Safety Evaluation of Sinusoidal Centerline Rumble Strips

Task 2: Literature Review

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INTRODUCTION

The Federal Highway Administration (FHWA) estimates that approximately one-half of all traffic fatalities are the result of a roadway departure, which is defined as an event in which the "vehicle crosses an edgeline, centerline, or otherwise leaves the traveled way" (*1*). Among the roadway departure fatalities, approximately 27 percent are head-on collisions. The principal characteristics of head-on roadway departure crashes are that they occur on high-speed, undivided rural highways.

One strategy to keep vehicles in the intended travel lane is to install rumble strips. Longitudinal rumble strips are intended to generate in-vehicle noise and vibration to alert drivers that they have left the intended travel lane. They may be installed along the edge line, shoulder, or along the centerline of roadways. The auditory or tactile warnings generated by the rumble strip pattern are most effective for inattentive, drowsy, or fatigued drivers. The FHWA designates both centerline and shoulder rumble strips (SRS) as proven safety countermeasures on two-lane rural highways (*2*). Centerline rumble strips (CLRS) are primarily intended to mitigate opposite direction head-on and sideswipe crashes, although they may reduce single-vehicle run-off-road crashes to the left of the travel lane (*3*, *4*). Studies suggest that vehicular crashes can be reduced by 35 to 45 percent as a result of rumble strip installation (*5*, *6*). However, conventional rumble strips may produce high exterior noise levels, which can adversely affect nearby residents. As such, transportation agencies have studied alternative patterns to mitigate this exterior noise while intending to retain the safety benefits. One potential alternative that may reduce noise and has the same potential for safety benefits is the installation of sinusoidal rumble strips (*7*–*9*). However, the safety effects of the sinusoidal rumble strips have not been investigated.

The Montana Department of Transportation (MDT) installed sinusoidal centerline rumble strips on over 600 miles of rural roadway during 2021. The purpose of this research project is to evaluate the safety effectiveness of the installed sinusoidal centerline rumble strips using an observational before-after study. Specifically, the safety performance of sinusoidal centerline rumble strips will be compared to the safety performance of conventional centerline rumble strips. The results will help MDT select the most appropriate countermeasure (conventional vs. sinusoidal rumble strips) for a given situation, improving the overall safety management process for two-lane rural highways.

As a first step, this document describes a review of the extant literature and current state and local transportation agency practices related to centerline rumble strip use and the differences between conventional and sinusoidal centerline rumble strips. This review is divided into four subsequent sections. The first describes the safety effects of centerline rumble strips. The second describes the acoustic effects of sinusoidal rumble strips. The third briefly discusses the visibility and durability of rumble stripes. Finally, the concluding section summarizes key findings from the literature.

SAFETY EFFECTS OF CENTERLINE RUMBLE STRIPS

The FHWA Crash Modification Factor (CMF) Clearinghouse (*10*) is an online repository that contains estimates of safety performance of many commonly utilized highway safety countermeasures. The safety performance is measured using a CMF, which as defined by the *Highway Safety Manual* (*11*), is "an index of how much crash experience is expected to change following a modification in design or traffic control" at a particular location. Each CMF is a numerical value that provides the ratio of the expected number of crashes over some unit of time after a change is made to the expected number of crashes for the same time period had the change not been made. Equation 1 shows how the ratio is applied to develop a CMF for a particular countermeasure i:

$$CMF_i = \frac{Expected\ number\ of\ crashes\ if\ change\ i\ is\ made}{Expected\ number\ of\ crashes\ if\ change\ i\ is\ not\ made}. \quad (1)$$

The percent crash reduction associated with countermeasure i is $(1 - CMF_i) * 100\%$. Thus, CMF values less than 1.0 indicate that the change should reduce crash frequency, while CMF values greater than 1.0 indicate that the change should increase crash frequency. CMF values equal to 1.0 indicate that the change is expected to have no impact on crash frequency.

This reported value provides an estimate of the effectiveness of the potential change or countermeasure on crash frequency. Since the true CMF value is unknown, there is always some error associated with the point estimate of the CMF. The size of this error provides an indication of the precision of the point estimate. Small errors indicate that the point estimate is precise and the CMF is known with a high degree of certainty, while larger errors suggest that the true CMF may differ significantly from the point estimate.

The CMF Clearinghouse contains numerous CMFs for rumble strips installation. As a starting point to understand the potential safety impacts of sinusoidal centerline rumble strips, the research team identified all CMFs in the Clearinghouse for CLRS installed on two-way, two-lane rural roadway segments. These CMFs are summarized in Table 1 to Table 4. Table 1 provides CMFs for total crash frequency, Table 2 provides CMFs for head-on crashes, Table 3 provides CMFs for sideswipe crashes, and Table 4 provides CMFs for roadway departure crashes. Table 1 to Table 4 includes CMFs from various state Department of Transportations (DOTs) in the U.S. with one exception being a CMF for head-on crashes shown in Table 2, which was developed by researchers in Japan. Each table provides the CMF point estimate, standard error (SE), study design, star rating quality (on a one to five scale), study references, applicable AADT range, states included in the study, and relevant comments. While there were various studies in the Clearinghouse which include CMFs for CLRS based on combinations of two or more (e.g., head-on, sideswipe, and run-off-the-road) crash types, we only discuss the CMFs which refer to only one crash type or total crash frequency for brevity.

Table 1 summarizes the CMFs for CLRS on the following: 1) all roadway segments, 2) horizontal curves, and 3) tangents on rural two-way, two-lane (2W2L) roadway types. In almost all studies included in Table 1, the CMF values for the CLRS for total crashes is lower than 1.0 (ranging from 0.34 to 0.98), which suggests that the CLRS are found to be effective in reducing total crashes. For instance, the CMF of 0.34 refers to a 66% (=1-0.34*100%) reduction in total crashes on rural 2W2L roadway segments; however, this CMF is based on the crash data from Colorado (CO) and is applicable to summer months with an AADT ranging from 3540 to 5300 (*12*). On the other hand, a study conducted in Pennsylvania (PA) suggests only a 2% (CMF = 0.98) reduction in total crashes on the rural 2W2L roadway segments – this CMF is applicable to the AADT range of 574 to 17,591 (*13*). Please note that there are two CMFs which suggest a 2% increase (CMF = 1.02) in expected total crash frequency if the CLRS were implemented on rural 2W2L roadway segments (*13*). The aforementioned two CMFs were developed using crash data from PA and WA and are applicable to the AADT ranges of 2338 to 22,076 and 3167 to 20,784, respectively. Based on some of the studies in Table 1, installation of the CLRS along the horizontal curves and tangents on rural 2W2L roadway segments is expected to increase the total crashes (i.e., the CMFs for CLRS were found to be greater than 1.0). Still, the Clearinghouse shows several CMFs with values in the range of 0.749 to 0.966, and from 0.90 to 0.948 for total crashes if the CLRS were implemented along horizontal curves and tangents on rural 2W2L roadway segments. Another observation from Table 1 is that, among the studies that have a 5-star quality rating, the CMFs range from 0.842 to 1.16 for total crashes. A 5-star rating is indicative of a robust study with a large quantity of data and application of rigorous statistical analysis methods.

Table 1. CMFs for installing centerline rumble strips in CMFs Clearinghouse: Effects on total crashes

CENTERLINE RUMBLE STRIPS INSTALLED ON ALL ROADWAY SEGMENTS							
CMF	**Standard Error**	**Study Design**	**Star Quality**	**Study**	**AADT Range**	**State of Origin**	**Comments**
0.842	0.054	Empirical Bayes (EB) before-after analysis	5	(*14*)	1282 to 20433	KY	Excluded intersection-related and animal crashes. This may only reflect the benefit of added centerline rumble strips because shoulder rumble strips already existed.
0.89	0.058	Empirical Bayes (EB) before-after analysis	5	(*13*)	1336 to 13240	MN	
0.96	0.026	Empirical Bayes (EB) before-after analysis	5	(*13*)	574 to 20784	MN, PA, WA	
0.91	0.02	Empirical Bayes (EB) before-after analysis	5	(*13*)	574 to 20784	CA, CO, DE, MD, MN, OR, PA, WA	
0.831	0.016	Before-and-after analysis	5	(*15*)	240 to 18633	LA	This study not only computes CMFs for CLRS on rural 2W2L roads, but also investigates the safety effects of lane conversion (from 4 lanes undivided to 3 or 5 lanes undivided with two-way-left-turn lane) and restricted median openings on high-speed roads and roundabouts.
0.86	0.03	Empirical Bayes before–after procedure	4	(*16*)	5000 to 22000		
1.02	0.08	Empirical Bayes (EB) before-after analysis	4	(*13*)	2338 to 22076	PA	Urban roadway segments
0.98	0.033	Empirical Bayes (EB) before-after analysis	4	(*13*)	574 to 17591	PA	
1.02	0.081	Empirical Bayes (EB) before-after analysis	4	(*13*)	3167 to 20784	WA	
0.842	0.002	Empirical Bayes (EB) before-after analysis	3	(*17*)	---	MI	

CMF	Standard Error	Study Design	Star Quality	Study	AADT Range	State of Origin	Comments
0.925	0.03	Empirical Bayes (EB) before-after analysis	3	(*18*)	2100 to 18000	VA	CMF for both all segments (both tangents and horizontal curves)
0.77	0.09	Empirical Bayes (EB) before-after analysis	3	(*12*)	3238 to 5855	WY	
0.51	0.09	Empirical Bayes (EB) before-after analysis	3	(*12*)	3238 to 5855	WY	This CMF is for summer months crashes.
0.72	0.11	Empirical Bayes (EB) before-after analysis	3	(*12*)	3238 to 5855	WY	This CMF is for winter months crashes.
0.59	0.05	Empirical Bayes (EB) before-after analysis	3	(*12*)	3540 to 5300	CO	
0.34	0.04	Empirical Bayes (EB) before-after analysis	3	(*12*)	3540 to 5300	CO	This CMF is for summer months crashes.
0.59	0.07	Empirical Bayes (EB) before-after analysis	3	(*12*)	3540 to 5300	CO	This CMF is for winter months crashes.
0.525	0.018	Before-after analysis	2	(*19*)	2005 - 2013	MI	
0.585	0.044	Before-after analysis	2	(*19*)	AADT < 2500	MI	CMF applies to roadways with AADT less than 2,500
0.516	0.031	Before-after analysis	2	(*19*)	2500 to 5000	MI	CMF applies to roadways with AADT 2500-5000
0.518	0.033	Before-after analysis	2	(*19*)	5000 to 7500	MI	CMF applies to roadways with AADT 5000-7000
0.492	0.039	Before-after analysis	2	(*19*)	AADT > 7500	MI	CMF applies to roadways with AADT >7500
CENTERLINE RUMBLE STRIPS INSTALLED ON HORIZONTAL CURVES							
CMF	**Standard Error**	**Study Design**	**Star Quality**	**Study**	**AADT Range**	**State of Origin**	**Comments**
0.966	0.07	Empirical Bayes (EB) before-after analysis	3	(*18*)	2100 to 18000	VA	
1.01	0.08	Empirical Bayes (EB) before-after analysis	3	(*18*)	2100 to 18000	VA	CMF for roads with design speeds of 60 mph or more.

0.749	0.14	Empirical Bayes (EB) before-after analysis	3	(*18*)	2100 to 18000	VA	CMF for roads with design speeds of 55 mph or lower.
1.16	0.092	Empirical Bayes (EB) before-after analysis	5	(*13*)	574 to 17591	PA	
0.83	0.096	Empirical Bayes (EB) before-after analysis	4	(*13*)	1336 to 13240	MN	
1.04	0.065	Empirical Bayes (EB) before-after analysis	4	(*13*)	574 to 20784	MN, PA, WA	
1.03	0.16	Empirical Bayes (EB) before-after analysis	3	(*13*)	3167 to 20784	WA	
CENTERLINE RUMBLE STRIPS INSTALLED ON TANGENT SEGMENTS							
CMF	**Standard Error**	**Study Design**	**Star Quality**	**Study**	**AADT Range**	**State of Origin**	**Comments**
0.948	0.04	Empirical Bayes (EB) before-after analysis	3	(*18*)	2100 to 18000	VA	
0.9	0.055	Empirical Bayes (EB) before-after analysis	5	(*13*)	1336 to 13240	MN	
0.92	0.043	Empirical Bayes (EB) before-after analysis	5	(*13*)	574 to 20784	MN, PA, WA	.
0.9	0.084	Empirical Bayes (EB) before-after analysis	4	(*13*)	574 to 17591	PA	
1.02	0.093	Empirical Bayes (EB) before-after analysis	4	(*13*)	3167 to 20784	WA	

For the safety effects of the CLRS on head-on crashes and sideswipe crashes (Table 2 and Table 3, respectively), the Clearinghouse shows that significant reductions in these two crash types could be achieved if the CLRS were implemented on rural 2W2L roadway segments. For roadway departure crashes (Table 4), most of the studies included in the Clearinghouse show CMFs lower than 1.0 (ranging from 0.537 to 0.96), which indicates that the CLRS have significant potential to reduce run-off-the-road crashes on the aforementioned roadway segments. We note that there is one study in the Clearinghouse which indicates a 8.5% (CMF = 1.085) increase in roadway departure crashes if the CLRS were implemented along the rural 2W2L roadway segments (*17*). We also note that CLRS installed along horizontal curves on rural 2W2L segments are found to be less effective in reducing roadway departure crashes when the design speed on the segments is higher (i.e., for the design speed of 55 miles per hour or slower, the CMF for roadway departure crashes is 0.58; whereas, for the design speeds of 60 miles per hour or higher, the CMF is 0.999). Furthermore, compared to the rectangular shaped CLRS, the Clearinghouse shows that the football shaped CLRS are more effective in reducing run-off-the-road crashes on rural 2W2L roadway segments (*18*).

Table 2. CMFs for installing centerline rumble strips in CMFs Clearinghouse: Effects on head-on crashes

CMF	Standard Error	Study Design	Quality	Study	AADT Range	State of Origin	Comments
0.48	0.142	Empirical Bayes (EB) before-after analysis	4	(*11*)	1282 to 20433	KY	Exclude intersection-related and animal crashes. This may only reflect the benefit of added centerline rumble strips because shoulder rumble strips already existed.
0.492	0.055	Before-after analysis	2	(*16*)	---	MI	
0.450	---	---	1	(*19*)	---	Japan	

Table 3. CMFs for installing centerline rumble strips in CMFs Clearinghouse: Effects on sideswipe crashes

CMF	Standard Error	Study Design	Quality	Study	Difference	State of Origin	Comments
0.891	0.21	Empirical Bayes (EB) before-after analysis	4	(*14*)	1282 to 20433	KY	Excludes intersection-related and animal crashes. This may only reflect the benefit of added centerline rumble strips because shoulder rumble strips already existed.

Table 4. CMFs for installing centerline rumble strips in CMFs Clearinghouse: Effects on roadway departure crashes

INSTALL CENTERLINE RUMBLE STRIPS								
CMF	**Standard Error**	**Study Design**	**Quality**	**Area Type**	**Study**	**AADT Range**	**State of Origin**	**Comment**
0.613	0.073	Empirical Bayes (EB) before-after analysis	5	Rural	(*14*)	1282 to 20433	KY	Exclude intersection-related and animal crashes. This may only reflect the benefit of added centerline rumble strips because shoulder rumble strips already existed.
1.085	0.405	Before-after analysis	1	Rural	(*20*)	---	WA	Exposure is VMT. Before MVMT = 242.42; After MVMT = 428.57. Crash type is total run off the road right
0.808	0.141	Bayesian before-and-after analysis	3	Rural	(*21*)	200 to 8000	KS	
0.96	0.013	Cross-sectional and case-control methods	3	Rural	(*22*)	30 to 15900	KS	CMF for lane departure crashes on tangent road segment
0.94	0.023	Cross-sectional and case-control methods	3	Rural	(*22*)	50 to 8550	KS	CMF for lane departure crashes on curved road segments
0.537	0.022	Before-after analysis	2	Rural	(*19*)	---	MI	
INSTALL CENTERLINE RUMBLE STRIPS ALONG HORIZONTAL CURVES								
CMF	**Standard Error**	**Study Design**	**Quality**	**Area Type**	**Study**	**AADT Range**	**State of Origin**	**Comment**
0.905	0.1	Empirical Bayes (EB) before-after analysis	3	Rural	(*18*)	2100 to 18000	VA	CMF for off-road fixed object and run-off-road crashes

CMF	Standard Error	Study Design	Quality	Area Type	Study	AADT Range	State of Origin	Comment
INSTALL CENTERLINE RUMBLE STRIPS								
0.999	0.12	Empirical Bayes (EB) before-after analysis	3	Rural	(*18*)	2100 to 18000	VA	CMF for off-road fixed object and run-off-road crashes. Roads with design speeds 60mph or higher.
0.58	0.16	Empirical Bayes (EB) before-after analysis	3	Rural	(*18*)	50 to 8550	VA	CMF for off-road fixed object and run-off-road crashes. Roads with design speeds 55 mph or lower.
INSTALL CENTERLINE RUMBLE STRIPS ON TANGENTS								
CMF	**Standard Error**	**Study Design**	**Quality**	**Area Type**	**Study**	**AADT Range**	**State of Origin**	**Comment**
0.743	0.05	Empirical Bayes (EB) before-after analysis	3	Rural	(*18*)	2100 to 18000	VA	CMF for off-road fixed object and run-off-road crashes
INSTALL FOOTBALL SHAPED CENTERLINE RUMBLE STRIPS								
CMF	**Standard Error**	**Study Design**	**Quality**	**Area Type**	**Study**	**AADT Range**	**State of Origin**	**Comment**
0.45	0.279	Bayesian before-and-after analysis	4	Rural	(*21*)	200 to 8000	KS	
INSTALL RECTANGULAR SHAPED CENTERLINE RUMBLE STRIPS								
CMF	**Standard Error**	**Study Design**	**Quality**	**Area Type**	**Study**	**AADT Range**	**State of Origin**	**Comment**
0.849	0.155	Bayesian before-and-after analysis	3	Rural	(*21*)	200 to 8000	KS	run off road crashes

Several studies were also identified that were not included in the CMF Clearinghouse. These studies are summarized in Table 5. In general, the results are consistent with the findings that are incorporated within the Clearinghouse. For instance, these studies indicate a 42% (*23*) and 15% (*24*) reduction in total crashes due to the provision of conventional CLRS on rural 2W2L roadway segments. Referring to the potential change in total head-on crashes, the studies summarized in Table 5 reveal that a 34% (*25*) and 40% (*26*) reduction can be expected in total head-on crashes due to the CLRS on rural 2W2L roadways. Similarly, the overall sideswipe crashes are expected to decline by 36.5% (*25*), while overall crossover crashes are likely to reduce by 43% (*23*) and 48% (*27*) when CLRS are installed on rural 2W2L roadway segments.

Table 5. Summary of key studies about safety effects of conventional rumble strips along centerline not included in CMF Clearinghouse

Study	Study Area	Type of Rumble Strip and Roads	Number of Sites	Length (miles)	Methodology	Key Findings
(*26*)	California	CLRS along rural 2W2L highways	---	---	Naïve before-after analysis	Provision of CLRS led to: • 90.0% reduction in fatal head-on crashes • 40.0% reduction in total head-on crashes
(*25*)	Colorado	CLRS along with 2W2L mountainous highways	---	17 miles	Naïve before-after analysis	Provision of CLRS led to: • 34.0% reduction in head-on crashes • 36.5% reduction in sideswipe crashes
(*23*)	Minnesota	CLRS along with rural 2W2L roads	---	---	Cross-sectional comparison	Provision of CLRS led to: • 42% and 73% reduction overall and FI crashes, respectively • 43% reduction in overall crossover crashes • 17% increase in crossover FI crashes
(*27*)	Pennsylvania	CLRS	---	---	Naïve before-after analysis	Provision of CLRS led to a 48% reduction in cross-over crashes
(*24*)	Louisiana	CLRS and SRS along 2W2L urban and rural roads	380 and 41 segments of rural and urban 2W2L roads, respectively	1593.1 and 97.51 miles of rural & urban 2W2L roads, respectively	Multiple	• The CMFs for rural 2W2L roads for CLRS, SRS, and both were 0.845, 0.95, and 0.764, respectively. • The CMFs for urban 2W2L roads for CLRS, SRS, and both CLRS and SRS were 0.677, 0.655, and 0.839, respectively.

ACOUSTIC EFFECTS OF SINUSOIDAL RUMBLE STRIPS

As noted previously, the conventional rumble strip pattern may produce high levels of external noise, which may cause discomfort to nearby residents (*7–9*, *28*, *29*). While both conventional and sinusoidal rumble strips patterns are milled, the unique milling pattern of the sinusoidal rumble strips makes them distinct from conventional rumble strips. Noise impacts from the transportation system can lead to adverse health effects, including disturbance in sleep (*30–34*), cardiovascular effects (*35*), annoyance (*36*), hypertension issues (*37*), and learning impairment (*38*, *39*). Sounds with frequencies in the range of 10 to 250 Hz are considered to cause an interruption in sleep and can result in stress and disorders in heart rhythm (*40*). Studies suggest that the negative consequences of noise could be minimized by reducing the amount of noise generated, or by reducing the amount of noise experienced at the receiver end (through appropriate insulation settings in the building or homes) (*31*, *41*).

To mitigate the noise generated from rumble strips, the sinusoidal pattern has been designed and implemented (*7–9*, *28*, *29*, *40*). Numerous studies were conducted to compare the external and internal noise generated by the sinusoidal rumble strip pattern relative to conventional rumble strips (*7–9*, *28*, *29*). A summary of these findings is highlighted below:

- After comparing the exterior sound generated by sinusoidal rumble strips to conventional rumble strips, it was found that passenger cars and vans, each hitting the sinusoidal rumble strips, produced lower exterior sound (3.1 dBA) than the conventional rumble strips (van = 4.6 dBA; passenger car = 5.4 dBA) (*8*). While heavy vehicles were also considered in the experiment, findings for such vehicles were complex (i.e., due to wider cuts in the SRS, there was a significant increase for heavy vehicles in the exterior noise) (*8*).
- One study compared both interior and exterior noise generated by sinusoidal rumble strips to conventional rumble strips at two different speeds (70 km/hr and 90 km/hr) (*7*). The findings suggest that sinusoidal rumble strips led to lower noise and vibration inside the car compared to the conventional rumble strips at both speeds (*7*). While noticing no significant difference in exterior noise by the two types of rumble strips at the speed of 70 km/hr, the findings indicate that sinusoidal rumble strips are quieter than the conventional rumble strips at a speed of 90 km/hr (*7*).
- A study conducted in Minnesota (U.S.) suggests that sinusoidal rumble strips generate less external noise (but similar internal noise) compared to conventional rumble strips (*9*).
- To compare noise produced by various rumble strips designs (raised pavement marker rumble strips, raised rounded rumble strips, and sinusoidal rumble strips) in California, the AASHTO Isolated Pass-by (SIP) method was used to test five different vehicles at a pass-by speed of 60 miles per hour (*28*). The findings reveal that exterior noise reduced

by 3 dBA and 6 dBA for heavy and light vehicles (hitting sinusoidal rumble strips compared to the baseline), respectively. In terms of interior noise and vibration, no significant difference was noted for the sinusoidal rumble strips (*28*).

- Research conducted in Indiana has also found that sinusoidal rumble strips were quieter than conventional rumble strips (*29*). For instance, after comparing the noise generated by three different types of sinusoidal rumble strips (with a wavelength of 12″, 18″, and 24″) to conventional rumble strips, the findings indicate that exterior noise reduced by 5-11 dBA while interior noise increased by 2-9 dBA (*29*).
- Findings from research conducted in North Carolina also suggests that sinusoidal rumble strips were found to be quieter than conventional rumble strips by 3 dBA and 9 dBA at distance of 100 and 200 feet from the road edge, respectively (*42*). However, there was no difference noticed in the exterior noise for both designs (sinusoidal rumble strips and conventional rumble strips) at a distance of 50 feet from the road edge line (*42*).

MDT recently completed a study to investigate whether SCLRS could reduce exterior noise at noise-sensitive locations (e.g., residences near the roadways in Montana) (*43*). The study provided useful insights about whether a specific SCLRS design could perform better in terms of producing lower noise compared to conventional CLRS installed by MDT. In 2018, besides the four different SCLRS designs, conventional CLRS and Chipseal Pavement were also installed on MT-39 where the latter was considered as a baseline for comparison. The specifications of the baseline, conventional CLRS, and four different types of SCLRS are summarized below:

1. Standard 12″ wide CLRS, 1/2″ to 5/8″ depth, milled in pairs, 36″ on center
2. SCLRS Design S1: 14″ longitudinal frequency, 12″ wide, 1/8″ to 1/2″ depth
3. SCLRS Design S2: 24″ longitudinal frequency, 12″ wide, 1/8″ to 1/2″ depth
4. SCLRS Design S3: 14″ longitudinal frequency, 14″ wide tapered, 1/8″ to 1/2″ depth
5. SCLRS Design S3A: 24″ longitudinal frequency, 14″ wide tapered, 1/8″ to 1/2″ depth
6. Chipseal Pavement (Type 1, 3/8″ aggregate) without striking the rumble strip (i.e., baseline)

The exterior noise produced by the baseline, MDT's conventional CLRS, and four different types of SCLRS were tested using three different vehicles (passenger vehicle, medium truck, and heavy truck) at three different speeds (30, 50, and 70 miles per hour). Based on the field observations, the key findings of the wayside noise study are summarized below:

- The wayside noise level was found to be similar for all four types of SCLRS across all three vehicle types (passenger car, medium truck, and heavy truck) tested and for each of the three test speeds (30, 50, and 70 miles per hour).
- All four SCLRS designs showed wayside noise levels that were similar to the baseline (chip-sealed pavement) for each vehicle-speed combination.
- Compared to conventional CLRS, the four SCLRS designs were found to be quieter in terms of the wayside noise levels. In general, the difference in the wayside noise level

between the CLRS and four types of SCLRS increased as speed increased for all three vehicle types. The largest difference was reported at a speed of 70 miles per hour.

While the interior noise levels were not explicitly measured in the study, drivers noted that the highest levels of interior noise and vibration was produced by the S3A SCLRS design.

VISIBILITY AND DURABILITY OF RUMBLE STRIPES

Rumble strips, when coated with a retroreflective paint, are termed "rumble stripes." The retroreflective coating increases the visibility and detectability of the edge line and centerline of the roadway during nighttime and during adverse weather conditions (*29*). Several studies have investigated the performance and durability of rumble stripes. For instance, one of the relevant studies compared the performance and durability of rumble stripes and conventional painted lines after a winter maintenance season. The findings indicate that the rumble stripes not only increased detectability (visibility) at nighttime both in wet and dry weather conditions, but also enhanced durability (*44*). Similar findings were revealed by another study after comparing six different types of pavement markings over an almost two-year period, which revealed that rumble stripes or painted markings on the grooves had the highest visibility (retroreflectivity) and experienced the lowest damage compared to the other pavement marking types (*45*). Other studies show similar findings – that rumble stripes provide higher levels of retroreflectivity and improved durability relative to conventional pavement markings (*46*, *47*). It is important to mention that studies have also performed retroreflectivity testing for the sinusoidal rumble stripes which have shown higher reflectivity than the minimum requirements set by the transportation agency (Indiana Department of Transportation in this case) (*29*).

SUMMARY OF KEY FINDINGS

In summary, the review of the research literature reveals that numerous studies have evaluated the safety effects of the conventional CLRS on rural 2W2L roadway types. The key takeaways about the safety effectiveness of the milled CLRS are as follows:

- Most of the studies suggest a significant reduction in total crashes after installation of the conventional milled CLRS on rural 2W2L roadway segments (Table 1).
- Based on all of the relevant studies, it is found that the total head-on crashes and total sideswipe crashes are expected to decrease due to the provision of the milled CLRS on rural 2W2L roadway segments (details shown in Table 2 and Table 3, respectively).
- Similar to total crashes, most of the studies in Table 4 suggest a potential reduction in run-off-the-road crashes after installation of the milled CLRS on rural 2W2L roadway segments.

As highlighted above, the existing literature provides useful insights about the safety effectiveness of the conventional CLRS on rural 2W2L roadways; however, none of the studies have quantified the safety effects of the sinusoidal CLRS. The need to assess the safety effects of sinusoidal CLRS is clear since studies suggest that sinusoidal CLRS lead to lower exterior noise than conventional CLRS. Fortunately, the studies suggest that in-vehicle vibration and noise is comparable between sinusoidal rumble strips and conventional rumble strips designs. This suggests that the safety impacts should be similar; however, this finding will be verified as a part of this research.

References

1. Federal Highway Administration. Roadway Departure Strategic Plan - Safety | Federal Highway Administration. https://safety.fhwa.dot.gov/roadway_dept/strat_approach/strategic_plan.cfm. Accessed Mar. 15, 2022.
2. Federal Highway Administration. Longitudinal Rumble Strips and Stripes. 2017.
3. Karkle, D. E., M. J. Rys, and E. R. Russell. Safety Effectiveness of Centerline Rumble Strips in Kansas. *Journal of Transportation Safety & Security*, Vol. 5, No. 1, 2013, pp. 1–26. https://doi.org/10.1080/19439962.2011.642069.
4. Sayed, T., P. deLeur, and J. Pump. Impact of Rumble Strips on Collision Reduction on Highways in British Columbia, Canada: Comprehensive before-and-after Safety Study. *Transportation research record*, Vol. 2148, No. 1, 2010, pp. 9–15.
5. Bucko, T., and A. Khorashadi. Evaluation Of Milled-In Rumble Strips, Rolled-In Rumble Strips And Audible Edge Stripe. 2001.
6. Brennan, T. M., S. R. Mitkey, and D. M. Bullock. *Alternatives to Raised Pavement Markers (RPMs)*. Indiana. Dept. of Transportation, 2014.
7. Vadeby, A., A. Anund, U. Björketun, and A. Carlsson. Safe Accessibility, Summarized Results. *VTI, Sweden*, 2013.
8. Horne, D., H. Jashami, D. S. Hurwitz, C. M. Monsere, and S. Kothuri. Mitigating Roadside Noise Pollution: A Comparison between Rounded and Sinusoidal Milled Rumble Strips. *Transportation Research Part D: Transport and Environment*, Vol. 77, 2019, pp. 37–49.
9. Terhaar, E., and D. Braslau. *Rumble Strip Noise Evaluation*. Minnesota Department of Transportation, Research Services & Library, 2015.
10. Federal Highway Administration. Crash Modification Factors Clearinghouse. http://www.cmfclearinghouse.org/. Accessed Mar. 15, 2022.
11. American Association of State Highway and Transportation Officials. *Highway Safety Manual*. 2010.
12. Ahmed, I. U., and M. M. Ahmed. *Impact of Adverse Wintry Conditions on the Effectiveness of Centerline Rumble Strips-A Case Study of Wyoming and Colorado Using Before-After Empirical Bayes Design*. 2021.
13. Torbic, D. J., J. M. Hutton, C. D. Bokenkroger, K. M. Bauer, D. W. Harwood, D. K. Gilmore, J. M. Dunn, J. J. Ronchetto, E. T. Donnell, and H. J. Sommer III. NCHRP Report 641: Guidance for the Design and Application of Shoulder and Centerline Rumble Strips. *Transportation Research Board of the National Academies, Washington, DC*, 2009.
14. Persaud, B., C. Lyon, K. Eccles, and J. Soika. *Safety Evaluation of Centerline plus Shoulder Rumble Strips*. 2015.
15. Sun, X. *Investigating Safety Impact of Centerline Rumble Strips, Lane Conversion, Roundabout and j-Turn Features on Louisiana Highways:[Research Project Capsule]*. Louisiana Transportation Research Center, 2015.

16. Persaud, B. N., R. A. Retting, and C. A. Lyon. Crash Reduction Following Installation of Centerline Rumble Strips on Rural Two-Lane Roads. *Accident Analysis & Prevention*, Vol. 36, No. 6, 2004, pp. 1073–1079.
17. Kay, J., P. T. Savolainen, T. J. Gates, T. K. Datta, J. Finkelman, and B. Hamadeh. Safety Impacts of a Statewide Centerline Rumble Strip Installation Program. *Transportation research record*, Vol. 2515, No. 1, 2015, pp. 34–40.
18. Babiceanu, S. E., and M. D. Fontaine. *Examining the Safety Effect of Centerline Rumble Strips on Curves on Rural Two-Lane Roads*. 2018.
19. Datta, T. K., P. T. Savolainen, T. J. Gates, J. J. Kay, N. B. Nicita, S. Parajuli, and J. Finkelman. *Evaluation of Non-Freeway Rumble Strips-Phase II*. Michigan. Dept. of Transportation. Office of Research Administration, 2015.
20. Olson, D., M. Sujka, and B. Manchas. *Performance Analysis of Centerline and Shoulder Rumble Strips Installed in Combination in Washington State*. Washington (State). Dept. of Transportation. Design Policy Research, 2013.
21. Rys, M. J., D. E. Karkle, and E. R. Russell. *Study of KDOT Policy on Lane and Shoulder Minimum Width for Application of Centerline Rumble Strips*. Kansas. Dept. of Transportation, 2012.
22. Galgamuwa, U., and S. Dissanayake. Evaluation of the Safety Effectiveness of Lane-Departure Countermeasures on Two-Lane Undivided Roadways Using Crash Modification Factors. *Journal of Transportation Safety & Security*, Vol. 11, No. 4, 2019, pp. 377–397.
23. Briese, M. *Safety Effects of Centerline Rumble Strips in Minnesota*. Minnesota. Dept. of Transportation, 2008.
24. Khanal, S. *Safety Effectiveness of Centerline Rumble Strips and Shoulder Rumble Strips on Louisiana Two-Lane Highways*. University of Louisiana at Lafayette, 2021.
25. Outcalt, W. S. *Centerline Rumble Strips*. Colorado. Dept. of Transportation. Research Branch, 2001.
26. Fitzpatrick, K. *Accident Mitigation Guide for Congested Rural Two-Lane Highways*. Transportation Research Board, 2000.
27. Golembiewski, G., R. Haas, B. Katz, and T. Bryer. Evaluation of the Effectiveness of PennDOT's Low Cost Safety Improvement Program (LCSIP). *Science Applications International Corporation*, 2008.
28. Donavan, P., and D. Buehler. Design and Acoustic Evaluation of Optimal Sinusoidal Rumble Strips versus Conventional Ground-In Rumble Strips (Tech. No. CTHWANP-RT18-365.01. 2). *California Department of Transportation, Sacramento, CA*, 2018.
29. Mathew, J. K., A. D. Balmos, D. Plattner, T. Wells, J. V. Krogmeier, and D. M. Bullock. Assessment of Alternative Sinusoidal Rumble Stripe Construction. 2018.
30. Can, A., and P. Aumond. Estimation of Road Traffic Noise Emissions: The Influence of Speed and Acceleration. *Transportation Research Part D: Transport and Environment*, Vol. 58, 2018, pp. 155–171.

31. Murphy, E., and O. Douglas. Population Exposure to Road Traffic Noise: Experimental Results from Varying Exposure Estimation Approaches. *Transportation Research Part D: Transport and Environment*, Vol. 58, 2018, pp. 70–79.
32. de Kluizenaar, Y., S. A. Janssen, F. J. van Lenthe, H. M. Miedema, and J. P. Mackenbach. Long-Term Road Traffic Noise Exposure Is Associated with an Increase in Morning Tiredness. *The Journal of the Acoustical Society of America*, Vol. 126, No. 2, 2009, pp. 626–633.
33. Soares, F., E. Freitas, C. Cunha, C. Silva, J. Lamas, S. Mouta, and J. A. Santos. Traffic Noise: Annoyance Assessment of Real and Virtual Sounds Based on Close Proximity Measurements. *Transportation Research Part D: Transport and Environment*, Vol. 52, 2017, pp. 399–407.
34. Muzet, A. Environmental Noise, Sleep and Health. *Sleep medicine reviews*, Vol. 11, No. 2, 2007, pp. 135–142.
35. Babisch, W., B. Beule, M. Schust, N. Kersten, and H. Ising. Traffic Noise and Risk of Myocardial Infarction. *Epidemiology*, 2005, pp. 33–40.
36. Fredianelli, L., S. Carpita, and G. Licitra. A Procedure for Deriving Wind Turbine Noise Limits by Taking into Account Annoyance. *Science of the total environment*, Vol. 648, 2019, pp. 728–736.
37. Van Kempen, E., and W. Babisch. The Quantitative Relationship between Road Traffic Noise and Hypertension: A Meta-Analysis. *Journal of hypertension*, Vol. 30, No. 6, 2012, pp. 1075–1086.
38. Chetoni, M., E. Ascari, F. Bianco, L. Fredianelli, G. Licitra, and L. Cori. Global Noise Score Indicator for Classroom Evaluation of Acoustic Performances in LIFE GIOCONDA Project. *Noise Mapping*, Vol. 3, No. 1, 2016.
39. Lercher, P., G. W. Evans, and M. Meis. Ambient Noise and Cognitive Processes among Primary Schoolchildren. *Environment and Behavior*, Vol. 35, No. 6, 2003, pp. 725–735.
40. An, D.-S., S.-A. Kwon, J. Lee, and Y.-C. Suh. Investigation of Exterior Noise Generated by Vehicles Traveling over Transverse Rumble Strips. *Journal of Performance of Constructed Facilities*, Vol. 31, No. 2, 2017, p. 04016092.
41. Hurwitz, D. S., D. Horne, H. Jashami, C. M. Monsere, and S. Kothuri. *Quantifying the Performance of Low-Noise Rumble Strips*. 2019.
42. Findley, D., P. C. Vaughan, P. D. Coble, J. Poslusny, and A. Lahare. Comparison of Noise-Level and Frequency of Standard Rumble Strip and Sinusoidal Rumble Strip Designs. 2020.
43. Big Sky Acoustics. *Rumble Strip Wayside Noise Study*. Publication Experimental project MT-18-02, UPN 937000, BSA Project #19134.
44. Mitkey, S. R., T. M. Brennan Jr, S. M. Remias, A. M. Hainen, R. Morris, P. Michael, and D. M. Bullock. *Retroreflectivity Durability Comparison of Rumble Stripes Versus Painted Line*. 2012.
45. Gibbons, R. B., and B. M. Williams. *Assessment of the Durability of Wet Night Visible Pavement Markings: Wet Visibility Project Phase IV*. Virginia Center for Transportation Innovation and Research, 2012.

46. Hawkins, N., O. Smadi, S. Knickerbocker, and P. Carlson. *Rumble Stripe: Evaluation of Retroreflectivity and Installation Practices*. Minnesota Department of Transportation, Research Services & Library St. Paul …, 2016.
47. Zitowsky, R. Evaluation of Centerline Audible Roadway Delineators (CARDs) in New York State. *Transportation research record*, Vol. 2675, No. 4, 2021, pp. 105–115.