Decision Support Guide for the Installation of Shoulder and Center Line Rumble Strips on Non-Freeways

FHWA Safety Program

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Federal Highway Administration

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Center line and shoulder rumble strips are proven safety countermeasures for reducing roadway departure crashes, including head-on crashes and run-off-road crashes. The purpose of this guide is to provide a decision-support framework to inform center line and shoulder rumble strip installation. It describes methods for identifying appropriate locations for installation, assessing the potential crash reductions and benefit-cost ratio, and developing performance metrics for safety. Additionally, this guide discusses special considerations for rumble strip installations, identifies variability in current practices, and provides a decision-support framework for installing rumble strips. The framework covers policy development for systematic rumble strip installation and provides a flowchart for decision-making for sites that can benefit from installation but do not meet criteria for systematic installation. The framework can also be applied to sites that are identified based on crash history, such as for Highway Safety Improvement Program selection. Within this framework, this guide describes who may be involved in the decision-making process, at what points, and provides an overview of safety performance measures that can be presented to policy makers and stakeholders. Performance metrics described in this guide can be used to inform stakeholders of rumble strip benefits.</td></tr>
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SI* (MODERN METRIC) CONVERSION FACTORS

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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ACRONYMS

AADT	annual average daily traffic
B/C	benefit-cost
CLRS	center line rumble strip
CMF	crash modification factor
CRF	crash reduction factor
DOT	Department of Transportation
EB	empirical Bayes
ELRS	edge line rumble strip or stripe
FARS	Fatality Analysis Reporting System
FHWA	Federal Highway Administration
HSIP	Highway Safety Improvement Program
HSM	Highway Safety Manual
MDOT	Michigan Department of Transportation
MnDOT	Minnesota Department of Transportation
NCHRP	National Cooperative Highway Research Program
ROR	run-off-road
RPM	raised pavement marking
RTM	regression-to-the-mean
SPF	safety performance function
SRS	shoulder rumble strip
TxDOT	Texas Department of Transportation

INTRODUCTION

BACKGROUND

Center line and shoulder rumble strips are proven safety countermeasures for reducing roadway departure crashes, including head-on crashes and run-off-road (ROR) crashes. According to a recent study, ROR left or right crashes account for 64.4 percent of all single-vehicle crashes and, of those, 95.1 percent of the time the critical reasons were driver related.(1) Further analysis indicated the dominant critical reasons for passenger cars were internal driver distraction, steering overcompensation, poor directional control, too fast for curve, and sleeping. The dominant critical reason for large trucks was sleeping. According to the Fatality Analysis Reporting System (FARS) data, approximately 55 percent of fatal crashes are those targeted by rumble strips.(2) Moreover, for rural two-lane highways, that number increases to approximately 66 percent. According to a 2009 National Highway Traffic Safety Administration study using events from the 100-Car Naturalistic Driving Study, approximately 66 percent of ROR events were departures to the right and 31 percent were to the left.(3) Furthermore, Leuer found, using 2009 to 2013 data, that 13.4 percent of fatal crashes on Minnesota rural, two-lane highways were ROR left and 16.7 percent were ROR right, indicating that center line rumble strips are as important at preventing ROR crashes as shoulder rumble strips.(4) In a separate study, Leuer found that while head-on crashes account for only 5 percent of crashes on Minnesota rural, two-lane highways, they account for more than 18 percent of the fatal crashes.(5) Further analysis indicated that approximately 65 percent of fatal head-on crashes were the result of the vehicle drifting over the centerline and 31 percent were the result of control loss.

Rumble strips are a relatively low-cost countermeasure and economic analyses have indicated benefit-cost (B/C) ratios that exceed 100 to 1 (i.e., 100 dollars saved for every 1 dollar spent). For this reason, shoulder rumble strips have been installed nearly system wide for the Interstate system and most freeways and expressways. However, agencies have had varying degrees of success installing center line and shoulder rumble strips on multilane and two-lane roadways. The three primary concerns for rumble strips for these highway types include the following:

- Inconvenience for bicyclists. Standard rumble strip dimensions used by most agencies are difficult to traverse if bicycle gaps are not provided, as they make the rider uncomfortable and may lead to loss of control.
- External noise pollution. Rumble strips alert motorists through noise and vibration. The noise generated by rumble strips is different than background traffic noise and is intermittent. This can create a disturbance for nearby residents and for special

environmental conditions (e.g., noise-sensitive wildlife habitats) if there are frequent incidental contacts.

- Pavement durability. There is concern that milling rumble strips into longitudinal joints or into the wearing course will allow water infiltration causing premature pavement deterioration.

PURPOSE OF THIS GUIDE

The purpose of this guide is to inform agencies on center line and shoulder rumble strip installation. It 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 practices, and provides a decision-support framework for installing rumble strips.

The framework covers policy development for systematic rumble strip installation and provides a flowchart for decision-making for sites that can benefit from installation but do not meet criteria for systematic installation. Rumble strips fulfill a systemic need; however, the framework is also applied to sites that are identified based on crash history, such as for Highway Safety Improvement Program (HSIP) selection. Within this framework, this guide describes who may be involved in the decision-making process, at what points, and provides an overview of safety performance measures that can be presented to policy makers and stakeholders. Performance metrics described in this guide can be used to inform stakeholders of rumble strip benefits.

Intended Audience

This guide is intended for practitioners in transportation planning, highway design, traffic operations, highway maintenance, and traffic safety concerned with reducing target crashes through the installation of center line and shoulder rumble strips. This includes practitioners in Federal, State, local, and Tribal agencies tasked with improving highway safety using proven, low-cost, safety strategies. This also includes consultants working for these agencies.

Guide Organization

The guide is organized as follows:

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

- Rumble strips and safety management. This section discusses the methodologies for implementing rumble strips as a safety countermeasure and methodologies for estimating the safety effectiveness and economic impact.
- Special considerations. This section 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 practices. This section identifies current practices agencies use for installation of rumble strips and identifies successful practices and methods for installing rumble strips based on high crash corridor analyses.
- Decision-support framework for rumble strip installation. This section provides a framework for agencies to follow based on current successful practices of agencies with widespread rumble strip installation.
- Case studies. This section includes case study examples where agencies weighed the decision to install rumble strips when there was potential concern for roadway users other than vehicles, nearby residents, and pavement condition.
- Other resources. This section provides links to related resources.

Scope of this Guide

The information presented in this guide focuses on rural, non-freeway applications. Additional information is presented for urban areas as appropriate. The guide does not focus on freeways, as there are fewer trade-off concerns and agencies have generally been successful at installing rumble strips on these facilities. The guide supports the installations of both center line and shoulder rumble strips.

How to Use this Guide

It is recommended that the entire guidance document be reviewed before application. This guide provides an overview of installation approaches and provides methodology for selecting high crash corridors for treatment, estimating countermeasure effectiveness, and conducting B/C analysis. These methods can be used to inform decision-making for the following:

- Systemic safety issues.
- HSIP selections.
- Recommendations stemming from road safety audits.
- Trade-off analysis when considering multiple options for treatment or non-treatment.

Additionally, this guide provides an overview of current agency practices and a model decision-making framework for installing rumble strips. This information can be used to inform rumble strip policy development and for identifying alternative designs for rumble strip installation where the standard practice cannot be applied.

KEY DEFINITIONS

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

Placement

Rumble strip placement is defined as center line (CLRS), shoulder (SRS), or their combination (CLRS+SRS). SRS can be further defined by their offset from the edge line pavement marking. If the SRS is applied in conjunction with the pavement marking, then it is characterized as an edge line rumble strip or stripe (ELRS). If the SRS is located outside the pavement marking, then it is simply referred to as SRS. Throughout the document SRS and ELRS are collectively referred to as SRS, unless specifically talking about ELRS. Figure 1 shows and installation of combined CLRS and SRS.

Transverse rumble strips are placed within the lane to warn drivers of upcoming unexpected changes, such as traffic signals, changes in alignment, or the need to change lanes. Transverse rumble strips are not a focus application for this guide and will not be discussed further.

Figure 1. Photograph. Combination milled CLRS and SRS.

Type

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 tire to drop into the groove, which creates both sound and vibration. The sound level has been studied and has been shown to be 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 agencies have also begun 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.

Although research suggests that milled rumble strips are the most effective application type, raised rumble strips have been applied in States with warmer climates in cases 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 visibility and, may have some very limited rumble characteristics. Figure 2 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 2. Photograph. Example profiled thermoplastic pavement marking.

Dimensions

Figure 3 provides a graphical representation of rumble strip dimensions, which is explained as follows:[6]

A. Offset: This is the distance from the pavement marking (delineating the edge of the traveled way) to the inside edge of the rumble strip.
B. Length: 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.
C. Width: Dimension of the strip that is parallel to the travel direction of the roadway.
D. Depth: The maximum distance from the surface of the roadway to the bottom of the rumble strip.
E. Spacing: The distance between adjacent rumble strips. It is most often measured from the center of the strip to the center of the adjacent strip.
F. Gap: The distance from edge of rumble strip to edge of 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 CLRS, and to allow for turning movements at intersections and driveways.

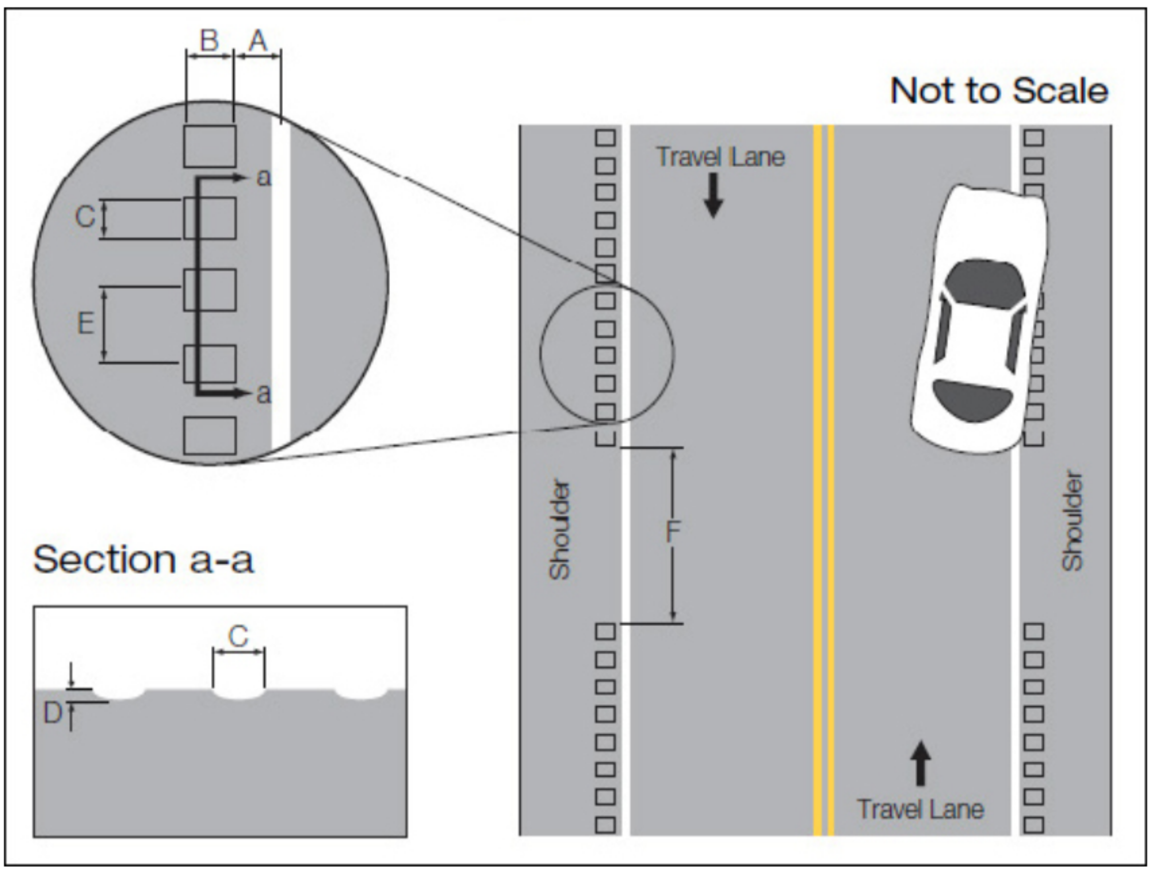

Figure 3. Illustration. Rumble strip dimensions.[6]

RUMBLE STRIPS AND SAFETY MANAGEMENT

SRS and CLRS on rural, two-lane highways are proven safety countermeasures. National Cooperative Highway Research Program (NCHRP) Report 641: Guidance for the Design and Application of Shoulder and Centerline Rumble Strips documented significant crash reductions for SRS and CLRS on rural, two-lane highways. SRS were found to provide a 36-percent reduction in ROR fatal and injury crashes while CLRS were found to provide a 44-percent reduction in head-on fatal and injury crashes.(7) However, researchers have found that rumble strips are not equally effective for all roadway geometries and traffic volumes. Additionally, rumble strips can be used to target drowsy or distracted driving, while other roadway treatments do not fulfill this need. Rumble strips are most effective and should be considered in corridors with the greatest need. This section provides an overview of methodologies for selecting sites for installation, identifying rumble strip effectiveness, and conducting B/C analysis for treatments.

SELECTING SITES FOR INSTALLATION

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. High crash locations often prove to be difficult to identify, although more success can be found in identifying high crash corridors. As noted in the 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.(8) Additionally, agencies utilize an additional systematic component for installing rumble strips based on agency-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 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, agencies implement rumble strips on corridors based on risk features that are correlated with higher severity focus crash types (e.g., K and A severities on the KABCO 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 crashes outcomes. Severe crash types are typically addressed using a systemic approach since they are often less concentrated than total crashes, but tend to be over-represented 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 annual average daily traffic (AADT) greater than 400 and less than 2,000, lane width less than 12 feet, shoulder width less than 4 feet, curve density greater than 2 curves per mile, 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

Agencies 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. Agencies often consider the crash rate in relation to the statewide average to determine if a corridor should be examined further for rumble strip installation. Most often, they base installation recommendations on three to five 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." [9] Commonly this is 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 (RTM) bias. This methodology will tend to focus on corridors with a short-term rate that is above average; which, for two-lane rural highways could be subject to one 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 is a function of the AADT and corridor 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 utilized for several methods for identifying high crash corridors that are more statistically valid than the crash rate method.[9] The following performance measures utilize SPFs:

- Level of Service of Safety.
- Excess Predicted Average Crash Frequency using SPFs.
- Expected Average Crash Frequency with empirical Bayes (EB) adjustment.
- Equivalent Property Damage Only Average Crash Frequency with EB adjustment.
- Excess Expected Average Crash Frequency with EB Adjustment.

The Excess Predicted Average Crash Frequency using SPFs is the easiest to compute, as this performance measure simply compares the difference between the SPF predicted average crash frequency and the observed average crash frequency. However, this performance measure cannot account for RTM bias. The Excess Expected Average Crash Frequency with EB Adjustment performance measure goes one step further, to calculate the expected average crash frequency. The expected average crash frequency is a weighted average of the observed average crash frequency and predicted average crash frequency from the SPF. The expected average crash frequency accounts for RTM bias. The expected average crash frequency is compared to the predicted average crash frequency and the difference is the excess expected average crash frequency. If this value is greater than zero, then a site experiences more crashes than is expected and may be a better candidate for an improvement. See Chapter 4 of the HSM for more details on performance measures and their strengths and limitations.

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 to installation that are based on policy. Most agencies have policies outlining criteria for systematic rumble strip installation. Criteria for installation are based on special considerations, including accommodating bicycles, minimizing noise disturbance, and avoiding potential pavement quality issues. For CLRS, the systematic approach is typically based on pavement condition, posted speed limit, and lane or pavement width. For SRS, 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 environment.

IDENTIFYING RUMBLE STRIP EFFECTIVENESS

Rumble strip safety effectiveness is established through the development and use of crash modification factors (CMFs). A CMF is an index of the expected change in safety performance following a change in traffic operations or installation of a countermeasure. The percent change in crashes is calculated as 100*(1-CMF); thus, a CMF of 0.70 with a standard deviation of 0.12 indicates a 30 percent reduction in crashes with a standard deviation of 12 percent.

Users may apply the CMF directly to the expected number of crashes without treatment to estimate the number of crashes with treatment, or to estimate the change in crashes. Alternatively, the upper limit of the confidence interval provides a conservative estimate of the expected change in crashes. The upper 95-percent confidence limit of the CMF is determined by multiplying the standard deviation by 1.96 and adding this to the CMF. [Note this is approximated by CMF+2×standard error.] In this example, the analyst can use 0.70 or a conservative value of 0.94. Users may choose to use the upper limit if the CMF is of lower quality (explained in further detail in the next section) or if it is unlikely that the specified reduction can be achieved.

The CMF Clearinghouse and the HSM Part D contain CMFs for center line and shoulder rumble strips and their combination. Part D of the HSM contains CMFs that passed a screening process or met expert panel approval for adequate reliability and stability. The CMF Clearinghouse is a living website that contains all CMFs for treatments, including those in the HSM Part D. The CMFs in the Clearinghouse range from high quality to low quality. The Clearinghouse is updated quarterly and contains the most up-to-date CMFs related to rumble strips on all facility types. Further information about CMFs in the Clearinghouse is presented in the next section.

CMF Clearinghouse

There are more than 500 research-based CMFs relevant to rumble strips located in the CMF Clearinghouse. This section provides a brief overview of identifying the most appropriate CMFs and searching for CMFs in the CMF Clearinghouse. More details on using the CMF Clearinghouse are located at www.cmfclearinghouse.org; select the "About the CMF Clearinghouse" tab.

Identifying the Most Appropriate CMF(s)

Having identified the countermeasure of interest, the user navigates a list of CMFs to identify which CMF best approximates the reduction that can be expected for proposed installation or policy. CMFs can be generally applicable (e.g., all rural, two-lane highways), or may be specific to a unique set of factors (e.g., rural, two-lane highway horizontal curves with a shoulder width less than or equal to five feet). The applicable factors may be found in the countermeasure name or they may be buried in the CMF details. The CMF details are discussed in more detail in the "Searching for CMFs" in the CMF Clearinghouse section.

Major factors in identifying the most relevant CMF include the following:

- Countermeasure name. The countermeasure name may be more general and widely applicable, or in some cases, specific, immediately narrowing the applicability of the CMF. The countermeasure name will specify if the CMF applies to CLRS, SRS, or their combination.
- Number of lanes and area type. These two factors, used in combination, specify the appropriate facility type targeted by the countermeasure for the CMF. Often, one or both of these factors may be left blank, indicating that the information was not provided. Alternatively, these factors may show that the CMF applies to multiple facility types rather than targeting one specific facility type.
- Crash type. The CMF may be developed for all (i.e., total) crashes or for a specific crash type. CLRS typically target head-on crashes (and ROR left) while SRS typically target ROR crashes. Analysts should identify the crash type of interest when comparing CMFs.
- Crash severity. As with crash type, CMFs can be developed for all severities or for a specific set of severity levels (e.g., fatal and injury crashes). Analysts should identify the appropriate crash severity when comparing CMFs.

Additional factors may be used to help narrow the list of applicable CMFs for rumble strips. The following list includes additional minor factors used to help identify the most applicable CMF.

- Speed limit.

- Traffic volume (minimum and maximum).
- Time of day.
- Jurisdiction(s).
- Geometric character.

CMFs are often developed for a specific value of minor characteristics or the researchers will provide the values of minor characteristics for which the CMFs were developed. However, some minor factors, such as speed limit, are often unreported. The reported minor factors for the CMFs can be used to identify which is closest to the applicable scenario if multiple CMFs remain after screening based on the major factors. Traffic volumes and jurisdictions (most often States) are reported for many CMFs. Geometric characteristics may be more difficult to determine—see the “Searching for CMFs” in the CMF Clearinghouse section for more details—however, geometric characteristics, such as applicability for horizontal curves or for certain shoulder widths are available for several CMFs.

In addition to relevance, CMFs are characterized based on quality. The quality is provided as a star rating. The CMF may be rated from 0 to 5 stars, with higher quality CMFs having a higher star rating. Higher quality CMFs control for potential biases, have larger sample sizes, and are more generalizable (i.e., are developed from more diverse geography). Sample 5-star and 4-star CMFs from the CMF Clearinghouse are provided in Appendix A for CLRS, SRS, and their combination. These CMFs represent the highest quality currently available in the CMF Clearinghouse and provide an example of the breadth in applicability for CMFs in the Clearinghouse. See Appendix A for further details and descriptions of information available for the sample CMFs.

Searching for CMFs in the CMF Clearinghouse

This section discusses searching the CMF Clearinghouse for the most appropriate CMF based on the factors covered in the Identifying the Most Appropriate CMF(s) section. This discussion is focused on using the website to identify CMFs specifically for rumble strips. For further information, visit the CMF Clearinghouse website.

The CMF Clearinghouse homepage allows users to search for CMFs based on the countermeasure name, research study information, and CMF ID. The countermeasure name will be the most useful for most practitioners, and specificity in search terms is important. For example, if searching “rumble strip,” the search will return (at the time of this publication) more than 500 CMFs. If looking for CMFs related to CLRS, entering “center line rumble strips” returns more than 100 CMFs. Leaving the search terms blank will return all CMFs in the clearinghouse.

Having conducted a search, users can browse the returned CMFs by category (e.g., roadway) and subcategory (e.g., roadway rumble strips). Additionally, users can filter the search to include only CMFs of a certain star rating or other major factors. Using the filtered list, users can explore the remaining countermeasures for applicable CMFs. Countermeasure names may vary in terms of specificity, and it is possible more than one countermeasure name will apply to a search. At this point, the CMF, quality, crash type, crash severity, and area type are presented; users can choose to select one CMF for further details, or can select a check box to compare multiple CMFs.

When selecting one CMF for further evaluation, the CMF/crash reduction factor (CRF) details page will appear. This contains information on the following relevant CMF characteristics:

- Star Quality Rating.
- CMF/CRF.
- Applicability.
- Development Details.
- Other Details.

The applicability section defines several important major and minor factors for which the CMF is appropriate. The section provides details on the applicable crash type, crash severity, roadway types, number of lanes, road division type, speed limit, area type, traffic volume, and time of day for the CMF. The development details section provides further useful information for selecting an appropriate CMF, including the municipality(ies), State(s), or country(ies) from which the CMF was developed. If multiple CMFs are relevant, the selection may be made on the State or municipality that is more similar to the user's State or municipality. Finally, the other details section includes comments related to the CMF. The comments box is used to provide further information on other details of the CMF that do not fit into the other categories. For example, there may be comments on whether the CMF applies only to horizontal curves or tangents among other potential geometric characteristics.

Alternatively, multiple CMFs may be applicable, and users can select up to six for comparison. The comparison function provides side-by-side details of the major and minor factors and highlights any differences with a light blue bar. The light blue bars can be used to look for differences, and the countermeasure name and the comments section can be reviewed for any further details that will help to identify the most appropriate CMF.

Figure 4 provides an example comparison for CLRS. Consider a scenario where a user is interested in determining the CMF for CLRS for all fatal and injury crashes on rural, two-lane highways with curves. CMF ID 3387 is not applicable because the crash type and severity do not match the desired scenario. CMF IDs 3350 and 3383 apply to the same crash type and severities (and are identical for all other factors not shown here). However, from the countermeasure name, CMF ID 3350 applies to general roadway corridors while CMF ID 3383 applies only to tangent sections (i.e., non-curve locations). In this case, the user would select the first CMF of 0.91 for further evaluation because the desired scenario includes both tangents and curves.

Countermeasure Name	Install centerline rumble strips	Install centerline rumble strips on tangent sections	Install centerline rumble strips on tangent sections
CMF ID	3350	3383	3387
CMF	0.91	0.85	0.51
Study Reference	Torbic et al., 2009	Torbic et al., 2009	Torbic et al., 2009
Unadjusted Standard Error CMF	0.035	0.059	0.069
CMFunction			
Star Rating	★★★★★	★★★★★	★★★★★
Crash Type	All	All	Head on,Sideswipe
Crash Severity	Fatal,Serious injury,Minor injury	Fatal,Serious injury,Minor injury	All
Crash Time of Day	All	All	All
Area Type	Rural	Rural	Rural
Road Division Type	Undivided	Undivided	Undivided
Road Type	Not Specified	Not Specified	Not Specified
Number of Lanes	2	2	2

Figure 4. Screen capture. CMF Clearinghouse comparison for CLRS.

B/C Analysis

A B/C analysis is an important tool for determining if the proposed treatment is worthwhile. The B/C analysis compares the present value of annual benefits divided by the present value of total costs. Total costs include installation costs and annual operating or maintenance costs. A ratio greater than 1.0 indicates the benefits are greater than costs and a ratio less than 1.0 indicates the benefits are less than costs.

The safety benefits for rumble strips are measured by the change in crash costs, which is computed by multiplying the change in crashes per year by the average cost of a crash. It is important to note the average crash cost should match the crash type used in the analysis. For example, if the CMF is for fatal and injury crashes, then the average crash cost should reflect the cost for fatal and injury crashes, not all crashes. The FHWA report *Crash Cost Estimates by Maximum Police-Reported Injury Severity within Selected Crash Geometries* provides crash costs by severity level, crash geometry, and speed limit, based on 2001 dollars.[10] The HSM also provides crash costs by severity level, which are based on the FHWA report. The 2001 values can be updated using the ratio of most recent United States Department of Transportation value of a statistical life and the 2001 value of 3.8 million dollars. Using the 2015 value (9.4 million dollars), the unit cost multiplier is approximately 2.47 as shown in Figure 5.

$$2015\ Value = 2001\ Value * 2.47$$

Figure 5. Equation. Conversion from 2001 dollars to 2015 dollars.

From the FHWA report, the 2001 average cost for a property damage only crash is 7,428 dollars and the average cost for a fatal or injury crash is 158,177 dollars. If a corridor targeted for SRS has a 2001 weighted (by severity) crash cost of 82,803 dollars, then the updated average crash cost would be 204,523 dollars (82,803 × 2.47). The annual benefit is computed by multiplying the average crash cost by the estimated change in crashes per year.

The present value is computed by multiplying the annual benefit or cost by the Capital Recovery Factor, as shown in Figure 6.

$$Present\ Value = A * \frac{(1+i)^n - 1}{i * (1+i)^n}$$

Figure 6. Equation. Present value of uniform annual benefit or cost.

Where:

A = annual benefit or cost.
i = inflation rate.
n = service life.

The present value equation applies only to annual costs and is not applied to the installation cost. The service life for rumble strips is often assumed to be the time until the next pavement overlay, unless the rumble strip is deemed to still be effective after a thin overlay or chip seal. Most commonly, the service life is reported to be 7 to 10 years, but has been reported to be as high as 15 to 20 years. The Office of Management and Budget Circular A-4 suggests a conservative real discount rate of 7 percent for i.[11]

Rumble strip installation costs vary widely among and within States. Unit prices for rumble strips range between 500 dollars and 6,000 dollars per mile. There are many factors that can influence the cost, and they are provided in detail on the FHWA Rumble Strips and Rumble Stripes website.[12] For economic analysis, agencies can use historical data for installations to determine an average installation unit price. Typically, the unit price for SRS is for one side of the road, and would be multiplied by two for installation on both shoulders for two-lane roadways, or on the inside and outside shoulder for a directional analysis of multilane roadways.

Example Application 1 – Systemic Installation

An agency has identified 7,500 miles of rural, two-lane highways for retrofit installation of ELRS. Before recommending installation, a B/C ratio was calculated. The necessary assumptions for analysis are provided below as well as the results of the study. See Appendix B for details on calculating the results shown. The analysis focuses on fatal and injury ROR crashes.

Assumptions:

- ELRS cost per mile: 1,500 dollars per line.
- Annual fatal and injury ROR crashes: 125 crashes.
- Rumble strip life expectancy: 7 years.
- CMF for ELRS for fatal and injury ROR crashes: 0.67.
- 2001 crash cost for fatal and injury crashes: 158,177 dollars.

Results:

- Annual crashes reduced: 41.25.
- 2015 crash cost for fatal and injury crashes: 390,697.20 dollars.
- Annualized construction cost: 4,174,947 dollars.
- Annual benefits: 16,116,259 dollars.
- B/C ratio: 3.86.

The results indicate that while the targeted facilities experience an average 0.017 fatal and injury ROR crashes per mile, the installation is economically justified. The analysis indicates that approximately 41 fatal and injury ROR crashes would be reduced per year.

Example Application 2 – High Crash Corridor Installation

For a 2.5-mile section of rural, two-lane highway, an analyst identified the following information from a roadway inventory, crash database, and safety performance function:

- AADT 5,500.
- 2012 ROR Crashes: 8 Observed, 3.67 Predicted.
- 2013 ROR Crashes: 7 Observed, 3.67 Predicted.
- 2014 ROR Crashes: 9 Observed, 3.67 Predicted.
- Percent fatal and injury ROR crashes: 50 percent.

Given information for CLRS and SRS include the following:

- CMF for ROR crashes: 0.70.
- 2001 crash cost for fatal and injury crashes: 158,177 dollars.
- 2001 crash cost for property damage only crashes: 7,428 dollars.
- Installation cost: 1,500 dollars per mile.
- Rumble strip life expectancy: 7 years.

Results:

- Expected number of ROR crashes: 5.88 crashes/year.
- Excess expected ROR crashes: 2.21 crashes/year = candidate for CLRS and SRS.
- Annual crashes reduced per mile: 0.70 crashes/mile.
- 2015 crash cost for fatal and injury crashes: 204,522 dollars per crash.
- Annualized construction cost: 835 dollars per mile.
- Annual benefits: 143,984 dollars.
- B/C ratio: 172.4.

The upper 95-percentile estimate of the CMF is 0.79, resulting in a reduction of 0.49 ROR crashes per mile per year. The annualized benefit is calculated to be 101,018 dollars per mile. The resulting B/C ratio is 121.0, indicating that even a conservative estimate of the reduction results in a highly cost-effective solution.

SPECIAL CONSIDERATIONS

While rumble strips help reduce ROR crashes and are a proven low-cost safety countermeasure, they can negatively impact bicyclist activity, generate disturbing noise, and may impact pavement quality or future maintenance activity. These special considerations are generally acknowledged in agency policies and are covered in the FHWA Rumble Strips and Rumble Stripes website.[12] The website contains implementation fact sheets targeting those involved in rumble strip design or installation and contains implementation guides targeting those making decisions on individual projects or setting standards. A brief summary follows, and the implementation guides and fact sheets can be reviewed for further details regarding bicycle accommodation, noise issues, and pavement issues.

- **Bicycle accommodation:** Agency systematic policies are generally based on providing an adequate clear shoulder width between the outside edge of the rumble strip and the edge of pavement. Bicyclists have a variety of basic requirements that need to be accommodated on shared roadways with vehicles. Additional factors that affect bicyclists on roadways with rumble strips are clean pavements and the ability to cross rumble strips safety. Agencies should work with the bicycle community to understand their needs, to develop policies or solutions that accommodate bicycles and increase safety, and to identify higher and lower priority corridors for bicycles. Technical specialists making decisions on individual projects or setting standards can find more information in the Rumble Strip Implementation Guide: Addressing Bicycle Issues on Two-Lane Roads.[13] Additional information can be found in the FHWA Technical Advisory on Shoulder and Edge Line Rumble Strips. [14]
- **Noise issues:** Most agencies address the consideration of potential noise issues in a general sense (i.e., acknowledging the possibility). Few States have specific policies regarding installation proximity to dwellings and businesses. Technical specialists making decisions on individual projects or setting standards can find more information about noise accommodation in the Rumble Strip Implementation Guide: Addressing Noise Issues on Two-Lane Roads.[15] Additional information can be found in the FHWA Technical Advisory on Shoulder and Edge Line Rumble Strips and in the FHWA Technical Advisory on Center Line Rumble Strips.[14]
- **Pavement issues:** Pavement considerations typically include current pavement condition, pavement depth, time to future surface overlay, and location of the rumble strip in relation to longitudinal joints. Little connection has been found between pavement condition at the time of installation and increased pavement degradation. Additionally, preventative maintenance treatments, such as chip seals, ultra-thin hot mix asphalt, and micro-surfacing have traditionally been considered to be incompatible with rumble strip installations. Recent experiences have shown that these worries may be unfounded. Technical specialists making decisions on individual projects or setting

standards can find more information in the Rumble Strip Implementation Guide: Addressing Pavement Issues on Two-Lane Roads.(17) Additional information can be found in the FHWA Technical Advisory on Shoulder and Edge Line Rumble Strips and in the FHWA Technical Advisory on Center Line Rumble Strips.(14)

Agencies use several different cross-section and rumble strip designs based on these special considerations including the following:

- Different rumble strip configuration.
- Different rumble strip placement. For example, moving SRS under the pavement marking to create an edge line rumble strip. The goal is to maintain a four-foot clear space, if possible. The goal is generally five feet if curb or guardrail is present.
- Consider omitting rumble strips at locations with guardrail and/or curbing if adequate clear space cannot be maintained.
- Reduce the depth of the rumble strip to 3/8 in.
- Changing lane configurations. For example, narrowing the travel lane to accommodate a wider shoulder.
- Widening the shoulder to accommodate rumble strips and clear space for bicyclists.
- Utilizing raised rumble strips.
- Terminating rumble strips in residential areas or providing breaks near residences (as necessary).

If accommodations cannot be made, alternative safety strategies may be considered and implemented, if justified. However, alternative strategies may not focus on distracted or drowsy driving, which are targeted by rumble strips. For example, agencies may elect to enhance delineation as an alternative to rumble strips, in noise sensitive areas (e.g., curve signing, delineators, raised pavement markings [RPMs]). Potential alternatives to rumble strips include the following:

- Improving horizontal curve delineation by:
    - Installing or upgrading advance warning signs.
    - Installing advisory speed plaques.
    - Installing Chevrons or a Large Arrow plaque.
    - Installing delineators and/or raised pavement markers.
    - Installing wider pavement markings.
- Applying high friction surface treatments.

Additional alternatives for horizontal curves can be found in the Low-Cost Treatments for Horizontal Curve Safety 2016.[8] The CMF Clearinghouse and the HSM Part D can be consulted to determine the potential safety effectiveness of alternative options.

OVERVIEW OF CURRENT AND SUCCESSFUL INSTALLATION PRACTICES

Nearly all State agencies have a systematic policy providing standard drawings for CLRS and SRS on rural, two-lane, undivided highways or multilane, divided highways. Few agencies use different rumble strip designs for the outside shoulder for the two facility types. Most agencies that distinguish between the two facility types provide drawings specifying rumble strips on the inside and outside shoulders on multilane divided highways. Nearly all agencies supplement the systematic approach with a high crash corridor approach for roadways that do not meet systematic policy. This flexibility is important because roadways with the highest risk for ROR crashes (i.e., roadways with narrow lane and shoulder widths) often do not meet the criteria for systematic policies. Flexibility is also important for modifying standard designs to accommodate both their installation and the needs of those affected by their presence. This section provides an overview of current agency systematic policies and successful high crash corridor installation practices.

CURRENT SYSTEMATIC POLICIES

Agencies use systematic policies to develop a set of 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 on-site performing other activities and ensures the pavement is in good condition and will not be resurfaced again in the near term. Alternatively, agencies 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 agency).

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 agencies 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 drawing may provide information on bicycle gaps.

Agencies have found increased buy-in for rumble strips when stakeholders are included in developing the language for systematic policies. For example, the Montana Department of Transportation engaged the bicycle 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."[18] The Montana Department of Transportation has modified the design to allow for bicycles and has used quality control to try to ensure that the 4-foot space is 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, 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 sections provide an overview of systematic installation policies and standards for SRS and CLRS, respectively. These sections highlight the variability in current practices and the practices of the agencies 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.

Shoulder and Edge Line Rumble Strips

Table 1 provides an overview of SRS and ELRS design dimensions and systematic installation criteria. Note that offset dimensions show the maximum under the agency's policy. The offset is zero for ELRS. The following installation criteria are commonly used by agencies (note blank cells indicate no policy specifically dealing with that particular criterion):

- Minimum posted speed limit. The minimum posted speed limit typically serves as a surrogate for level of urbanization. Rumble strips are used in rural areas and are typically avoided in urban areas, unless justified by crash history, due to noise complaints.
- Shoulder width. The minimum width is most commonly specified to allow for adequate room for bicycle activity; however, several agencies provide rumble strips on narrower shoulders due to increased risk for severe crashes, while other agencies do not specify a minimum shoulder width.
- Minimum distance to nearby residences. Few agencies specify a minimum distance to nearby residences, but for those that do, the distance is most commonly near 650 ft.
- Asphalt condition. There are several criteria used for asphalt condition:
- Structural condition. Several agencies look for the asphalt condition to be "good."
- Maximum pavement age. In addition to new pavements, several agencies utilize pavement age as a criterion in lieu of structural condition.
- Minimum pavement depth. Several agencies note a minimum depth for the surface coat that allows for rumble strip installation within the surface.

- ELRS option. This column shows agencies that have policies specifying the use of ELRS. In the case of those marked N (no), their policy did not directly address the possibility of combining the SRS and edge line marking, or their policy only indicated a SRS with a specified offset distance from the edge line marking or pavement joint.

Other installation criteria not shown below include the following:

- Minimum AADT. Few State agencies specific a minimum AADT threshold for installation. Minimum AADT thresholds range from 400 to 3,000 vehicles per day.
- Minimum pavement width. Several states specify SRS or ELRS in lieu of CLRS if the pavement width is below a certain value.
- Minimum distance to residences. A few states have a minimum distance to nearby residences. Specified distances range from 100 ft to 2,000 ft. The distance is most commonly about 650 ft.

Figure 7 provides an overview of the dimensions used in Table 1. The dimensions are consistent with those provided in the Key Definitions section.

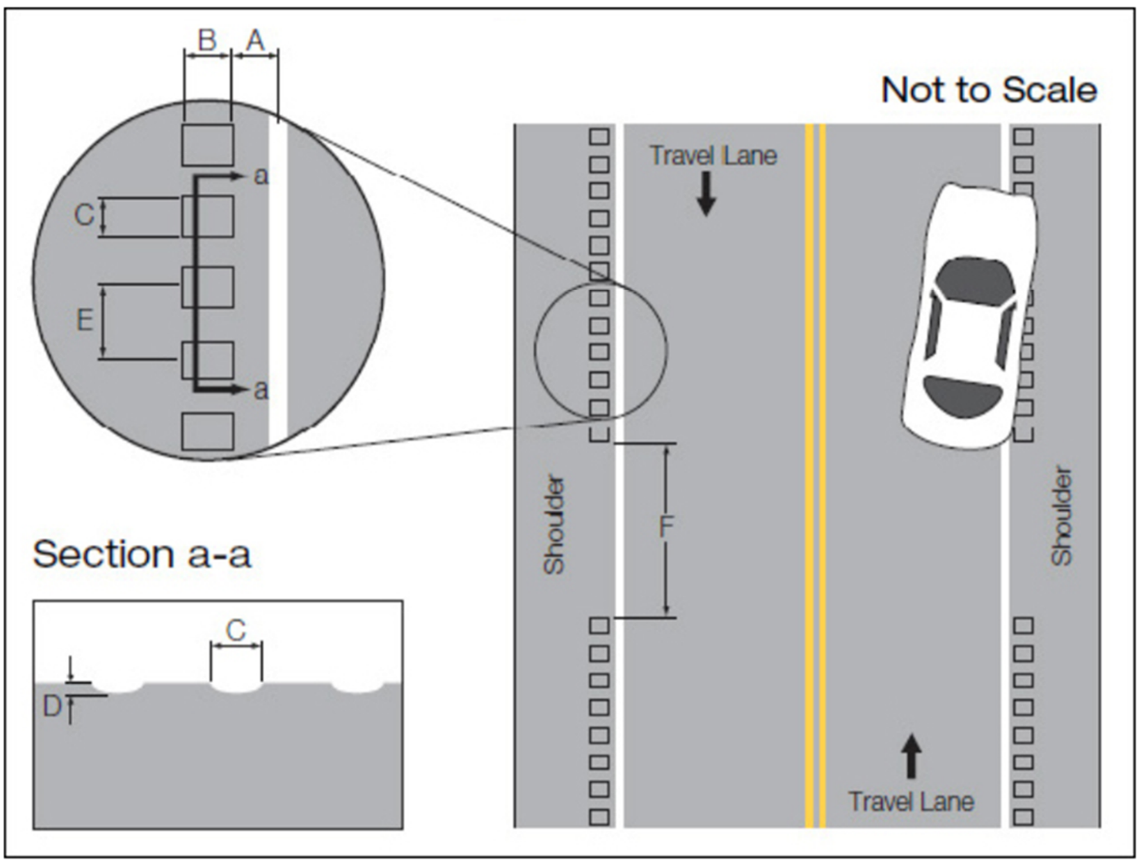

Figure 7. Illustration. SRS rumble strip dimensions.[6]

Table 1. Agency systemic SRS installation criteria.

State	A†	B†	C†	D†	E†	Bike Gap Run (ft)	Bike Gap Gap (ft)	Posted Speed (mph)	SW** (ft)	Asphalt Condition	ELRS
AL	—	8-12	—	—	—	—	—	45	2	Good	Y
AK	4	16	7	½	12	68	12	50	6	Good, >2 in.	N
AZ	10	6-12	7	3/8	12	30	10	—	5	Avoid joint	Y
AR	4	6-16	5	3/8	12	48	12	50	5 ¼	Good	Y
CA	6	6-12	5	5/16	14	—	—	40	5 ½	—	Y
CO	—	12	7	3/8	12	48	12	—	5	—	N
CT*	6	16	7	½	12	—	—	—	—	—	N
DE	6	6	7	3/8	12	40	12	40	5	New	Y
FL*	12	16	7	½	12	—	—	—	—	—	N
GA	12	6-16	7	½	12	28	12	55	4	—	Y
HI	2	6-12	5	3/8	12	47	13	40	4	—	Y
ID	12	6-16	6-7	3/8	12	48	12	—	2	Good	Y
IL	—	8-16	7	7/16	12	48	12	—	—	—	Y
IN	—	16	7	½	12	50	10	—	—	—	Y
IA	6	12	7	½	12	48	12	50	4	—	N
KS	—	12	7	½	12	—	—	—	2	New, >1 in.	N
KY	12	8-16	7	3/8	12	50	10	50	1	—	Y
LA	—	6-12	7	½	14	40	10	50	—	Avoid joint	Y
ME	6	16	7	½	12	48	12	45	4	<5 years, > 3 in.	Y
MD	12	6-12	5-7	3/8	12	48	12	40	5	Good	Y
MA	4	16	6	3/8	12	64	16	40	8	—	N
MI	12	12	7	3/8	12	48	12	55	6	—	N
MN	4	8-12	7	3/8	12	48	12	55	<4	—	Y
MS	—	12	7	3/8	12	—	—	—	2	—	Y
MO	—	12	7	7/16	12	—	—	50	2	>1.75 in.	Y
MT	6	6-12	7-8	½	12	47	13	50	4	—	Y
NE	—	8-16	6	5/8	12	—	—	50	2	Good, >2.5 in.	Y

State	A†	B†	C†	D†	E†	Bike Gap Run (ft)	Bike Gap Gap (ft)	Posted Speed (mph)	SW** (ft)	Asphalt Condition	ELRS
NV	—	5-16	7	½	12	48	12	—	4	—	Y
NH	—	12	8	½	12	48	12	40	5	—	Y
NJ*	4	16	7	½	12	—	—	—	6	>4 in.	N
NM	16	12	7	½	12	48	12	—	<6	Good	Y
NY	12	12	5-7	3/8	24	48	12	50	6	Good, >0.75	N
NC	6	8-16	7	½	12	30/50	6/12	—	4	—	Y
ND	6	6-12	7	½	12	40	10	50	<2	—	Y
OH	10	6-16	5-7	3/8	12	48	12	50	2	PCR>80	Y
OK	12	16	7	½	12	50	10	50	4	—	N
OR	12	6-16	7	3/8	12	30	10	—	—	—	Y
PA	4	6-16	5	3/8	11	48	12	<55	4	Good	Y
RI	4	12-16	7	—	—	48	12	40	6	New, <5 years	Y
SC	—	4-12	7	3/8	12	48	12	45	<1	Good	Y
SD	6	8-12	7	½	12	40	12	50	4	—	Y
TN	—	4-16	5	7/16	12	60	15	40	0	>1.5 in.	Y
TX	4	8-16	7	½	12	40/60	10/12	50	<2	<3 years >2 in.	Y
UT	12	6	5	5/16	12	48	12	—	1	—	Y
VT	—	—	—	—	—	—	—	—	—	—	N
VA	6	12	7	½	12	48/52	12/16	45	4	>2 in.	Y
WA	6	12-16	5	3/8	12	28/48	12	45	4	Good	N
WV	6	12-16	7	3/8	12	48	12	45	4	—	N
WI	6	8	7	½	12	48	12	55	3	Good	Y
WY	12	12-16	7	3/8	12	48	12	50	2	—	N
Fed Land	12	8	5	½	12	48	12	—	—	Good, >2 in.	Y

*Policy and criteria are not specific to rural, two-lane highways. Standards developed for freeways.

**Agencies requiring a four-foot shoulder typically require five feet if barrier or curb is present.

†A, B, C, D, and E represent dimensions depicted in Figure 7.

"—" Blank cells indicate no information was available. Posted speed limit and shoulder width are minimum values.

Table 1 also provides the standard dimensions and bicycle gaps agency use in practice. Agency practices vary most in the length dimension used for rumble strips. Two surveyed agencies have a standard 4-inch rumble strip application while many agencies have a minimum standard of 12 inches or more. Two agencies had policies that were not specific to non-freeway applications and one agency had no standard drawings or referenced dimensions. There is also wide variety in the run length for bicycle accommodation, although most agencies apply a 10- to 12-foot gap for bicycle crossing.

Many of the agencies listed have one design pattern for all installations and have no flexibility built into the policy. Other agencies have built-in flexibility. The flexibility is most commonly specifying rumble strip length and offset based on shoulder width. For example, Tennessee standards include rumble strip length from 4 to 16 inches and offset ranging from edge line to 12 inches. The dimension and location of the rumble strip varies based on the available shoulder width. For available paved shoulder widths 8 feet or greater, rumble strips are 16 inches with a 12-inch offset. For available paved shoulder widths of 2 to 8 feet, rumble strips are 8 inches and ELRS are specified. For shoulders less than 2 feet, a 4-inch ELRS is specified. Many agencies allow for variable rumble strip length and offset to maximize the clearance (allow for 4-foot shoulder).

Flexibility should be built into the policy. Flexibility is important in policy, especially if the policy specifies parties that are involved in the decision-making process. For example, the Minnesota Department of Transportation (MnDOT) policy provides districts discretion for lateral placement to abate noise concerns and accommodate bicyclists.[19] 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® or wider shoulder is installed.

Center Line Rumble Strips

Table 2 provides an overview of CLRS design dimensions and systematic installation criteria. Note that the spacing is listed as 12/24 inches for several agencies. This indicates that the spacing is 12 inches between rumbles followed by a 24-inch gap. The following installation criteria are commonly used by agencies:

- Minimum posted speed limit. The minimum posted speed limit typically serves as a surrogate for level of urbanization. Rumble strips are used in rural areas and are avoided in urban areas, unless justified by crash history, due to noise complaints.
- Minimum pavement, lane, or shoulder width.

- Minimum distance to nearby residences. Few agencies specify a minimum distance to nearby residences, but the distance is most commonly near 650 ft.
- Asphalt condition. There are several criteria used for asphalt condition:
  - Structural condition. Several agencies look for the asphalt condition to be "good."
  - Maximum pavement age. In addition to new pavements, several agencies utilize pavement age as a criterion in lieu of structural condition.
  - Minimum pavement depth. Several agencies note a minimum depth for the surface coat that allows for rumble strip installation within the surface.
- Passing zone option. Fifty percent of the agencies surveyed had no specific policy regarding CLRS and passing zones. Of those agencies with policies, 22 out of 25 indicate that rumble strips should continue through passing zones. Note that one of the three agencies specifying CLRS be discontinued in passing zones is reviewing its policy to allow CLRS installation in passing zones. A recent study in Minnesota reviewed all two-lane fatal head-on crashes and found that passing is rarely a contributing factor.(5) Based on this finding, breaking at passing zones would be counter-productive.

Other installation criteria not shown below include:

- Minimum AADT. Few State agencies specify a minimum AADT threshold for installation. Minimum AADT thresholds range from 1,500 to 3,000 vehicles per day.
- Shoulder width. Few States have a minimum shoulder width requirement; however, some States use the minimum shoulder width to specify whether edge line rumble strips may be used in place of CLRS.
- Minimum distance to residences. A few states have a minimum distance to nearby residences. Specified distances range from 100 feet to 2,000 feet. The distance is most commonly about 650 feet.

Figure 8 provides an overview of the dimensions used in Table 2. The dimensions are consistent with those provided in the Key Definitions section.

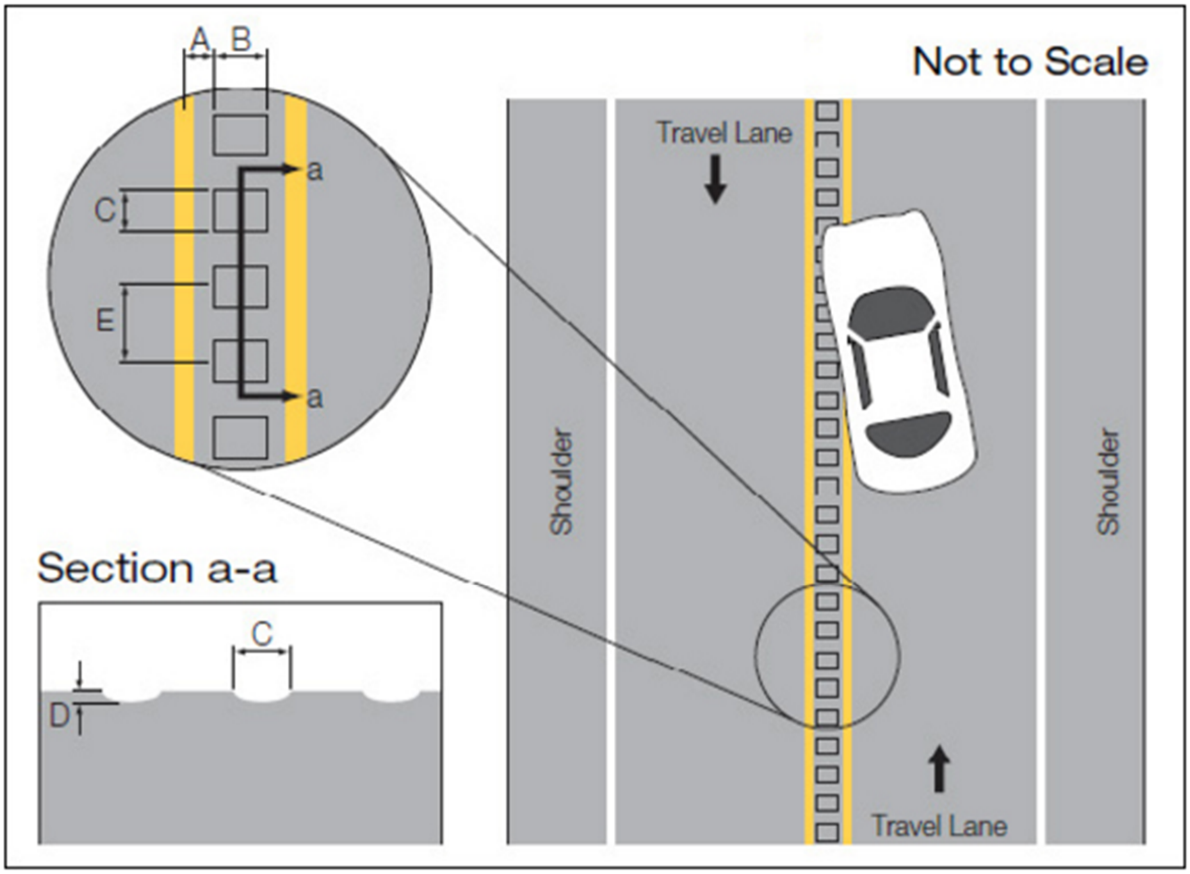

Figure 8. Illustration. CLRS rumble strip dimensions.[(6)]

As with SRS, the length dimension varies most for CLRS among agency practices. The most common applications are 12 and 16 inches, but range from 8 to 20 total inches. Several agencies use two rumble strips, straddling the center line joint; however, most agencies mill one rumble strip centered on the joint. Agencies also differ in spacing for CLRS. SRS are nearly universally spaced 12 inches center-to-center, whereas CLRS are sometimes spaced 12 inches, or 12 inches and then 24 inches. Agencies do this to differentiate the noise and vibration between CLRS and SRS. The intention is to alert drivers to which direction they have drifted in order to maneuver in the appropriate direction.

There is less flexibility in rumble strip length for CLRS than for SRS; however, it is important that systematic policies address flexibility for noise mitigation and design standards address rumble strip placement with respect to RPMs.

Table 2. Agency systematic center line rumble strip installation criteria.

State	B†	C†	D†	E†	Min Width – Pave (ft)	Min Width – Lane (ft)	Posted Speed (mph)	Asphalt Condition	Pass Zone
AL	8-12	—	—	—	—	11	—	Good	Y
AK	12	7	3/8	12	28	—	45	Good, >2 in.	Y
AZ	6	7	3/8	12	—	11	45	—	Y
AR	16	5	3/8	12	28	10	45	Good	N
CA	6-12	5	5/8	12	—	—	40	—	Y
CO	12	7	3/8	12	—	—	—	—	Y
CT	12	7	3/8	24	26	—	40	Good	N
DE	16	7	3/8	12	—	10	40	New	—
FL	—	—	—	—	—	—	—	—	—
GA	16	7	½	12	—	—	—	—	—
HI	16-20	6-9	½	12	—	—	40	—	—
ID	12	7	½	12	24	—	—	Good	N*
IL	—	—	—	—	—	—	—	—	—
IN	16	7	½	12/24	—	—	—	—	—
IA	16	7	½	12/24	—	11	50	<5 years	—
KS	12	7	½	12	—	—	—	New, >1.5 in.	—
KY	8-12	7	3/8	12	—	11	50	—	—
LA	6-12	7	½	14	24	11	50	Avoid joint	
ME	12	7	½	24	—	11	45	<5 years, >1.5 in.	Y
MD	16	7	½	24/36	—	10	40	Good	Y
MA	—	—	—	—	—	—	—	—	—
MI	16	7	3/8	12/24	26	—	55	—	Y
MN	16	7	3/8	12	—	11	55	—	Y
MS	—	—	—	—	—	—	—	—	—
MO	12	7	7/16	12/24	—	10	50	>1.75 in.	Y
MT	6-12	7-8	½	12/24	—	—	50	—	—
NE	—	—	—	—	—	11	50	Good, >2.5 in.	—

State	B†	C†	D†	E†	Min Width – Pave (ft)	Min Width – Lane (ft)	Posted Speed (mph)	Asphalt Condition	Pass Zone
NV	12	7	½	12	—	—	—	—	Y
NH	12	7	½	12	28	—	40	Good, >1.25 in.	Y
NJ	16	7	½	12	—	10	35	Good, SDI>3	Y
NM	16	7	½	12/24	26	12	50	Good	Y
NY	12	7	3/8	24	26	—	45	Good, >0.75	Y
NC	—	—	—	—	—	—	—	—	—
ND	6-12	7	½	12/24	—	—	50	—	—
OH	16	5	3/8	12/24	—	—	—	—	—
OK	—	—	—	—	—	—	—	—	—
OR	16	7	½	24/48	—	—	—	—	Y
PA	14-18	7	½	24/48	—	10	—	Good, >2.5 in.	Y
RI	12	7	—	12	—	11	40	New, <5 years	Y
SC	12	7	3/8	14	—	10	45	Good	—
SD	12	5	3/8	12	—	—	50	—	—
TN	12	7	7/16	24	—	12	40	Avoid joint	Y
TX	16	7	½	24	—	11	50	<3 years >2 in.	Y
UT	6	8	5/8	12	—	—	—	—	Y
VT	12-18	7	3/8	12/24	28	—	45	Good	Y
VA	14	7	½	12	—	11	45	>4 in.	Y
WA	12	7	½	12	24	—	—	Good	Y
WV	—	—	—	—	—	11	45	—	—
WI	8	7	3/8	12/24	—	12	55	Good	—
WY	12	7	½	12	—	—	50	—	—

*Policy being reviewed currently. Note that blank rows indicate no policy indicated.

†A, B, C, D, and E represent dimensions depicted in Figure 8.

"—" Blank cells indicate no information was available. Posted speed limit, pavement, and lane width are minimum values.

SUCCESSFUL 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. Highway corridors, with narrow shoulders for example, 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 to identify the need for and potential benefits of rumble strips in these corridors. Most agencies reviewed do not provide specific guidelines for how and when to install rumble strips in these cases. Additionally, these corridors will have the greatest potential for installation issues due to special considerations. Consideration of the potential benefits and trade-offs is paramount, and the agencies with the most success installing rumble strips have written processes or requirements, including who is involved in the final decision-making. Successful policies include relevant stakeholders in the decision-making process once identifying the need.

Several agencies identify key personnel involved with decision-making or identify personnel who are typically included in a rumble strip decision-making committee. Examples of personnel who may be involved in the decision-making process include the following (note that agencies 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 bicycle groups, and adjacent roadway property owners and residents. Their feedback is critical, and should be considered in combination with potential safety benefits. This also provides the agency an opportunity to provide stakeholders with information on the safety benefits, including specific performance measures calculated in the safety analyses. This may help the agency to promote rumble strips to stakeholders.

A few agencies 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 why. Documentation is also important for explaining the benefits to stakeholders and to those who may perceive a disbenefit to their installation. The Texas Department of Transportation (TxDOT) noted that if they demonstrate the historical crash reduction factors for rumble strip installations to the general public they have fewer complaints after installation.

The Montana Department of Transportation has a specific process for new construction, reconstruction, rehabilitation, and overlay corridors where the shoulder width is greater than 1 foot but less than 4 feet. The procedure includes the following steps:(18)

1. Complete an economic analysis targeting roadway departure crashes to determine if rumble strips are justified.
2. The Planning Division determines if and how bicyclists use the highway corridor using bicycle route maps, bicycle use 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 District. Other divisions are included on an as-needed basis.

MODEL DECISION-SUPPORT FRAMEWORK FOR RUMBLE STRIP INSTALLATION

OVERVIEW OF MODEL DECISION-MAKING PROCESS

Agencies that have successfully installed CLRS and SRS on their rural, two-lane and multilane systems generally have formalized processes for systematic installation and for decision-making 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. This section outlines general model guidance for steps that may be included in a decision-making process, factors to consider, and who may be involved in such a process. Figure 9 provides an overview of the model decision-making framework, which is based on a detailed review of current agency practices across the country. The framework is not intended to be directly applicable to every agency as 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.

This model framework is based on an analysis due to systematic installation (e.g., the 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 3 of the decision-making process presented in Figure 9. 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 Decision-Making Process

This section describes the decision-making process shown in Figure 9. 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 decision-making. The final decisions include installing standard rumble strips, installing modified rumble strips, installing alternate treatments, or no installation.

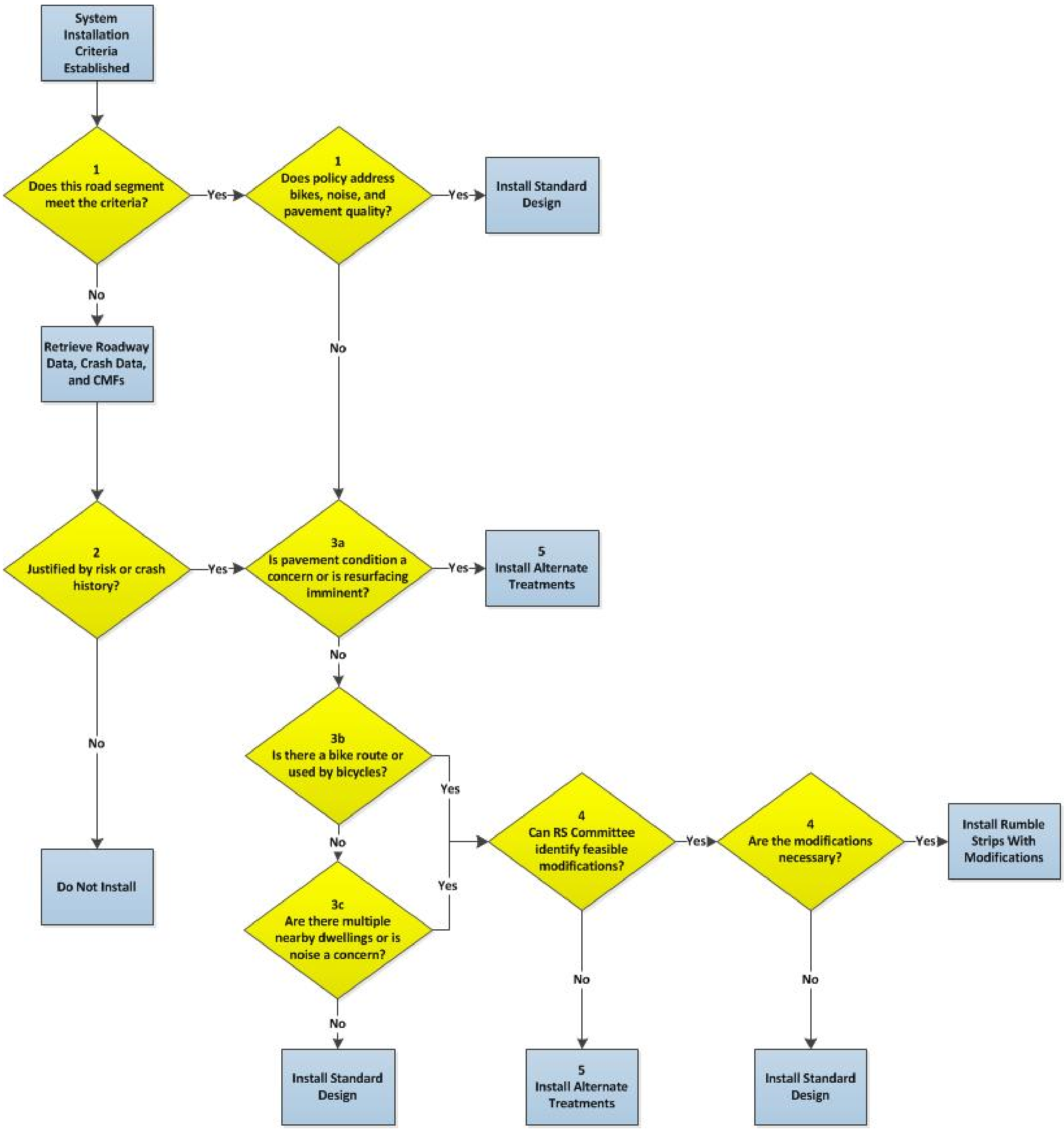

Figure 9. Illustration. Model decision-making framework for rumble strip installation.

Step 1. Systematic Installation

This step identifies whether or not a corridor is a candidate for installation based on systematic policy. This step typically involves the designer or design team and necessitates information on roadway attributes and operations attributes and generally coincides with resurfacing, rehabilitation, or new construction. If the corridor meets the policy criteria and the policy explicitly considers bicyclists, external noise, and pavement condition, then the standard design can be installed. If the policy does not include these special considerations, then they are addressed in Step 3 (and Step 2 can be skipped). If the corridor does not meet the criteria for systematic installation, then move forward to Step 2.

Step 2. Systemic and High Crash Corridor Installation

This step identifies the need for rumble strip installation based on the methods provided in the Rumble Strips and Safety Management section. Although the corridor does not qualify for systematic installation, the corridor may benefit from rumble strip installation. Agencies may consider using a systemic (i.e., risk-based) approach and a high crash corridor approach.

In the systemic approach, analysts identify corridors based on a combination of risk factors, rather than crash history. Crash history can be combined with CMFs for candidate countermeasures in order to determine the potential crash reduction and cost-effectiveness of the proposed measure(s). The systemic approach typically focuses on fatal and severe injury crashes, which are not normally clustered, but provide an opportunity for cost-effective widespread implementation.

In the high crash corridor approach, staff use historical (observed) crashes, expected crashes, predicted crashes, or some combination thereof to identify the need for mitigation. As noted in the High Crash Corridor Safety Approach section, the preferred methods use predicted crashes or expected crashes in the selection of high crash corridors. Once potential mitigation measures are identified, staff apply CMFs in order to determine the potential crash reduction and cost effectiveness of the proposed measures.

In this step, the designer may need to consult with traffic engineers or safety engineers/analysts to develop the justification for installation. If the corridor does not warrant installation, then the decision will be for no installation. If the corridor does warrant installation, then the designer or analyst would document the need and potential safety benefit and move forward to Step 3.

Step 3. Special Considerations

There are three special considerations within this step: pavement condition, bicycle accommodation, and noise accommodation. Each of these are discussed individually.

Step 3a: Pavement Condition

The pavement should be in good condition (i.e., minimal cracking) and have adequate pavement depth when rumble strips are installed. There is little evidence showing accelerated degradation due to rumble strip installation, but agencies have noted accelerated degradation when the pavement surface was in poor condition. Maintenance personnel may be involved in the decision-making process if the pavement quality is in question, or a pavement quality database can be consulted. If the installation is part of a pavement resurfacing, rehabilitation, or a new construction, then pavement condition is not a concern. Refer to the FHWA Rumble Strip Implementation Guide: Addressing Pavement Issues on Two-Lane Roads for more details on pavement issues.[17] If the pavement condition is adequate or a major reconstruction is more than 3 to 5 years away, then move forward to Step 3b. If the pavement condition does not support installation, then move forward to Step 5.

Step 3b: Bicycle Accommodation

If bicyclists are not considered in the development of the standard rumble strip design, there are likely to be modifications needed for some installations. Bicyclists have difficulty traversing rumble strips and need adequate clear space on the shoulder and periodic breaks to cross over rumble strips. A non-motorized transportation coordinator (typically the bicycle and pedestrian coordinator) and local stakeholders are consulted to determine if 1) the corridor is a designated bicycle route or 2) if bicyclists utilize the corridor. This consultation utilizes maps of designated bicycle corridors, crowdsourcing technology that identifies bicycle usage, or discussion with those who have local knowledge. Refer to the FHWA Rumble Strip Implementation Guide: Addressing Bicycle Issues on Two-Lane Roads for more details on bicycles issues and accommodation.[13] If it is determined that bicycles use the route, and the standard installation will result in inadequate clear space, then move forward to Step 4. If bicycle accommodation is not a concern, then move forward to Step 3c.

Step 3c: Noise Accommodation

If noise accommodation is not considered in the development of the standard rumble strip design, there are likely to be modifications needed for some installations. Vehicles traversing over rumble strips result in noise that differs from background highway noise, which can disturb nearby residents. An environmental specialist with a background in noise can be consulted to determine if noise is a potential concern for this installation. Refer to the FHWA Rumble Strip Implementation Guide: Addressing Noise Issues on Two-Lane Roads for more details on noise issues and accommodation.[15] The number of receptors, locations of residences, traffic volume, and traffic characteristics are of interest where your agency has no formal policy on noise mitigation. This work utilizes plan-view mapping, site visits, discussion with residents, or discussion with those who have local knowledge. If it is determined that noise accommodation is necessary, then move forward to Step 4. If noise accommodation and bicycle accommodation is not a concern, then the standard rumble strip design may be installed.

Step 4: Alternative Rumble Strip Designs for Accommodating Bicycles and/or Noise

Step 4 applies to corridors identified to have bicycle accommodation and/or noise accommodation concerns and roadway elements do not allow for standard installations (e.g., shoulder width too narrow to allow for bicycle clear space). In this step, a rumble strip committee may be consulted to come to a consensus about rumble strip installation and to determine any potential changes to the standard design. The rumble strip committee may include a roadway designer, a non-motorized coordinator, a noise specialist, a traffic or safety engineer/analyst, and an individual from maintenance. At this point, the rumble strip committee can consult with outside stakeholders (e.g., local stakeholders) to weigh the potential safety benefits versus the special considerations. The rumble strip committee will consider the installation of the standard design, potential modifications (e.g., those listed in the Special Considerations section), or not installing rumble strips. Modifications to the design, such as a shallower rumble strip or sinusoidal pattern, may provide adequate warning for motor vehicles and accommodate bicycle and noise concerns. If the committee determines there are too few safety benefits, which do not outweigh other concerns, then move forward to Step 5, otherwise install the recommended design (standard or modified).

Step 5: Alternative Treatments

If the analyst determines rumble strips are not a viable solution in Step 3a or Step 4, and there is a documented safety problem, then the analyst may consider alternative treatments. The Special Considerations section presents a short list of alternatives for consideration; however, other treatments may not focus on distracted or drowsy driving. The CMF Clearinghouse (www.cmfclearinghouse.org), HSM Part D, the Low-Cost Treatments for Horizontal Curve Safety 2016 guide, and the NCHRP Report 500: Guidance for Implementation of the AASHTO Strategic Highway Safety Plan series may be consulted for additional potential countermeasures. Alternative strategies may be considered based on their effectiveness in reducing the crash type or types of interest. The final decision should be documented along with the expected safety benefit. The rumble strip committee may be involved in the decision-making or the designer can consult with traffic engineering or safety analysts. If no viable alternatives are identified, then the committee or individual may recommend not to install any countermeasures. In this case, the decision should also be documented.

CASE STUDIES

This section includes case study examples where agencies weighed the decision to install CLRS or SRS when there was potential concern for roadway users other than vehicles, nearby residents, and pavement condition. Examples include cases where rumble strips were installed and later removed after working with local residents as well as an economic analysis of systemic rumble strip installation. These examples show the importance of involving local residents, advocacy groups, and rumble strip committees in policy-making and implementation decision-making. Case studies were provided by Michigan Department of Transportation (MDOT), MnDOT, and TxDOT.

RUMBLE STRIP CASE STUDY FROM MICHIGAN

Accommodating Amish in Rumble Strip Policy

Michigan policy indicates that non-freeway SRS should be used on all rural, two-lane, four-lane, and divided trunk lines where the posted speed limit is 55 miles per hour and the paved shoulder is at least 6 feet wide. If safety concerns outweigh other issues, such as noise and bicycle use, non-freeway SRS can be installed on roadways with narrower shoulders. Early on in the expansion of MDOT's non-freeway rumble strip program (around 2008), MDOT was made aware of concerns from the Amish community in the southwestern part of the State regarding SRS and the effect on their buggies and horses. The horses would not cross the rumble strips, both CLRS and ELRS. As mitigation, when calling for SRS, designers tried placing the rumble strips very close to the edge line rather than the standard 12-inch offset to leave more room between the rumbles and the edge of the paved shoulder. However, the Amish did not like the resulting tight squeeze and used the travel lane. When a vehicle would pass them, they would cross the CLRS, scaring the horses. Along the same line, the horses did not like to cross the rumble strips because the rumble strips made it difficult for them to set their feet down. There was at least one instance of a horse getting hurt because of stepping into the rumble strips.

As a result of these issues, several sections of non-freeway rumble strips were filled-in to accommodate the horses and buggies. Additionally, rumble strips were omitted in some areas for which they were planned. Within a few months of the concerns being raised, MDOT's design guidance was modified to take these unique road users into account. The guidance now indicates that "in locations where horse-drawn buggies utilize the roadway, do not use shoulder corrugations unless a crash history exists. Document this as a context sensitive design decision. When a correctable crash history does exist, consider using corrugations and widening the shoulder 2 ft to accommodate both."

Accommodating Pavement Preservation in Rumble Strip Policy

The expanding use of rumble strips has resulted in changes to how Michigan roadways are constructed and maintained. Due to concerns that cutting CLRS into an asphalt joint could expedite the joint deterioration, the MDOT adopted a joint density specification to ensure the center line pavement was sound. A field visit with FHWA representatives determined that a single chip seal over rumble strips allowed the rumble strips to maintain functionality; however, a double chip seal significantly reduced the effectiveness. MDOT has updated their Special Provisions for chip seals to indicate that when performing a double chip seal only the top layer crosses the rumble strips. Upon finding that microsurfacing treatments essentially nullified rumble strips but still reflected the grooves (which would be hard to line up on for cutting), MDOT updated their Special Provision for microsurfacing to indicate rumble strips should be filled-in with microsurfacing material prior to the surface treatment such that rumble strips can be re-cut afterwards.

RUMBLE STRIP CASE STUDIES FROM MINNESOTA

Highway 19 near New Prague

Near New Prague on Highway 19, MnDOT installed CLRS in 2014 in compliance with the State Technical Memorandum. Due to frequent hits of these rumble strips, several residents in the vicinity started to send complaints to the District 6 office (located in Rochester, MN). The district responded by investigating the highway and working with the residents to identify the locations that were generating the noise pollution. After determining which locations, the district removed the rumble strips at the identified locations and has since replaced them with an experimental sinusoidal rumble strip that should create less nuisance noise. Since installation, the district has not received any complaints from the residents. The efforts to remove the rumbles and repave the removed areas did consume both time and money by MnDOT Maintenance and Engineering sections. MnDOT did have to pay for the rumble strip contractor to mobilize and cut in the sinusoidal rumble strips on the one section of roadway.

Highway 61 in Northern Minnesota

Along the North Shore in Minnesota, Highway 61 closely follows the shore of Lake Superior. In compliance with both the State Technical Memorandum regarding rumble strips, and with the State strategic initiatives to apply systemic safety countermeasures, MnDOT's District 1 (headquartered in Duluth, MN) installed CLRS along the highway in 2013. Approximately 40 miles of CLRS were installed north of Grand Marais under a districtwide CLRS project and 9 miles of CLRS were installed between Two Harbors and Beaver Bay on a mill and overlay project. Shortly after the installation, complaints started to be received from residents and others with lake/vacation homes. The noise created by hitting the rumble strips was creating noise pollution that many near the highway found to be unacceptable. After significant outcry and organization by the local population (the Cook County Board played a very active role), a noise study was conducted to better understand the issue and potential solutions. The noise study had some findings that the noise would carry further and with greater amplification then was initially assumed. With these findings, District 1 management decided to fill-in or remove certain rumble strips that were near residential locations along significant portions of the highway. All told, nearly 46 miles (with the exception of approximately 3.5 miles near the Canadian Border) of rumble strips were filled in to the satisfaction of area residents. Since the removal, very few complaints have been received. The District is looking into the idea of using sinusoidal rumble strips as a potential countermeasure on any future projects. This project helped jump start a MnDOT initiative to find a quiet yet effective rumble strip. As of the summer of 2016, MnDOT has approved a sinusoidal rumble strip that provides internal vibration and acceptable noise levels, while producing very little noticeable external noise.

Highway 14 from Mankato to Nicollet

Highway 14 is a major arterial in southern Minnesota, spanning from South Dakota to Wisconsin. The highway connects farms to population centers and manufacturing and trade hubs, and is considered a part of the Interregional Corridor System. Highway 14 is also a combination of designs, including two-lane highway, high-speed expressway, and full freeway design. In 2012, near Mankato, a two-lane section of the highway was determined to have a statistically significant above-average rate of fatal head-on crashes. As a response to this issue, MnDOT agreed to expand the highway to a four-lane expressway. However, this would not be completed until the 2016-2017 timeframe. Rather than doing nothing during the project initiation and design phases, District 7 (headquartered in Mankato, MN) made the decision to try an interim typical section to prevent or reduce the chances of a fatal crossover crash. The typical section changed from 10-foot shoulders and 12-foot lanes (total 44-foot width paved top) to a typical section of 7-foot shoulder – 11-foot lane – 8-foot buffer (with tube delineators) – 11-foot lane – 7-foot shoulder. The buffer was a double striped yellow line with rumbles, and was on each side of the delineators (see Figure 10 for an example from Bing Streetside). This was completed in October of 2012. The after results, though a small sample size, appear to be promising. Before the application, this 7-mile segment was experiencing an average of one fatal or severe head-on crash per year, and has only had one minor crossover crash since implementation (through 12/31/2015). In the time frame from 2006 to September 2012 (6.75 years), there were 59 crashes of all types, and from November 2012 through the end of 2015 (3 years), there have been 20 crashes, resulting in nearly a 30 percent total crash reduction. On the target crash type (head-on, ROR-left, and sideswipe) the corridor has gone from 20 crashes in the before period (from 2006 to September 2012 - 6.75 years), to only 4 crashes (from November 2012 to December 2015 – 3 years) after; resulting in a nearly 60 percent total target crash reduction. Fatal and serious injury crashes have gone from 6 to 0.

Figure 10. Photograph. Buffer median on Highway 14 from Bing Streetside.[20]

RUMBLE STRIP CASE STUDY FROM TEXAS

Systemic Installation of Rumble Strips

Currently (since 1999), TxDOT requires that rumble strips be used for rural, four-lane or more divided highways with a speed limit greater than 45 miles per hour. Rumble strips on rural, undivided highways are installed based upon a B/C analysis of the crash history at that location. The higher the B/C ratio, the more likely they will be installed.

In 2016, the Texas Traffic Safety Force conducted an economic analysis of installing CLRS and ELRS on 20,000 miles of rural undivided highways with adequate pavement width.[21] Assuming an average installation cost of 18,000 dollars per mile, the total cost of installations was estimated to be 360 million dollars. The CLRS and ELRS installations would target ROR and head-on crashes, with an estimated 170 to 180 lives saved per year and 2,800 to 2,900 crashes prevented per year. With a conservative estimate of a 5-year service life, the potential lives saved over service life was estimated to be 850 to 900 lives. The estimated cumulative benefit for was estimated to be 4.3 billion dollars, resulting in a B/C ratio of 12 dollars for every dollar spent.

The task force recommended installing CLRS and ELRS on rural undivided highways with adequate lane and shoulder widths. Additionally, further installations were noted to be implemented through collaboration between TxDOT districts and the Maintenance and Traffic Operations Divisions.

OTHER RESOURCES

The FHWA maintains a Rumble Strips and Rumble Stripes website, which is accessible at safety.fhwa.dot.gov/roadway_dept/rumble_strips/. The website contains resources on safety; design and construction; accommodating all users; mitigating noise; pavement and maintenance; and policies, guidance, and research. The website also contains implementation fact sheets for designers and implementation guides for technical specialists focusing on noise, pavements, and bicycle accommodation. The FHWA also has technical advisories on Rumble Strips for Shoulder and Edge Line Rumble Strips (T 5040.39, Revision 1) and Center Line Rumble Strips (T 5040.040, Revision 1).

For more information on rumble strip or alternative countermeasure effectiveness, visit the CMF Clearinghouse at www.cmfclearinghouse.org.

For more information on the HSM, visit www.highwaysafetymanual.org.

APPENDIX A—EXAMPLE CMF TABLES

Appendix A contains CMFs available on the CMF Clearinghouse for CLRS, SRS, and their combination in the following tables:

- Table 3: Sample CMF Clearinghouse CMFs for CLRS on Rural, Two-Lane Highways.
- Table 4: Sample CMF Clearinghouse CMFs for SRS on Rural, Two-Lane Highways.
- Table 5: Sample CMF Clearinghouse CMFs for SRS on Rural, Multilane Highways.
- Table 6: Sample CMF Clearinghouse CMFs for CLRS and SRS on Rural, Two-Lane Highways.

Each table provides 5-star and 4-star CMFs covering a breadth of crash types, crash severity, jurisdictions, AADTs, and geometric conditions. The tables report the ID for each CMF, the estimated CMF, and the lower and upper 95-percent confidence intervals. These are currently the highest quality CMFs available for each installation type. Note the countermeasure name, number of lanes and area type are already accounted for in these tables. Also note there is little variability in minor factors for each installation type for these CMFs. The CMFs in Table 3, Table 4, and Table 6 , apply to rural, two-lane highways and the CMFs in Table 5 apply to rural, multilane highways. These CMFs are mainly distinguishable by their applicable crash type and crash severity. However, a few CMFs are applicable to specific geometric characteristics as noted in the final column of each table.

The specific characteristics listed in the final column help to identify where the treatment may be more effective. For example, Table 6 provides separate CMFs for AADT less than 3,200 and AADT greater than or equal to 3,200. While the difference is not statistically different, the average CMF for the higher volume is 0.70 versus 0.85 for the lower volume, indicating that shoulder and CLRS may be more effective on high-volume roadways. Comparing CMFs provides insights into which crash types, severities, and locations the treatment is more effective at mitigating.

Table 3. Sample CMF Clearinghouse CMFs for CLRS on rural, two-lane highways.

ID	Stars	CMF	L95	U95	Crash Type	Crash Severity	Jurisdiction	Min AADT	Max AADT	Specific Characteristic
3350	5	0.91	0.84	0.98	All	F & I	MN, PA, WA	574	20,784	—
3355	5	0.63	0.53	0.73	Head-on, Sideswipe	All	MN, PA, WA	574	20,784	—
3360	5	0.55	0.43	0.68	Head-on, Sideswipe	F & I	MN, PA, WA	574	20,784	—
3361	5	0.91	0.87	0.95	All	All	CA, CO, DE, MD, MN, OR, PA, WA	574	20,784	—
3362	5	0.88	0.83	0.94	All	F & I	CA, CO, DE, MD, MN, OR, PA, WA	574	20,784	—
3363	5	0.7	0.61	0.79	Head-on, Sideswipe	All	CA, CO, DE, MD, MN, OR, PA, WA	574	20,784	—
3375	5	0.53	0.34	0.72	Head-on, Sideswipe	All	MN, PA, WA	574	20,784	Horizontal Curves
3383	5	0.85	0.73	0.97	All	F & I	MN, PA, WA	574	20,784	Horizontal Tangents
3387	5	0.51	0.38	0.65	Head-on, Sideswipe	All	MN, PA, WA	574	20,784	Horizontal Tangents
3367	4	1.04	0.91	1.17	All	All	MN, PA, WA	574	20,784	Horizontal Curves
3371	4	0.94	0.78	1.10	All	F & I	MN, PA, WA	574	20,784	Horizontal Curves
3379	4	0.92	0.84	1.00	All	All	MN, PA, WA	574	20,784	Horizontal Tangents
5398	4	0.71	0.52	0.90	Other	All	KS	200	8,000	—
5400	4	0.81	0.53	1.08	ROR	All	KS	200	8,000	—
7244	4	0.73	0.72	0.73	Target	All	MI	—	—	—
7245	4	0.47	0.47	0.47	Target-Wet	All	MI	—	—	—
7246	4	0.99	0.98	0.99	Target-Winter	All	MI	—	—	—
7247	4	0.57	0.57	0.57	Target-Passing	All	MI	—	—	—
7248	4	0.71	0.71	0.72	Target-Impaired	All	MI	—	—	—
7250	4	0.68	0.68	0.68	Target	A Inj.	MI	—	—	—
7251	4	0.61	0.60	0.61	Target	B Inj.	MI	—	—	—
7252	4	0.72	0.72	0.72	Target	C Inj.	MI	—	—	—
7253	4	0.84	0.83	0.84	Target	PDO	MI	—	—	—

"—" Blank cells indicate no information was available.

Table 4. Sample CMF Clearinghouse CMFs for SRS on rural, two-lane highways.

ID	Stars	CMF	L95	U95	Crash Type	Crash Severity	Jurisdiction	Min AADT	Max AADT	Specific Characteristic
3442	5	0.84	0.68	1.00	ROR	All	MN, MO, PA	782	10,386	—
3454	5	0.64	0.45	0.83	ROR	F & I	MN, MO, PA	782	10,386	—
3394	4	0.67	0.43	0.91	ROR	F & I	MN, MO, PA	180	12,776	Edge Line (0 in. to 8 in.)
3408	4	0.57	0.29	0.86	ROR	F & I	MN, MO, PA	180	12,776	Edge Line (0 in. to 8in., 5 ft recovery area
3418	4	1.06	0.95	1.17	All	All	MN, MO, PA	782	10,386	—
3430	4	0.92	0.76	1.08	All	F & I	MN, MO, PA	782	10,386	—
3582	4	1.18	0.88	1.48	ROR, wet road	All	MN, MO, PA	782	10,386	—
3603	4	0.89	0.64	1.14	ROR, night	All	MN, MO, PA	782	10,386	—
3627	4	0.46	0.21	0.71	ROR	F & I	MN, MO, PA	180	12,776	5 ft Shoulder
3651	4	0.62	0.33	0.91	ROR	F & I	MN, MO, PA	180	12,776	9 in. to 20 in. offset from EL
7255	4	0.67	0.67	0.68	Target	All	MI	—	—	—
7256	4	0.44	0.44	0.45	Target-Wet	All	MI	—	—	—
7257	4	0.95	0.94	0.96	Target-Winter	All	MI	—	—	—
7258	4	0.64	0.64	0.65	Target-Passing	All	MI	—	—	—
7259	4	0.60	0.59	0.61	Target-Impaired	All	MI	—	—	—
7261	4	0.68	0.67	0.68	Target	A Inj.	MI	—	—	—
7262	4	0.46	0.46	0.47	Target	B Inj.	MI	—	—	—
7263	4	0.65	0.64	0.66	Target	C Inj.	MI	—	—	—
7264	4	0.72	0.71	0.72	Target	PDO	MI	—	—	—

"—" Blank cells indicate no information was available.

Table 5. Sample CMF Clearinghouse CMFs for SRS on rural, multilane highways.

ID	Stars	CMF	L95	U95	Crash Type	Crash Severity	Jurisdiction	Min AADT	Max AADT	Specific Characteristic
3414	5	1.18	1.03	1.33	All	All	MN, MO, PA	4,959	20,763	—
3438	5	1.40	1.16	1.64	ROR	All	MN, MO, PA	4,959	20,763	—
3450	4	0.97	0.71	1.23	ROR	F & I	MN, MO, PA	4,959	20,763	—
3426	4	0.90	0.70	1.10	All	F & I	MN, MO, PA	4,959	20,763	—
6649	4	0.76	0.65	0.87	All	All	FL	2,000	50,000	4 ft to 12 ft Shoulder
6650	4	0.64	0.50	0.79	All	F & I	FL	2,000	50,000	4 ft to 12 ft Shoulder
6653	4	0.61	0.41	0.82	All	All	FL	2,000	50,000	4 ft to 6 ft Shoulder
6654	4	0.57	0.30	0.83	All	F & I	FL	2,000	50,000	4 ft to 6 ft Shoulder
6655	4	0.79	0.67	0.92	All	All	FL	2,000	50,000	8 ft to 12 ft Shoulder
6653	4	0.66	0.49	0.83	All	F & I	FL	2,000	50,000	8 ft to 12 ft Shoulder
6665	4	0.61	0.49	0.72	All	All	FL	2,000	50,000	Widen Shoulder
6667	4	0.54	0.37	0.71	ROR	All	FL	2,000	50,000	Widen Shoulder
6669	4	0.35	0.23	0.47	All	All	FL	2,000	50,000	Widen Original 4 ft to 6 ft Shoulder
6671	4	0.81	0.62	1.00	All	All	FL	2,000	50,000	Widen Original 8 ft to 12 ft Shoulder
4780	4	0.76	0.63	0.89	All	F & SI	MO	—	—	Edge Line and Wider Marking
4781	4	0.74	0.67	0.81	All	F & I	MO	—	—	Edge Line and Wider Marking
4782	4	0.86	0.77	0.95	All	F & I	MO	—	—	Edge Line and Wider Marking on Urban
4787	4	0.75	0.51	0.99	All	F & I	MO	—	—	Shoulder and Wider Marking

"—" Blank cells indicate no information was available.

Table 6. Sample CMF Clearinghouse CMFs for CLRS and SRS on rural, two-lane highways.

ID	Stars	CMF	L95	U95	Crash Type	Crash Severity	Jurisdiction	Min AADT	Max AADT	Specific Characteristic
6850	5	0.80	0.75	0.85	All	All	KY, MO, PA	154	25,796	—
6851	5	0.77	0.70	0.84	All	F & I	KY, MO, PA	154	25,796	—
6852	5	0.74	0.66	0.82	ROR	All	KY, MO, PA	154	25,796	—
6853	5	0.63	0.47	0.80	Head-on	All	KY, MO, PA	154	25,796	—
6854	5	0.77	0.58	0.96	Sideswipe	All	KY, MO, PA	154	26,118	—
6973	5	0.85	0.68	1.03	ROR	All	KY, MO, PA	154	3,199	AADT < 3,200
6974	5	0.70	0.61	0.79	ROR	All	KY, MO, PA	3,200	26,118	AADT ≥ 3,200
4790	4	0.62	0.43	0.81	All	F & I	MO	—	—	Edge Line and Wider Marking
"—" Blank cells indicate no information was available.										

APPENDIX B—DETAILED EXAMPLE APPLICATIONS

Example Application 1 – Systemic Installation

An agency has identified 7,500 miles of rural, two-lane highways for retrofit installation of ELRS. The following information was identified for developing a B/C analysis of rumble strip implementation.

Assumptions:

- ELRS cost per mile: 1,500 dollars per line.
- Annual fatal and injury ROR crashes: 125 crashes.
- Rumble strip life expectancy: 7 years.
- CMF for ELRS for fatal and injury ROR crashes: 0.67.
    - CMF should be for fatal and injury ROR crashes.
    - CMF should be for ELRS if possible, SRS if no information available.
    - Use CMF 3394 from CMF Clearinghouse.
- 2001 crash cost for fatal and injury crashes: 158,177 dollars.

Costs:

- Installation cost = 1,500 dollars × 2 sides of the roadway = 3,000 dollars per mile.
- Total cost = 3,000 dollars per mile × 7,500 miles = 22,500,000 dollars.
- Capital Recovery Factor = $((1 + 0.07)^7 - 1)/(0.07 \times (1 + 0.07)^7) = 5.39$.
- Annualized construction cost = 22,500,000/5.389 = 4,174,947 dollars.

Benefits:

- Annual fatal and injury ROR crashes saved = 125 crashes × (1 – 0.67) = 41.25 crashes.
- 2015 Crash Cost = 158,177 dollars × 2.47 = 390,697.20 dollars per crash.
- Annual benefit from crashes saved = 41.25 crashes × 390,697.20 = 16,116,259 dollars.

B/C Ratio:

- B/C ratio = 16,116,259/4,174,947 = 3.86.

Results:

- Annual fatal and injury ROR crashes reduced: 41.25.
- 2015 crash cost for fatal and injury crashes: 390,697.20 dollars.

- Annualized construction cost: 4,174,947 dollars.
- Annual benefit from crashes saved: 16,116,259 dollars.
- B/C ratio: 3.86.

The results indicate that while the targeted facilities experience an average 0.017 fatal and injury ROR crashes per mile, the installation is economically justified. The analysis indicates that approximately 41 fatal and injury ROR crashes would be reduced per year.

Example Application 2 – High Crash Corridor Installation

For a 2.5-mile section of rural, two-lane highway, an analyst identified the following information from a roadway inventory, crash database, and safety performance function:

- AADT 5,500.
- 2012 ROR Crashes: 8 Observed, 3.67 Predicted.
    - o Predicted crashes from SPF for rural, two-lane highways.
    - o In this example, SPF is assumed to be for ROR crashes.
    - o Crashes/year = $5{,}500 \times 2.5 \times 365 \times 10^{-6} \times e^{(-0.312)} = 3.67$.
    - o Overdispersion parameter = $0.236 / L = 0.236 / 2.5 = 0.0944$.
- 2013 ROR Crashes: 7 Observed, 3.67 Predicted.
- 2014 ROR Crashes: 9 Observed, 3.67 Predicted.
- Percent fatal and injury ROR crashes: 50 percent.

The analyst is considering implementing CLRS and SRS in combination, for which the CMF Clearinghouse indicates the CMF to be 0.70. Other given information include the following:

- 2001 crash cost for fatal and injury crashes: 158,177 dollars.
- 2001 crash cost for property damage only crashes: 7,428 dollars.
- Installation cost: 1,500 dollars per mile.
- Rumble strip life expectancy: 7 years.

Expected Number of Crashes:

- Observed crash frequency = 8 + 7 + 9 = 24 crashes / 3 years = 8 crashes/year.
- Annual correction factor = 1.0 for each year.
- The weighted adjustment, $w = 1 / (1 + 0.0944 \times 11.01) = 0.49$.

- The EB adjusted expected average crash frequency for year 1 = 0.49 × 3.67 + (1 – 0.49). × 24/3 = 5.88 crashes
- The excess expected average crash frequency = 5.88 – 3.67 = 2.21 crashes/year

This identifies that the corridor is a candidate for treatment for excess ROR crashes. The analyst determines that CLRS and SRS are candidate countermeasures and examines them further.

Costs:

- Installation cost = 1,500 dollars × 2 edge lines + center line = 4,500 dollars per mile.
- Capital Recovery Factor = $((1 + 0.07)^7 - 1)/(0.07 \times (1 + 0.07)^7) = 5.39$.
- Annualized construction cost = 4,500/5.389 = 835 dollars per mile.

Benefits:

- Annual ROR crashes saved = 5.88 crashes/year × (1 – 0.70) = 1.76 crashes/year.
- Annual ROR crashes saved per mile = 1.76 / 2.5 = 0.70 crashes per mile.
- Average crash cost = 158,177 × 0.50 + 7,428 × 0.50 = 82,803 dollars.
- 2015 Crash Cost = 82,803 dollars × 2.47 = 204,522 dollars per crash.
- Annual benefit from crashes saved = 0.70 crashes × 204,522 = 143,984 dollars.

B/C Ratio:

- B/C ratio = 143,984 / 835 = 172.4.

Results:

- Expected number of ROR crashes: 5.88 crashes/year.
- Excess expected ROR crashes: 2.21 crashes/year = candidate for CLRS and SRS.
- Annual crashes reduced per mile: 0.70 crashes/mile.
- 2015 crash cost for fatal and injury crashes: 204,522 dollars per crash.
- Annualized construction cost: 835 dollars per mile.
- Annual benefits: 143,984 dollars.
- B/C ratio: 172.4.

The upper 95-percentile estimate of the CMF is 0.79, resulting in a reduction of 0.49 ROR crashes per mi per year. The annualized benefit is calculated to be 101,018 dollars per mile. The resulting B/C ratio is 121.0, indicating that even a conservative estimate of the reduction results in a highly cost-effect solution.

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For More Information:

Visit http://safety.fhwa.dot.gov/roadway_dept/pavement/rumble_strips/

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