strip designs (note that all designs had 16-inch length and that the section was 125 ft long):

- **Strip 1**: Seven-inch width, 12-inch center-to-center spacing, and 0.5-inch depth.
- **Strip 2**: Five-inch width, 12-inch center-to-center spacing, and 0.5-inch depth.
- **Strip 3**: Five-inch width, 12-inch center-to-center spacing, and 0.375-inch depth.
- **Strip 4**: Five-inch width, 11-inch center-to-center spacing, and 0.5-inch depth.
- **Strip 5**: Five-inch width, 11-inch center-to-center spacing, and 0.375-inch depth.
- **Strip 6**: Five-inch width, 12-inch center-to-center spacing, and 0.25-inch depth.

Three runs were made at 45 and 55 mi/h for each strip and were compared to the baseline travel lane noise level. The authors found a greater noise level difference at 55 mi/h than at 45 mi/h in general.(14) Additionally, the test patterns with the most depth (0.5 inch) generated the largest noise level difference, with 10 to 15 dB at 45 mi/h and 16 to 23 dB at 55 mi/h. Test pattern 6 generated the least sound level difference, with 6.3 dB at 45 mi/h and 13.0 dB at 55 mi/h.

Additionally, a recent study has investigated rumble strips intended to provide sufficient internal noise while reducing external noise.(6) Rumble strips with a sinusoidal profile (sinusoidal rumble strips) were considered as an alternative to traditional milled rumble strips. A study by the Minnesota Department of Transportation (MnDOT) compared noise levels between two 8-inch sinusoidal designs and a conventional rumble strip that was 16 inches long.(6) They collected interior sound data of vehicles traveling over ELRSs on two-lane rural roads in Minnesota. Table 2 shows three designs of rumble strips that were tested in the study.

Table 2. Rumble strip designs adapted from Terhaar and Braslau.(6)

Design	Spacing (inches)	Depth (inches)	Length (inches)
California sinusoidal	14	$^{1}/_{32}$ to $^{5}/_{8}$	8
Pennsylvania sinusoidal	24	$^{1}/_{8}$ to $^{1}/_{2}$	8
Minnesota conventional	12	$^{3}/_{8}$ to $^{1}/_{2}$	16

A sound level meter was mounted on a tripod propped against the back seat and next to the driver. Three vehicles were included in the test: a sedan, a pickup, and a semi-tractor truck. A total of nine tests were conducted, with three tests for each speed (30, 45, and 60 mi/h). Measurements began at the start of acceleration and continued for approximately 5 s after. One-third octave band readings were taken with simultaneous audio recording. To permit evaluation of time histories, 1-s readings were taken. Additionally, meteorology information, including wind speed and direction, temperature, and relative humidity, was obtained. A handheld wind meter was used to check the obtained wind speed. The results showed that the interior sound level increased with traffic speed and vehicle weight. The Minnesota and California designs produced similar sound levels, while the Pennsylvania design produced the lowest levels. Since the study did not use the same dimensions, it is unknown whether the noise difference was due to dimension differences or sinusoidal designs.

Further research by Terhaar et al. examined external noise for the following five rumble strip designs:(15)

- Sinusoidal design 1, 14-inch center-to-center wavelength, 14-inch length, and $^{1}/_{16}$- to $^{3}/_{8}$-inch depth.
- Sinusoidal design 2, 14-inch center-to-center wavelength, two 8-inch-length strips separated by 4-inch gap, and $^{1}/_{16}$- to $^{1}/_{2}$-inch depth.
- Sinusoidal design 3, 14-inch center-to-center wavelength, 14-inch length, and $^{1}/_{16}$- to $^{1}/_{2}$-inch depth.
- Sinusoidal design 4, 14-inch center-to-center wavelength, two 8-inch-length strips separated by 4-inch gap, and $^{1}/_{16}$- to $^{3}/_{8}$-inch depth.
- Non-sinusoidal, 16-inch length, and $^{3}/_{8}$-inch depth.

The research team examined the external noise level for these CLRS designs using a passenger car, pickup truck, and dump truck. They measured sound levels at 50 and 75 ft from the CLRS. For this study, the researchers recorded sound levels every second and reported the sound level as the equivalent A-weighted decibel. The maximum A-weighted decibel was used to compare sound levels.

The results indicated that sinusoidal designs 1 and 4 generated lower exterior sound level increases than designs 2 and 3 but generated similar interior sound levels. Sinusoidal designs 2 and 3 produced the largest sound level increases inside the pickup truck and dump truck, while designs 1 and 2 produced the largest sound increase inside the passenger car. The authors recommended rumble strip design 3 (14-inch length with $^{1}/_{16}$- to $^{1}/_{2}$-inch depth) be considered for further implementation in Minnesota. They noted that all of the sinusoidal designs provided adequate feedback for passenger cars, but design 3 gave the best results for pickup trucks. They recommended rumble strip design 1 for areas where there is extreme sensitivity to noise.

Outside Vehicle

Rumble strips generate noise outside the vehicle in addition to inside the vehicle. Outside noise does little to help the driver detect the rumble strips and can be a nuisance to nearby residences. Exterior rumble strip noise can be difficult to collect and adequately compare to ambient traffic noise levels. Ambient noise level is typically measured as a constant value, which may be a function of many characteristics (e.g., speed and traffic volume), while rumble strip noise is more intermittent, and a maximum value is typically used. Rumble strip noise measurement considers the time-length of the rumble strip strike.

Researchers are continually testing noise level collection methods. There are several methods documented in the literature for obtaining wayside or pass-by noise data, as well as an on-board sound intensity method for measuring tire-pavement noise. This section characterizes noise level collection outside the vehicle and summarizes research and guidelines related to mitigating external noise.

Finley and Miles evaluated the effects of rumble strip applications on external noise levels using a sedan at 55 and 70 mi/h and a heavy truck at 55 mi/h in Texas.[(16)] Measurements were taken 50 ft from the exterior edge of CLRS and SRS applications and were compared to baseline noise data from the testing vehicles. The results indicated that button applications typically resulted in a sound level change of 4 dB and milled rumble strips resulted in an 8- to 12-dB change for the sedan and a 6-dB change for the heavy truck. Rumble strip length was shown to have the strongest association with change in sound level, with the greatest changes occurring for the longest rumble strip applications. Chip seal pavements had a 5-dB or less change in sound level, while hot-mix asphalt (HMA) pavements had an 11- to 16-dB increase.

Rys et al. and Karkle evaluated external sound levels of rectangular and football-shaped CLRSs at 10 sites in Kansas.[(17,18)] The noise meters were located 50, 100, and 150 ft from the center line of the roadway, and measurements were taken for smooth asphalt and rumble strips at 40 and 65 mi/h using a large van and a sedan. The author found that external noise depends on speed, vehicle type, and distance from the rumble strip.[(18)] Both rumble strip types were found to significantly increase external noise, and a distance of 200 ft was found to be the estimated limit for noise greater than 60 A-weighted decibels (dBA).

Gates and Noyce documented survey results of local road users for CLRS on Wisconsin State Trunk Highway 142 in Kenosha County, WI.[(19)] Responses were received from a variety of road users, including residents, business owners/employees, general roadway users, motorcyclists, truck drivers, and law enforcement. The survey revealed that most of the roadway users had no physical problems traveling over CLRSs (e.g., discomfort, handling problems, overreaction, instrument problems, etc.), including fire/ambulance drivers, police officers, truck drivers, and park rangers. Nonetheless, one-third of those interviewed were against the CLRS uses largely due to the noise issue. Motorcyclists were not in favor of CLRSs because of discomfort when driving over them and the potential for the CLRSs to hold water and ice in winter. The majority of truck drivers were against CLRSs because they felt the money should be spent somewhere else—a response not related to safety or maneuverability.

The Danish Road Institute compared sinusoidal and milled rumble strips in terms of noise levels.[(20)] They tested five types of rumble strips made by milling indentations in the pavement of two-lane roads. Two sinusoidal rumble strips were 0.28 and 0.16 inch deep, respectively. The conventional rumble strips were 0.4, 0.16, and 0.31 inch deep. The sound data were collected using a microphone at 25 ft from the center line and at a height of 4 ft above the road surface. The study found that sinusoidal rumble strips' external noise was only 0.5 to 1 dB above ambient noise, which was less than conventional indentations. However, researchers were unable to determine whether the noise difference was a result of dimension differences or sinusoidal designs.[(6)]

Datta et al. performed a field study to evaluate roadside noise produced by rumble strips in Michigan; they considered depth, location, and pavement surface type.[(21)] A sound meter was located 50 ft from the roadway center line at a height of 5 ft above the pavement surface. The sound meter was programmed to measure the fastest possible rate, which was one measurement per 125 ms. A minivan made 40 passes through each of 12 sites at 55 mi/h. The van passed near the rumble strips 20 times and made contact with them on an additional 20 passes. The results indicated an 8-dBA increase above the test vehicle's peak noise level for CLRSs and a 10-dBA increase for SRSs. The levels were not significantly different, and the SRSs produced a sound level similar to that of tractor trailers that were observed in the study sections. Ambient noise measurements showed a low rate of vehicular contact with rumble strips. The authors recommended that rumble strips be milled at depths between 0.25 and 0.50 inch to prevent unnecessary roadside noise.[21]

Sexton evaluated wayside noise levels from CLRS design using a sport utility vehicle in Washington to determine overall sound levels and one-third-octave band frequencies.[22] The noise measurement collection methodology was performed consistently with the American Association of State Highway and Transportation Officials (AASHTO) specification in TP 98-13, *Determining the Influence of Road Surfaces on Vehicle Noises Using the Statistical Isolated Pass-By Method*.[23] Two primary microphones recorded 10-s measurements 25 ft from the center of the near travel lane and 50 ft from the center of the near travel lane. Nine rumble strip patterns were tested, with depths of 0.375 and 0.5 inch, widths of 6 and 6.9 inches, lengths of 8 to 12 inches, and spacing of 12 to 24 inches. The results indicated that the CLRS designs with the lowest exterior noise levels included the following:

- Depth of 0.375 to 0.5 inch.
- Width of 6 to 6.9 inches.
- Length of 8 inches.
- Spacing of 12 inches.

These design dimensions all resulted in interior noise levels within the target range (6 to 11 dB) recommended by Torbic et al.[8]

MnDOT monitored external sound levels of ELRSs of rural two-lane roads in Minnesota.[6] Three types of designs were examined, as shown earlier in table 2. MnDOT placed one sound level meter at 50 ft from the edge of the pavement and a second sound meter at 100 ft from the edge of the pavement. Meters were mounted on tripods 5 ft above the ground with wind screens. A video camera was placed next to the meter at 50 ft to capture all of the tests. Three types of vehicles were used: a sedan, a pickup, and a semi-trailer truck. A total of nine tests were conducted with three tests for each speed (30, 45, and 60 mi/h). Measurements were started approximately 5 to 7 s before the pass-by and continued for approximately 5 s after the pass-by. One-third octave band readings were taken with simultaneous audio recording. One-second readings were used to establish the maximum pass-by level. The measurement was conducted at dry condition. Additionally, wind speed and direction, temperature, and relative humidity were obtained. A handheld wind meter was used to check the reported wind speed. The results showed that the exterior noise produced by the sinusoidal rumble strips was less than that produced by the conventional rumble strips. The Pennsylvania design had the lowest exterior sound levels. However, it is unknown whether the noise difference was a result of dimension differences or sinusoidal designs. Subsequent analyses indicated that deeper sinusoidal rumble strips produced higher external sound level differences than those that were $^{1}/_{8}$ inch shallower.[15] However, all sinusoidal rumble strips produced less external noise than the standard milled rumble strip design.

Ahmed et al. surveyed 50 respondents investigating the effect of SRS external noise on nearby residents in Wyoming.(24,25) Nearly 90 percent of the respondents lived within 500 ft of rumble strips, and only 27 percent of those surveyed indicated that noise is not an issue. A total of 84 percent of nearby residents find the noise level acceptable, while 98 percent reported the noise to be tolerable since rumble strips save lives. The authors concluded that residents would mostly prefer a quieter design, and several reported the idea of using sound barriers.(24,25) A separate survey of State practices indicated that many States consider nearby residents when installing rumble strips, considering crash experience and the use of shallower depth rumble strips. More than 30 percent of States reported using 0.375-inch-deep rumble strips to mitigate noise in residential areas.

IMPACTS ON BICYCLISTS AND MOTORCYCLISTS

Rumble strips are designed to produce a change in audible noise and vibration to warn drivers of passenger cars and heavy trucks. While heavy trucks require larger rumble strip design dimensions in order to produce the required noise and vibration, bicyclists and motorcyclists may have even greater difficulty traversing rumble strips of this design. The following subsections cover rumble strip research related to bicyclists and motorcyclists.

Bicyclists

The AASHTO *Guide for the Development of Bicycle Facilities* indicates that rumble strips or raised pavement markers are not recommended where shoulders are used by bicyclists unless there is a minimum clear path of (1) 1 ft from the rumble strip to the traveled way, (2) 4 ft from the rumble strip to the outside edge of the paved shoulder, or (3) 5 ft to an adjacent guardrail, curb, or other obstacle.(26) The guidance also emphasizes that if existing conditions preclude achieving the minimum desirable clearance, then the length of rumble strip may be decreased or other appropriate alternatives should be considered. The recommended rumble strips have a length of 16 inches.

Elefteriadou et al. studied six different rumble strip designs in order to identify the most bicyclist-friendly SRS for non-freeway applications.(14) The objective was to develop a rumble strip configuration that decreases vibrations experienced by bicyclists while providing adequate noise and vibration for motorists. Potential designs were ranked by their ability to alert drivers and by controllable ride for bicyclists. Two designs were recommended: one for higher-speed roadways and one for lower-speed roadways. For 55-mi/h roadways, the rumble strip with 5-inch width, 7-inch spacing, and 0.375-inch depth was recommended. For roadways with lower operating speeds (near 45 mi/h), the test pattern with 5-inch width, 6-inch spacing, and 0.375-inch depth was recommended. For this research, the spacing refers to the flat portion between rumble strip cuts.(14)

Moeur evaluated the impacts of milled rumble strips that were 0.5 inch deep and 7 inches wide and had 12 inches center-to-center spacing on bicyclists in Arizona.(27) Due to the design of the rumble strips, bicycle tires were noted to drop the entire 0.5 inch at every rumble strip, creating severe impacts on bicycle handling and bicyclist comfort since there is no shock absorption. The authors suggested that gaps be placed in the pattern to allow bicyclists to cross the rumble strips as needed. Twenty-eight test subjects of varying skills participated in a field study to test gap sizes based on raised pavement markers (to simulate rumble strips) installed at the end of a moderate downgrade. Gap spacing was tested in 2-ft increments in ranges from 10 to 20 ft. In all cases, bicyclists were able to clear the gaps without contacting the raised pavement markers, but the participants noted that the gap started to become difficult at 12 ft (considering 20- to 28-mi/h speeds reached due to the downgrade approach). The author recommended a 12-ft gap in the rumble strip pattern for bicyclists using a 40- or 60-ft cycle for the rumble strip and gap.(27) Additionally, the author noted that this design should be considered regardless of rumble strip dimension design.

Outcalt compared three styles of rumble strips to identify a design adequate for motorists without making the shoulder unusable for bicyclists.(28) The standard design for SRSs in Colorado is 12-inch length, 5-inch width, 0.375-inch depth, 12-inch spacing, and a 12-ft gap every 60 ft. For this study, the standard design was used, and depths of 0.75, 0.5, 0.375, 0.25, and 0.125 inch were tested and considered. Additionally, rumble strips with 12-inch length, 2-inch width, and 0.5-inch (0.375-inch at one section) depth were installed for analysis. The 2-inch-wide rumble strips had spacing that varied from 7 to 12 inches. A group of 29 volunteer bicyclists rode each of the configurations and rated the configurations for comfort and controllability. Most bicyclists were very experienced or had intermediate experience, and most used road bikes with narrow, high-pressure tires. Two participants used mountain bikes with fat, low-pressure tires.

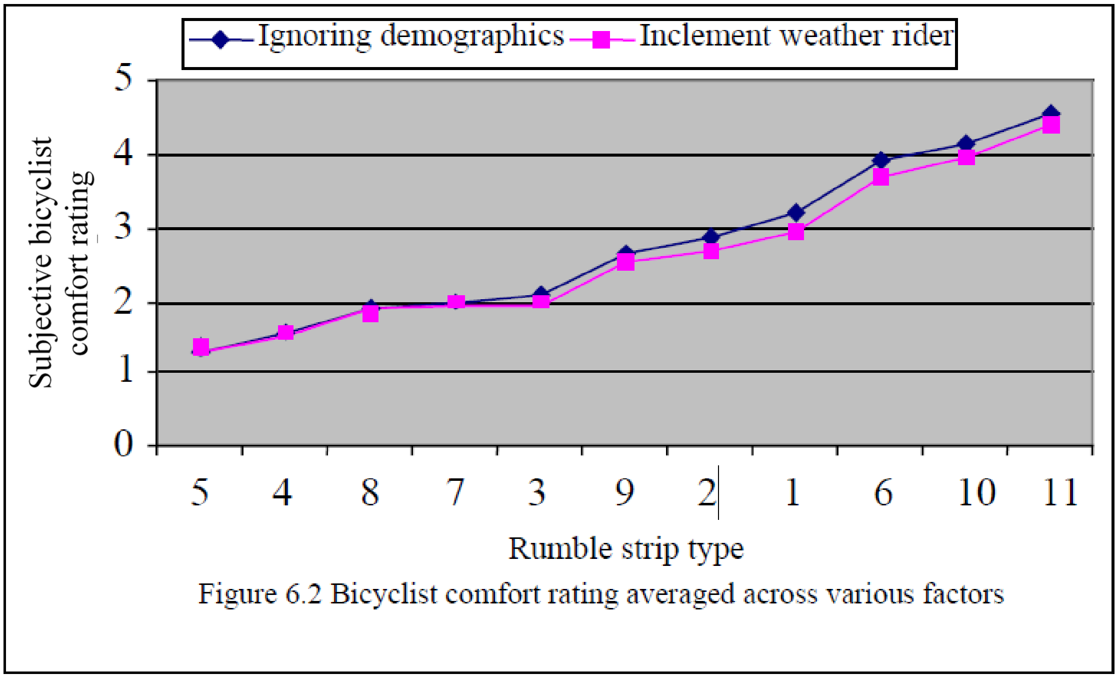
In addition to bicyclist testing, the sound level increase was tested for a station wagon, van, pickup truck, and dump truck. The sound level inside the vehicle above the travel lane was measured at 55 and 65 mi/h. The authors found that there is no ideal solution; the best rumble strips from the sound viewpoint were the lowest rated from the bicyclists. The newer 2-inch rumble strips did not produce a noticeable noise increase (defined as 6 dB in this study) for the dump truck. The authors recommended the standard design with the 0.375-inch depth with 12-ft gaps every 60 ft. The surveys indicated that 0.5-inch depth grooves can cause severe control problems for bicyclists. Additionally, the authors recommended a warning for bicyclists at the beginning of the SRSs.

O'Brien et al. evaluated the impact of SRS gap length and shoulder width on bicycle maneuverability at high speeds.(29) The authors noted that bicyclists on steeper downgrades reached higher speeds than those tested by Moeur. A similar protocol to Moeur was used to simulate rumble strips that were 12 inches long. Participants attempted to cross each 12- to 24-ft gap in the pattern on a 6.6-percent downgrade. Additionally, the shoulder width was varied from 4 to 8 ft to determine the impact on bicyclist speeds. The authors concluded that additional gap length on downgrades decreased bicyclist maneuver errors and increased comfort. They also concluded that 4-ft shoulders were sufficient, and shoulders more than 4 ft did not affect bicyclists' ability to maneuver through gaps or result in a change in speed. However, the study was not able to identity a clear relationship between shoulder widths and comfort for a given gap size. Gap sizes of 16 to 18 ft were sufficient for vehicles to encounter 12-inch rumble strips. Gap size for ensuring that a vehicle would strike the rumble strips decreased as the width of the rumble strip decreased and as the departure angle increased.

Bucko and Khorashadi intended to identify a rumble strip that is effective as well as bicyclist friendly.(11) The following types of strips with various dimensions were installed and tested in a testing field:

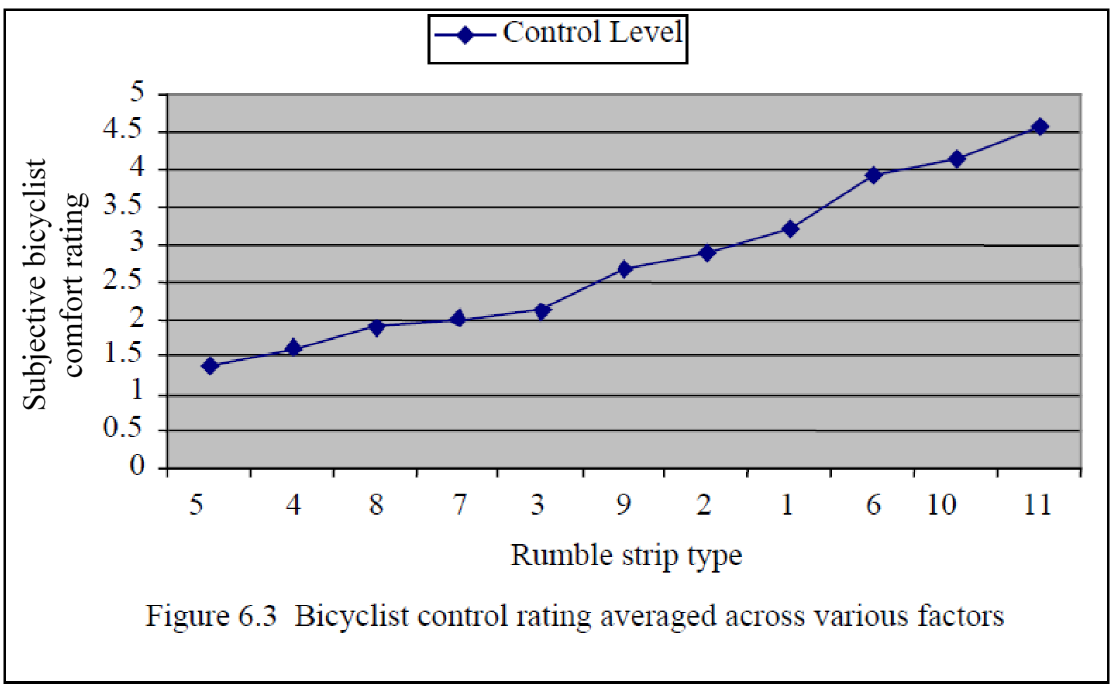
- Rolled rumble strips with 24-inch length, 2-inch width, 1-inch depth, and 7.9-inch center-to-center spacing.
- Milled rumble strips with 16-inch length, 4.8-inch width, 0.2-inch depth, and 12-inch center-to-center spacing.
- Milled rumble strips with 16-inch length, 5.9-inch width, 0.4-inch depth, and 12-inch center-to-center spacing.
- Milled rumble strips with 16-inch length, 6.9-inch width, 0.5-inch depth, and 12-inch center-to-center spacing.
- Milled rumble strips with 16-inch length, 7.6-inch width, 0.6-inch depth, and 12-inch center-to-center spacing.
- A chip seal application.
- Raised pavement marker single run on 12-inch centers.
- Raised pavement marker skewed double run on 12-inch centers. The second run was placed 6 inches to the right of the first and skewed 6 inches for two skewed runs of pavement markers.
- Rumble strip bars placed 2 ft on center and 2 ft wide.
- Raised and inverted thermoplastic stripe.
- Raised thermoplastic stripe.

The researchers conducted an objective bicyclist test and an instrumented vehicle test.(11) A total of 55 bicyclists of various experience levels, ranging in ages from 26 to over 60, participated in the field testing using 1 of 18 provided bicycles or their own bicycle. Bicyclists rode over 11 different rumble strip types at varying speeds and angles in groups and as single bicyclists. They also rated the level of comfort and control on a scale of 1 to 5, with 1 being the least comfortable and 5 being the most. The results indicated that strips 6, 10, and 11 provided a higher level of comfort and control compared to strip 1 (baseline), as shown in figure 5 and figure 6. Strips 1, 2, and 9 provided approximately the same level of comfort and control for bicyclists. Rumble strip 3 provided approximately 70 percent of the comfort level reported for strip 1. The statistical analysis of vehicle data showed that with the exception of rumble strips 2, 6, 10, and 11, all of the other rumble strips produced higher levels of noise and vibration compared to strip 1 (baseline). Based on findings from the tests and the costs of installation and maintenance, Bucko and Khorashadi recommended strip 3 because it provided superior levels of noise and vibration for vehicles and acceptable comfort level for bicyclists.



Note: 5 indicates most comfortable and 1 indicates least comfortable.

Figure 5. Graph. Bicyclist comfort rating.[11]



Note: 5 indicates most control and 1 indicates least control.

Figure 6. Graph. Bicyclist control rating.[11]

Datta et al. evaluated driver behavior in the presence of bicyclists in Michigan to determine the impacts of CLRSs.[21] They collected observational data using pole-mounted cameras on a 0.5-mi study segment using bicyclists from the research team riding in a prescribed lateral position. The data indicated that significantly fewer vehicles contacted the center line when passing a bicyclist when the CLRSs were present. Additionally, a bicyclist opinion survey of CLRS and SRS perceptions was conducted, with 213 responses received. The responses indicated that 88 percent of riders operated differently on roadways with rumble strips, and 52 percent avoided roadways with rumble strips. A total of 60 percent of responses indicated that 6 ft is an appropriate minimum shoulder width, while 40 percent indicated that a wider shoulder was necessary. Most responses indicated that a 12-ft gap between SRS installation cycles is not long enough, particularly on steep downgrades.

Ahmed et al. examined rumble strip practices across the United States and found that five States had no provisions for bicyclists or have no rumble strip guidelines.[24,25] A survey of 29 States indicated that departments typically provide gaps in rumble strips on the order of 12 ft every 48 ft, 10 ft every 30 ft, and 20 ft every 60 ft.[24] Additionally, the survey found that many State departments do not install rumble strips if there is not enough space for bicyclists to use the shoulder (typically if the shoulder is less than 6 ft). The researchers also surveyed 56 bicyclists from different locations, genders, ages, and levels of riding experience to study the effects of SRSs on bicyclists' comfort and safety. A total of 95 percent of the survey participants have encountered rumble strips and felt that the barrier between their bicycle and traffic improved safety. A total of 96 percent indicated that they have never had a crash due to control loss while traveling on the rumble strips. A total of 27 percent of bicyclists indicated that a 3-ft clear shoulder width would be sufficient, while 33 percent indicated 4 ft would be sufficient, 19 percent indicated 5 ft would be sufficient, and 21 percent indicated 6 ft would be sufficient. The majority of respondents also indicated a preference for a 12-ft gap in rumble strips on 60-ft cycles. Participants were asked to rank several features for better accommodating bicyclists, and the results indicated that increased shoulder width was the most preferable, while not installing rumble strips on roads with significant bicycle travel was ranked the lowest.

Motorcycles

In the study by Bucko and Khorashadi, the California Highway Patrol also conducted a subjective motorcyclist field test and found no significant deficiencies for motorcyclists traveling 50 and 65 mi/h over the different types of rumble strip patterns.[11] They also found that both raised pavement markers and rumble strip bars became slick when wet.

Miller evaluated the effects of CLRS on motorcycles and concluded that CLRS did not pose a hazard to motorcyclists.[30] The author analyzed crash data from 1999 to 2006 in Minnesota and found that only 29 of 9,845 motorcycle crashes occurred where rumble strips were present. Road surface was a potential factor in only three crashes. MnDOT also performed an observation of rural highways with CLRS.[30] The results showed that rumble strips did not inhibit any passing opportunities. Additionally, they observed motorcyclists' behaviors on a 1-mi closed course with two sections of CLRS. A total of 32 motorcyclists and 2 riders of three-wheeled vehicles with experience levels from 0 to 41 years of street riding participated the examination. No steering, braking, or throttle adjustments were found during rumble strip crossing. Post-examination interviews confirmed that no riders had difficulty or concern with crossing rumble strips.

Rys et al. interviewed 44 motorcyclists traveling on undivided highways with CLRSs.(17) A total of 25 of the 44 respondents indicated that they had driven over or had come in contact with CLRSs. Approximately half of the motorcyclists who had traveled over CLRSs encountered motorcycle handling problems. Of the respondents who encountered a motorcycle handling problem, 75 percent rated the difficulty a level 2 or 3 on a scale of 1 to 5 (1 for low and 5 for high). The other three levels (1, 4, and 5) had one rating each. The authors concluded that there was little difficulty in motorcycle handling faced when riders encountered CLRSs.(17) In fact, 68 percent of responders were in favor of CLRSs, and 72 percent believed in their effectiveness in reducing head-on collisions. Furthermore, motorcyclists noted that when they were aware of the installation of CLRSs, they would not have difficulty crossing CLRSs. Overall conclusions indicated that motorcyclists were in favor of CLRS installation and encountered no handling issues when they were aware of their presence. The authors suggested that warning signs such as "Centerline Rumble Strips Ahead" would warn motorcyclists of the upcoming rumble strips.

Terhaar et al. used the principal component analysis method to examine the relationship between rumble strip design and motorcyclist comfort, control, and function.(15) Upon entering the study, motorcyclists indicated favorable views of CLRSs and ELRSs. Approximately 2 percent of motorcyclists viewed ELRSs as high-risk features, and 10 percent viewed CLRSs as high-risk features. Each participant drove over seven rumble strip designs and rated their level of agreement by control, comfort, and function. The results indicated that motorcyclists were concerned about designs with 6- or 8-inch-long rumble strips separated by a 4-inch raised strip. Additionally, participants had some concern with the tapered edge and preferred a straight edge.

PAVEMENT CONDITION IMPACTS

There has been concern that milling into the roadway surface to create rumble strips on new pavements—particularly center line and at shoulder longitudinal joints—can cause accelerated pavement deterioration. Additionally, there has been concern that milling into older, degraded pavements for SRSs can result in excess damage to the shoulder, especially for narrow shoulders. This section summarizes literature focused on the impacts of rumble strips on pavements and methods used to preserve pavements and pavement joints.

In research by Lyon et al., the Kentucky Transportation Cabinet noted that for CLRS retrofits, visual analysis was used to identify pavement condition as an installation requirement.(31) Additionally, the Kentucky Transportation Cabinet noted that rumble strips make the center line joint look worse when the joint begins to fail; however, it did not appear to accelerate the deterioration of the joint. Missouri noted that most locations remained in good shape after several freeze/thaw cycles. When locations have failed, the Missouri Department of Transportation (MoDOT) allows gaps up to 200 ft in anticipation of repairs. Pennsylvania recommended only applying rumble strips where pavement is less than 3 years old, and less than 1 year is ideal. A noted maintenance challenge is that rumble strips are sometimes being covered by thin overlays and not being reinstalled.

FHWA published a guide to address pavement issues on two-lane roads where rumble strips were installed.(32) The guide consists of compiled information based on interviews and experience. The guide notes a 2014 Ohio Department of Transportation survey of pavement engineers through the AASHTO Research Advisory Committee. Twenty-four States responded, and most indicated that only isolated locations experienced accelerated pavement deterioration along the joint, with States indicating that most of these locations were not in good condition prior to installation of the rumble strips. The FHWA guide also suggests that pavement age, condition, type, and thickness are important factors when deciding to install rumble strips.(32) Rumble strip application can cause accelerated wearing for older pavements in poor condition, and the most recent surface layer should be thicker than the rumble strip depth to prevent water infiltration. Some States recommend milling rumble strips prior to chip seals and thin overlays. This may reduce the dimension of the rumble strip, but it will better seal the roadway from infiltration.

Donnell et al. synthesized best practices from State transportation departments regrading installation and reinstallation of rumble strips on pavements treated with a thin pavement overlay.(33) The authors developed guidance based on published literature, the results of a survey of current practices, and professional engineering judgment. The guidance for reinstalling rumble strips on thin pavement overlays (seal coat, HMA, or microsurfacing) considers $^1/_2$- or $^3/_8$-inch rumble strip depths for CLRSs, SRSs, or ELRSs. The authors developed separate design-decision matrices for highways with ELRSs or SRSs only, highways with CLRSs only, highways with CLRSs and ELRSs or SRSs, and installations of new rumble strips on thin pavement overlays, respectively. The decision matrices considered the thin overlay type (i.e., HMA, seal coat, microsurfacing, overlay depth, number of coats, and whether the material will or will not fill the rumble strip groove). For existing rumble strips, the decision matrices identified whether existing rumble strips should be milled, the mill dimensions, inlay materials, and re-milled rumble strip depth. If the existing rumble strips should not be milled, then a recommended depth of $^3/_8$ inch or greater should be maintained. For thin pavement overlays receiving new rumble strips, the decision matrix specifies pre-rumble strip milling surface preparation and milled rumble strip depth based on the thin overlay type and overlay depth.

Additionally, in a survey conducted by Torbic et al., States showed a large variance in practices for placement of rumble strips near longitudinal joints.(8) For roadways where the joint is in poor condition, departments tend to use a lateral offset from the joint. Also, the pavement type impacted the placement of the rumble strips. For portland cement concrete surfaces, rumble strips are not placed directly on top of the joints. Some States use two 8-inch rumble strips on either side of the center line joint with a 4-inch gap between.

PAVEMENT MARKING VISIBILITY

This section summarizes research that examined the impacts of rumble strips and rumble stripes on pavement marking visibility. Historically, there has been some concern that milled rumble stripes can reduce marking visibility, while others have surmised that it can increase pavement marking visibility, particularly for wet pavements.

Rys et al. evaluated the retroreflectivity of pavement markings at three locations in Kansas.(17) Two of the locations had rectangular rumble strips with 16-inch length, 7-inch width, and 0.6-inch depth. One location had football-shaped rumble strips with 16-inch length, 9-inch width, and 0.5-inch depth. Measurements were taken at 30, 162, and 215 d marking age at the first site; 144, 283, and 336 d at the second site; and 1,269, 1,408, and 1,461 d at the third site. The authors found that sites without rumble strips had wet pavement marking retroreflectivity 41 percent greater than dry retroreflectivity.(17) For locations with rumble strips, the dry retroreflectivity values were 47 percent higher than the wet retroreflectivity. For dry conditions, the locations with rumble strips produced insignificantly better retroreflectivity values than locations without rumble strips. For wet conditions, locations without rumble strips had significantly better retroreflectivity than locations with rumble strips. However, the authors noted that rumble strips were 80 percent filled with water, which could not be reproduced on smooth pavements. The small layer of water on the pavement surface enhanced the retroreflectivity, while the deeper layer of water in the rumble strips decreased retroreflectivity. The authors noted that in heavy rain situations, overall visibility is reduced, but the vibration of the rumble strips would alert the driver. Additionally, the authors noted that the results may have been affected by the data collection characteristics of the retroreflectometer used in this study.

Henrichs and Luger attempted to examine the retroreflectivity of rumble stripes during wet conditions at night.(3) The test section has rumble stripes on both shoulders of a two-lane U.S. highway in North Dakota. Retroreflectivity readings of the rumble stripe were taken approximately 1 inch apart to determine whether retroreflectivity varied with the markings position in the milled groove of the rumble strip. Retroreflectivity readings of the flat pavement markings were taken in the 10-ft space between intermittent rumble strips. The study found that rumble stripes appeared to have better visibility than the usual edge line markings in both wet and dry conditions.

Carlson et al. examined wet-night visibility of pavement markings using experimental drivers on a closed rain tunnel.(4,5) Nine different treatments were tested in random orders, and perception distance was measured for each sample location. The drivers alerted the researcher when they observed a marking and when the type could be determined. Rumble stripes were tested as part of this research. The findings suggest that there was little difference between flat thermoplastic lines and rumble strip lines at low rainfall rates. However, the detection distance was 13 to 38 percent greater for rumble strip lines for medium and heavy rainfall rates.

OPERATIONAL EFFECTIVENESS

Rumble strips have the potential to affect the operating speed and lane positioning of vehicles, especially on horizontal curves. This section summarizes research related to the operational impacts of SRSs and ELRSs.

Finley et al. evaluated the operational effects of shoulder and rumble strips on two-lane undivided roadways.(34) In this study, the authors compared the lateral placement data at the comparison sites and sites with CLRSs only, with SRSs only, and with combination of CLRSs and ELRSs. The study revealed that at sites with narrow shoulders (1 to 3 ft), drivers tended to travel closer to the center of the travel lane where CLRSs or both CLRSs and ELRSs were installed. In contrast, on roadways with wide shoulders (greater than or equal to 9 ft), neither CLRSs nor a combination of CLRSs and ELRSs would practically affect the lateral position of vehicles in the travel lane. Researchers also found that SRSs located near the edge line may cause drivers to travel closer to the center line in some cases. Furthermore, the results showed that SRSs located more than 35 inches from the edge line did not practically affect the lateral position of vehicles in the travel lane. A follow-up experiment was conducted to determine the minimum shoulder width required for drivers to recover from running over SRSs. The researchers analyzed shoulder widths of 4, 6, 8, and 10 ft. The analysis showed that a 16-inch SRS in the middle of shoulders at least 4 ft wide should provide enough remaining shoulder width for 85 percent of distracted drivers.

Briese found that CLRSs had little effect on the lateral placement of vehicles on horizontal tangents.[35] Additionally, CLRSs were found to dramatically decrease center line encroachments on both the inside and outside of horizontal curves. For travel speeds, CLRSs were found to have no impact on both horizontal curves and tangents.

Porter et al. investigated the effect of CLRS lateral position on two-lane highways in Pennsylvania.[36] The authors observed 387 vehicles before CLRS application and 449 vehicles after application. The results show that vehicle lateral placement shifted 5.5 inches away from the center line for roadways with 12-ft travel lanes and 3 inches away for roadways with 11-ft travel lanes.

Miles et al. examined the impacts of CLRSs and ELRSs on passing operations and lateral position on Texas highways using video data.[37] After application of milled CLRSs on no-passing and passing zones, the authors found no change in passing opportunities or the percentage of vehicles that pass. However, center line crossing time increased significantly, irrespective of the speed of the data recording vehicle used to induce passing maneuvers. The gap distance decreased significantly, irrespective of the speed of the data recording vehicle. For lateral position, vehicle placement shifted farther from the center line after implementation of CLRSs. After implementation of ELRSs, shoulder encroachments decreased by approximately 50 percent, and a significant reduction in "other" encroachments was found, which included inadvertent contact with the edge line.

Datta et al. examined operational impacts of CLRSs and SRSs on rural two-lane roadways in Michigan.[21] The researchers evaluated 10 study segments, each with at least 1 passing zone in both travel directions. The researchers collected video data at each segment 30 days after rumble strips installation. The results of the study indicated no significant change in total passing attempts as a percentage of total vehicles, total passing attempts as a percentage of vehicles in passing position, or aborted passing attempts as a percentage of total passing attempts. Lateral positioning increased toward the center of the lane for CLRSs only and for CLRS and SRS sections. The results were consistent for tangents and horizontal curves, regardless of direction. Correspondingly, there were fewer center line and edge line encroachments with rumble strip installation.

SAFETY EFFECTIVENESS

SRSs

Patel et al. evaluated the effectiveness of SRS in reducing single-vehicle run-off-road (SVROR) crashes on Minnesota rural two-lane highways.[38] The analysis included 183 mi of treated highways in an empirical Bayes (EB) before-after evaluation. The researchers found a 13-percent reduction in all SVROR crashes and an 18-percent reduction in injury SVROR crashes.

Torbic et al. examined the safety effectiveness of SRS on rural two-lane highways.(8) The EB before-after results indicated no change in crashes after application of SRSs for total crashes and fatal and injury crashes for combined data from Minnesota, Missouri, and Pennsylvania. The results indicated a significant 16-percent decrease in SVROR crashes and a significant 36-percent decrease in SVROR fatal and injury crashes at combined sites. Additional analyses indicated that Pennsylvania observed a significant 24-percent reduction in total crashes, 44-percent decrease in SVROR crashes, and 37-percent decrease in SVROR fatal and injury crashes. In consideration of all analytical methods employed, the authors recommended the following CMFs for SRSs on rural two-lane roads based on their research:(8)

- 0.84 for SVROR crashes.
- 0.64 for SVROR fatal and injury crashes.

Additionally, the researchers quantified the impact of SRS placement on safety, focusing on SVROR fatal and injury crashes. The researchers defined *placement* as edge line and non-edge line, which were compared to no rumble strips. The researchers defined *ELRSs* as rumble strips with an offset distance of 0 to 8 inches, and non-ELRSs were defined as having an offset of 9 inches or more. For two-lane rural roadways, there was no significant or practical difference between ELRSs and non-ELRSs. Also, the researchers found no evidence that suggests SRSs result in a reduction of SVROR crashes involving heavy vehicles.

Khan et al. evaluated the safety benefits of SRSs on rural two-lane highways in Idaho.(39) The authors conducted an EB before-after analysis using data from 178.63 mi of data from treatment sites. The results indicated a 14-percent reduction in ROR crashes. Further analysis indicated a 33-percent reduction in ROR crashes for sections with an annual average daily traffic (AADT) of less than 1,000. Additionally, SRSs were most effective on horizontal tangents and horizontal curves with moderate curvature. SRSs were found to be most effective for paved shoulder widths of 3 ft and more.

CLRSs

Torbic et al. examined the safety effectiveness of CLRSs on rural two-lane highways.(8) The EB analyses indicated no change in total crashes for combined data from Minnesota, Pennsylvania, and Washington. However, the results indicated significant reductions in fatal and injury crashes, total target crashes, and target fatal and injury crashes by 9.4, 37.0, and 44.5 percent, respectively. The researchers defined target crashes as head-on and sideswipe opposite-direction crashes. Additional analyses indicated that there was no difference in effectiveness for CLRSs on horizontal curves and tangents based on total target crashes.

The authors recommended CMFs from this research in combination with results by Persaud et al., which include the following:(40)

- 0.91 for total crashes.
- 0.88 for fatal and injury crashes.
- 0.70 for total target crashes.
- 0.56 for target fatal and injury crashes.

As shown in table 3, Torbic et al. identified a comprehensive list of studies examining the safety impacts of CLRSs prior to the publication of NCHRP Report 641.[8] The table identifies location(s) of the evaluation, type of facility, collision types targeted, estimated impacts, and analysis methodology used. All evaluations were conducted on two-lane roads or included two-lane roads in the analysis. Only one study used an EB before-after analysis methodology; however, the results of other studies were relatively consistent in direction and magnitude of effects for the various crash types analyzed.

Olson et al. evaluated the effectiveness of CLRSs on 493 mi of Washington rural two-lane highways.[41] The study examined the impacts of CLRSs on cross-center line crashes and ROR right collisions. Infrastructure elements, such as posted speed, curvature, lane width, and shoulder widths, were considered to identify the best placement of the treatment. Results indicated a 24.9-percent reduction in all lane departure crashes and a 37.7-percent reduction in fatal and serious injury lane departure crashes. ROR right crashes decreased by 6.9 percent (19.5 percent for fatal and serious injuries only), and cross-center line crashes decreased by 44.6 percent (48.6 percent for fatal and serious injuries only). CLRSs were slightly more effective on horizontal tangents than horizontal curves. The findings of this research recommended that CLRSs continue to be installed in accordance with current guidelines, with investment priority being given to locations with AADT less than 8,000, combined lane/shoulder width of 12 to 17 ft, and posted speeds of 45–55 mi/h.

Table 3. List of studies examining safety effects of CLRS adapted from table 5 of NCHRP Report 641.[8]

State	Type of Facility	Type of Collision Targeted	Percent Decrease (−) or Increase (+) in Target Collision Frequency from Application of CLRSs (95-Percent Confidence Interval)	Type of Analysis
California[42]	Rural two-lane road	Head-on (total)	−42	Naive before-after
California[42]	Rural two-lane road	Head-on (fatal)	−90	Naive before-after
Colorado[43]	Rural two-lane road	Head-on	−34	Naive before-after
Colorado[43]	Rural two-lane road	Sideswipe	−60	Naive before-after
Delaware[44]	Rural two-lane road	Head-on	−95	Naive before-after
Delaware[44]	Rural two-lane road	Drove left of center	−60	Naive before-after
Delaware[44]	Rural two-lane road	Property damage only (PDO)	+13	Naive before-after
Delaware[44]	Rural two-lane road	Injury	+4	Naive before-after
Delaware[44]	Rural two-lane road	Fatal	N/A	Naive before-after
Delaware[44]	Rural two-lane road	Total	−8	Naive before-after
Massachusetts[45]	Rural two-lane road	Head-on	Inconclusive	Before-after with comparison group
Massachusetts[45]	Rural two-lane road	Opposite direction angle	Inconclusive	Before-after with comparison group
Massachusetts[45]	Rural two-lane road	Opposite-direction sideswipe	Inconclusive	Before-after with comparison group
Massachusetts[45]	Rural two-lane road	SVROR with center line encounters	Inconclusive	Before-after with comparison group
Minnesota[35]	Rural two-lane road	Total	−42	Cross sectional comparison
Minnesota[35]	Rural two-lane road	Total (fatal and severe injury)	−73	Cross sectional comparison
Minnesota[35]	Rural two-lane road	Head-on/opposite-direction sideswipe/ SVROR-to-the-left (all severities)	−43	Cross sectional comparison

State	Type of Facility	Type of Collision Targeted	Percent Decrease (−) or Increase (+) in Target Collision Frequency from Application of CLRSs (95-Percent Confidence Interval)	Type of Analysis
Minnesota[35]	Rural two-lane road	Head-on/opposite-direction sideswipe/ SVROR-to-the-left (fatal and severe injury)	+13	Cross sectional comparison
Oregon[46]	Rural two- and four-lane highways	Cross-over crashes	−69.5	Naive before-after
Oregon[46]	Rural two- and four-lane highway	Cross-over crashes	−79.6	Before-after with comparison group
Multiple[40]	Rural two-lane road	Total	−14 (8–20)	EB before-after
Multiple[40]	Rural two-lane road	Injury	−15 (5–25)	EB before-after
Multiple[40]	Rural two-lane road	Frontal/opposite-direction sideswipe (total)	−21 (5–37)	EB before-after
Multiple[40]	Rural two-lane road	Frontal/opposite-direction sideswipe (injury)	−25 (5–45)	EB before-after

N/A = Not applicable.

SRSs and CLRSs

Potts et al. evaluated the safety impacts of wider pavement markings with both CLRSs and ELRSs with resurfacing on rural two-lane highways in Missouri.[47] The EB analysis indicated a significant 47.4-percent reduction in fatal and disabling injury crashes and a significant 38.3-percent reduction in fatal and all injury crashes. A B/C evaluation indicated a B/C ratio of 35.6 for wide markings and both CLRSs and ELRSs with resurfacing on rural two-lane roadways.

Lyon et al. evaluated the safety impacts of combined SRSs and CLRSs using data from Kentucky, Missouri, and Pennsylvania.[31] Kentucky data included SRSs as well as ELRSs, and the final data included sites where SRSs/ELRSs and CLRSs were installed concurrently as part of a resurfacing effort or where CLRSs had been installed as retrofits. Table 4 provides the dimensions of the rumble strips implemented in each of the three States. Note that Pennsylvania had two typical applications for CLRSs and an alternative design for bicyclist-tolerable rumble strips.

Table 4. Rumble strip dimensions from Lyon et al.[31]

Location	Type	Width (inches)	Length (inches)	Depth (inches)	Spacing (inches)
Kentucky	CLRS	7–7.5	12	½ to $^{5}/_{8}$	24
Kentucky	SRS	$7 \pm {}^{1}/_{2}$	16	${}^{1}/_{2} \pm {}^{1}/_{8}$	12 ± 1
Missouri	CLRS	$7 \pm {}^{1}/_{2}$	12	${}^{7}/_{16} \pm {}^{1}/_{16}$	12 and 24
Missouri	SRS	$7 \pm {}^{1}/_{2}$	12	${}^{7}/_{16} \pm {}^{1}/_{16}$	12
Pennsylvania	CLRS 1	$7 \pm {}^{1}/_{2}$	16	${}^{1}/_{2} \pm {}^{1}/_{16}$	24 and 48
Pennsylvania	CLRS 2	$7 \pm {}^{1}/_{2}$	14–18	${}^{1}/_{2} \pm {}^{1}/_{16}$	24
Pennsylvania	ELRS	$5 \pm {}^{1}/_{2}$	6	${}^{1}/_{2} \pm {}^{1}/_{16}$	7
Pennsylvania	Bike-tolerable SRS[1]	$5 \pm {}^{1}/_{2}$	16	${}^{3}/_{8} \pm {}^{1}/_{16}$	7
Pennsylvania	Bike-tolerable SRS[2]	$5 \pm {}^{1}/_{2}$	16	${}^{3}/_{8} \pm {}^{1}/_{16}$	6

[1]Indicates that the roadway's posted speed limit was greater than or equal to 55 mi/h.
[2]Indicates that the roadway's posted speed limit was less than 55 mi/h.

The EB analysis indicated the following significant CMFs for combined States:

- 0.80 for total crashes (excluding intersection-related and animal crashes).
- 0.77 for fatal and injury crashes.
- 0.74 for ROR crashes.
- 0.63 for head-on crashes.
- 0.77 for sideswipe-opposite-direction crashes.
- 0.70 for head-on and sideswipe-opposite-direction crashes.
- 0.73 for ROR, head-on, and sideswipe-opposite-direction crashes.

Further disaggregate analyses indicated that significant reductions were found in Kentucky and Missouri, while there were not significant reductions in Pennsylvania. The authors surmised that earlier installations (used in NCHRP Report 641 research) were higher-crash locations, while more recently treated sites did not have a high target crash issue (and therefore no safety benefit).(31,8) Additional analysis indicated the following:

- Larger reductions in ROR crashes for higher traffic volumes (greater than 3,200 AADT).
- Larger reductions in head-on and sideswipe-opposite-direction crashes for lower traffic volumes (less than 9,200 AADT).

A B/C analysis estimated a B/C ratio between 20.2 and 54.7 based on estimated service lives of 7 to 12 years and estimated annual costs of $557 to $1,511/mi.

Sayed et al. evaluated the safety effectiveness of CLRSs and SRSs alone and combined on rural two- and four-lane divided highways in British Columbia using an EB before-after study design.(48) The combined application on rural two-lane highways resulted in a 21.4-percent reduction in off-road right, off-road left, and head-on collisions combined. For rural two-lane highways, SRS applications resulted in a 26.1-percent reduction in off-road right collisions, and CLRS applications resulted in a 29.3-percent reduction in off-road left and head-on collisions.

Torbic et al. evaluated the effect of combined CLRSs and SRSs using data from approximately 80 mi of treated roadways in Mississippi.(49) The target crash types evaluated included SVROR crashes left or right, sideswipe-opposite-direction crashes, and head-on crashes. Crash severities evaluated individually included total crashes, fatal and injury crashes, and fatal and serious injury crashes. The results of the EB before-after analysis indicated a significant 35-percent reduction in total target crashes, significant 40-percent reduction in fatal and injury target crashes, and an insignificant 12-percent increase in fatal and serious injury target crashes.

Kay et al. evaluated the safety impacts of CLRSs and combined CLRSs and SRSs on rural two-lane highways in Michigan.(50) The EB before-after analysis examined approximately 3,000 mi of CLRS applications and 1,075 mi of combined CLRS and ELRS applications. The results for CLRS indicated the following significant reductions:

- 15.8 percent for total crashes.
- 27.3 percent for target crashes.
- 52.9 percent for target wet pavement crashes.
- 1.4 percent for target wintry pavement crashes.
- 42.8 percent for target passing crashes.
- 28.8 percent for target impaired driving crashes.
- 44.2 percent for target fatal crashes.
- 32.0 percent for target disabling injury injury crashes.
- 39.3 percent for target evident injury crashes.
- 27.9 percent for target possible injury crashes.
- 16.2 percent for target property damage only crashes.

The results for combined CLRSs and SRSs indicated the following significant reductions:

- 17.2 percent for total crashes.
- 32.8 percent for target crashes.
- 55.6 percent for target wet pavement crashes.
- 4.6 percent for target wintry pavement crashes.
- 35.7 percent for target passing crashes.
- 39.9 percent for target impaired driving crashes.
- 51.4 percent for target fatal injury crashes.
- 32.5 percent for target disabling injury crashes.
- 53.7 percent for target evident injury crashes.
- 35.2 percent for target possible injury crashes.
- 28.5 percent for target property damage only crashes.

Target crashes were identified as crashes involving a vehicle crossing the roadway center line.

Olson et al. conducted a before-after evaluation of combined CLRSs and SRSs on rural two-lane highways in Washington.(51) The analyses compared simultaneous installations, installations where CLRSs were later added to sections with SRSs, and installations where SRSs were later added to sections with CLRSs. Additionally, the authors analyzed composite conditions where there were no rumble strips in the before period and conditions with both CLRSs and SRSs without regard as to when they were installed.

For simultaneous installations, the application resulted in a 63.3-percent reduction in lane departure crashes, a 65.4-percent reduction in crossover crashes, and a 61.4-percent reduction in ROR right crashes. Installations were noted to be more effective at higher speeds and for sections with shoulders greater than 4 ft.

For sections where CLRSs were added to SRSs, the application resulted in a 64.7-percent reduction in crossover crashes and an 8.5-percent increase in run off the road right crashes, resulting in a combined 44.6-percent reduction in lane departure crashes. For sections where SRSs were added to CLRSs, the application resulted in a 47-percent reduction in ROR right crashes and a 6.8-percent reduction in crossover crashes, resulting in a 37.2-percent reduction in lane departure crashes.

The composite analysis indicated a 66-percent reduction in lane departure crashes and a 56-percent reduction in fatal and serious injury crashes. The combined application was noted to be slightly more effective for 11-ft lane widths than 12-ft lane widths.

Kubas et al. evaluated the safety effectiveness of combined CLRSs and SRSs and SRSs only on rural two-lane highways in North Dakota.(52) The authors compared before and after crash rates to estimate the effectiveness of rumble strip applications for various crash types. The installation of CLRSs and SRSs resulted in a 2-percent decrease in total crashes, 45-percent decrease in fatal crashes, 21-percent increase in injury crashes, 5-percent decrease in PDO crashes, and 29-percent decrease in ROR crashes based on a limited sample. The installation of SRSs resulted in a 15-percent decrease in total crashes, 22-percent decrease in PDO crashes, and 97-percent increase in ROR crashes based on a limited sample. It should be noted that no CMFs from this study received more than a two-star rating in the *Crash Modification Factors Clearinghouse*.[1]

EXPERT SYSTEM DEVELOPMENT

Ahmed et al. developed an interactive guidebook system for rumble strips/stripes implementation criteria for the Wyoming Department of Transportation.[24,53] The expert system was developed from a synthesis of research reports, journal articles, and department surveys. Rumble strips were classified as being SRSs or CLRSs. SRSs were further classified by roadway type, with a separate category for rural two-lane highways. CLRS guidelines were summarized within a combined class. The following list provides the factors the researchers identified as those that State transportation departments most often consider before installing rumble strips:

- Roadway type.
- Pavement condition.
- Minimum shoulder width.
- Minimum lane width.
- Speed limit.
- Bicycle traffic.
- Nearby residences.
- ADT.
- Motorcycle traffic.

Figure 7 provides the screen from the interactive system for rural two-lane highways from the interactive system. The categories represent the governing criteria identified from the department survey, ranked left to right according to importance. Information is read from left to right to determine if all criteria fall within the green zone, and if so, SRSs are recommended. If one or more criteria fall within the yellow zone, the recommendation is provided in the box. Criteria in the red zone represent uncommon practice and rumble strips should not be installed. Criteria should be checked from left to right and the final decision should be made based on engineering judgment, considering crash history. Within the boxes, States are grouped together by similar practices. The table provides links for each included State, which takes the user to State’s guideline or policy. The table also provides additional links to Wyoming survey results gathered for each question.

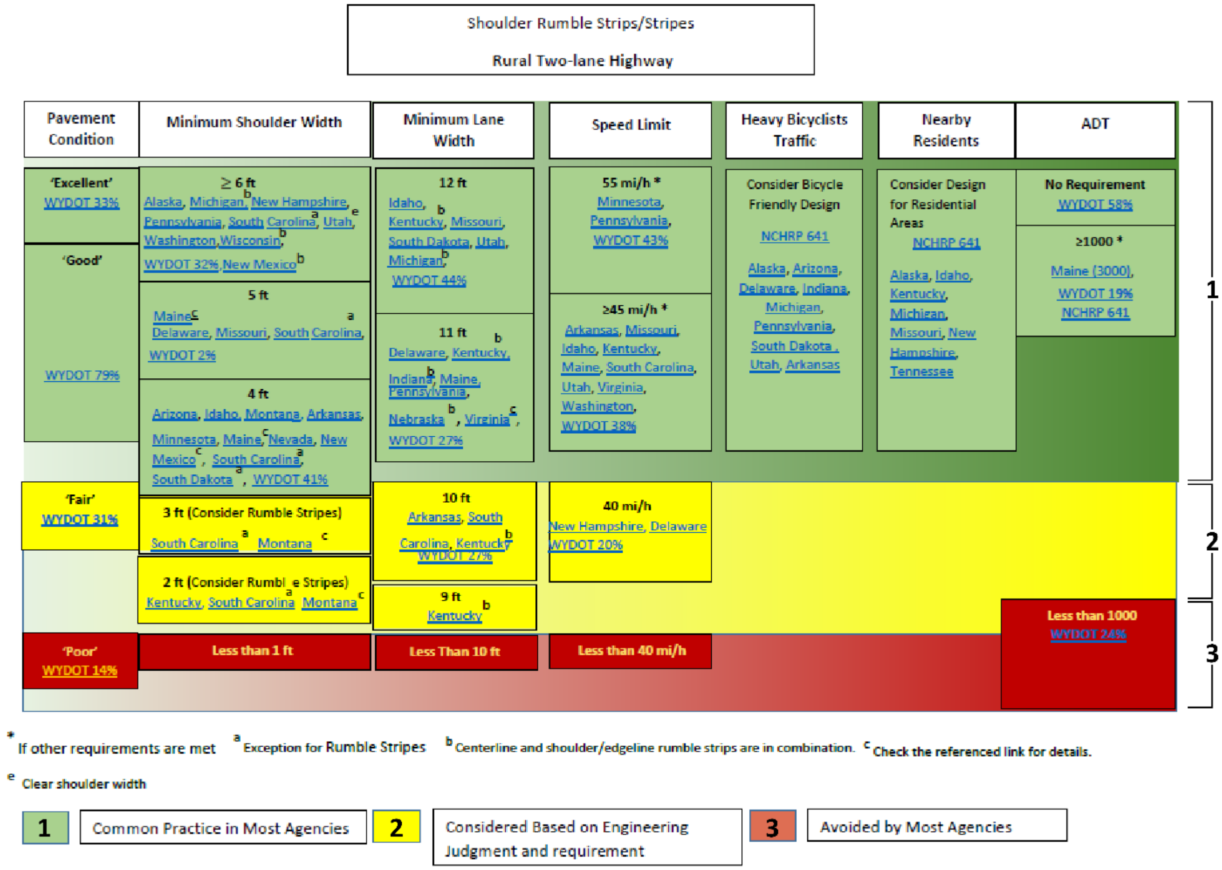


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Figure 7. Screenshot. Expert system for rural two-lane highways.[24,53]

LITERATURE REVIEW CONCLUSIONS

There has been ample research quantifying the safety effectiveness of standard dimension CLRSs and SRSs on target crash frequency and severity but not on the reduced dimensions that are becoming more common to address bicyclist accommodation and noise issues. Most research has focused on the overall effects of either CLRSs, SRSs, or the combination of both. However, few research studies have performed disaggregate analyses to identify where rumble strip applications are most effective, and no studies have considered the impact of rumble strip design on safety (other than rumble strip offset).

Rumble strip effects on bicyclists and external noise have been reviewed independent of each other and independent of safety effects. To date, no studies attempted to link the relationship between sound level and safety effectiveness. Rumble strip designs have been tested by bicyclists extensively, but no research studies have looked at the impacts on bicyclist activity or bicyclist safety. Several studies have looked at the impacts of rumble strips on pavement deterioration, but no consensus has been reached on whether rumble strips accelerate pavement or joint degradation.

Few research studies recommend one practice of rumble strip design over another. The current practices review and focus group review provided more information on decisionmaking for State transportation departments with full implementation of CLRSs and SRSs as well as anecdotal evidence of best practices for accommodating bicyclists, noise, and pavement condition concerns.

CHAPTER 3. CURRENT PRACTICES REVIEW

PURPOSE OF CURRENT PRACTICE REVIEW

The purpose of the current practices review was to identify rumble strip implementation criteria, design features, and special considerations followed by State transportation departments. The review also examined what issues departments have faced in implementing rumble strips and how they overcame them. The methodology followed included a review of States' Web sites and follow-up interviews. The project team reviewed Web sites, published materials for all State transportation departments and for FHWA's EFL, and conducted follow-up interviews with five departments and FHWA's EFL to gain further insights into issues in which they have struggled and to identify practices that have helped them. Several departments have had success with systematic CLRS and SRS application, while others have struggled to find support for implementation on their rural two-lane highways. The needs for these departments are summarized as part of the department interviews. The results of this review guided the development of the rumble strips decision support guide.(1)

The current practices review focused on department policies related to rural two-lane highways and includes policies from other facility types that are applied to two-lane highways (e.g., a department SRS policy may apply to both rural undivided and divided roadways) or when a policy for rural two-lane highways could not be found. This chapter is organized as follows:

- **Identification of Noteworthy Practice Departments**: This section identifies the process used to identify noteworthy practice departments. This includes departments identified to have had successful implementation and departments that have struggled with implementation. Follow-up interviews were conducted with five departments identified in this section and FHWA's EFL.

- **Rumble Strip Implementation Strategies**: This section provides a brief overview of safety strategies that departments use for rumble strip implementation decisionmaking.

- **Current Rumble Strip Design Dimensions and Selection Criteria in Systematic Installation Policies**: This section provides an overview of current SRS and CLRS dimensions used by departments and provides an overview of the breadth of selection criteria that departments use in their systematic installation policies.

- **Systematic Installation Selection Criteria**: This section provides more details on the breadth of policies for systematic installation selection criteria. Additional criteria used by departments are presented along with discussion of department policies.

- **High-Crash Corridor Installation Practices**: This section provides a brief overview of high-crash corridor practices that departments use, including typical positions that are included in the process.

- **Special Considerations and Rumble Strip Modification**: This section provides an overview of rumble strip special considerations and a list of modifications that have been applied by departments.

- **Conclusions**: This section includes the general findings from the current practices review and follow-up department interviews.

IDENTIFICATION OF NOTEWORTHY PRACTICE DEPARTMENTS

The objective of the follow-up interviews was to identify noteworthy practices and potential implementation issues with departments leading in CLRS and SRS applications on rural two-lane highways as well as departments struggling with rumble strip implementation. The project team was tasked with identifying five follow-up interview departments. Potential follow-up interview departments were to include three departments with notable practices and two departments struggling with implementation. Considering both perspectives allowed for the development of a rumble strip decision support guide that is useful for all agencies.

Prior to developing selection criteria for identifying candidate departments, FHWA identified MnDOT and the Texas Department of Transportation (TxDOT) as two candidate departments for interview. The following selection criteria were used to identify a set of candidate departments to be interviewed in addition to MnDOT and TxDOT:

- Rumble strip/stripe implementation criteria, including departments that have specific criteria and methodology for selecting eligible roadways using existing criteria (e.g., speed greater than 45 mi/h). Examples of selection methods and criteria include the predictive or crash history-based approach, systematic approach (i.e., blanket installation), and the systemic approach.

- Process for rumble strip consideration. Does a department try signage, striping, and other enhanced delineation before considering rumble strips? Will the department consider rumble strips if the short-term improvements do not provide the intended crash reduction?

- Established rumble strip/stripe implementation policy (including design criteria, public outreach plan, minimum standards, and officially accepted policy of relevant stakeholders).

- Installation of CLRSs or SRSs on rural two-lane roads.

- Combined use of CLRSs and SRSs on rural two-lane roads.

- Installation of rumble strips/stripes near residential areas.

- Installation of rumble strips/stripes on roadways with bicycle travel.

- Considerations for vehicle types (i.e., motorcycles and/or heavy vehicles).

- States struggling with issues requiring the removal of rumble strips and revamping policies to continue the rumble strip program.

Rumble strip mileage was not a consideration in order to include struggling departments; however, some installations on rural two-lane roads were required in order to measure the issues the department has been facing since installation.

Table 5 lists departments with successful rumble strip implementation, and table 6 lists those struggling with implementation obstacles recommended for follow-up interviews. The tables provide reasons why they were recommended for follow-up interviews. The candidate list was provided for FHWA to approve the final list of interview departments, with the research team conducting a total of five follow-up interviews. The research team indicated that they would follow up with potentially one or two successful departments and one or two struggling departments based on FHWA's preference. FHWA selected MnDOT, TxDOT, the Louisiana Department of Transportation and Development (LaDOTD), the Montana Department of Transportation (MDT), and the Connecticut Department of Transportation (ConnDOT) for follow-up interviews. Additionally, FHWA requested that FHWA's EFL be included in the follow-up interviews as a department struggling with rumble strip implementation.

Table 5. List of potential succeeding departments.

Succeeding Departments
California Department of Transportation (Caltrans) • Uses bicyclist-friendly rumble strips (sinusoidal) and has many stipulations regarding bicyclist accommodations. • Considers rumble strips in all resurfacing projects. • Has advocacy groups for bicyclist interaction, which are involved in projects due to be constructed in 2016. • Has knowledge regarding measuring noise. Patent pending on $^{5}/_{16}$-inch rumbles. • Has an unspecified number of rumble strip miles.
Hawaii Department of Transportation (HDOT) • Uses a systemic approach to rumble strips. • Installs bicyclist-friendly rumble strips on new, reconstructed, and resurfaced shoulders. • Offers local agencies High-Risk Rural Road funds and rumble strips for local departments' projects. • Has an unspecified number of rumble strip miles.
LaDOTD • Installed 2,000 mi of rumble strips on new asphalt on rural two-lane roadways consisting of 6-inch rumble with thermoplastic striping and raised pavement markers; analysis coming soon. • Applied rumble strips on all projects with speeds greater than 45 mi/h where applicable. • Conducted safety studies for rumble strips not meeting criteria to determine whether rumble strips would be beneficial and how they would be accommodated if possible.
MDT • Strikes a balance between accommodating bicyclists and installing rumbles, as evidenced by the recent rumble strip guidance coordination with Bike/Walk Montana. • Plans to ramp up CLRS installation by installing four thousand mi over the next 4 years. • Uses chip and fog seals when installing rumbles depending on their criteria. • Employs proactive local road safety plans.
Virginia Department of Transportation (VDOT) • Uses different shapes and sizes of rumble strips for different projects. • Implements standards to get more SRSs deployed on rural roads. • Has more than 58,000 mi of "local-esque" roads. • Has more than 200 mi of CLRSs and SRSs.

Table 6. List of potential struggling departments.

Struggling Departments
EFL • Rumbles were not installed properly in Great Smoky Mountains National Park; created issues with future buy-ins. • Roads are rural and highly recreational. • Department has the choice to install rumble strips or not and have their own guidance. • Has an unspecified number of rumble strip miles.
ConnDOT • Removed rumble strips. • Has no official policy for CLRSs and not specific regarding rural two-lane roadways. • Is concerned about bicyclists and limited shoulders. • Proceeds with rumble strips despite controversy. • Installed 15 mi of CLRSs in 2014, installed 25 mi in 2015, and plans to install 200 mi in 2017.
North Carolina Department of Transportation (NCDOT) • Struggles with facilities that are not controlled access due to noise and bicyclist issues. • Struggles with rural two-lane roads, particularly with narrow shoulders. • Removed rumble strips due to noise exceeding town's noise ordinance. • Has an unspecified number of rumble strip miles.
Rhode Island Department of Transportation (RIDOT) • Removed rumble stripes and strips due to public sentiment. • Received public backlash after High Risk Rural Road trial run. • Has struggled with rural two-lane roadways due to public issues. • Is revising policies to gain more public acceptance before installing additional rumble strips. • Has an unspecified number of rumble strip miles.
Vermont Agency of Transportation (VTrans) • Removed rumble strips. • Has not implemented ELRSs on rural two-lane roadways due to public acceptance. • Conducted an evaluation of the effectiveness of CLRSs on rural roads in March 2015. • Has an unspecified number of rumble strip miles.

Appendix A provides a list of interview questions provided to each department in advance of the phone interview. The interview departments responded to the questions prior to the interview or during the phone interview. The follow-up interview notes are provided in appendix B. The takeaways from the interviews are included in the discussion in each section throughout the document. The interview information supplements that information found in the policies for each department and FHWA's EFL.

Previous to this effort, FHWA conducted detailed in-person interviews and field inspections with the following departments:

- Michigan Department of Transportation (MDOT).
- MoDOT.

- Pennsylvania Department of Transportation (PennDOT).
- South Carolina Department of Transportation (SCDOT).
- Washington State Department of Transportation (WSDOT).

FHWA provided the interview notes to the research team. The takeaways from these interviews are included in the discussion in each section throughout the document and supplements information found in the policies for each department as well.

RUMBLE STRIP IMPLEMENTATION STRATEGIES

Overview of Implementation Strategies

Roadway departure crashes, which include ROR crashes and head-on crashes, are typically a systemic problem, meaning that they account for a high number of crashes, but their density is often low. Consequently, high-crash locations prove difficult to identify, although more success can be found in identifying high-crash corridors. As noted in *Low-Cost Treatments for Horizontal Curve Safety 2016*, the most effective safety improvement processes include both a systemic component and site analysis or, in this case, corridor analysis component.[54] Additionally, departments use an additional systematic component for installing rumble strips based on department-level policy.

Systemic and corridor analyses are most commonly used to identify corridors for retrofit installations. Retrofit installations are projects in which the objective is to install rumble strips where they did not previously exist. Systematic analyses are most commonly used for installing rumble strips on new, reconstructed, or resurfaced roadways (i.e., rumble strips are applied on corridors while workers are on site performing other activities). Each of these approaches is defined below and explained in further detail in terms of rumble strip safety.

Systemic Safety Approach

Using the systemic safety approach, departments implement rumble strips on corridors based on risk features that are correlated with higher severity focus crash types (e.g., fatal and incapacitating injury severities on the fatal, incapacitating injury, nonincapacitating injury, possible injury, and no injury scale). In this approach, corridor crash history is not considered for identifying rumble strip treatment locations. Rather, crash data analyses are used to identify risk factors associated with fatal and severe injury ROR crashes, fatal and severe injury head-on crashes, or other focus crash outcomes. Severe crash types are typically addressed using a systemic approach because they are often less concentrated than total crashes but tend to be overrepresented at locations with more risk factors. Risk factors for severe ROR crashes often include characteristics such as lane width, shoulder width, and traffic volume, among others. Analyses are conducted across all corridors within a facility type (e.g., rural two-lane highways) to identify factors that contribute to increased risk of focus crash outcomes. Risk factors may be combined in a weighted manner to identify specific corridors for treatment.

For example, analysis of all rural two-lane highway corridors within a jurisdiction may identify risk factors for fatal and severe ROR crashes as being AADT greater than 400 and less than 2,000, lane width less than 12 ft, shoulder width less than 4 ft, curve density greater than

2 curves per mi, and roadside hazard rating greater than 3. The jurisdiction may prioritize corridors with all of these risk factors for rumble strip installation or may develop weights for each risk factor and prioritize segments with the highest combined ranking of risk factors within a given budget.

High-Crash Corridor Safety Approach

Departments have traditionally used crash frequency (e.g., locations with a high number of crashes or higher than expected number of crashes) to justify additional corridors for installing rumble strips on an as-needed basis. This approach may also be referred to as a "case-by-case" approach because installation must be considered for each corridor based on multiple factors, and the decision to install or not is made independently in each instance based on these factors. Departments often consider the crash rate in relation to the statewide average to determine whether a corridor should be examined further for rumble strip installation. Most often, they base installation recommendations on 3 to 5 years of historical crash data.

The *Highway Safety Manual* (HSM) defines the crash rate as "the number of crashes that occur at a given site during a certain time period in relation to a particular measure of exposure."[(55)](p. 3-13) This is commonly computed as the average crash frequency, or crashes per year, divided by the average traffic volume (expressed as AADT) for the same time period. At this point, the crash rate for a corridor is compared to the average crash rate for all corridors within the specific facility type (e.g., rural two-lane highways). Typically, the corridors with the highest crash rates or crash rates that are above average are selected for treatment. This methodology is simple to employ; however, it suffers from the following limitations:

- It assumes that the impact of traffic volumes is linear, which has been shown through many studies to not be a valid assumption, particularly for rural two-lane highways. Crash rates should not be compared for roadways with significantly different AADTs.

- It does not account for regression-to-the-mean bias. This methodology tends to focus on corridors with a short-term rate that is above average; which, for two lane rural highways, could be subject to 1 year with an abnormal number of crashes.

- It can focus on low-volume roadways that have had one crash in the study period. Many research studies have found that rumble strips are more effective on roadways with higher AADTs, and the influence of one crash can be large for roadways with very low AADTs.

- The average crash rate for all corridors is not the most valid threshold for comparing to the predicted number of crashes for corridors with similar characteristics. Safety performance functions (SPFs) provide a more rigorous approach to identifying predicted crashes at similar corridors.

SPFs provide the predicted number of crashes for corridors based on data from corridors with similar characteristics, and SPFs typically include the corridor's AADT and length. SPFs account for the non-linear relationship between traffic volume and crash frequency, as well as potential differences in characteristics for short versus long corridors. As noted in the HSM, the SPF prediction can be used for several methods for identifying high-crash corridors that are more statistically valid than the crash rate method.[55] (See chapter 4 of the HSM for more details on performance measures and their strengths and limitations.[55])

Systematic Safety Approach

While the systemic approach to safety focuses on identifying locations for rumble strip installation based on risk, the systematic approach to safety focuses on installing rumble strips system-wide, often while completing other construction activities, with exceptions for installations that are based on policy. Most departments have policies outlining criteria for systematic rumble strip installation. Criteria for installation are based on special considerations, including accommodating bicyclists, minimizing noise disturbance, and avoiding potential pavement quality issues. For CLRSs, the systematic approach is typically based on pavement condition, posted speed limit, and lane or pavement width. For SRSs, the systematic approach is typically based on pavement condition, posted speed limit, shoulder width, and presence of curb or guardrail. Posted speed limit is often used as a surrogate measure for built-up environments.

Review of Current Implementation Practices

Most departments implement CLRSs and SRSs based on crash history and/or systematically. Many departments with a systematic approach note that installations are required for new construction, rehabilitation, or overlay projects. Several departments go on to specify that implementation may also take place on existing pavements that meet "good condition" requirements, have a specified surface depth, and have no scheduled pavement work for the next 2–3 years. Additionally, for segments that do not meet the systematic criteria, crash history is often used to recommend installations. Documentation is typically required, and, in most cases, consultation with a bicycle coordinator or committee is recommended to consider all factors before making a final decision. However, several interview departments, including FHWA's EFL, noted that rumble strips can be a difficult to implement, even though they are shown to be effective. Engaging a committee, decisionmakers, and stakeholders may allow for flexibility in implementation and identification of alternative solutions or treatments.

TxDOT and LaDOTD are examples of State transportation departments that employ a systematic approach to rumble strip application in conjunction with a crash history/hot-spot approach. TxDOT generally requires a 2-ft shoulder width in order to maintain a 13-inch recovery area on the paved shoulder beyond the ELRS. However, if the crash data support installation, then the department will install rumble strips on narrower shoulders. TxDOT noted that if they demonstrate the historical crash reduction factors (CRFs) for rumble strip installations to the general public, then they have fewer complaints upon installation. LaDOTD implements SRSs on all rural two-lane highways with a paved surface width greater than 22 ft and employs a crash analysis for rural two-lane highways with a paved surface width of 22 ft or less. CLRSs are applied systematically when the paved surface width is greater than or equal to 28 ft, and shoulders are greater than or equal to 2 ft. If the paved surface width is 24 to 28 ft and the shoulder width is greater than or equal to 1 ft, then a crash analysis is required. If the crash analysis does not warrant CLRSs, then SRSs or ELRSs are to be used. The following section provides an overview of current department systematic policies. This is followed by current practices for rumble strip installation on high-crash corridors.

CURRENT RUMBLE STRIP DESIGN DIMENSIONS AND SELECTION CRITERIA IN SYSTEMATIC INSTALLATION POLICIES

Departments use systematic policies to develop criteria that, if met, automatically qualify corridors for rumble strip installation. Systematic policies most often apply to new construction, reconstruction, or resurfacing. This work is performed while the contractor is already onsite performing other activities and ensures the pavement is in good condition and will not be resurfaced again in the near term. Alternatively, departments install rumble strips as a retrofit if the pavement quality is sufficient and there is no scheduled paving activity in the near term. The length of time varies by department.

Systematic policies provide criteria for installation and a standard specification for rumble strip dimension and layout. Criteria for installation are generally not crash- or risk-based; they are based on roadway geometry, roadway users, and traffic operations. The written policy specifies minimum (or maximum) values for which rumble strips may be considered. The SRS and CLRS sections provide examples of criteria that departments use for systematic policies. Standard drawings provide details on basic rumble strip dimensions, locations, and breaks. Rumble strips are typically broken for intersections and bridges; standard drawings may provide details on where the breaks occur and may address non-standard applications at locations such as tapers, auxiliary lanes, and driveways (if necessary). Additionally, the standard drawings may provide information on bicycle gaps.

Departments have found increased buy-in for rumble strips when stakeholders are included in developing the language for systematic policies. For example, MDT engaged the bicyclist community in developing their policy and received feedback on language such as "The ideal clear space between the shoulder rumble strip and the edge of the paved shoulder is 4 ft."[(56)](p. 3) MDT modified the design to allow for bicyclists and used quality control to try to ensure that the 4-ft gap was maintained. Engaging stakeholders also increases buy-in and leads to better solutions for high-crash corridor solutions when the corridor does not meet the criteria for systematic installation. If stakeholders feel that their voice is heard, then they will be more open to understanding the effectiveness of rumble strips and will be more willing to work toward a solution that includes more system-wide installation, even on roadways with bicycle activity.

The next two subsections provide an overview of systematic installation policies and standards for SRSs and CLRSs, respectively. These sections highlight the variability in current practices and the practices of the departments that have been more successful in obtaining buy-in for rumble strip installation for non-freeway applications. The discussion focuses on rural two-lane highways and applies to multilane highways.

SRSs and ELRSs

Table 7 provides key SRS and ELRS design dimensions and systematic installation criteria for all States and the FHWA Office of Federal Lands. Note that offset dimensions show the maximum under the department's policy. The offset is zero for ELRSs. Figure 4 illustrates the dimensions used in table 7, which are consistent with those provided in the Rumble Strip Definitions section in chapter 1.

Table 7. Department systematic SRS design dimensions and installation criteria.

State	A[1]	B[2]	C[3]	D[4]	E[5]	Bike Gap—Run (ft)	Bike Gap—Gap (ft)	Posted Speed (mi/h)	Shoulder Width[6] (ft)	Asphalt Condition	Use ELRS (Y/N)
Alabama	—	8–12	—	—	—	—	—	45	2	Good	Y
Alaska	4	16	7	1/2	12	68	12	50	6	Good, > 2 inches	N
Arizona	10	6–12	7	3/8	12	30	10	—	5	Avoid joint	Y
Arkansas	4	6–16	5	3/8	12	48	12	50	5-¼	Good	Y
California	6	6–12	5	5/16	14	—	—	40	5-½	—	Y
Colorado	—	12	7	3/8	12	48	12	—	5	—	N
Connecticut[7]	6	16	7	1/2	12	—	—	—	—	—	N
Delaware	6	6	7	3/8	12	40	12	40	5	New	Y
Florida[7]	12	16	7	1/2	12	—	—	—	—	—	N
Georgia	12	6–16	7	1/2	12	28	12	55	4	—	Y
Hawaii	2	6–12	5	3/8	12	47	13	40	4	—	Y
Idaho	12	6–16	6–7	3/8	12	48	12	—	2	Good	Y
Illinois	—	8–16	7	7/16	12	48	12	—	—	—	Y
Indiana	—	16	7	1/2	12	50	10	—	—	—	Y
Iowa	6	12	7	1/2	12	48	12	50	4	—	N
Kansas	—	12	7	1/2	12	—	—	—	2	New, > 1 inch	N
Kentucky	12	8–16	7	3/8	12	50	10	50	1	—	Y
Louisiana	—	6–12	7	1/2	14	40	10	50	—	Avoid joint	Y
Maine	6	16	7	1/2	12	48	12	45	4	< 5 years, > 3 inches	Y
Maryland	12	6–12	5–7	3/8	12	48	12	40	5	Good	Y
Massachusetts	4	16	6	3/8	12	64	16	40	8	—	N
Michigan	12	12	7	3/8	12	48	12	55	6	—	N
Minnesota	4	8–12	7	3/8	12	48	12	55	< 4	—	Y
Mississippi	—	12	7	3/8	12	—	—	—	2	—	Y

State	A[1]	B[2]	C[3]	D[4]	E[5]	Bike Gap—Run (ft)	Bike Gap—Gap (ft)	Posted Speed (mi/h)	Shoulder Width[6] (ft)	Asphalt Condition	Use ELRS (Y/N)
Missouri	—	12	7	7/16	12	—	—	50	2	> 1.75 inches	Y
Montana	6	6–12	7–8	1/2	12	47	13	50	4	—	Y
Nebraska	—	8–16	6	5/8	12	—	—	50	2	Good, > 2.5 inches	Y
Nevada	—	5-16	7	1/2	12	48	12	—	4	—	Y
New Hampshire	—	12	8	1/2	12	48	12	40	5	—	Y
New Jersey[7]	4	16	7	1/2	12	—	—	—	6	> 4 inches	N
New Mexico	16	12	7	1/2	12	48	12	—	< 6	Good	Y
New York	12	12	5–7	3/8	24	48	12	50	6	Good, > 0.75	N
North Carolina	6	8–16	7	1/2	12	30/50	6/12	—	4	—	Y
North Dakota	6	6–12	7	1/2	12	40	10	50	< 2	—	Y
Ohio	10	6–16	5–7	3/8	12	48	12	50	2	Pavement Condition Rating > 80	Y
Oklahoma	12	16	7	1/2	12	50	10	50	4	—	N
Oregon	12	6–16	7	3/8	12	30	10	—	—	—	Y
Pennsylvania	4	6–16	5	3/8	11	48	12	<55	4	Good	Y
Rhode Island	4	12–16	7	—	—	48	12	40	6	New, < 5 years	Y
South Carolina	—	4–12	7	3/8	12	48	12	45	< 1	Good	Y
South Dakota	6	8–12	7	1/2	12	40	12	50	4	—	Y
Tennessee	—	4–16	5	7/16	12	60	15	40	0	> 1.5 inches	Y
Texas	4	8–16	7	1/2	12	40/60	10/12	50	< 2	< 3 years > 2 inches	Y
Utah	12	6	5	5/16	12	48	12	—	1	—	Y
Vermont	—	—	—	—	—	—	—	—	—	—	N
Virginia	6	12	7	1/2	12	48/52	12/16	45	4	>2 inches	Y
Washington	6	12–16	5	3/8	12	28/48	12	45	4	Good	N

State	A[1]	B[2]	C[3]	D[4]	E[5]	Bike Gap—Run (ft)	Bike Gap—Gap (ft)	Posted Speed (mi/h)	Shoulder Width[6] (ft)	Asphalt Condition	Use ELRS (Y/N)
West Virginia	6	12–16	7	3/8	12	48	12	45	4	—	N
Wisconsin	6	8	7	1/2	12	48	12	55	3	Good	Y
Wyoming	12	12–16	7	3/8	12	48	12	50	2	—	N
Federal land	12	8	5	1/2	12	48	12	—	—	Good, > 2 inches	Y

[1]A represents dimension A (in inches) depicted in figure 4.
[2]B represents dimension B (in inches) depicted in figure 4.
[3]C represents dimension C (in inches) depicted in figure 4.
[4]D represents dimension D (in inches) depicted in figure 4.
[5]E represents dimension E (in inches) depicted in figure 4.
[6]Departments requiring a 4-ft shoulder typically require 5 ft if guardrail is present.
[7]Policy and criteria are not specific to rural two-lane highways (standards developed for freeways).
—No information was available.

All State transportation departments except VTrans have a specific policy regarding SRSs and/or ELRSs. A few departments, such as the Florida Department of Transportation, do not have policies or standard drawings specific to rural two-lane highways, while other departments have combined guidance (e.g., rural non-freeway SRSs).

As shown in table 7, the typical SRS designs are 12 or 16 inches long, 7 inches wide, 0.5 inches deep, and spaced 12 inches apart. These typical SRS dimensions are similar to SRS recommendations from NCHRP Report 641, *Guidance for the Design and Application of Shoulder and Centerline Rumble Strips*.[8]

ELRSs have much more variety in applications of dimensions. ELRSs range from 4 to 16 inches long, with 6 inches being the most commonly specified length. However, 8- and 12-inch lengths are regularly specified. The most common width is 7 inches, but 5 inches is also used. Additionally, 0.375-inch depths are common for ELRSs, and 0.375 to 0.5 inch represent the majority of cases.

Many States allow rumble strips to be placed on the edge line or offset onto the shoulder. The decision is typically based on the paved shoulder width but may be influenced by the available pavement width between the rumble strip and the edge of the pavement. The most common reason for providing space between the SRS and the outside edge of the pavement is to provide adequate space for bicyclists (i.e., 4 ft of clear space, or 5 ft if curbing or guardrail is present); however, TxDOT noted the importance of providing recovery area on the shoulder. Their research indicates that a recovery area of at least 13 inches should be provided when possible.

Many States shown in table 7 have a standard rumble strip length based on a specified width of shoulder. As the shoulder width changes, the standard rumble strip dimension will changes correspondingly. For example, TxDOT specifies a minimum milled rumble strip length of 8 inches; therefore, in consideration of a 13-inch recovery area outside of the rumble strip, the minimum shoulder width for systemic installation is 2 ft. Typically, 2-ft shoulders are recommended for milled rumble strip implementation; however, as justified by crash need, ELRSs will be milled into roadways with narrower shoulders. Alternatively, raised pavement markers may be used, but milled rumble strips are preferred if the pavement thickness allows. If the shoulder is more than 2 ft but less than 4 ft wide, ELRSs with lengths of 8 to 16 inches may be used. However, rumble strips may be offset from the edge line if the paved shoulder width is wide enough to provide for a 13-inch recovery area. For shoulders equal to or greater than 4 ft, 16-inch rumble strips offset at least 4 inches from the pavement marking are typically recommended. The Tennessee Department of Transportation (TDOT) specifies that if the paved shoulder width is 0 to 4 ft, then 4-inch rumble strips are used in combination with the edge line pavement marking. If the paved shoulder is 2 ft or wider, then 8-inch rumble strips are used as an ELRS. If the paved shoulder width is 8 ft or wider, then 16-inch rumble strips are used with a 12-inch offset. These are two examples of departments that have adapted policies to allow rumble strips to be placed on nearly all two-lane roadways. Many departments have one rumble strip design that may be applied, and may apply minimum criteria (as defined in the minimum criteria section) for a roadway to be eligible for installation.

Flexibility is important in department policy, especially if the policy specifies parties that are involved in the decisionmaking process. For example, the MnDOT policy allows districts to use discretion for lateral placement to abate noise concerns and accommodate bicyclists.[57] Additionally, the policy provides flexibility in rumble strip length based on pavement width, flexibility in offset to accommodate bicyclists with input from the State Bicycle Coordinator, and flexibility to gap rumble strips on the inside of horizontal curves with nearby residences if a Safety Edge^{SM} or wider shoulder is installed. The Safety Edge^{SM} provides a recoverable 30-degree pavement edge rather than a vertical drop-off at the pavement edge.

CLRSs

Table 8 lists CLRS design dimensions and systematic installation criteria for each State transportation department and FHWA Office of Federal Lands. Note that the spacing is listed as 12/24 inches for several departments, which indicates that the spacing is 12 inches between rumbles followed by a 24-inch gap. Figure 8 illustrates the dimensions used in table 8, which are consistent with those provided in the Key Definitions section.

Table 8. Department systematic CLRS design dimension and installation criteria.

State	B[1]	C[2]	D[3]	E[4]	Minimum Width—Pave (ft)	Minimum Width—Lane (ft)	Posted Speed (mi/h)	Asphalt Condition	Used in Pass Zone (Y/N)
Alabama	8–12	—	—	—	—	11	—	Good	Y
Alaska	12	7	3/8	12	28	—	45	Good, > 2 inches	Y
Arizona	6	7	3/8	12	—	11	45	—	Y
Arkansas	16	5	3/8	12	28	10	45	Good	N
California	6–12	5	5/8	12	—	—	40	—	Y
Colorado	12	7	3/8	12	—	—	—	—	Y
Connecticut	12	7	3/8	24	26	—	40	Good	N
Delaware	16	7	3/8	12	—	10	40	New	—
Florida	—	—	—	—	—	—	—	—	—
Georgia	16	7	1/2	12	—	—	—	—	—
Hawaii	16–20	6–9	1/2	12	—	—	40	—	—
Idaho	12	7	1/2	12	24	—	—	Good	N[5]
Illinois	—	—	—	—	—	—	—	—	—
Indiana	16	7	1/2	12/24	—	—	—	—	—
Iowa	16	7	1/2	12/24	—	11	50	< 5 years	—
Kansas	12	7	1/2	12	—	—	—	New, > 1.5 inches	—
Kentucky	8–12	7	3/8	12	—	11	50	—	—
Louisiana	6–12	7	1/2	14	24	11	50	Avoid joint	—
Maine	12	7	1/2	24	—	11	45	< 5 years, > 1.5 inches	Y
Maryland	16	7	1/2	24/36	—	10	40	Good	Y
Massachusetts	—	—	—	—	—	—	—	—	—
Michigan	16	7	3/8	12/24	26	—	55	—	Y
Minnesota	16	7	3/8	12	—	11	55	—	Y
Mississippi	—	—	—	—	—	—	—	—	—
Missouri	12	7	7/16	12/24	—	10	50	> 1.75 inches	Y

State	B[1]	C[2]	D[3]	E[4]	Minimum Width—Pave (ft)	Minimum Width—Lane (ft)	Posted Speed (mi/h)	Asphalt Condition	Used in Pass Zone (Y/N)
Montana	6–12	7–8	$^1/_2$	12/24	—	—	50	—	—
Nebraska	—	—	—	—	—	11	50	Good, > 2.5 inches	—
Nevada	12	7	$^1/_2$	12	—	—	—	—	Y
New Hampshire	12	7	$^1/_2$	12	28	—	40	Good, >1.25 inches	Y
New Jersey	16	7	$^1/_2$	12	—	10	35	Good, Surface Distress Index > 3	Y
New Mexico	16	7	$^1/_2$	12/24	26	12	50	Good	Y
New York	12	7	$^3/_8$	24	26	—	45	Good, > 0.75	Y
North Carolina	—	—	—	—	—	—	—	—	—
North Dakota	6–12	7	$^1/_2$	12/24	—	—	50	—	—
Ohio	16	5	$^3/_8$	12/24	—	—	—	—	—
Oklahoma	—	—	—	—	—	—	—	—	—
Oregon	16	7	$^1/_2$	24/48	—	—	—	—	Y
Pennsylvania	14–18	7	$^1/_2$	24/48	—	10	—	Good, > 2.5 inches	Y
Rhode Island	12	7	—	12	—	11	40	New, < 5 years	Y
South Carolina	12	7	$^3/_8$	14	—	10	45	Good	—
South Dakota	12	5	$^3/_8$	12	—	—	50	—	—
Tennessee	12	7	$^7/_{16}$	24	—	12	40	Avoid joint	Y
Texas	16	7	$^1/_2$	24	—	11	50	< 3 years > 2 inches	Y
Utah	6	8	$^5/_8$	12	—	—	—	—	Y

State	B[1]	C[2]	D[3]	E[4]	Minimum Width—Pave (ft)	Minimum Width—Lane (ft)	Posted Speed (mi/h)	Asphalt Condition	Used in Pass Zone (Y/N)
Vermont	12–18	7	$^{3}/_{8}$	12/24	28	—	45	Good	Y
Virginia	14	7	$^{1}/_{2}$	12	—	11	45	> 4 inches	Y
Washington	12	7	$^{1}/_{2}$	12	24	—	—	Good	Y
West Virginia	—	—	—	—	—	11	45	—	—
Wisconsin	8	7	$^{3}/_{8}$	12/24	—	12	55	Good	—
Wyoming	12	7	$^{1}/_{2}$	12	—	—	50	—	—

[1]B represents dimension B (in inches) depicted in figure 4.
[2]C represents dimension C (in inches) depicted in figure 4
[3]D represents dimension D (in inches) depicted in figure 4.
[4]E represents dimension E (in inches) depicted in figure 4.
[5]Policy being reviewed currently.
—No information was available.

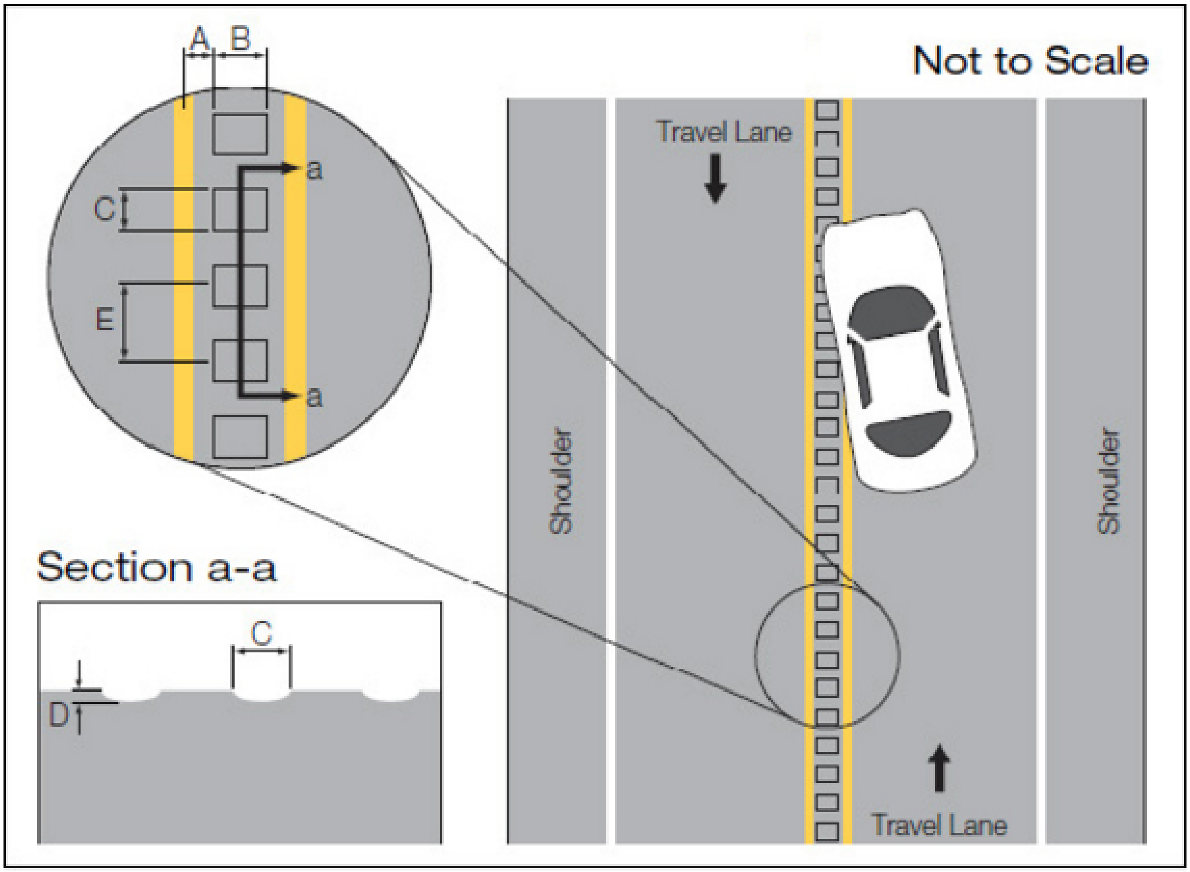


Figure 8. Illustration. CLRS dimensions.[7]

A total of 46 State departments, including the Federal Lands Highway Division Safety Team, currently have CLRS design standards, which were collected and compiled into a matrix. Of the five departments that did not have identifiable standards, NCDOT noted that CLRSs could be considered on a case-by-case basis dictated by crash history; however, no design policy was found for NCDOT.

As shown in table 8, the typical CLRS design standard is 12 or 16 inches long, 7 inches in wide, approximately 0.5 to 0.625 inch deep, and 12 inches in spacing. These typical CLRS dimensions are similar to recommendations from the NCHRP Report 641, *Guidance for the Design and Application of Shoulder and Centerline Rumble Strips*.[8]

While 12- and 16-inch CLRSs were the most prevalent of those identified in the department policies, the practices were not universal. Department policies included a minimum of 6 inches for rumble strip length and 16 inches as the maximum. A few departments (e.g., LaDOTD) specify rumble strip length based on roadway characteristics. In Louisiana, 6-inch rumble strips are used if the pavement width is 24 to 28 ft, with at least 1 ft of paved shoulder, while 12-inch rumble strips are used if the paved surface width is 28 or more ft. The most common application is a 12- or 16-inch milled rumble strip centered on the center line joint with pavement markings applied over the rumble strip. Other departments, (e.g., TDOT and the Nebraska Department of Roads (NDOR)) do not allow milled rumble strips on the center line joint. TDOT specifies 6-inch milled rumble strips, with each straddling a 4-inch gap for the center line joint, while

NDOR places two 8-inch rumble strips with a 4-inch gap between them on either side of the center line joint. The double-yellow pavement markings are placed directly on top of the milled rumble strips, and the rumble strips are discontinued when the pavement markings are discontinued.

Departments are nearly universally specifying a rumble strip width of 7 inches for CLRSs and have policies for rumble strip depth that allow for some tolerances. Most commonly, 0.5 inch is specified for rumble strip depth, and tolerances range from 0.25 to 0.063 inch.

Departments commonly specify continuous CLRS spacing or may require a skip pattern for CLRS spacing. The skip pattern is used to allow for raised pavement markers or to provide a differentiation from SRSs/ELRSs. The idea is that the difference in sound will alert the driver as to which side he or she is drifting, since drivers most commonly assume they have drifted to the right and will correct to the left. The majority of departments specify 12-inch center-to-center CLRS spacing, but several departments specify 24-inch center-to-center continuous spacing. For skip patterns, it is most common to skip every third rumble, creating a 12-inch center-to-center run with a 24-inch center-to-center skip.

Gaps

Departments provide gaps, or breaks, in the continuous patterns at many locations. Bicycle gaps are discussed separately in the Bicyclists section in chapter 3 and are not characterized here. Gaps for noise reduction are also discussed separately in the Noise Impacts section in chapter 3. Policies for gaps are commonly similar for CLRS and SRS/ELRS policy within a department. Profile rumble strips and raised rumble strips do not require gaps at bridges and overpasses and may be placed instead of milled rumble strips.

Gaps in milled rumble strips are commonly provided at intersections, auxiliary lanes, bridges and approach slabs, private and commercial driveways, locations with curbs and gutters or guardrails in combination with narrow shoulders, and railroad crossings. There is large variation in department policies for distance prior to bridge decks and intersections to break the continuous rumble strips. The most common practice is to provide a break 50 ft prior to bridge decks; however, some departments provide breaks 25 ft prior to bridge decks. VTrans allows CLRSs on bridges if there is at least 2.5 inches of bituminous overlay.

There is variation on providing gaps for intersections. Several departments define the *break* as a distance prior to the intersection, while other departments define the break by the location of the point of curvature for intersections. There is too much variation to characterize common practices in terms of distance before an intersection or point of curvature for an intersection; however, the range covers 25 to more than 100 ft. CLRSs are commonly broken where the center line pavement marking is broken for intersections and major commercial driveways.

Caltrans only breaks CLRSs at public street intersections and commercial driveways with at least 500 vehicles/d. Engineering judgment is recommended for ELRSs. LaDOTD only breaks CLRSs at major roadways because they feel safety is more important than the noise the rumble strips would generate for low-volume public streets and driveways. Department policies differ on providing gaps at passing zones for CLRSs. Several departments discontinue CLRSs at passing zones, while others, such as Caltrans and LaDOTD, provide CLRSs within passing zones. The Arizona Department of Transportation (ADOT) recommends that CLRSs be installed in rural areas with passing zones unless there will be a likelihood of significant noise generation in the vicinity of occupied residences.

SYSTEMATIC INSTALLATION SELECTION CRITERIA

This section describes the selection criteria for determining eligibility of roadways for systematic installation of rumble strips. The selection criteria are often exclusionary, meaning that rumble strips are eligible at locations unless the selection criteria indicate that they should be excluded from a location.

ADT

ADT is a measure of the total volume of vehicle traffic for a roadway for a day. Rumble strips are installed to alert drivers when they drift from their lane and are effective at reducing accidents; however, a certain amount of traffic volume may be necessary to make them cost effective.

Most departments have no specific ADT specifications for the installation of CLRSs or SRSs. A few departments do specify ADT requirements, such as ConnDOT, where the ADT must be greater than 2,000 to install CLRSs. NDOR and VTrans also have CLRS ADT requirements of 1,500 or greater. The Maine Department of Transportation (MaineDOT) requires all roadways with 3,000 ADT regardless of a crash history to have CLRS and SRS installations.

For SRSs, only three State transportation departments other than MaineDOT have ADT requirements. The Georgia Department of Transportation requires 400 ADT for ELRSs, NDOR requires 500 ADT or greater for SRSs/ELRSs on non-interstate roadways, and SCDOT generally installs SRSs/ELRSs if the ADT is greater than 500.

MnDOT, in its follow-up interview, mentioned that their ongoing research has shown that, based on fatal crashes, both CLRSs and SRSs should be installed on all roadways with ADT greater than 4,700.

Pavements

Departments typically consider pavement condition when determining whether to implement rumble strips because of the potential for increasing pavement deterioration. This criterion can include anything from pavement depth, pavement condition index, pavement type (e.g., new or reconstructed), or a time-based consideration. Most departments require that the pavement be in good condition, which is usually determined by a maintenance department or a specified group (e.g., district offices) at their State transportation department. Departments vary in their definition of good pavement condition, as shown in the following examples:

- MDOT installs CLRSs across asphalt joints but has improved their joint construction specification, having observed that the quality of the joint was the key factor in increased deterioration as a result of installing approximately 5,400 mi of CLRSs on all ages of pavement in a 3-year period. MDOT typically uses SRSs rather than ELRSs due to a concern that trucks will drive on the edge line and thereby on the joint, which could increase joint deterioration.

- TxDOT specifies that the roadway cannot be older than 3 years and must have a minimum of 2 inches of pavement thickness. TxDOT also notes that if the pavement condition or depth is not adequate, then profile or raised rumble strips should be considered.

- MaineDOT classifies good pavement condition as having a minimum of 1.25 inches of surface pavement depth or at least 3 inches in total depth and being less than 5 years old with no signs of distress.

- ADOT states that if the pavement is unsuitable for ground-in (milled) rumble strips, then they will consider alternative treatments such as raised pavement markers or profile pavement markers. Additionally, they avoid longitudinal joints where practical.

- ConnDOT has chosen to install CLRSs on State roads that have been repaved within 4 years of the installation date. This number comes from the paving management unit, which specified that the pavement remains in good condition for up to 4 years. Pavement conditions for local roadways comes from observation and input from the municipalities.

- LaDOTD defines good pavement conditions as the roadway having been installed within the last 10 years.

- The New York State Department of Transportation (NYSDOT) recommends that the asphalt surface course be greater than 0.75 inch for new paving or have no more than one longitudinal crack.

- PennDOT assesses pavement conditions by having the district pavement engineer conduct a field review. The district pavement engineer must determine that the pavement is in sufficiently good condition to retrofit rumble strips on existing pavement. Otherwise both the pavement and shoulders need to be upgraded prior to milling any rumble strips. Installation on bituminous pavement requires a bituminous wearing course surface with a bituminous concrete base course or better. Installation on concrete surfaces currently requires a minimum of 2.5 inches of overlay, but this may be revisited soon.

Additionally, a few departments, such as the Arkansas State Highway and Transportation Department (AHTD) and the Maryland State Highway Administration, note that future pavement preservation is a consideration in rumble strip installation. These departments note that installation may take place if no asphalt overlay is expected in the next 2 to 3 years.

While departments are consistent with developing policies requiring minimum pavement depth and/or condition for rumble strip implementation, their policies vary on the placement location of rumble strips in relation to the longitudinal joints. Some departments, such as MnDOT, have concerns regarding center line joint degradation, particularly for concrete pavements. TDOT and NDOR do not allow CLRSs to be milled onto the center line joint, instead opting for a pattern that straddles the longitudinal joint. However, most departments are allowing CLRSs to be milled over the center line joint, with the rumble strip centered on the longitudinal joint. CLRSs are being milled that are 12 to 16 inches long, with no departments reporting any issue with accelerated degradation when the pavement is in good condition. For SRSs and ELRSs, ADOT notes that the longitudinal joint should be avoided where practical, AHTD notes that the offset for SRSs may be increased to avoid longitudinal joints, and LaDOTD specifies that the longitudinal joint should be avoided for SRSs/ELRSs.

Additional considerations for rumble strip implementation include future pavement maintenance treatments on roads with rumble strips. These pavement maintenance treatments generally include thin treatments such as thin HMA overlays, chip seals, and microsurfacing. In a July 2010 New Hampshire Department of Transportation (NHDOT) report, *Preparation of Rumble Strips Prior to Overlayment*, the author initially recommended that existing rumble strips could simply be tacked and overlaid with a thin HMA overlay.(58) However, early implementation revealed several issues with this practice, including cracking of the new pavement and reflection of the original rumbles in the pavement surface. NHDOT ultimately elected to require that all rumble strips be milled and inlaid prior to placement of the overlay. Guidance from Donnell et al., developed for PennDOT, notes that existing rumble strips should be milled for HMA overlays, a second seal coat, or some forms of microsurfacing.(33) Separate guidance applies to CLRSs, SRSs, or their combination. The MDOT guidelines recommend that for HMA overlays (including surface milling with non-structural HMA overlay) and microsurfacing the overlay material should be used to fill in existing rumble strips.(59) Rumble strips should be reestablished after the HMA or microsurfacing overlay. However, the guidelines state that chip seals should be placed over existing rumble strips. If new rumble strips are desired for roadways to be chip sealed, then they should be milled into the pavement prior to the chip seal. Similarly, WSDOT's guidance states that chip seal surfacing should have a total thickness (including HMA applications) of at least 3 inches for milled rumble strip application.(60) The guidance notes that insufficient depth and exposure to freezing and thawing of moisture can lead to delamination. Further guidance states that chip seals can be placed over existing rumble strips once and still be effective. Roadways receiving subsequent chip seals are to be evaluated to determine whether the depth of the remaining rumble strips is adequate for an additional chip seal.

In the noteworthy practice department interviews, the Atlanta District of TxDOT mentioned through its interview that it uses preformed raised rumble strip bars. After roadway resurfacing over the existing preformed rumble bars with a thin HMA overlay, TxDOT found from field visits that the vibration and audible noise level from the rumble strips was still at an acceptable level with one overlay. Upon applying two thin HMA overlays the vibration and noise level of the rumble strips was lost.

If milled into pavements in good or better condition, there is no documented evidence that rumble strips themselves require maintenance. Several departments have used and continue to use fog seals (spray applications of diluted asphalt emulsion) with the expectation that it will reduce the risk of premature deterioration. Some departments have stopped using fog seals because they did not experience a benefit. Additionally, as noted by FHWA, fog seals are incompatible with thermoplastic pavement marking applications.(32)

Additionally, some States have expressed concern about the potential for water to collect in the depression made by milling rumble strips. TxDOT, along with other departments, had no mention of issues such as hydroplaning or debris build up due to rumble strips. Weather conditions, such as snow removal, have not been discussed within departments outside of the fact that most northern States do not use raised rumble strips due to snowplowing operations. However, northern State departments have noted that plow drivers use rumble strips for assistance in lane keeping when visibility is low, which is a maintenance benefit.

Speed Limit

Speed limits set the maximum and occasionally minimum speeds along particular roadways stretches in which it is legal for vehicles to travel. Speed limits are representative of the level of urbanization along a roadway. Across the United States, maximum speed limits on rural two-lane highways can vary from a low of 45 to a high of 75 mi/h. Speed limit restrictions do not transpose well across the United States because the demographics, geography, and urbanization varies greatly. Some States, such as Rhode Island or Hawaii, have limited rural undivided roadways with speeds over 45 mi/h, unlike Texas or other midwestern or western States where speed limits on rural two-lane highways are commonly 70 or 75 mi/h. This implies that a one-size-fits-all speed limit surrogate for urbanization is not appropriate. However, commonly used maximum speed limits for rumble strip implementation are provided.

CLRSs and SRSs are generally installed on roadways with a speed of 45 mi/h or greater. California, Connecticut, Hawaii, and New Jersey allow mainly CLRSs be installed on roadways with 35 mi/h or greater, while Delaware, Maryland, New Hampshire, and Rhode Island allow 40 mi/h for two-way conventional CLRSs and SRSs.

Lane Width

It is important to understand the interaction of design elements, especially minimum lane width, when implementing rumble strips along roadways. Operational and safety performance can be impacted by vehicles attempting to avoid unnecessary contact with rumble strips when lane widths are too narrow. Vehicles tend to shift away from rumble strips, potentially into adjacent lanes or the shoulder affecting the safety of other drivers, as well as non-motorized users such as bicyclists who may be using the adjacent lane or shoulder.

Across departments, minimum widths vary in relation to the type of rumble strip being implemented. CLRSs are often specified as requiring a minimum total pavement width and minimum lane width. SRSs and ELRSs are often specified as requiring a minimum total pavement width and minimum shoulder width. Most commonly, an 11-ft minimum lane width is required for CLRS and/or SRS installation, with 9 ft of effective lane width being the minimum and 12 ft as the maximum.

MDT is experimenting with the current standards by allowing lane narrowing by 6 inches and using ELRSs to make the shoulder as wide as possible without having to place the rumble strips on the outside edge of the mat. The goal is to provide at least a 4-ft clear space for bicyclists.

Shoulder Width

Bicyclist advocacy groups have expressed their concerns regarding rumble strip installation, particularly SRSs and ELRSs, due to inadequate shoulder width for bicyclists. Many departments have included these organizations into their advisory committees before determining design standards or include their input when proposing to install SRSs. Additionally, the paved shoulder width is important for providing a separation between the edge of pavement to the rumble strip for maintenance concerns and for providing adequate recovery areas for vehicles, especially where there is a narrow clear zone outside of the paved shoulder. TxDOT noted that their research has shown that at least 13 inches of recovery area should be provided outside of rumble strips on the paved shoulder.

TxDOT has a Bicycle Advisory Committee and Motorcycle Safety Coalition. These groups both have input into TxDOT policies, and, by involving these representatives of the public, TxDOT helps ensure effective communication with the bicyclist community. The bicyclists' perspectives are considered in the development of departmental policies affecting bicycle use, including the design, construction, and maintenance of highways. Additional bicycle information is discussed in the Bicyclists section in chapter 3.

Due to these organizations and advisory committees assisting with department designs, the majority of departments require a minimum shoulder width of 4 ft or greater for installing SRSs and ELRSs, especially in high bicycle traffic areas. WSDOT requires at least 4 ft of available width between the rumble strip and the edge of the pavement, except in rare cases, and 5 ft if there is barrier at the pavement edge. When a roadway does not have high bicycle traffic, some departments are using a smaller shoulder width of 2 ft. According to the data collected from departments, the minimum required shoulder width is 2 ft, and maximum required shoulder width is 6 ft. MDOT requires 6 ft of paved shoulder for systematic installation to accommodate bicyclists with trailers. If crash problems are identified on sections with less than 6 ft of paved shoulder, then they typically recommend adding 2 ft of shoulder in conjunction with installing the rumble strips. PennDOT does not install rumble strips if less than 4 ft of shoulder will remain. They consider bicyclists' needs a top priority, and, if there is a high departure crash rate, then they recommend using Highway Safety Improvement Program funds to widen the shoulder and add rumble strips.

These varying shoulder widths dictate dimensions and placement of rumble strips for many departments. For example, TxDOT allows for narrower rumble strips or ELRSs for narrower shoulders in comparison to their standard design. VDOT and NYSDOT allow for ELRSs if the specific area has a documented history of ROR crashes.

Since rumble strips are a low-cost, proven safety countermeasure, few departments discuss shoulder widening as a potential alternative when narrow shoulders are a concern. HDOT notes that paved shoulder widening should be considered if necessary to accommodate installation of SRSs/ELRSs.

It should be noted that these policies refer to systematic installation of SRSs and ELRSs. The interview departments noted that they will place ELRSs on narrower shoulders, so long as the crash data justify the need. These locations are typically identified using a hot spot approach to safety.

Total Pavement Width

Departments mainly specify a minimum total pavement width for CLRSs, although LaDOTD does specify a minimum of 22-ft pavement width for ELRS installation. The required minimum pavement width varies between departments from 22 to 28 ft, with the most commonly required minimum pavement width being 28 ft.

Additionally, ConnDOT is concerned about CLRS installation, with the concern coming from the bicyclist/pedestrian community, who note that vehicles may shift away from the roadway center line and encroach on the shoulder. ConnDOT has decided that due to this concern, it is best to install CLRSs on roads with a satisfactory shoulder for pedestrian use, and, based on feedback provided by the bicyclist and pedestrian communities, their advisory committee determined that a minimum width of 26 ft is needed to install CLRS.

HIGH-CRASH CORRIDOR INSTALLATION PRACTICES

Many high-risk locations may not qualify for systematic installation but may benefit from rumble strip installation based on crash history. For example, highway corridors with narrow shoulders may not provide adequate clear space for bicyclists with rumble strip implementation but may have a history of high ROR crash counts. Practitioners can use the methods provided in the Rumble Strips and Safety Management section of the decision support guide to identify the need for and potential benefits of rumble strips in these corridors.(1) Most departments reviewed do not provide specific guidelines for how and when to install rumble strips in these cases. Additionally, these corridors have the greatest potential for installation issues due to special considerations. Consideration of the potential benefits and trade-offs is paramount, and the departments with the most success installing rumble strips have written processes or requirements, including who is involved in the final decisionmaking. Successful policies include relevant stakeholders in the decisionmaking process once the need is identified.

Several departments have identified key personnel involved with decisionmaking or have identified personnel who are typically included in a rumble strip decisionmaking committee. Examples of personnel who may be involved in the decisionmaking process include the following (note that departments differ in the titles of individuals and names of key offices):

- Designers.
- Traffic engineers.
- Safety analysts.
- Bicycle or non-motorized coordinators.
- Environmental engineers.
- Planners.
- Maintenance personnel.

Each of these personnel may be considered at the local/county, regional/district, or State/central office level of the organization, and concurrence among personnel is paramount. Additionally, stakeholders may be included in the process or notified as early as possible to allow time for feedback. Potential stakeholders include municipalities, local bicyclist groups, and adjacent roadway property owners and residents. Their feedback is critical and should be considered in combination with potential safety benefits. This also gives the department an opportunity to provide stakeholders with information on the safety benefits, including specific performance measures calculated in the safety analyses. This may help the department promote rumble strips to stakeholders.

A few departments also note the importance of project decision documentation. Due to the potential safety impact of decisions, it is important to document the need and the decision whether or not to install rumble strips and the reasoning for the decision. Documentation is also important for explaining the benefits to stakeholders and others who may perceive a disbenefit for their installation. TxDOT noted that if they demonstrate the historical CRFs for rumble strip installations to the general public, they have fewer complaints after installation. MDOT requires documentation when the decision not to use SRSs is made for special cases where a crash history does not exist, such as locations where horse-drawn buggies use the roadway or the driveway density exceeds 30 access points within 0.5 mi.

MDT has a specific process for new construction, reconstruction, rehabilitation, and overlay corridors where the shoulder width is greater than 1 ft but less than 4 ft. The procedure includes the following steps:(56)

1. MDT completes an economic analysis targeting roadway departure crashes to determine whether rumble strips are justified.

2. The Planning Division determines if and how bicyclists use the highway corridor using bicycle route maps, heat maps, or other methods.

3. If rumble strips are justified and the roadway is determined to be a high-priority bicycle route, then a Rumble Strip Committee meeting is convened by the project design manager. The committee evaluates the route and recommends and documents the appropriate action in the appropriate report (such as the scope of work report). The members of the committee include members from the Traffic and Safety Bureau, Planning Division, Highways Bureau, and the MDT district. Other divisions are included on an as-needed basis.

SPECIAL CONSIDERATIONS AND RUMBLE STRIP MODIFICATION

Rumble Strip Special Considerations

This subsection describes the issues that departments encounter that alter their standard practice of rumble strip installation.

As mentioned previously, the typical design standards that were collected from department standards and policies are similar to those found in NCHRP Report 641, *Guidance for the Design and Application of Shoulder and Centerline Rumble Strips.*(8) Some departments alter their design for a variety of reasons, such as the results of peer exchanges, influence from public organizations, or legislation. For example, MnDOT had some legislative and public pushback when installing rumble strips. It forced the department to change its practices, ultimately leading

MnDOT to work with sinusoidal rumble strips. The goal was to allow for continued rumble strip implementation in consideration of the pushback on exterior noise generated by rumble strips. ConnDOT learned that the barriers were more perceived then actual because CLRSs and SRSs are still new concepts that people are not familiar with in Connecticut.

The three major influences that cause departments to adjust their standard practices include bicyclists, external noise impacts, and research. These subsections are described in detail in the following subsections.

Bicyclists

Bicyclists have a variety of basic requirements that need to be accommodated for their safe navigation on shared roadways with vehicles. As the AASHTO *Guide for the Development of Bicycle Facilities* shows in figure 9, the minimum operating width is 4 ft.(61) The CROW *Design Manual for Bicycle Traffic* additionally notes the need for 13 to 25 inches of clearance from fixed obstacles.(62) This distance provides for the width of the bicyclist as well as the necessary width to operate or maneuver the bicycle. Additional factors that affect bicyclists on roadways with rumble strips are clean pavements and the ability to cross rumble strips safely.

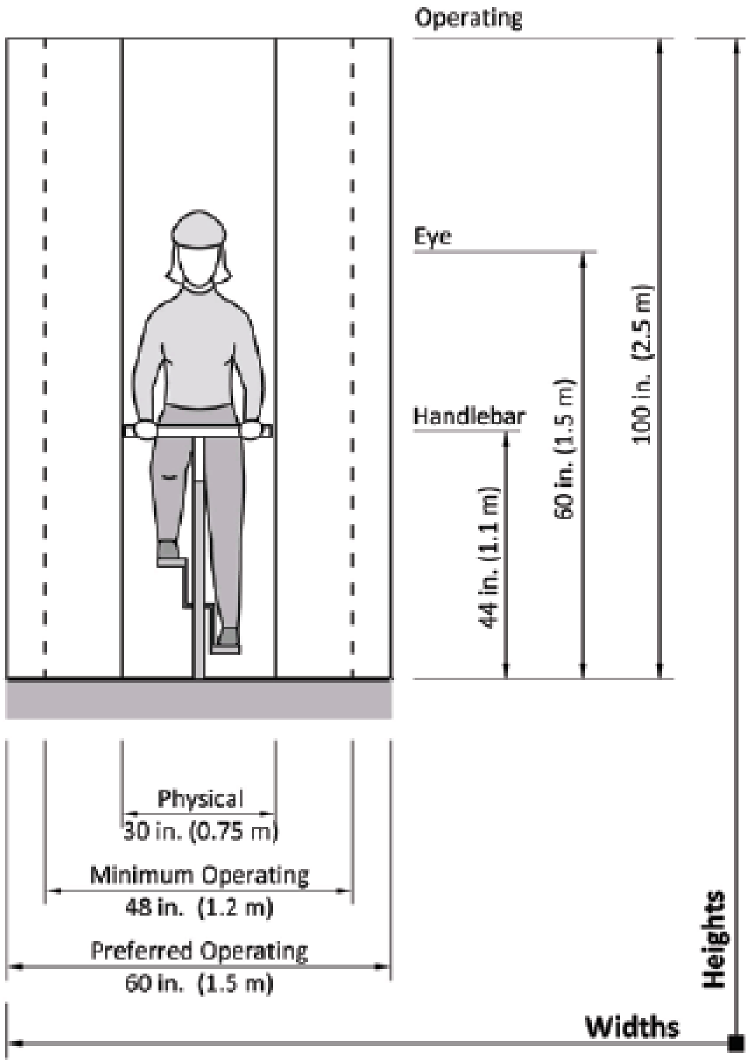


Figure 9. Illustration. Bicycle roadway requirement dimensions.[61]

Caltrans has conducted field testing and determined that the strip depths (0.313 ± 0.063 inch) are traversable by bicycles. Other departments such as the AHTD changed the depth of their rumble strips to 0.375 inch because this depth is less disruptive to bicyclists. For installation of CLRSs, ConnDOT generally requires that roadways be at least 26 ft wide. On roadways with high bicyclist activity, TxDOT gives consideration to bicyclists before the installation of ELRSs. Factors considered include the size of rumble strips, rumble strip material, and location of rumble strips on the shoulder. If the TxDOT designer determines that gaps are needed in the rumble strips due to bicyclist use of the road, the requirements provided in the FHWA Technical Advisory T5040.39 or the latest version detail of the spacing are included in the plans.[63]

Some departments have approached bicycle accommodations with rumble strips with an absolute consideration. Caltrans, the Delaware Department of Transportation, and HDOT require a 5-ft minimum shoulder if bicycles are permitted; however, if a 5-ft shoulder is unattainable, then ELRSs are recommended. Other State transportation departments, such as LaDOTD and

MnDOT, use a case-by-case approach that vets their bicycle accommodations through multiple advisory committees before recommending SRSs. These advisory committees may include FHWA representatives, upper management within the department (e.g., State pedestrian and bicycle coordinators), senior citizen advocacy group members, bicyclist groups, non-motorized vehicle committee members, and/or Complete Street policy advocates. In recent years, bicyclist organizations/associations have taken a much more vocal role in designing safer roadways that accommodate non-motorized vehicles. Departments have made a concerted effort to involve these organizations/associations into their roadway designs. For example, MnDOT has a Non-Motorized Advisory Committee that assists with the design and comments on where rumble strips are installed. Departments such as MaineDOT also specify that the concurrence of the Safety Office in consultation with the bicyclist/pedestrian coordinator is required if a 4-ft clear space cannot be maintained or if a 5-ft clear space in the presence of curbing or guardrail cannot be maintained. Departments are recognizing the need for clear space for bicyclists and may break the rumble strip pattern for a length if the clear space cannot be maintained (e.g., along a section of guardrail).

Rumble strip gaps are another strategy for helping with roadway rideability rather than omitting rumble strips on roadways with bicyclist activity. Gaps in the continuous rumble strip pattern allow the bicyclists to enter or cross the travel lane as necessary to make a turn or avoid an object ahead on the paved shoulder. Departments vary regarding bicycle gap design; however, the most common trend is a 12-ft gap every 60 ft. This implies that there is 48 ft of continuous rumble strips followed by a 12-ft gap. It is also common practice for departments to provide a 10-ft gap in rumble strips with a 30- to 40-ft run of continuous rumble strips. A few departments, such as NCDOT and VDOT, have lengthened the gap distance somewhat in the presence of steeper downgrades, recognizing the increased speeds of bicycles.

Some departments also involve the public at large when designing roadways with bicyclist accommodations. During the roadway design process, ConnDOT submits a bicyclist and pedestrian assessment form to the Office of Intermodal Planning for their consideration. From there, a letter is sent to all chief elected officials to explain the project and allow them to request a public meeting. MDOT has worked with the League of Michigan Bicyclists to survey bicyclists on several design related issues, including video and documentation of motorist vehicle placement when passing bicyclists. MDOT worked with the group during the design and implementation of the rumble program to help create a “Share the Road” public service announcement to help drivers understand how to pass bicyclists where CLRSs exist due to a concern that CLRSs would discourage motorists from crossing the center line while passing a bicyclist. WSDOT conducts outreach to bicyclist groups near proposed projects, involved a Bicycle and Pedestrian Advisory Committee during the development of the SRS policy for undivided highways, and has discontinued rumble strips on roadways that host annual bicycle races. SCDOT initiates discussions with bicyclist advocacy groups to obtain feedback when proposing installations on South Carolina bicycle routes. Recommendations for installations come from crash analyses, and SCDOT is proactive about gaining support from the bicyclist community in order to apply rumble strips on designated bicycle routes.

As noted earlier, when MDT was developing its *Rumble Strip Guidance*, it sent out modified guidance and received pushback on the initial language.[56] MDT engaged the bicyclist community to receive feedback on the language, and one relevant change was the statement that "The ideal clear space between the shoulder rumble strip and the edge of the paved shoulder is 4 ft."[(56)](p. 3) For narrower pavements, the text specifies that the lane width can be reduced by 6 inches or an ELRS can be used to try to obtain a 4-ft clear space. Additionally, MDT has implemented quality control measures as an effort to ensure that a 4-ft clear space is maintained through the installation process. MDT is stressing to construction departments the importance for quality in this case. MDT also identifies high-priority bicycle routes by engaging the pedestrian and bicyclist coordinator who interacts with the pedestrian and bicyclist groups to determine the protected routes. Additionally, they use tools such as online heat maps to identify high-usage bicycle routes. Heat maps are generated by fitness devices worn by bicyclists, identifying an exposure level for each route. Departments are being cognizant of designated routes and highly traveled bicycle routes and are using bicycle heat maps and State and local bicycle route maps as they update and construct new roadways.

Noise Impacts

Rumble strip effectiveness comes from the external noise and vibrations that are generated when a vehicle drives over them. The external noise level has been shown to be a function of the design characteristics of the rumble strip. MnDOT conducted a rumble strip noise study in May 2014 after they received complaints from residents expressing their concern regarding rumble strip noise.[(64)] After concluding this research, a moratorium was placed on rumble strips as MnDOT continued researching quieter options. The Kansas Department of Transportation also conducted research on different types of rumble strip designs to decrease the noise impact.[(65)] This study compared football-shaped rumble strips with rectangular rumble strips and concluded that there was no significant difference between the two designs. There is a current lack of research and information that addresses how to accommodate both safety and noise complaints especially in residential or similar areas.

Noise complaints from the public seem to generally occur in locations where the speed is low, the roadways are rural, and there is a certain degree of development. Most departments have a minimum speed limit threshold of 45 mi/h as a surrogate for urbanization. However, MDOT noted that most rural highways are posted at 55 mi/h, and including 45 mi/h roadways would only add about 70 mi of additional highway. Departments such as the AHTD and ADOT normally do not install rumble strips in urban areas because of higher population and lower speed limits; however, if an engineering study determines that rumble strips are needed to reduce roadway departure crashes, then it is deemed acceptable. The policy of TxDOT (which has a roadway criterion of 45 mi/h or greater for rumble strips) states that consideration should be given to noise levels when ELRSs are installed near residential areas, schools, churches, etc., and allows for a minimum of 0.375-inch depth in these areas. MDOT studied locations with noise complaints and changed their policy to allow rumble strip omission where the driveway density exceeds 30 driveways per 0.5 mi. MoDOT found that most noise complaints from new installations subside within a year. When complaints continue beyond a year, MoDOT has found that an evaluation is needed because there is a greater likelihood there is a problem at the location. In some cases, they have removed rumble strips in the stretch where the noise concern is concentrated.

ConnDOT, who uses a 35-mi/h or greater criteria for installing rumble strips, installed CLRSs in 1999 at high-crash locations yet removed the installations within a year due to the large number of noise complaints. It was not until 2014 that ConnDOT began installing CLRSs again. Due to the level of pushback, and subsequent moratorium, ConnDOT does not have a policy for installation of CLRSs. LaDOTD, which only installs rumble strips on roadways with speeds of greater than 50 mi/h and not in residential areas, reported not having any pushback or issues with the noise impact from rumble strips.

Several departments have criteria on when to discontinue rumble strips before residential areas that range from 130 ft (MnDOT) prior to residential/commercial areas to 1,000 ft (Nevada Department of Transportation (NDOT)) or 2,000 ft (ADOT). Practical constraints show that policies in rural Arizona and Nevada cannot be applied well in more urbanized States, such as those in the northeast. In general, most departments have a more blanket approach to noise impacts, such as the Alabama Department of Transportation (ALDOT), whose policy states that noise should be considered when determining whether to install CLRSs near residential or other sensitive receptors, but this guidance is secondary to safety.

Noise complaints are handled differently by every department due to differing levels of pushback. While TxDOT has removed rumble strips due to noise complaints, they noted that this has been a very rare circumstance. TxDOT and LaDOTD both noted that noise complaints have been minimal. MoDOT found that a widespread implementation program may have helped to reduce noise concerns. There is a perception that if only a few roads had rumble strips installed, or if the program had been over a much longer time period, then residents would have complained more about the noise because it would not have been fair. However, the program affected everyone equally and was associated with an improved roadway surface, and many drivers experienced the benefits of the warning firsthand. Alternatively, FHWA's EFL struggles with a variety of pushback from sign installation to rumble strip installation; moreover, FHWA's EFL noted that wildlife and environmental issues are typically a larger concern due to rumble strip noise, which impacts the surrounding wilderness. It is difficult for these departments to gain public approval of rumble strips, and FHWA's EFL noted that any additional information they can provide to emphasize their effectiveness would help achieve this objective.

Passing zones are another area where noise impacts are frequently found and where department policies vary substantially. Caltrans installs CLRSs continuously through passing and no-passing zones. ALDOT, AHTD, and NDOT policy states that CLRSs should be installed continuously through no-passing zones, while no CLRSs should be installed at passing zones. ConnDOT does not install CLRSs in passing zones and requires them to be discontinued 25 ft before the passing zone begins, with the main reason being noise created by vehicles hitting CLRSs legally/purposefully (as opposed to accidentally hitting them in a non-passing zone). RIDOT requires CLRSs to be installed consistently with the passing zone striping (8-ft strip and 32-ft gap), while VDOT requires the CLRSs be 0.375 inch deep in the passing zone areas with the possibility of increasing the spacing to 24 inches.

Additionally, PennDOT and WSDOT have discontinued ELRSs on the inside of horizontal curves due to nuisance strikes or off-tracking from heavy vehicles. Alternatively, the West Virginia Department of Transportation and MoDOT increase the offset to SRSs in locations where external noise may be a factor. MDOT uses a skip pattern on the center line and a 12-inch offset on the shoulder to help reduce noise generated by vehicle contact.

Rumble Strip Modification and Alternative Treatments

Departments noted that using several different cross section and rumble strip designs based on the following special considerations:

- Using a different rumble strip configuration.
- Using a different rumble strip placement (e.g., moving SRSs under the pavement marking to create an ELRS). The goal is to maintain a 4-ft clear space, if possible. The goal is generally 5 ft if a curb or guardrail is present.
- Omitting rumble strips at locations with guardrail and/or curbing if adequate clear space cannot be maintained.
- Reducing the depth of the rumble strip to $^3/_8$ inch.
- Changing lane configurations (e.g., narrowing the travel lane to accommodate a wider shoulder).
- Widening the shoulder to accommodate rumble strips and clear space for bicyclists.
- Using raised rumble strips.
- Terminating rumble strips in residential areas or providing breaks near residences (as necessary).

CONCLUSIONS FROM CURRENT PRACTICE REVIEW

Although most departments have their own standard design for CLRSs, SRSs and ELRSs, they do allow some flexibility to design standards, especially with sites that have a history of ROR crashes and bicyclist concerns. Most departments have policies for systematic rumble strip installation on reconstructed, resurfaced, or newer pavements, often specifying a minimum pavement width for CLRSs and minimum shoulder width for SRSs. However, most departments specify that high-crash locations can be identified through crash data and will choose to install rumble strips at these locations even if the systematic criteria are not met. However, it is important for the department to show the effectiveness of the rumble strip design because the installation may impact the usability of the roadway for bicyclists or may burden nearby residents with increased noise or perceived noise activity. While rumble strips are an effective systemic safety solution, systemic installation is not discussed in department policies, and the systematic approach is used instead.

Many departments struggle with these considerations, which is where a tool or guide can be most useful. In the context of transportation safety, a tool implies decisionmaking based on a series of inputs and a computer routine that arrives at a series of recommendations. For rumble strips, a blanket solution for all departments may not be feasible because each State already has a set of selection criteria and design policies in place. There is insufficient information for developing a tool that provides a recommended rumble strip design that may differ from a department's policy. However, the results of this effort can be used to help struggling departments shape their current policies, provide guidance based on how other departments handle the same decisions, and provide assistance in the decisionmaking process.

As a result of the current practices review, the project team recommended developing a rumble strip decision support guide, which was selected by the FHWA. The next chapter discusses the development of the decision support guide, the development of a model decisionmaking framework, and the vetting process used for departments to provide feedback on the guide.

CHAPTER 4. RUMBLE STRIP DECISION SUPPORT GUIDE DEVELOPMENT

INTRODUCTION

The purpose of the rumble strip decision support guide is to inform departments on CLRS and SRS installation. The guide describes methods for identifying appropriate locations for installation, assessing the potential crash reductions and B/C ratio, and developing performance metrics for safety. Additionally, this guide discusses special considerations for rumble strip installations, identifies variability in current designs and implementation criteria, and provides a decisionmaking framework for installing rumble strips.

The guide draws from the literature review and current practices review, and the decisionmaking framework is based on the best practices of departments that have been successful with installing CLRSs and SRSs. The next two sections describe the components of the guide that the project team incorporated from materials in addition to information found in the literature review and current practices review. These include discussion of rumble strips and safety-based implementation and the development of a model decisionmaking framework. Following these sections, the final section discusses the webinar review of the draft guide and concludes with a brief overview of the final guide.

EMPHASIS ON RUMBLE STRIPS AND SAFETY-BASED IMPLEMENTATION

Since rumble strips are implemented to improve safety, the emphasis of the guide is to provide a methodology for departments to assess the safety impacts, understand the potential benefits of rumble strip implementation, and develop implementation criteria that maximize safety benefits while minimizing impacts to non-motorists. The guide describes three implementation strategies: systemic, high-crash corridor, and systematic. The guide also provides information on the breadth of criteria used by State transportation departments for systematic installation and on performance measures that can be used for systemic and high-crash corridor installation. Further, the guide covers the determination of the following performance measures:

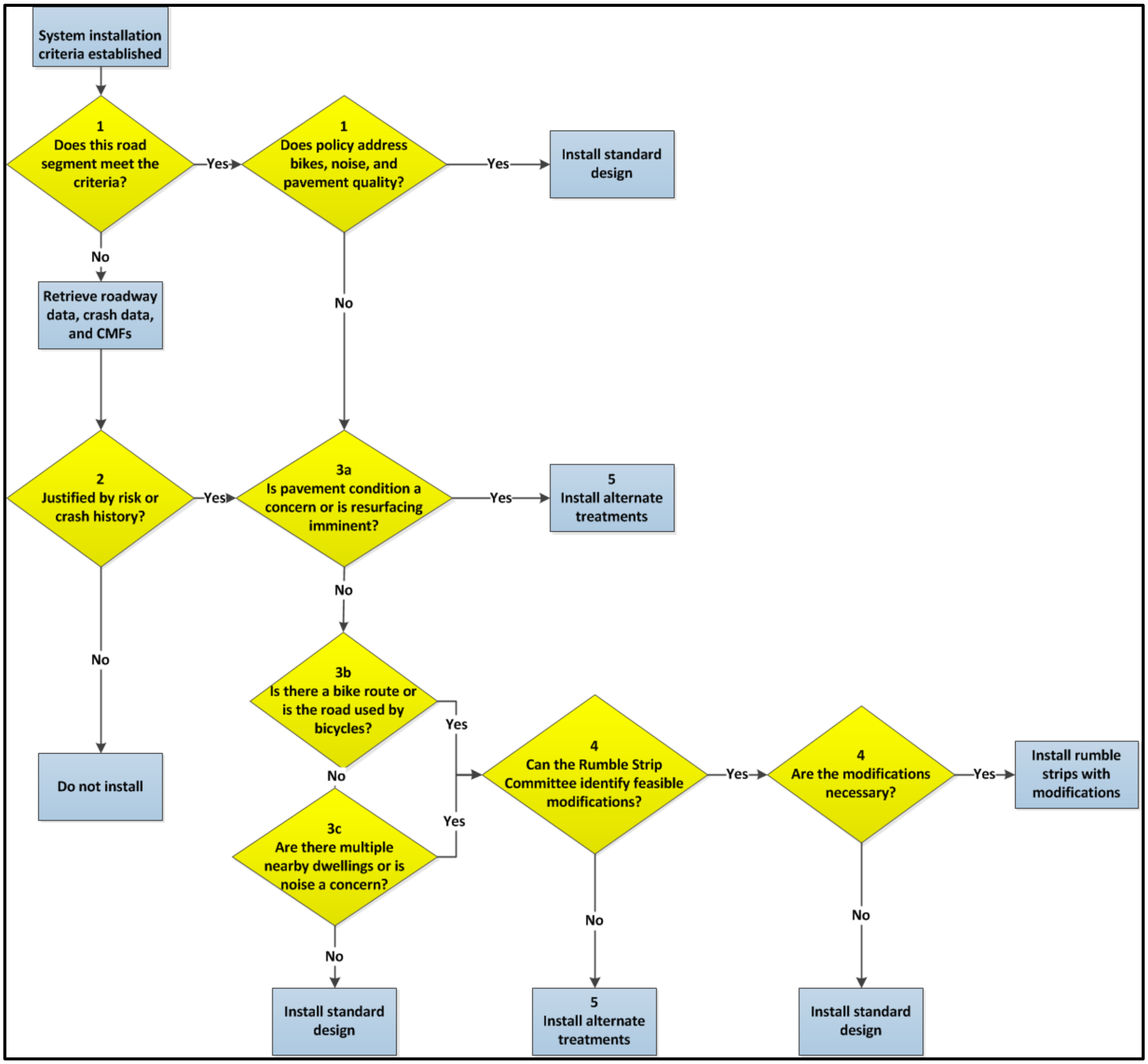
- Estimates of expected safety performance (e.g., expected crash frequency).
- Estimates of benefits through crash reduction by crash type.
- Estimates of benefits through crash costs reduced.
- B/C ratios for proposed installations.

Performance measures are used to identify potential sites that may benefit from installation, estimation of countermeasure effectiveness, and conducting of economic analyses. These measures bring a voice to the table for safety when considering benefits and trade-offs of installation.

The remainder of the guide focuses on a model decisionmaking framework based on best practices of departments successful with installing rumble strips on non-freeway highways. The next section discusses the development of a model decisionmaking framework for the guide.

DEVELOPMENT OF A MODEL DECISIONMAKING FRAMEWORK

Departments that have successfully installed CLRSs and SRSs on their rural two-lane and multilane systems generally have formalized processes for systematic installation and for decisionmaking on corridors that do not meet systematic criteria. It is important to identify corridors that can actually benefit from the treatment and to apply the most effective treatment possible while considering other roadway users and contexts. The guide provides a general model guidance for steps that may be included in a decisionmaking process, factors to consider, and who may be involved in such a process that can be used by departments struggling with implementation. Figure 10 provides an overview of the model decisionmaking framework. The framework is not intended to be directly applicable to every department because regulations, policies, practices, and organizational structure can vary across States. The framework offers a structured approach for increasing consistency and the chance of success in installing rumble strips to achieve safety benefits while providing a context-sensitive approach to reduce the impacts on non-motorists.



Source: VHB.

Figure 10. Flowchart. Model decisionmaking framework for rumble strip installation.

This model framework is based on an analysis of systematic installation (e.g., a roadway is being repaved and did not previously have rumble strips). Corridors may also be identified based on crash data analysis, and rumble strips may be selected as a candidate treatment. In this case, the installation has already been justified based on crash data, and the analyst would begin at step 3a of the decisionmaking process presented in figure 10. There are additional methods for project identification, and it is up to the analyst to determine which step to begin with in the process.

EXPLANATION OF MODEL DECISIONMAKING PROCESS

The guide contains a detailed description of the decisionmaking process shown in figure 10. Each decision point is "yes" or "no" after careful consideration by the appropriate parties. Each step includes an overview of the questions or trade-offs that may be considered, the parties involved, and what information is necessary for decisionmaking. The following steps are discussed in further detail:

1. Systematic installation.
2. Systemic and high-crash corridor installation.
3. Special considerations. These considerations include the following:
    - Step 3a: Pavement condition.
    - Step 3b: Bicyclist accommodation.
    - Step 3c: Noise accommodation.
4. Alternative rumble strip designs for accommodating bicyclists and/or noise.
5. Alternative treatments.

Each step is linked to a specific box in the model framework to show the flow and identify general relationships. The final decisions include installation of standard rumble strips, installation of modified rumble strips, installation of alternate treatments, or no installation.

WEBINAR REVIEW

The draft guide was reviewed by the project panel and then vetted by experts in the field. In order to accomplish the vetting process, 18 participants with experience with rumble strip implementation or oversight participated in a webinar review. The participants included representatives from State transportation departments and FHWA division offices. The vetting webinar participants provided extensive feedback on the guide both during the webinar and via electronic correspondence after the webinar.

Table 9 presents the State transportation departments and positions of participants in the guide review. Additionally, the contract manager, Dr. Abdul Zineddin, as well as Ms. Cathy Satterfield, Mr. Richard Albin, Mr. Andy Mergenmeier, and Ms. Aileen Varela from FHWA participated in the Web meeting.

Table 9. Webinar review participant affiliations and positions.

Affiliation	Position
Connecticut division of FHWA	Safety engineer/area engineer
ConnDOT	State safety engineer
Louisiana division of FHWA	Safety programs coordinator
LaDOTD	Highway safety manager
LaDOTD	Highway safety engineer intern
LaDOTD	Road design engineer administrator
Michigan division of FHWA	Safety and traffic operations engineer
MDOT	Pavement markings traffic engineer
Missouri division of FHWA	Safety and mobility engineer
MDT	Safety management system section supervisor
MDT	Traffic and safety bureau chief
Pennsylvania division of FHWA	Safety engineer
PennDOT	Safety engineering and risk management
South Carolina division of FHWA	Safety and traffic operations engineer
SCDOT	Safety program engineer
TxDOT	Safety engineer
TxDOT	Engineering assistant
Washington division of FHWA	Division safety/design engineer
WsDOT	Design policy and strategic analysis estimating manager

Members of the project team hosted the webinar. Webinar participants were given the draft guide prior to the meeting along with a request for written comments and a solicitation of case studies. The webinar was held on July 12, 2016, from 2–4 p.m. Participants were provided with a brief overview of the project history and background and a summary of each chapter in the guide. The project team then asked a series of targeted questions regarding the overall flow of the guide, specific information presented in each chapter, and other such questions. FHWA provided poll questions for several of the questions to direct the feedback received. Finally, the project team facilitated an open discussion that allowed for additional comments and feedback.

In addition to the webinar, the project team solicited written feedback on the guide and solicited potential case studies from participants. In total, six webinar participants (including the FHWA project team) provided written feedback on the guide. Overall, the feedback from participants was positive. They provided constructive and thoughtful comments that the project team considered afterward.

While many of the comments were minor, there were several suggested revisions that required further consideration. Those incorporated into the final guide included the following:

- The Selecting Sites for Installation section was rewritten to enhance the discussion of systemic, high-crash corridor, and systematic approaches to safety. Reviewers noted that rumble strips more often fulfill a systemic need (i.e., high-severity, low-density crashes) and are not often used to fulfill a hot spot type of approach. Therefore, emphasis was placed on systemic installation, and the hot spot approach was characterized as a high-crash corridor approach, indicating that rumble strips are applied on corridors. The introductory discussion notes that the most effective programs use a combination of approaches. Additionally, the systematic approach was further clarified from the systemic approach in that sites are excluded based on the needs of others and are not directly related to crash history or crash risk.

- The Identifying Rumble Strip Effectiveness section was shortened by removing example CMFs from the body of the guide and incorporating them in an appendix. The appendix can be used by readers to identify the highest-rated CMFs currently in the *Crash Modification Factors Clearinghouse*, but the body of the report focuses on using the clearinghouse itself. This emphasizes using the *Crash Modification Factors Clearinghouse* in the future to find high-quality CMFs that may not currently exist.

- Adjustments were made to the example problem. The original example problem (now example 2) was shortened in the body of the text to provide an overview of the necessary inputs and resulting performance measures. As requested by reviewers, the project team expanded on the example problem in an appendix and provided details on calculations for each step of the analysis. Additionally, a second example problem (example 1) was added to provide an example economic analysis for systemic rumble strip application.

OVERVIEW OF FINAL GUIDE

The final guide was published separately from this report and is a result of several review stages, initiated with a draft outline submitted to FHWA for review with the submission of the current practices review.(66) The project team reviewed FHWA's feedback, and the outline was further developed into a draft guide. The draft guide was once again reviewed by FHWA as well as webinar review participants. The feedback received at this time was very helpful, and the suggestions were used to revise the draft guide. The result is an approximately 60-page decision support guide entitled *Decision Support Guide for the Installation of Shoulder and Center Line Rumble Strips on Non-Freeways*, which can be found the FHWA Rumble Strips Web site.(1)

The guide comprises the following seven chapters:

- **Introduction**: This chapter provides background on the safety countermeasure, the purpose of the guide, and key definitions related to rumble strips.

- **Rumble Strips and Safety Management**: This chapter discusses the methodologies for implementing rumble strips as a safety countermeasure and methodologies for estimating the safety effectiveness and economic impact. Two examples are provided: one for systemic analysis and one for high-crash corridor analysis.

- **Special Considerations**: This chapter discusses key factors related to the impacts of rumble strips on bicyclists and motorcyclists, noise impacts on nearby residents, and perceived impacts to pavements.

- **Overview of Current and Successful Installation Practices**: This chapter identifies current practices that departments use for installation of rumble strips and identifies successful practices and methods for installing rumble strips based on high-crash corridor analyses.

- **Model Decision Support Framework for Rumble Strip Installation**: This chapter provides a framework for departments to follow based on current successful practices of departments with widespread rumble strip installation.

- **Case Studies**: This chapter includes case study examples where departments weighed the decision to install CLRSs or SRSs when there was potential concern for roadway users other than vehicles, nearby residents, and pavement condition. Examples are provided from Michigan, Minnesota, and Texas.

- **Other Resources**: This section provides links to related resources.

CHAPTER 5. INFORMATION GAP ANALYSIS AND ACTION PLAN

PURPOSE OF THE GAP ANALYSIS

The literature review and current practice review revealed several topics for which there is insufficient information. Additionally, research has been conducted for several areas related to rumble strips, but the state of knowledge has not converged on a consensus. The purpose of this section is to summarize the identified gaps, while the action plan identifies tasks and objectives necessary to fill in the knowledge gaps. The following is a list of identified gaps by topic area:

- **Rumble strip design**: The project team identified the following gaps for rumble strip design:
  - Departments have used a wide variety of designs; however, there is little evidence supporting the use of one design over another. Most evidence suggests that larger rumble strip dimensions (i.e., length and depth) increase the change in sound level over environmental noise inside and outside the vehicle; however, no studies have identified a safety differential based on rumble strip dimensions. Research has not converged on the best rumble strip design given constraints, including paved shoulder width, external noise pollution, and bicycle traversability.
  - The optimal offset for SRSs on non-freeway facilities has not been identified. NCHRP Report 641 noted that there is conclusive evidence that SRSs placed closer to the edge line are more effective on freeways.[8] However, non-freeways facilities have more considerations, including accounting for the trade-off between safety and the potential for incidental contacts. The optimal placement for the highest safety benefits with the lowest potential for incidental contacts is unknown.
  - NCHRP Report 641 indicated that rumble strips with smaller dimensions appear to be adequate for generating noise and vibration for passenger cars, while larger dimensions may be necessary for alerting drivers in heavy trucks.[8] Policies and standards that were reviewed did not discuss the potential for larger dimension rumble strips on roadways with heavy truck traffic. Additionally, policies did not discuss when a larger dimension rumble strip should be used if it was needed for trucks (i.e., a truck volume warrant).
- **Noise and vibration**: The project team identified the following gaps for noise and vibration:
  - Departments have made assumptions on the minimum level of sound necessary to alert a drowsy or inattentive driver; however, no research has been conducted to determine whether these assumptions are valid.
  - Due to the complexity of issues related to noise level, the literature review did not identify a standard method for assessing noise internal or external to the vehicle. The issue is complex due to the varying levels of ambient noise, nature of noise generated from rumble strips, and impacts of vehicle and tire characteristics on noise

generation. For internal noise, most studies used very similar equipment, but there were differences in the test speed and location of the sound level meter.

- Many departments struggle with handling noise impacts, defining locations where external noise will result in complaints, and managing the trade-off in providing gaps near residences and resulting offsets in terms of safety effectiveness. There is little consensus on how far rumble strips should be located away from residences, and residence density that may be required for gaps in the rumble strip pattern should be considered.

- Departments have been using two basic principles for mitigating noise. The first is to discontinue rumble strips in areas near residences or in areas where they will be inadvertently struck (i.e., intersections and driveways). The second is to use rumble strip patterns that reduce external noise through reduction in rumble strip length or depth or by using an alternative design such as sinusoidal. The safety impact of this decision is unclear. Discontinuing rumble strips results in the greatest reduction in external noise but has the potential for the greatest reduction in rumble strip effectiveness. Reducing the noise level generated by rumble strips will still create external noise but has the potential to provide a continuous benefit for preventing roadway departure crashes.

- Several departments noted that different patterns for CLRSs and SRSs are specified to differentiate between the two. However, this is not a consistent practice, and no studies have shown that drivers understand this to be the case for those States that do so.

- **Bicyclist, motorcyclist, and pedestrian impacts**: The project team identified the following gaps for bicyclist, motorcyclist, and pedestrian impacts:

  - As with noise mitigation, there have been two general principles for altering rumble strip patterns for bicyclists. The first is to create gaps in the pattern for bicyclists to cross, and the second is to use an alternative pattern that is more bicyclist friendly. It has not been substantiated how these changes impact rumble strip safety effectiveness.

  - There is little research examining adequate shoulder width from the rumble strips to the outside of the shoulder. None of the studies recommended a minimum shoulder width; however, the AASHTO guide did recommend a minimum shoulder width of 4 ft.(26)

  - No research studies to have studied the impacts of rumble strips on pedestrian or bicyclist safety. No CMFs have been developed for vehicle-pedestrian or vehicle-bicycle crashes, and the same is true for vehicle-motorcycle crashes.

- **Pavement condition impacts**: The project team identified the following gap for pavement condition impacts:
  - Most assessments of pavement condition are anecdotal in nature. There is little quantitative research identifying the impacts of rumble strips on pavements, particularly longitudinal joints, yet departments still often struggle to implement rumble strips in these locations. Additionally, further research is needed to more fully understand the impact of pavement depth, especially for thin overlays and chip seals.
- **Pavement marking visibility**: The project team identified the following gap for pavement marking visibility:
  - Research studies have not conclusively determined the impact of ELRSs and profiled thermoplastic pavement markings on wet nighttime pavement marking visibility. Smadi and Hawkins noted that very few States have measured wet retroreflectivity of rumble stripes.(9) Further research is needed to conclusively assess pavement marking visibility, particularly rumble stripes.
- **Safety effectiveness**: The project team identified the following gaps for safety effectiveness:
  - While the aggregate benefits of CLRSs and SRSs/ELRSs have been clearly demonstrated for standard installations of 12- and 16-inch rumble strips, departments are using alternative designs for reducing impacts on other roadway users and for reducing external noise. Research studies have not established whether there are trade-offs in safety benefits for narrower rumble strips, designs with gaps for bicyclists, or shallower "bicycle-friendly" rumble strips. Additional insights would also allow decisionmakers to consider shallower rumble strips for thin overlays if research shows no loss of safety effectiveness.
  - The safety effectiveness of profiled thermoplastic pavement markings or reflective pavement markers as rumble strips should be established to determine how the benefits compare to milled ELRSs.
  - Few of the safety studies reported the dimensions of the evaluated rumble strips. In the case of Torbic et al., the researchers noted that all designs were considered together because it was difficult to verify the dimensions of the strips being studied.(8) Future work should further examine the relationship between rumble strip design and safety effectiveness.
- **Development of an implementation tool**: The project team identified the following gaps for the development of an implementation tool:
  - Departments observed different needs and uses for a rumble strip tool to help with installation decisionmaking. Departments that have set design standards and clear policies for rumble strips seem more disinclined to the development of the rumble strip tool, whereas departments that were still developing or looking at research

were more apt to accept the idea of a tool. Some departments, such as FHWA's EFL, struggle with justifying the installation of rumble strips and have little to no rumble strips in their area. Alternatively, LaDOTD has clear policies and little pushback on rumble strip installation, which leads them to find little use for a tool that will help inform decisionmaking with a lack of hard evidence to back up decisionmaking. Although there are vast differences between the departments surveyed, there is a common theme that better information would help inform decisionmaking. Additionally, the interview departments indicated that there is rarely an instance where a blanket solution exists. Rumble strip installation typically involves the consideration of several users and the use of crash history and may require committee recommendations or vetting with outside groups, such as bicyclist groups. All departments indicated that they would be willing to consider a rumble strip tool, but successful departments' needs differ from those of struggling departments.

- Additionally, departments identified the following needs for a rumble strip implementation tool:
    - The ability to make optimized recommendations based on roadway and roadside characteristics.
    - The ability to exist as a warehouse or inventory for maintaining rumble strip data and mapping capabilities. This would allow the department to know where rumble strips are already in place and to conduct effectiveness evaluations more easily.
    - The ability to incorporate SPFs and CMFs to rate the effectiveness of potential installations. More positive evidence increases buy-in.
    - The ability to recommend alternatives to rumble strips for situations where rumble strip installation cannot be accommodated.

ACTION PLAN

The action plan serves as a list of objectives that are grouped under overarching goals. Ordering of goals and objectives are not sequential in nature; in most cases, projects can be executed in any order. However, some objectives should be ordered. For example, bicyclist- and noise-related performance measures should be established before researching the ideal design dimensions for further implementation. The following list provides overarching goals and objectives or potential future project objectives necessary to fulfill the goals:

- **Goal 1—Establish safety effects of rumble strips**: This goal includes the following objectives:
    - **Objective 1**: Identify safety impacts of rumble strip dimensions and determine whether decreasing dimensions reduces the safety effectiveness or whether crash reductions are retained. This research can use the many miles of rumble strips that are already in place that have not been evaluated. The findings of this research are important to determine whether larger rumble strips are necessary to achieve

reductions or whether smaller rumble strips will suffice. This is important for research related to special considerations (i.e., noise and bicyclists) and for interactions with roadway geometry (i.e., narrow rumble strips on narrow shoulders).

  - **Objective 2**: Identify safety impacts of noise-reducing rumble strips. Departments have been using shallower rumble strips as well as sinusoidal rumble strips to reduce external noise pollution. No research studies to date have identified the safety effects of shallower rumble strips or sinusoidal rumble strips as alternatives to more traditional design dimensions.

  - **Objective 3**: Identify safety impacts of rumble strips on bicyclists and identify crash-based optimal design of bicycle gaps if available (perhaps gaps can even be larger than current?). It is unclear how rumble strip placement and rumble strip bicycle gaps affect vehicle-bicycle crashes. Additionally, the safety effectiveness of bicyclist-friendly rumble strips is unclear.

  - **Objective 4**: Identify relationship between rumble strip safety effectiveness and roadway geometry. As with rumble strip placement (i.e., offset), future research should determine whether effectiveness varies by shoulder width and should determine whether there is an interaction between rumble strip dimensions, placement, and shoulder width. Additionally, future research should identify whether there is a differential effect on horizontal curves and horizontal tangents.

- **Goal 2—Identify performance measures for noise for trade-off analysis**: This goal includes the following objectives:

  - **Objective 1**: Develop a standardized testing method for external noise (i.e., vehicle speed and location). A standardized method may help departments develop external noise models and identify rumble strip design criteria based on proximity to residences. Noise models will need to consider the issues related to ambient noise level, characteristics of noise generated by rumble strips, and complexities associated with vehicle and tire characteristics and their impact on noise generation.

  - **Objective 2**: Smadi and Hawkins noted that only two departments have specifications for audible and palpable warnings.[9] Research should consider how powerful these warnings need to be to alert drowsy or distracted drivers at a minimum and how they can best be measured. Additionally, research should determine whether rumble strips can produce an optimal alert and whether a different pattern for the center line and shoulders can be readily apparent to distracted or drowsy drivers.

  - **Objective 3**: Quantify noise threshold and/or frequency of strikes for nearby residences. Defining these standards may help departments more successfully install the optimal design near residences. The optimal design should maximize safety, reduce noise as much as possible, and result in a level of incidental contacts that may be tolerable by nearby residents. Developing models for incidental contacts may help optimize rumble strip offset based on the roadway's geometric characteristics. In combination with assessing the safety impacts of rumble strip offset and shoulder width, an optimal location may be found.

- **Goal 3—Identify performance measures for bicyclists for trade-off analysis**: This goal includes the following objectives:
  - **Objective 1**: Develop performance measures for bicyclists for rumble strip trade-off analysis. Crash reduction and noise level changes can be quantified, but it is difficult to determine how rumble strips (or lack thereof) impact bicyclist activity or safety. Future research should develop performance measures that can objectively be weighed against other factors, such as rumble strip installation or shoulder widening with rumble strip installation for alternatives analyses.
  - **Objective 2**: Quantify high versus low or medium bicycle usage and methods for data collection. Departments often use bicycle usage as a factor for making the decision on whether or not to install rumble strips on narrow shoulders. However, there are no guidelines for determining how much activity would preclude a narrow shoulder for installation. Quantifying use may also help with alternatives analysis for higher cost solutions, such as combined shoulder widening and rumble strip installation.
- **Goal 4—Establish effects of pavement condition and depth on deterioration**: This goal includes the following objectives:
  - **Objective 1**: Quantify performance measures for pavement condition. Many departments specified that the pavement must be in good condition or it will not be resurfaced within the next few years for rumble strips to be placed. However, few States had specific measures of "good condition," and it is unclear whether rumble strips have a negative impact on already poor pavement that is scheduled for resurfacing.
  - **Objective 2**: Assess the impacts of rumble strips on pavement deterioration. This objective was identified in NCHRP Report 641 and by Smadi and Hawkins.[8,9] Smadi and Hawkins note that several departments have electronic databases with locations of rumble strips. This information can be used with pavement condition data to model the relationship between pavement deterioration and rumble strip presence.
  - **Objective 3**: Identify the maximum rumble strip depth by depth of the pavement top layer. Departments differ on the minimum depth of the top layer of pavement for rumble strip installation. Further guidance may be useful for considering the rumble strip dimensions that may be used by the pavement depth existing on the roadway.
- **Goal 5—Develop an optimization tool based on goals 1–4 and existing rumble strip implementation policies**: This goal includes the following objectives:
  - **Objective 1**: Identify preferable platform for housing the optimization tool. A Web-based tool may be easier to update with new information, but a spreadsheet tool may be easier for users to navigate.

- **Objective 2**: Develop decision logic for navigating user inputs and providing recommended rumble strip or alternative treatments. The logic should be based on best practices used by successful departments with performance measures and optimization algorithms developed based on research in goals 1–4.

- **Goal 6—Identify impacts of current in-vehicle technologies and future in-vehicle technologies on rumble strip needs**: While not directly addressed in this research, future in-vehicle technologies may impact the need for or effectiveness of rumble strips. With lane-keeping technology, the vehicle may alert the driver when the driver is leaving the travel lane. The effectiveness of this technology will depend on market penetration and the reliability of the assistive technology. This may eliminate the need for rumble strips altogether or may result in more conservative application for noise sensitive or recreational areas (i.e., areas with bicyclist activity).

- **Goal 7—Identify the impacts of rumble strips on driver behavior**: Researchers can use the second Strategic Highway Research Program Naturalistic Driving Study data to identify how the presence of SRSs, CLRSs, and their combination impact in-vehicle behaviors. Additionally, the data can be used to look at variations in rumble strip dimension and roadway geometry to further identify optimal rumble strip designs by roadway geometry.

APPENDIX A. INTERVIEW QUESTIONS

Appendix A includes the verbatim list of questions provided to the five State transportation departments and FHWA's EFL. The project team provided the questions in advance for review. ConnDOT, TxDOT, and FHWA's EFL provided direct responses to each of the questions. For all departments, the questions were used to drive the discussion during the interview. Questions were categorized into the following categories:

- General.
- Maintenance/installation/cost.
- Bicyclist accommodations.
- Noise policy.
- Approval/buy-in.

INTERVIEW QUESTIONS

General

1. How would you characterize your State's need for a rumble strip application tool?
2. What would be some preferred characteristics in terms of tool platform and functionality?
3. Do you have a policy for using shoulder, edge line, and/or centerline rumble strips on rural, two-lane, two-way roadways? If yes:
    a. Do you install on a case-by-case basis?
    b. On resurfacing projects are rumble strips a consideration/mandatory?
    c. Do you have a program to install rumble strips separate from paving projects?
    d. Under what conditions and circumstances does your State consider rumble strips? Are lower-cost delineation enhancements (e.g., signage and/or striping strategies) always considered first?
4. Does your State require a certain speed limit, or width of roadway for shoulder rumble strip and/or centerline rumble strip application?
5. Do you have a minimum shoulder width or remaining shoulder width beyond the rumble strip for use of shoulder or edge line rumble strips? If so, would you consider them facilities with lesser shoulders if there was a history of roadway departure crashes?
6. Would you consider narrower length (4-inch to 6-inch) rumble strips?
7. Does crash history dictate implementation of rumble strips? Is there a specific level of crash history and is there an expected level of crash reduction considered?
8. Has your State faced issues that had necessitated removal of rumble strips? How have you revamped your policies to continue the rumble strip program?

Maintenance/Installation/Cost

1. What are the effects of rumble strip installation on existing roadways especially regarding the pavement deterioration?

2. Does your State have a specific policy regarding pavement condition prior to rumble strip installation? If so, how is pavement condition assessed? If pavement condition is not adequate, are any modifications made to allow for installation?

3. Do you have a minimum offset specification for longitudinal joints or edge of pavement?

4. Does your State allow for raised rumble strips? If so, how does your State consider using raised rumble strips versus milled rumble strips? What is the lifecycle cost, pavement service life, and service life of raised rumble strips?

5. Do you have guidelines with rumble strips regarding snow removal, or have weather related issues due to excess rain and hydroplaning? Are rumble strips implemented in areas of bad weather for guidance when visibility is poor?

6. Have you experienced debris collecting in the rumble strips?

7. Do you use fog seal when applying rumble strips? Does the fog seal enhance the rumble strip longevity/performance? Is the fog seal a hindrance during application? Does the fog seal show any positive return results? Is it only an issue when the pavement marking is located directly over top of the rumble strip?

8. Do you install rumble strips on open-graded friction course (OGFC) pavements? If so, what are the impacts?

9. Are there any pavement types where rumble strips are not used? Is there a difference for new installations versus existing pavement?

10. Has your State ever researched the use of one-sided rumble strips? If so how might they be used or implemented in your State?

11. What is your centerline rumble strip policy for passing zones? Has safety been analyzed in regards to centerline rumble strips for passing zones?

12. Does your State have an AADT threshold for installation of a centerline rumble strip? Does your State have an AADT threshold for installation of shoulder rumble strips?

13. Does your State have a policy regarding edge line rumble stripes? How do you decide when to use edge line rumble stripes or to offset the rumble strips on the shoulder?

14. Does your State have any specific criteria for installing centerline and shoulder rumble strips in combination?

15. Do you have any policies in place for gaps in the rumble strip pattern other than for bicyclists? For example, do you have gaps for passing zones, at driveways, intersections, or on the inside of horizontal curves?

16. Do you install rumble strips on bridge decks? If so, how are rumble strips installed?

Bicyclist Accommodations

1. How does your State accommodate bicyclists? Are bicyclists considered for every shoulder rumble strip installation or only when bicyclists are expected? Do you have separate standards for bicycle locations and non-bicycle locations?

2. Does your State provide gaps for bicyclists? If so, what pattern do you use (e.g., 12 ft every 60 ft)?

3. Do you have a minimum shoulder width specified for bicyclists? Does this differ from the required minimum shoulder width if bicyclists are not expected?

4. How do you address bicycle outreach? Are there any outspoken bicyclist or motorcycle unions that have input into your policies?

5. Do you consider alternative designs for areas with potential bicyclist concerns? For example, would you consider a shorter length, shorter depth, or an alternative pattern (e.g., sinusoidal design)?

Noise Policy

1. Does your State struggle with noise complaints, despite outreach prior to installation? If so, how do you address these complaints? What public outreach did you perform before the installation of rumble strips?

2. Does your State have distance criteria from residences? If so, is the criteria based on expected noise level or is it a pre-defined distance?

3. In regards to hamlets (small villages along a rural corridor), what are your equivalent policies/procedures regarding installation adjacent to residential areas?

4. Has your State found that rumble strips impact nearby wildlife?

5. If nearby noise is within an acceptable limit (specified in question 2), how do you address the public due to the different type of noise that the rumble strips produce?

6. Has your State conducted noise studies? How do you apply the findings to rumble strips?

7. Do you consider alternative designs for areas with potential noise concerns? For example, would you consider a shorter length, shorter depth, or an alternative pattern (e.g., sinusoidal design)?

Approval/Buy-In

1. What outreach has your agency conducted prior to installation? Who has the outreach targeted (e.g., motorcycle groups, bicycle croups, neighborhoods)?

2. What methods have you used to gain upper management/elected officials approval/buy-in?

3. What type of material do you use to gain public acceptance and perceptions regarding rumble strips? Flyers, informative videos, DOT Web site dedicated to rumble strip information and installation?

4. How do you sell rumble strips in residential areas with documented crash histories?

APPENDIX B. FOLLOW-UP PHONE INTERVIEWS

Appendix B includes notes taken from follow-up interviews with departments and FHWA's EFL. Additionally, verbatim department responses to the questionnaire provided in appendix A are included for those States and/or agencies that submitted responses, which include the following:

- ConnDOT.
- FHWA's EFL.
- LaDOTD.
- MnDOT.
- MDT.
- TxDOT.

Additionally, ConnDOT, FHWA's EFL, and TxDOT provided direct responses to the appendix A questionnaire. The following sections provide notes from each follow-up interview. The notes include whether the discussion is from the project team or the transportation department.

CONNECTICUT

Follow-up Interview Meeting Notes

Date: Wednesday, March 02, 2016

- The project team asked if a policy review module would help ConnDOT with decisionmaking in addition to providing safety benefits?
    - ConnDOT was unclear what exactly the tool would contain, so the project team briefly reviewed the tools general concept.
    - ConnDOT stated that the tool would benefit them and would prefer a standalone tool instead of combining it with anything else. Also, ConnDOT would like to see the tool automate the process of outputting the depth and width, among other dimensions, for the rumble strip.
- The project team asked what the barriers to implementation have been and how has ConnDOT begun to overcome those barriers? What issues are ConnDOT still wrestling with for SRSs?
    - ConnDOT has a very active cyclist community.
    - The barriers are more perceived then actual because CLRSs and SRSs are still in their infancy and rumble strips are a new concept that people are not familiar with in CT.
- The project team asked if ConnDOT is developing or has developed standards for SRSs or ELRSs on rural two-lane highways.

- ConnDOT does not have any official standards yet but they are working on them and making adjustments as they go. They attended a peer exchange and learned about sinusoidal rumble strips and the most current trends. ConnDOT noted that they have adjusted their standards accordingly.

- The project team asked if there is anything that can help move the SRS/ELRS program forward. Would being able to see what other States do (especially nearby States) help with their decisionmaking?
  - ConnDOT stated that more funding would always be helpful.
  - ConnDOT learned in a recent peer exchange about the CLRS and the different types of rumble strips. They discussed these options in-house and have adopted California's standard for CLRSs.
- ConnDOT mentioned that the public has perceived that rumble strips help traffic calming. ConnDOT uses them for safety; however, it has helped making rumble strips more accepted within communities.
- ConnDOT has held a few public meetings regarding rumble strip installation but not a lot of people have attended.
- ConnDOT's main struggle has been internal. ConnDOT historically has identified hot spots and has completed projects based on risk factors so it has been a challenging getting the agency to buy-into systemic application.

Interview Questions

General

1. How would you characterize your State's need for a rumble strip application tool? **If a tool was developed that could show/rate the effectiveness (CMF) of installing CLRS on a road it would help the design process as well as allow for a chance to give Cities/Towns more positive evidence to increase buy in.**
2. What would be some preferred characteristics in terms of tool platform and functionality? **The tool would need to have adjustments for ADT, Lane Width, etc. to be able to predict the number of expected crashes at a proposed location**.
3. Do you have a policy for using shoulder, edge line, and/or centerline rumble strips on rural, two-lane, two-way roadways? If yes: **Centerline rumble strips are new to CT with approximately 40 mi of CLRS installed and 200 more mis set to be installed in 2016. Because they are new, they have only been considered/used as a systemic treatment. CT does not currently have any shoulder rumble strips on two lane roadways**.
4. Do you install on a case by case basis? **See Above – a**.

5. On resurfacing projects are rumble strips a consideration/mandatory? **No. CLRS are being installed systemically. CT does install Shoulder RS on all Limited Access Highways**.

6. Do you have a program to install rumble strips separate from paving projects? **Yes, there have been two RS projects constructed and two more in design since 2014 that have been standalone RS projects**.

7. Under what conditions and circumstances does your State consider rumble strips? Are lower-cost delineation enhancements (e.g., signage and/or striping strategies) always considered first? **See Above – a**.

8. Does your State require a certain speed limit, or width of roadway for shoulder rumble strip and/or centerline rumble strip application? **CLRS are installed to reduce head-on and sideswipe opposite crashes and are most effective in reducing injuries and fatalities at higher speeds. Due to the nature of the CT State highway system, CT's minimum speed limit for CLRS is 35 MPH. A major concern with CLRS comes from the bike/ped community who are worried about cars not wishing to cross the CL and encroaching on the shoulder. It is best to install CLRS on roads with a satisfactory shoulder for pedestrian use and in CT we've chosen a minimum width of 26' to install CLRS**.

9. Do you have a minimum shoulder width or remaining shoulder width beyond the rumble strip for use of shoulder or edge line rumble strips? If so, would you consider them facilities with lesser shoulders if there was a history of roadway departure crashes? **The minimum shoulder width for installing Shoulder RS is 3'. Shoulder RS are only installed on limited access highways**.

10. Does crash history dictate implementation of rumble strips? Is there a specific level of crash history and is there an expected level of crash reduction considered? **Due to the infancy of the CT CLRS program, there have only been systemic installations of CLRS and not enough data to develop any CT tailored crash reduction factors. Crash history can certainly dictate that CLRS "should" be installed but there is no policy for it in CT**.

11. Has your State faced issues that had necessitated removal of rumble strips? How have you revamped your policies to continue the rumble strip program? **Connecticut previously installed rumble strips at a high-crash location in 1999. These rumble strips were removed within a year due to the large number of noise complaints, and it took until 2014 to begin trying installing CLRS again**.

Maintenance/Installation/Cost

1. What are the effects of rumble strip installation on existing roadways especially regarding the pavement deterioration? **CT doesn't have enough data to document any negative effects**.

2. Does your State have a specific policy regarding pavement condition prior to rumble strip installation? If so, how is pavement condition assessed? If pavement condition is not adequate, are any modifications made to allow for installation? **No. However, CT has chosen to install CLRS on State roads that have been repaved within 4 years of the installation date. This number comes from the paving management unit which told us**

that the pavement remains in good condition for up to 4 years. Pavement condition for local roads comes from observation and input from the municipalities. **CT has not modified any existing roadways to exclusively accommodate rumble strips**.

3. Does your State allow for raised rumble strips? If so, how does your State consider using raised rumble strips versus milled rumble strips? What is the lifecycle cost, pavement service life and service life of raised rumble strips? **No**.

4. Do you have guidelines with rumble strips regarding snow removal, or have weather related issues due to excess rain and hydroplaning? Are rumble strips implemented in areas of bad weather for guidance when visibility is poor? **No, CT has no guidelines for snow removal but for that reason does not use raised rumble strips. CLRS have only been installed systematically. CT's smaller size lends to believe the whole state receives similar weather. It is understood that the CLRS may improve CL delineation, but it has not been causation for installation. CT municipalities have shown interest in CLRS for traffic calming reasons**.

5. Have you experienced debris collecting in the rumble strips? **CT has not had any problems with debris**.

6. Do you use fog seal when applying rumble strips? Does the fog seal enhance the rumble strip longevity/performance? Is the fog seal a hindrance during application? Does the fog seal show any positive return results? Is it only an issue when the pavement marking is located directly over top of the rumble strip? **CT does not use fog seal**.

7. Do you install rumble strips on open-graded friction course (OGFC) pavements? If so, what are the impacts? **N/A. CT uses some Ultra thin bonded HMA**.

8. Are there any pavement types where rumble strips are not used? Is there a difference for new installations versus existing pavement? **Previously, chip sealed pavements were avoided for installation of rumble strips. After hearing from a RS peer exchange that chip sealed do not show any extra deterioration from RS, CT has decided to accept chip sealed roads in future projects**.

9. What is your centerline rumble strip policy for passing zones? Has safety been analyzed in regards to centerline rumble strips for passing zones? **CT does not install CLRS in passing zones, with the main reason being trying to limit any noise created by vehicles hitting CLRS legally/purposefully (as opposed to accidentally hitting them in a non-passing zone)**

10. Do you have any policies in place for gaps in the rumble strip pattern other than for bicyclists? For example, do you have gaps for passing zones, at driveways, intersections or on the inside of horizontal curves? **CT does not install CLRS in passing zones, where there is a break in the centerline or on bridge decks**.

Bicyclist Accommodations

1. How does your State accommodate bicyclists? Are bicyclists considered for every shoulder rumble strip installation or only when bicyclists are expected? Do you have separate standards for bicycle locations and non-bicycle locations? **The only consideration for bicycle activity is to install CLRS on roadways 26' wide or more. CT has not installed shoulder rumble strips, and therefore bike gaps, on SR's**.

2. Does your State provide gaps for bicyclists? If so, what pattern do you use (e.g., 12 ft every 60 ft)? **N/A**

3. Do you have a minimum shoulder width specified for bicyclists? Does this differ from the required minimum shoulder width if bicyclists are not expected? **Minimum shoulder width for shoulder rumble strips on Limited Access Highways is 3'. No bicycle activity on LAH**.

4. How do you address bicycle outreach? Are there any outspoken bicyclist or motorcycle unions that have input into your policies? **During design, a bicycle and pedestrian assessment form is submitted to the Office of Intermodal Planning for their consideration. A letter is sent to all chief elected officials to explain the project and allow them to request a public meeting**. **There is no CLRS policy so there has not been any feedback from the community**.

5. Do you consider alternative designs for areas with potential bicyclist concerns? For example, would you consider a shorter length, shorter depth, or an alternative pattern (e.g., sinusoidal design)? **Connecticut does have a complete streets policy that does have designers consider bicyclists everywhere. CT has one standard application for CLRS**.

Noise Policy

1. Does your State struggle with noise complaints, despite outreach prior to installation? If so, how do you address these complaints? What public outreach did you perform before the installation of rumble strips? **Only a few complaints thus far. These noise complaints were handled by a staff member who explained the safety benefits of rumble strips. A letter was sent to the chief elected official as well as the local traffic authority informing them of the project and allowing a chance for the municipality to request a public hearing/informational meeting**.

2. Does your State have distance criteria from residences? If so, is the criteria based on expected noise level or is it a pre-defined distance? **There is no defined distance from house to road. Design takes into consideration proximity and density of residences along candidate locations**.

3. In regards to hamlets (small villages along a rural corridor), what are your equivalent policies/procedures regarding installation adjacent to residential areas? **N/A**

4. If nearby noise is within an acceptable limit (specified in question 2), how do you address the public due to the different type of noise that the rumble strips produce? **In Connecticut's**

noise analysis of our own CLRS, it was found that during busy traffic periods, the rumble strips produced a noise with a db level similar to the ambient traffic. The issue with our complaints have been at quieter hours when the rumble strips are hit and produced a noise higher than the ambient level, and also the pitch of the sound was different. Our strategy has been to try and educate the public on the safety benefits of CLRS, and that helps offset concerns about noise.

Approval/Buy-In

1. What outreach has your agency conducted prior to installation? Who has the outreach targeted (e.g., motorcycle groups, bicycle croups, neighborhoods)? **A letter is sent to the chief elected official and LTA of the city/town and a request is made to concur with the project or request a public hearing/informational meeting**.

2. If a Public meeting is requested, a press release is circulated in a mainstream newspaper to inform the public of the meeting. At the meeting a presentation is given and followed up by a Q&A. **We have not had any outreach to any other groups such as motorcycle or bicycle groups**.

3. What methods have you used to gain upper management/elected officials approval/buy-in? **Install CLRS on both State and locally owned roads, under State projects so municipalities do not have to pay. Describe the safety benefits of CLRS and offer help to choose quality candidate locations. CLRS fit under the strategies of Connecticut's Strategic Highway Safety Plan, which has helped gain internal support for their installation**.

4. What type of material do you use to gain public acceptance and perceptions regarding rumble strips? Flyers, informative videos, DOT Web site dedicated to rumble strip information and installation? **The State is preparing these rumble strip projects to install them on State and Local roads at no cost to the municipalities. There is a link on the CT DOT Web site which brings you to a brochure on the benefits of CLRS**.

5. How do you sell rumble strips in residential areas with documented crash histories? **Our efforts to sell rumble strips will center around their safety benefits**.

FHWA'S EFL

Follow-up Interview Meeting Notes

Date: Monday, February 29, 2016

- EFL provided a brief overview of the role of EFL and what they do. EFL's role includes the following:
    - Provides technical assistance to Federal agencies.
    - Provides planning, engineering, and construction (including road safety) but does not own any roadways.

- Noted that wildlife and environmental issues are typically a large concern; noise is a huge concern.

- The project team asked a follow-up to EFL's comment in the written interview questions, regarding using signage, striping etc. before using rumble strips. The discussion included the following:
  - The EFL noted that around curves they suggest chevron signage or even pavement markings.
    - A lot of roads do not have edge lines or signage because the partners (customers) do not like the visual clutter or how the stripes effect the wildlife. When asked if signage has been effective, EFL noted that no-one has complained that signage has not been working.
    - The EFL installed rumble strips in the Great Smoky Mountain National Park but they were installed improperly, so there has been some push back regarding rumble strips.
    - EFL has a new project coming in to hopefully fix the rumble strips.
  - The project team asked if there was any buy-ins or approvals needed when the Smoky rumble strips were installed?
  - The EFL responded that they do not believe so.

- The project team asked the EFL what they would like to see in a rumble strip tool and if they would prefer it to be stand alone or in another tool? The EFL responded that it needs to be user friendly. If it is too complicated their engineers will not even open it. They recently received a striping tool that was in excel and it was easy to use and generally accepted with the engineers. The EFL made several additional notes, including the following:
  - They would like to see an alert for minimum lane width and shoulder widths. Also, they would like the tool to specify how to apply rumble strips in different situations.
  - They mentioned a picture from a peer review exchange with a rumble strip located right next to a rock wall and noted how this might not be very useful since the driver might hit the rock anyways. They would like to see a tool that would address different situations (e.g., alerts for narrow lane width, narrow shoulder width, or narrow roadside).
  - They noted that the tool could recommend alternatives to rumble strips.
  - They noted that from the Peer Exchange most States are providing rumble strips everywhere; therefore, the tool may not help these States, but it could help States that are struggling.

    - They also noted a lack of consistency between customers; there are hundreds of people (e.g., park managers) to say no and it is difficult to sell the effectiveness.

- The project team asked if EFL has proposed rumble strips in other areas. The following discussion ensued:

    - The EFL has proposed rumble strips in other areas and received push back. But they receive push back for everything from edge line striping to signage and rumble strips. They usual justify their decision by crashes.

    - The project team asked if having figures and results showing the usefulness of rumble strips would be helpful?

    - The EFL noted that yes it would be helpful in defending their safety suggestions.

    - The project team asked if there is currently a threshold for percent crashes or other circumstances that makes installing rumble strips, edge line and signage easier to justify?

    - The EFL noted that there is no threshold.

- The project team asked if the EFL has any standards or details for bicycle use and rumble strips. The EFL responded that they do not but would need to look into this if they installed rumble strips. They noted that many professional bicyclers go very fast on EFL roadways.

- The project team asked if the EFL has any approvals or buy-ins when suggesting rumble strips. The EFL responded with No. Projects are approved unit by unit, so each situation is approved by different individuals.

- The EFL noted that they are currently looking into systemic installation of rumble strips. There has been positive change in opinions regarding rumble strips recently. Also, the unit manager makes the ultimate decision regarding which application to use on each project.

- The project team asked if the EFL has any standards or details regarding rumble strips? When the EFL was involved in the peer exchange they noticed a lot of states are just using systemic installation of rumble strips. This halted the current standards that Central Federal Lands was working on. They do not have finalized plans but they do have a word document that EFL will send to the project team.

Interview Questions

1. If FHWA develops a rumble strip application tool, will you use it? **Yes.** Do you see the usefulness of the tool in the near-term or potential tool requirements in the future? **Yes.** Would you have preferences as to what you would like in the tool platform and/or its functionality? **I am not sure what platform you are able to develop. At least an Excel**

type file would work if that is what you are thinking. Something user friendly and not too laborious so engineers here can use it.

2. When does a State consider rumble strips? Does a state try signage, striping, and other enhanced delineation before considering rumble strips if the short-term improvements don't provide the intended reduction in crashes? **In the case of Federal lands, yes, we try signage, striping and other delineation before proposing rumble strips since our partners (customers) are very sensitive to the noise rumble strips would create to the environment.**

Maintenance/Installation/Cost

1. On resurfacing projects are rumble strips a consideration/mandatory? **No.**

LOUISIANA

Follow-up Interview Meeting Notes

Date: Tuesday, March 8, 2016

- The LaDOTD began by explaining that they have a complete streets policy for non-motorized vehicles that focuses on pedestrians along with a safety coalition. These groups have to report progress to the legislature. They also have an advisory council (12–13 people that meet quarterly), which includes FHWA, upper management, senior citizen advocates, and bicycle groups with an additional internal steering committee. LaDOTD has a lot of groups that advise and review plans before rumbles are even installed.

- The project team asked the LaDOTD to characterize their need for a rumble strip application tool. The LaDOTD responded by stating that they already have a standing policy with no push back so they would have no use for the tool. However, they may consider using it depending on tool information and interface.

  - The project team asked the LaDOTD for their thresholds for rumble strips installation. The LaDOTD responded with the following criteria: 50 mi/h threshold.

  - CLRS program requires a minimum of 22 ft of pavement that isn't older than 10 years.

  - 10 ft every 40 ft on everything except limited access roadways.

  - 4-ft minimum shoulder for shoulder rumble strips and occasionally less than 4 ft.

  - For SRS on greater than 22-ft paved roadway.

  - For CLRS and ELRS on greater than 28-ft paved roadway.

  - Milled rumble strips—Raised markings on bridges and approach slabs because LaDOTD does not allow milling on bridges.

- Concrete—Can form them as long as they are the same as the milled rumble strips.

- The project team asked if LaDOTD had faced any issues with rumble strips. The LaDOTD indicated no push back for CLRS or ELRS but rumble strips are not installed in residential areas.

- The project team asked if LaDOTD noticed any effects of rumble strip installation on existing roadways, especially regarding the pavement deterioration. The LaDOTD responded that they have not noticed any deterioration at rumble strips. They currently have a pilot program with fog seal. The LaDOTD believed Georgia was having issues with deterioration.

MINNESOTA

Follow-up Interview Meeting Notes

Date: Friday, March 04, 2016

- MnDOT noted that they have the following rumble strip guidelines:
  - If a project is being resurfaced they install rumble strips.
  - If the shoulder is greater than 4 ft, they install rumble strips—2 inches away from joint.
  - If the shoulder is less than 4 ft, they install the rumble strips as far as possible on the edge of the pavement.
  - Motorcycle riders have been consulted and do not mind the rumble strips.
  - Have not researched pavement issues.
  - Rumble strips are installed on a case-by-case basis.
- MnDOT noted that early on they installed a lot of ELRSs. Because people hug the edge line and there have been a lot of noise issues, so MnDOT moved towards CLRSs instead. MnDOT maintenance has concerns with centerline joint degredation.
- MnDOT noted that they have a Non-Motorized Advisor Committee that assists with the design and comments of where rumble strips are installed.
- In regards to old roadways pavements, MnDOT noted the following:
  - They do install rumble strips.
  - There has been push back in regards to installing rumble strips in old pavements.
  - Installations have mostly taken place on county roads.

- MnDOT noted the following challenges with buy-in:
  - They struggle with installing rumble strips systemically.
  - In the past they have had to remove CLRSs due to noise issues.
  - Some districts in MN are not on board at all with rumble strips and do not install any.
  - They have had some legislative and public push back, which made them change their practices and with ultimately led them to sinusoidal rumble strips. Sinusoidal rumbles are being considered in areas of noise concerns (A technical memo will be written from MnDOT regarding their findings this summer). MnDOT is looking at another design, calling it the MN mumble strip. MnDOT contractors have a machine that can change and adapt to their changes to rumble strip installation.
- MnDOT is conducting a study currently regarding optimization study for rumble strips. MnDOT provided the following information regarding the study:
  - South Dakota, North Dakota, and Washington have been in contact and are waiting on MnDOT results.
  - The have had a small wrinkle in the research regarding motorcyclists, which they are currently working through.
  - They are meeting next week to discuss the design.
  - The study should be complete March/April.
  - The interim design will be applied along 200 mi or roadway in MN and then reviewed.
- Regarding the development of the FHWA tool, MnDOT provided the following feedback:
  - MnDOT feels they have no use for the tool.
  - The public does not understand just by statistics or crashes why rumble strips should be installed. They need something in the tool to help change the opinions of the public regarding rumble strips.
  - Research should be conducted looking at whether rumble strips increase the degradation of the pavement.
  - They do not know where rumble strips are located within the state. They need a database of where rumble strips are located.
  - They would like to see safety results in regards to narrower rumble strip widths.

    - They would like to see research on rumble strips on concrete pavement.

- Sinusoidal rumble strips are only currently used on CLRSs of MnDOT. Districts are considering using it for SRSs. They are looking at installing recessed reflective pavement markers in with sinusoidal rumble strips.

- MnDOT is working on a research study regarding rumble strips. The results indicate the following:

    - CLRSs and SRSs should be installed on all roads with 4,700 ADT and above. The research was based on fatal crashes.

    - Crashes at passing areas were generally not due to cars passing.

MONTANA

Follow-up Interview Meeting Notes

Date: Monday, February 29, 2016

- The project team asked if there were any criteria to not use rumble strips. MDT indicated the following:

    - There is no AADT criteria.

    - Speeds less than 45 mi/h are excluded from installation (used as a surrogate for urbanization).

    - If the shoulder is greater than 4 ft wide, MDT only avoids for noise concerns.

    - If there are several houses within 600 ft of the rumble strips, they will likely choose not to install, if there is only one receptor or house the will go ahead and put them in. However, MDT noted that there are no definitive criteria.

    - MDT noted that if there is noted bicycle usage, crash data justify rumble strips, and the shoulder width is less than four ft that is when they will get together and use a committee to come to a consensus about that particular installation.

    - MDT noted that they will use signing to address crashes as necessary.

- The project team asked if MDT receives feedback or buy-in from bicycle groups.

    - MDT noted that they sent out modified guidance and received pushback on the language. MDT engaged the bicycle community to receive feedback on things such as designers should be aware that there is a “goal to have 4 ft clear.”

  - MDT modified the design to allow for bicycles and use quality control to try to ensure that 4 ft is maintained. They are stressing to the construction folks the importance for quality in this case.
  - MDT identifies high priority bicycle routes by engaging the pedestrian and bicycle coordinator who interacts with the pedestrian and bicycle groups to determine the protected routes. Additionally, they will utilize tools such as bicycle heat maps to identify high-usage bicycle routes.
- MDT noted that they struggle to utilize innovative treatments due to difficulties for contractors. For example, they have not tried anything similar to Minnesota's mumble strips due to a lack of information on whether the contractor's need to modify existing equipment or buy new equipment to implement them. MDT is waiting for research to show the effectiveness before trying out innovative treatments.
- The project team asked if the ELRS usage on highways with 4-ft shoulders came from the bicycle community.
  - MDT noted that this is something that they have been researching because of perceived maintenance issues. Rather than using rumble strips on the outside edge of the pavement, they have decided to try narrowing the lane by 6 inches to create a rumble stripe to make the shoulder as wide as possible. The goal is to provide at least a 4-ft bicycle lane.
- The project team provided an overview of the proposed FHWA tool and asked for MDT's reaction and interest in such a tool. MDT provided the following reactions:
  - It would be difficult to use anything other than their standard drawings.
  - Guidance drives practice.
  - Once they get over the initial hurdle, it is easier to implement rumble strips.
  - They borrowed North Dakota's CLRS design and have installed about 110 mi of CLRSs. They have noticed a different sound between their SRSs/ELRSs and CLRSs. They like the sound difference because it alerts a driver to which side they are striking the rumble strips.
  - MDT noted that the struggle is that they only provided rumble strips on roadways with shoulder four ft or wider, but over 60 percent of crashes on in areas with less than 4-ft shoulders.
  - They would be interested in a tool that could perform some sort of analysis to look at trade-offs in known bicycle use in crash data.

TEXAS

Follow-up Interview Meeting Notes

Date: Friday, February 26, 2016

- The project team asked what tools TXDOT currently uses.
- TxDOT noted that they are developing an application for collecting information on rumble strips. The current issue is that they do not know where they have rumble strips installed. TxDOT noted that they are ahead of the curve for developing a systematic approach; however, the biggest challenge is determining where they already are within the database of roads that qualify or systemic-based installation. They also suggested that the tool would probably be most useful inside of more popular tools.
- TxDOT noted that the big news is that they are now looking into a systematic approach to rumble strip safety since they are looked at as being very favorably within the district.
    - They are planning installations for two-lane rural highways, with posted speed limit greater than 45 mph, adequate widths, and 2-ft shoulders.
    - Commonly use the following three types of rumble strips:
        - Milled.
        - Profiled thermoplastic.
        - Raised ceramic buttons.
    - Seal coats are their kryptonite—they often do not have adequate depth and profiled thermoplastic pavement markings cannot be placed until 4 to 6 months after seal coat application.
- TxDOT noted that they are in favor of rumble strips. They follow FHWA guidance on placement and gaps—the next update may be more specific.
    - They are currently inventorying designated bicycle routes to build a bikeway map that is logical, and add to as needed. Once this map is constructed the Bicycle and Pedestrian Coordinator would review the bicycle paths.
    - Designated bicycle routes are required to have a minimum 4-ft shoulder.
- TxDOT noted that the biggest challenge is knowing where they are right, identifying where they should be, and then having the districts identify if they have them or a project is planned. Gaps will identify where they are not. The Bicycle and Pedestrian Coordinator will identify which are bicycle routes. Additionally, they noted the following:

    - Districts are seeing a shift in how bicycle routes are designated.
    - Additionally, there is less pushback now.
- TxDOT noted that rumble strips are allowed in urban areas if there is a crash problem. Additionally, they noted the following:
    - They do not typically have a noise problem because of the 45 mi/hr cut-off.
    - They get a few complaints and they try to sell the effectiveness.
    - They have had to remove rumble strips due to noise complaints, but it has had no long-term impacts on their ability to install them.
    - They look at each installation on a case by case basis but the 45 mi/hr is the main threshold. Rural versus urban designation is a secondary threshold. They leave it up to districts to obtain the feel for the designation.
- TxDOT noted that they have talked to motorcycle groups but do not go talk to homeowners to sell before installation. Future work can be tracked on project tracker. The motorcyclists are heavily in favor of rumble strips. They also noted that ceramic buttons are very dangerous for bicycles and motorcycles. They are the least type used and are not recommended on bike routes.
- TxDOT mentioned that they have a few bicycle groups that are involved on projects as an advisory committee. Anything bike related they bring it up for their input. They have a research project looking at widening roadways due to bicycle use.
- TxDOT mentioned that the Atlanta district also uses bars (they will sending the standard drawings), which are best for installations that will eventually be covered by a seal coat. However, they do not do well with snow plows. TxDOT mentioned that only use one seal coat on the preformed bars and retain the audible noise. Two coats removes the audible noise from the preformed rumble strips.
- TxDOT noted that they look at shoulder widths for profiled pavement markings versus milled edge line rumble stripes. Additionally, TxDOT noted that in addition to the systemic approach, crash history will dictate the use of rumble strips on roadways with shoulders less than 2 ft in width. Safety Improvement Index is used for crash history-based installation.
- TxDOT explained that they install rumble strips in the locations with the highest Safety Improvement (SI) benefit. Most of the rumble strip projects have the highest SI cost benefits so they rank and complete rumble strip projects based on the highest SI. It was stated that rumble strips reduced fatal crashes by approximately 50 percent. It was not determined what type of crashes.

- TxDOT noted that they would be interested in looking at the tool but TXDOT might be ahead of the tool in policy and execution. TxDOT also noted that that they would prefer the tool be added onto an existing tool.

Interview Questions

1. How would you characterize your State's need for a rumble strip application tool? **Texas has a rumble strip policy which requires edge line rumble strips on all rural 4 lane or more divided highways. That policy has been in place since 1999. Texas is in the process of developing a Systematic Rumble Strip policy for undivided highways. Texas is in agreement that a rumble strip application tool would be useful, but Texas is working to incorporate rumble strips as a standard on Texas highways**.

2. What would be some preferred characteristics in terms of tool platform and functionality? **Mapping capabilities.**

3. Do you have a policy for using shoulder, edge line, and/or centerline rumble strips on rural, two-lane, two-way roadways? **Rumble strips are required for 4 lane or more divided rural highways with a speed limit greater than 45 MPH. For all other highways, rumble strips are currently not required. The Systematic Rumble Strip study is recommending edge line and centerline rumble strips for rural highways with speed limits greater than 45 mi/h and at least 26 ft of paved surface width (2 or more ft of shoulder width)**. If yes:

    a. Do you install on a case by case basis? **Currently rumble strips are installed on a case by case basis on rural, two-lane, two-way roadways.**

    b. On resurfacing projects are rumble strips a consideration/mandatory? **No, rumble strips are not considered mandatory on resurfacing projects.**

    c. Do you have a program to install rumble strips separate from paving projects? **Yes, the Texas Highway Safety Improvement Program (HSIP) programs rumble strip projects based upon a benefit-cost analysis**.

    d. Under what conditions and circumstances does your State consider rumble strips? **Rumble strips are required for 4 lane or more divided rural highways with a speed limit greater than 45 mi/h. Rumble strips are considered for rural highways with at least 26 ft of paved surface width (2 or more ft of shoulder width).** Are lower-cost delineation enhancements (e.g., signage and/or striping strategies) always considered first? **Rumble strips are typically one of the first considerations due to their high benefit-cost ratios**.

4. Does your state require a certain speed limit, or width of roadway for shoulder rumble strip and/or centerline rumble strip application? **The speed requirement for rumble strips is for highways with speed limits greater than 45 mi/h**.

5. Do you have a minimum shoulder width or remaining shoulder width beyond the rumble strip for use of shoulder or edge line rumble strips? If so, would you consider them facilities with lesser shoulders if there was a history of roadway departure crashes? **Paved surfaces of**

26 ft or greater (2 ft of shoulder width) are preferred to allow drivers need about 15 to 18 inches to recover from a roadway departure but Texas will consider locations with narrower shoulders, if the site has a history of run off the road crashes.

6. Does crash history dictate implementation of rumble strips? Is there a specific level of crash history and is there an expected level of crash reduction considered? **Rumble strips are required for 4 lane or more divided rural highways with a speed limit greater than 45 mi/h. Currently rumble strips on undivided highways are installed based upon a benefit-cost analysis of the crash history at that location. The higher the benefit-cost ratio; the more likely they will be installed**.

7. Has your State faced issues that had necessitated removal of rumble strips? How have you revamped your policies to continue the rumble strip program? **The policy of installing rumble strips in rural areas minimizes the need to remove rumble strips. Texas has removed rumble strips due to noise complaints but that is a very rare circumstance**.

Maintenance/Installation/Cost

1. What are the effects of rumble strip installation on existing roadways especially regarding the pavement deterioration? **The Texas Rumble Strip Standard sheets require a pavement depth of 2 inches to install milled rumble strips**.

2. Does our State have a specific policy regarding pavement condition prior to rumble strip installation? **The Texas Rumble Strip Standard sheets require a pavement depth of 2 inches to install milled rumble strips. If so, how is pavement condition assessed? The pavement condition is assessed by the pavement experts in the TxDOT District offices. If pavement condition is not adequate, are any modifications made to allow for installation? If the pavement condition will not support milled rumble strips, profile rumble strips or raised rumble strips can be installed**.

3. Does your State allow for raised rumble strips? **Yes** If so, how does your State consider using raised rumble strips versus milled rumble strips? **Milled rumble strips are preferred, but raised rumble strips (ceramic buttons) are allowed. Raised rumble strips are not widely used throughout the state; milled rumble strips and profile rumble strips are more common. The type of rumble strip is determined by pavement depth and district preference.** What is the lifecycle cost, pavement service life and service life of raised rumble strips? **Raised rumble strips have a 2 year service life whereas profile pavement markings have a 5 year service life, and milled rumble strips have a 10 year service life**.

4. Do you have guidelines with rumble strips regarding snow removal, or have weather related issues due to excess rain and hydroplaning? **No, there are no guidelines for snow removal. Currently the Amarillo district is testing raised rumble strips and profile rumble strips to determine the effect by snow plows. There have been no reports of hydroplaning incidents due to rumble strips to our knowledge.** Are rumble strips implemented in areas of bad weather for guidance when visibility is poor? **Rumble strips are not used for visibility purposes, but may have a positive impact for visibility**.

5. Have you experienced debris collecting in the rumble strips? **Nothing has been brought to our attention**.

6. Do you use fog seal when applying rumble strips? **A few TxDOT Districts use fog seal when applying rumble strips, but the majority of districts do not use fog seal.** Does the fog seal enhance the rumble strip longevity/performance? **No studies to verify enhanced longevity or performance.** Is the fog seal a hindrance during application? **Not aware of any hindrances.** Does the fog seal show any positive return results? **No studies to verify positive results.** Is it only an issue when the pavement marking is located directly over top of the rumble strip? **N/A.**

7. Do you install rumble strips on open-graded friction course (OGFC) pavements? **Yes** If so, what are the impacts? **Seal coat highways typically do not have the minimum pavement thickness required to install a milled depression (pavement thickness of 2 inches or more is required), and the installation of profile pavement markings and traffic buttons is not recommended for at least six months to a year after the seal coat is installed so that the grade 3 or 4 rocks have adequate time for embedment**.

8. Are there any pavement types where rumble strips are not used? **No** Is there a difference for new installations versus existing pavement? **The installation of profile pavement markings and traffic buttons is not recommended for at least six months to a year after a seal coat is installed so that the grade 3 or 4 rocks have adequate time for embedment**.

9. What is your centerline rumble strip policy for passing zones? **Continue centerline rumble strip through the passing zone.** Has safety been analyzed in regards to centerline rumble strips for passing zones? **No specific study related to passing zones has been conducted**.

10. Do you have any policies in place for gaps in the rumble strip pattern other than for bicyclists? For example, do you have gaps for passing zones, at driveways, intersections or on the inside of horizontal curves? **Yes, gaps are used at intersections, driveways, entrance ramps, exit ramps, and turnarounds. For milled in rumble strips gaps are used on bridges and overpasses. Profile rumble strips and raised rumble strips do not require gaps at bridges and overpasses**.

Bicycle Accommodations

1. How does your State accommodate bicyclists? **On roadways with high bicycle activity, consideration is given before the installation of edge line rumble strips. Things considered include size of rumble strips, rumble strip material and location of rumble strips on the shoulder. If the designer determines that gaps are needed in the rumble strips due to bicycle use of the road, the requirement shown in FHWA Technical Advisory T5040.39, or latest version detail of the spacing are included in the plans.** Are bicyclists considered for every shoulder rumble strip installation or only when bicyclists are expected? **Only on roadways with high bicycle activity.** Do you have separate standards for bicycle locations and non-bicycle locations? **No. The requirement shown in FHWA Technical Advisory T5040.39, or latest version detail of the spacing are used**.

2. Does your State provide gaps for bicyclists? **Yes**. If so, what pattern do you use (e.g., 12 ft every 60 ft)? **A typical pattern is gaps of 10 to 12 ft between groups of the milled-in elements at 40 to 60 ft.**

3. Do you have a minimum shoulder width specified for bicyclists? **In order to be considered a bike lane, 4 ft of shoulder width is needed, although a bicycle may use the main lane of a road.** Does this differ from the required minimum shoulder width if bicyclists are not expected? **There are no extra requirements for rumble strip application for a road that expects to have bicycles other than the gaps in edge line rumble strips described above.**

4. How do you address bicycle outreach? **Texas has a Bicycle Advisory Committee (BAC). By involving representatives of the public, including bicyclists and other interested parties, Texas helps ensure effective communication with the bicycle community. The bicyclist's perspective is considered in the development of departmental policies affecting bicycle use, including the design, construction and maintenance of highways.** Are there any outspoken bicyclist or motorcycle unions that have input into your policies? **See above for bicyclists. Texas also has a Motorcycle Safety Coalition. The bicycle and motorcycle groups both have input into Texas policies.**

5. Do you consider alternative designs for areas with potential bicyclist concerns? **Yes.** For example, would you consider a shorter length, shorter depth, or an alternative pattern (e.g., sinusoidal design)? **Things considered include size of rumble strips, rumble strip material and location of rumble strips on the shoulder**.

Noise Policy

1. Does your State struggle with noise complaints, despite outreach prior to installation? **No** If so, how do you address these complaints? **Complaints are minimal. Consideration is given to noise levels when edge line rumble strips are installed near residential areas, schools, churches, etc. A minimum of $^{3}/_{8}$ inches depth of milled rumble strip may be considered in these areas.** What public outreach did you perform before the installation of rumble strips? **None**

2. Does your State have distance criteria from residences? **No** If so, is the criteria based on expected noise level or is it a pre-defined distance? **Rumble strips are recommended in rural areas. Rural areas are defined as areas with populations less than 5,000 people. There are no pre-defined distances or noise levels that are required. Installation is looked at on a case by case basis.**

3. In regards to hamlets (small villages along a rural corridor), what are your equivalent policies/procedures regarding installation adjacent to residential areas? **Consideration is given to noise levels when edge line rumble strips are installed near residential areas, schools, churches, etc. A minimum of $^{3}/_{8}$ inches depth of milled rumble strip may be considered in these areas.**

4. If nearby noise is within an acceptable limit (specified in question 2), how do you address the public due to the different type of noise that the rumble strips produce? **N/A**

Approval/Buy-In

1. What outreach has your agency conducted prior to installation? **Not aware of any outreach at locations that rumble strips are installed. Texas reaches out to bicycle and motorcycle groups concerning the rumble strip policies.** Who has the outreach targeted (e.g., motorcycle groups, bicycle croups, neighborhoods)? **Bicycle Advisory Committee and Motorcycle Safety Coalition**

2. What methods have you used to gain upper management/elected officials approval/buy-in? **Demonstrated the historical crash reduction factor for rumble strip installations.**

3. What type of material do you use to gain public acceptance and perceptions regarding rumble strips? **None** Flyers, informative videos, DOT Web site dedicated to rumble strip information and installation? **None**

4. How do you sell rumble strips in residential areas with documented crash histories? **Other types of rumble strips are considered to minimize noise complaints.**

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