SAFETY EVALUATION OF SINUSOIDAL CENTERLINE RUMBLE STRIPS

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16. Abstract
The Montana Department of Transportation installed nearly 600 miles of sinusoidal centerline rumble strips (SCLRS) in 2021. These were mostly installed on high-speed, two-lane rural highways, in the Kalispell Division and Missoula area. The sinusoidal pattern produces lower exterior noise levels than conventional centerline rumble strips, but the safety effects of the pattern have not been quantified. This study performed an observational before-after analysis of the SCLRS installation on two-lane rural highways using the Empirical Bayes (EB) methodology. Crash modification factors (CMFs) for a variety of crash types were less than 1.0, indicating that SCLRS were associated with a reduction in crash frequency. The CMF associated with total target crashes—defined as opposite direction collisions—was 0.711 while the CMF associated with fatal plus injury target crashes was 0.624. The only CMF that exceeded 1.0 was for the single-vehicle run-off-the-road crash type; however, this result was not statistically significant. This study also compared the safety performance of the SCLRS to that of conventional centerline rumble strips in Montana. Because the installation dates of the conventional pattern were unknown, a causal inference framework was used for evaluation. The results indicate that the CMFs for the conventional and sinusoidal patterns have confidence intervals that overlap, suggesting similar safety performance associated with the two patterns. An economic evaluation found that both centerline rumble strips patterns have a benefit-cost ratio exceeding 1.0.

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Centerline rumble strips; crash modification factors; Empirical Bayes; causal inference; two-lane highways

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CHAPTER 1. 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 when 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 was to evaluate the safety effectiveness of the installed sinusoidal centerline rumble strips using an observational before-after study. In addition, the safety performance of sinusoidal centerline rumble strips was compared to the safety performance of conventional centerline rumble strips using a causal inference framework. A benefit-cost analysis of both centerline rumble strips patterns was completed to provide MDT with a decision-making framework to improve safety management on two-lane rural highways.

The remainder of this report is organized into several chapters. Chapter 2 includes a review of the extant literature and current state and local transportation agency practices related to centerline rumble strips use and the differences between conventional and sinusoidal centerline rumble strips. The literature review provides a summary of the safety effects of centerline rumble strips, as well as the noise, visibility, and durability of rumble strips and stripes. Chapter 3 summarizes the data collection methodology used to assemble the observational data used in the present study. Chapter 4 provides an overview of the methodological approach used to evaluate the safety effectiveness of the sinusoidal centerline rumble strips, as well as the causal inference framework to compare the safety effects of the sinusoidal to the conventional centerline rumble strips patterns. Chapter 5 summarizes the findings from the safety evaluations, while Chapter 6 includes the benefit-cost analysis results. Chapter 7 includes a summary of the study findings and recommendations for future research.

CHAPTER 2. LITERATURE REVIEW

This chapter of the report is organized into four sections. The first summarizes 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 review.

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 (TWTL) 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 TWTL 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 TWTL 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 TWTL 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 TWTL 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 TWTL 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 TWTL 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 TWTL 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 TWTL roadway segments (*17*). We also note that CLRS installed along horizontal curves on rural TWTL 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 TWTL 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

CMF	Standard Error	Study Design	Quality	Area Type	Study	AADT Range	State of Origin	Comment
INSTALL CENTERLINE RUMBLE STRIPS								
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

INSTALL CENTERLINE RUMBLE STRIPS								
CMF	**Standard Error**	**Study Design**	**Quality**	**Area Type**	**Study**	**AADT Range**	**State of Origin**	**Comment**
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 TWTL 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 TWTL 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 TWTL 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 TWTL 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 TWTL 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 TWTL 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 TWTL urban and rural roads	380 and 41 segments of rural and urban TWTL roads, respectively	1593.1 and 97.51 miles of rural & urban TWTL roads, respectively	Multiple	• The CMFs for rural TWTL roads for CLRS, SRS, and both were 0.845, 0.95, and 0.764, respectively. • The CMFs for urban TWTL 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 were 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 TWTL 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 TWTL 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 TWTL 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 TWTL roadway segments.

As highlighted above, the existing literature provides useful insights about the safety effectiveness of the conventional CLRS on rural TWTL 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. The studies suggest that in-vehicle vibration and noise is comparable between sinusoidal rumble strips and conventional rumble strips designs.

Chapter 3. Data Collection

This first section of this chapter describes how study sites were identified for inclusion in the study. The second section describes how the analysis database was created to develop CMFs for SCLRS and CLRS. The final section of this chapter explains how supplemental data were collected to expand the site-specific information available in MDT electronic records.

Identification of Study Sites

This section describes how the treatment sites (i.e., those with SCLRS and CLRS) and reference group sites (those with no rumble strips) were identified for inclusion in the present study.

SCLRS Treatment Sites

An inventory of sites with SCLRS was provided by MDT for the purpose of this study. The treatment group includes a total of 86 roadway segments comprising a total centerline length of 587.4 miles. The SCLRS were installed on roadway segments in two areas of Montana: Kalispell Division and Missoula Area. In the Kalispell Division, SCLRS were installed along 48 segments consisting of a total of 372.3 miles of roadway (see Table 6 for details). In the Missoula area, SCLRS were installed on 38 segments consisting of a total of 215.1 miles of roadway (see Table 7 for details). The majority of SCLRS were installed during 2021. The lone exceptions were three segments where SCLRS were installed in 2021, along with temporary pavement markings. These three segments were re-striped with standard MDT pavement markings in 2022. A review of these sites revealed that the majority of the SCLRS installation occurred on two-lane rural roadway segments. Note also from Table 6 that two different maximum groove depths were used in the SCLRS installation in Kalispell due to contractor differences.

Table 6. Details of SCLRS Treatment Sites in the Kalispell Division

Site	Route	Beginning reference mile	End reference mile	Length (miles)	Centerline repaired before installing CLRS?	Maximum depth
1	U 6734	0.0	0.5	0.5	No	1/2″
2	S 292	0.5	9.3	8.8	No	1/2″
3	US 2	15.4	29.9	14.5	No	1/2″
4	US 2	36.6	42.5	5.9	Yes	1/2″
5	US 2	42.5	48.5	6.0	No	1/2″
6	US 2	53.8	65.6	11.8	No	1/2″
7	US 2	69.0	81.0	12.0	No	1/2″
8	US 2	81.0	85.0	4.0	Yes	1/2″
9	US 2	85.0	100.0	15.0	No	1/2″
10	US 2	100.0	103.0	3.0	Yes	1/2″

Site	Route	Beginning reference mile	End reference mile	Length (miles)	Centerline repaired before installing CLRS?	Maximum depth
11	US 2	169.0	184.0	15.0	Yes	1/2″
12	US 2	184.0	189.8	5.8	No	1/2″
13**	MT 37	1.0	17.0	16.0	No	1/2″
14	MT 37	62.0	67.0	5.0	No	1/2″
15	S 260	0.0	3.5	3.5	No	1/2″
16	S 482	1.5	6.4	4.9	No	1/2″
17	MT 56	0.0	17.0	17.0	No	1/2″
18	MT 56	31.4	34.0	2.6	No	1/2″
19	MT 35	1.3	23.3	22.0	No	1/2″
20	MT 35	27.7	30.5	2.8	No	1/2″
21	MT 35	32.8	33.6	0.8	No	1/2″
22	MT 35	33.9	40.3	6.4	No	1/2″
23	MT 83	45.8	54.0	8.2	No	1/2″
24	MT 83	54.0	60.8	6.8	No	1/2″
25	MT 83	60.8	70.4	9.6	Yes	1/2″
26	MT 83	72.5	82.5	10.0	No	1/2″
27	S209	0.0	4.9	4.9	No	1/2″
28	S 211	1.0	9.7	8.7	No	1/2″
29	S 354	1.3	12.5	11.2	No	1/2″
30	MT 28	21.2	36.2	15.0	No	1/2″
31	S 352	0.0	5.9	5.9	No	1/2″
32	US 93	61.7	93.0	31.3	No	5/8″
33	US 93	102.0	104.0	2.0	No	5/8″
34	US 93	107.5	110.0	2.5	No	5/8″
35	US 93	123.0	125.0	2.0	No	5/8″
36	US 93	134.0	143.5	9.5	No	5/8″
37	US 93	143.5	149.5	6.0	Yes	5/8″
38	US 93	149.5	158.0	8.5	No	5/8″
39	US 93	158.0	161.0	3.0	Yes	5/8″
40	US 93	161.0	174.0	13.0	No	5/8″
41	US 93	180.0	186.0	6.0	No	5/8″
42	S 503	1.2	8.4	7.2	No	1/2″
43	S 503	8.4	10.5	2.1	Yes	1/2″
44	U6708	0.0	1.2	1.2	No	1/2″
45	S 424	2.1	5.4	3.3	No	1/2″
46	S 424	5.9	13.5	7.6	No	1/2″
47	S 424	13.5	15.8	2.3	Yes	1/2″
48	MT 40	3.3	4.5	1.2	No	1/2″
Total miles in Kalispell Division				**372.3**		

Table 7. Details of SCLRS Treatment Sites in Missoula Area

Site	Route	Beginning reference mile	End reference mile	Length (miles)	Centerline repaired before installing CLRS?	Maximum depth
49	MT200	23.8	29.5	5.7	No	1/2″
50	MT200	46.2	49.0	2.8	No	1/2″
51	MT200	52.0	56.9	4.9	No	1/2″
52	MT200	59.1	70.3	11.2	No	1/2″
53	MT200	72.9	74.0	1.1	No	1/2″
54	MT200	77.0	87.0	10.0	No	1/2″
55	MT200	87.0	90.0	3.0	Yes	1/2″
56	MT200	90.0	98.7	8.7	No	1/2″
57	MT135	0.0	12.9	12.9	No	1/2″
58	US93	44.1	46.0	1.9	No	1/2″
59	US93	37.4	44.1	6.7	Yes	1/2″
60	US93	33.3	37.4	4.1	No	1/2″
61	US93	29.3	32.5	3.2	No	1/2″
62	US93	27.8	29.1	1.3	No	1/2″
63	US93	22.6	26.7	4.1	No	1/2″
64	US93	18.7	22.6	3.9	No	1/2″
65	US93	6.0	17.0	11.0	No	1/2″
66	S212	8.3	17.6	9.3	No	1/2″
67	S474	0.0	3.1	3.1	No	1/2″
68	U8135	3.1	3.9	0.8	No	1/2″
69	S263	4.5	5.5	1.0	No	1/2″
70	U8123	3.5	4.5	1.0	No	1/2″
71	MT83	0.0	4.8	4.8	No	1/2″
72	MT200	32.0	52.5	20.5	No	1/2″
73	U8133	1.0	3.0	2.0	No	1/2″
74	US12	16.2	30.0	13.8	No	1/2″
75	S203	10.1	12.0	1.9	No	1/2″
76	S269	1.4	12.0	10.6	No	1/2″
77	U5301	1.0	1.4	0.4	No	1/2″
78	US93	87.7	90.0	2.3	No	1/2″
79	US93	84.8	85.9	1.1	No	1/2″
80	US93	75.5	82.5	7.0	No	1/2″
81	US93	62.8	68.3	5.5	No	1/2″
82	US93	52.1	62.0	9.9	No	1/2″
83	US93	49.4	51.8	2.4	No	1/2″
84	US93	38.7	45.9	7.2	No	1/2″
85	US93	16.2	23.2	7.0	Yes	1/2″
86	US93	0.0	7.0	7.0	No	1/2″
Total miles in Missoula Area				**215.1**		

Conventional CLRS Treatment Sites

The MDT staff provided an initial list of CLRS locations to the research team. Based on discussions with the MDT project panel, the veracity of this list was unknown. Thus, the research team verified the presence of CLRS at these locations using Montana's Pathpoints system. Additionally, the team performed supplemental data collection to identify additional sites with CLRS using Google Earth Pro imagery and MDT's Pathpoints video log. It was determined that there are approximately 3,000 miles of CLRS installed on state-maintained roadways.

Reference Group Sites

The research team identified sites without any rumble strips – including both CLRS and SRS – for use as reference sites in the CMF development. These sites served as comparison sites with which to compare the safety performance of the sites with conventional and sinusoidal centerline rumble strips. These sites were verified using Montana's Pathpoints system.

Development of analysis database

This section of the chapter includes a discussion of the roadway inventory and crash data used to form the analysis database. In addition to the MDT roadway inventory files, supplemental data was collected using several sources, which are also described in this section of the report.

Roadway Inventory

MDT maintains a state road database in a GIS format (Statewide_Routes) that served as the basis for the development of the analysis database. However, individual roadway sections in the Statewide_Routes layer were defined using corridors that span the entire length of the route. These corridors have safety-influencing features that vary across their length and thus would not be suitable for analysis purposes as defined. To alleviate this, the research team worked with MDT to segment the state routes into smaller, homogeneous sections (referred to hereafter as roadway segments) that share similar features. Each of these roadway segments were used to create the analysis database.

The analysis database contained a unique row for each segment-year combination. Unique columns were used to designate the following attributes that define each segment:

- Corridor ID
- Starting milepost
- Ending milepost
- Segment length

- Unique segment identifier (based on corridor ID and number of the segment along the corridor)
- Year
- Presence of shoulder rumble strips
- Year rumble strip was installed (if applicable)

The MDT completed an internal project to identify sites with SRS, which are included in the geospatial files that MDT developed for the research team. In this file, there were approximately 4,800 miles of SRS. The presence of SRS was verified using Montana's Pathpoints system.

In addition to identifying the attributes above, each roadway segment was appended with the following features that are available via MDT's existing GIS database:

- Traffic volume (in average annual daily traffic)
- Number of lanes
- Roadway width
- Posted speed limit
- Area type (urban vs. rural)
- Pavement surface type

The research team collected the above data for the current year (2021), future years (2022 to 2024), and previous years (2018 to 2020). The annual data files were examined to determine significant changes in the roadway network during the evaluation period. Roadway segments with significant changes were either updated for the years that the change was made (e.g., if the posted speed limit changed) or removed if the change was significant (e.g., lane addition). Based on the 2022 data, all segments with a posted speed limit of 45 mph or lower were omitted. Where discrepancies in speed limits were found for the same segments across different years in the database, they were manually corrected by verifying the speed limit using the Pathpoints videolog. Roadway segments with length greater than one mile were subdivided into segments between 0.1 and 1 mile. These segments were then screened to retain only two-lane undivided roads by eliminating one-way sections, multi-lane segments, and segments containing two-way left-turn lanes.

Supplemental Roadway Inventory Data

The supplemental data elements are safety-influencing features that past research has indicated may be associated with crash frequency or severity. These variables were not included in Montana roadway inventory files and were collected using alternative sources, such as video photologs or satellite imagery. These data elements and the source/tools used to collect these data are summarized in Table 8.

Table 8. List of supplement data elements

Data Element	Source
Paved shoulder width	MDT spreadsheet file
Curve length, radius and degree of curvature	ArcGIS Pro, Civil 3D, Google Earth Pro
Presence of centerline rumble strips	Google Earth Pro
No. of driveways	Google Earth Pro
Presence of 'Curve Warning' sign	Pathpoints Videolog / Google Earth Pro
Average absolute gradient (%)	MDT geodatabase file

The following sections describe the sources used to collect the supplemental data, the elements collected using each source and offer illustrative examples of the data collection procedure. The supplemental data elements were appended to existing crash and roadway inventory data, to form the safety analysis database for the sinusoidal centerline rumble strips evaluation.

Source: MDT Geospatial Data Files

Data on the presence of shoulder rumble strips was extracted from a MDT geodatabase file. The information on paved shoulder width was provided by MDT in .csv format, which was extracted from the 'route segment plan' data file. For the purposes of this project, it was assumed that the paved shoulder width remained unchanged throughout the analysis period. The rumble strip and shoulder width data files contain milepost information corresponding to the start and end points of the rumble strip or shoulder widths. These files were merged with other roadway inventory data provided by MDT using the route ID and milepost details. To calculate the average absolute gradient, each segment was divided into sub-segments approximately 20-foot long. The absolute gradient for each sub-segment was obtained from the elevation differential between endpoints divided by its length. These values were then averaged to calculate a representative gradient for the entire segment.

Source: ArcGIS Pro and Civil 3D

Horizontal curve geometry information was obtained by extracting geospatial data from shapefiles of Montana roadways using ArcGIS Pro and Civil 3D software. Both the radius (or degree of curvature) and the length of each horizontal curve was collected at the segment level. If a segment had no curve or the entire curve fell within the segment limits, this was noted in the analysis files. For curves that crossed into other segments, the length of the curve within each segment was recorded in the analysis database.

Simple circular curves connect two tangent road segments with an arc of constant radius. Spiral curves, also known as transition curves, connect tangents to simple circular curves, but the spiral curves on either end of the simple curve have a continuously-changing radius, in order to provide a smooth transition between the tangent and simple curve segments. Figure 1 illustrates the difference between a simple circular curve and a spiral curve. Equations 1 and 2 illustrate how the "degree of curvature" is calculated when no spirals are present and when they are present.

For simple circular curves:

$$Degree\ of\ curvature = 100 \times \frac{|\Delta_i|}{L_{c_i}} \tag{2}$$

For curves with spirals:

$$Degree\ of\ curvature = 100 \times \frac{|\Delta_i|}{(2L_s + L_{c_i'})} \tag{3}$$

where:
Δ_i is the deflection angle for curve i
Lc_i is the length of the single circular curve (shown by black broken line in figure 1)
Lc'_i is the length of the circular curve between the spirals
$L_{s,i}$ is the length of the spiral on either side of the circular curve

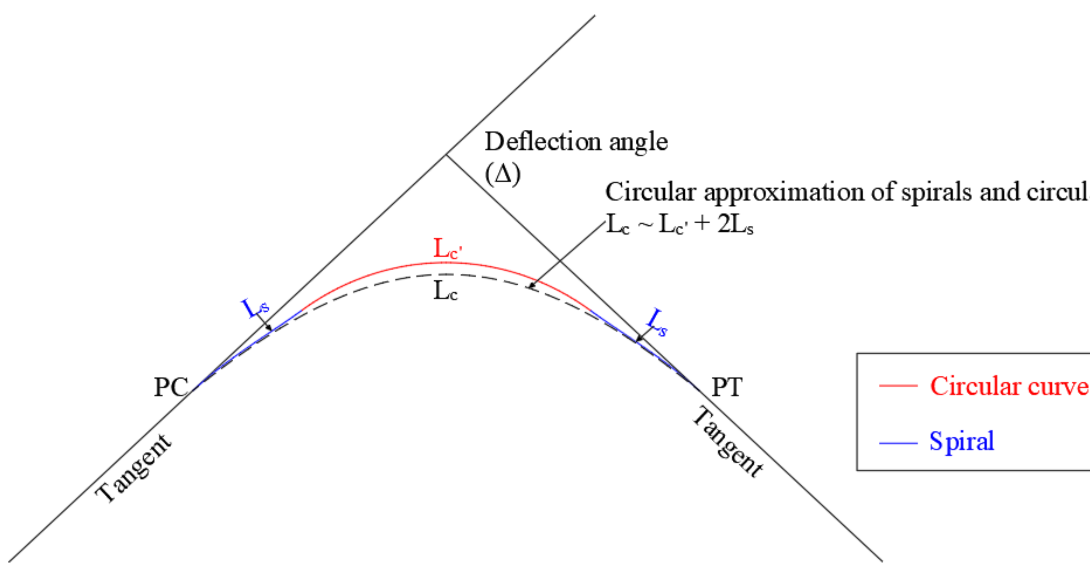


Figure 1. Horizontal curve with spirals + circular curve combination and circular approximation of the same

As shown in Figure 1, the deflection angle is the same in both cases. Although the length of the spirals plus the circular curve is slightly longer than a single circular curve, the difference is small when the deflection angle is small. For the current project, we approximated the degree of curve or radius of curve near the mid-point of the simple or spiral curve, in order to measure the arc with a constant radius. The detailed process for extracting this information is described in Appendix A.

Using the length, radius and degree of curvature of horizontal curves, the following segment level data was also collected as follows:

1. Curve density = # curves in a segment / L
2. Average Radius = $\sum R_i / n$
3. Ratio of the curve length to the total length of the segment = $\sum Lc_i / L$
4. Degree of curvature per mile = $\frac{\sum|\Delta_i|}{\sum Lc_i} \times \frac{100}{L}$

Where:
L = length of segment in miles
R_i = Radius of curve 'i' in ft
n = number of horizontal curves in a road segment
Lc_i = length of curve for curve 'i' in miles

Δ_i = Deflection angle of curve 'i' in degrees

Source: Pathpoints

Pathpoints is a LiDAR-based tool that contains point cloud data, along with a videolog taken from the drivers perspective, of roads in Montana. The data are not publicly available and access to Pathpoints requires login credentials. The perspective images in Pathpoints display forward-facing and right-shoulder camera views. For the purpose of supplemental data collection, perspective images consisting of the videolog for 'Montana 2021 Roads' were used. It was assumed that the data elements collected using the year 2021 video information did not differ before and after SCLRS installation. For the roadway segments for which the videologs were not available, Google Earth Pro was used to collect the required information. The information that was collected using this method are as follows:

- Presence of centerline rumble strips: Presence of centerline rumble strips were verified by running the roadway videolog from the 'Perspective Images' window (Figure 2).
- Presence of curve warning signs: After identifying curve locations from the previous section, the videolog for the corresponding roadway segment was used to check for the presence of curve warning signs before the curve in both directions (Figure 3).

While collecting data on the presence of centerline rumble strips or curve warning signs using Google Earth Pro imagery and Pathpoints videologs, it was noted that for many segments, imagery was either unavailable, or too outdated to verify the presence of rumble strips. Therefore, segments with no available imagery, imagery older than 2017, or route IDs lacking Pathpoints videologs were omitted from the dataset.

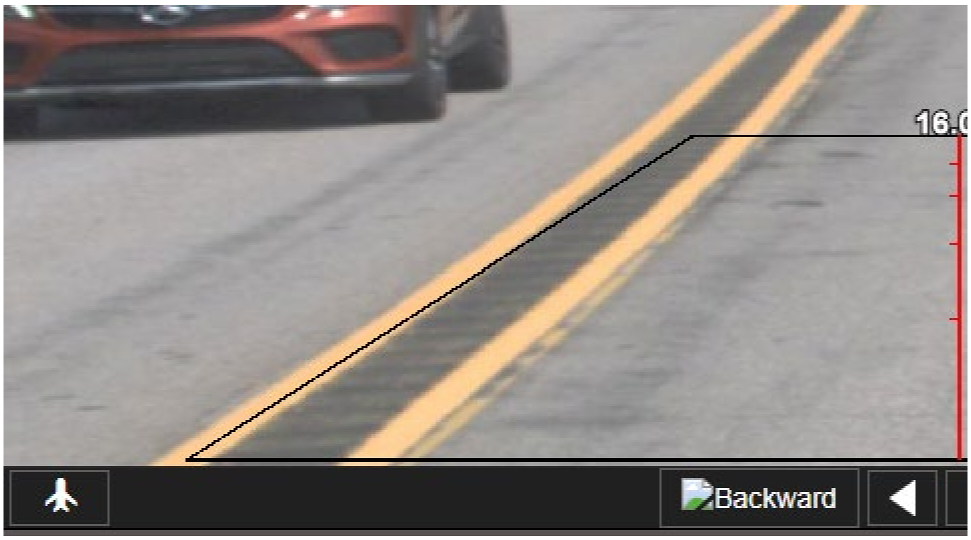


Figure 2. Screen capture of the Pathpoints window showing centerline rumble strips

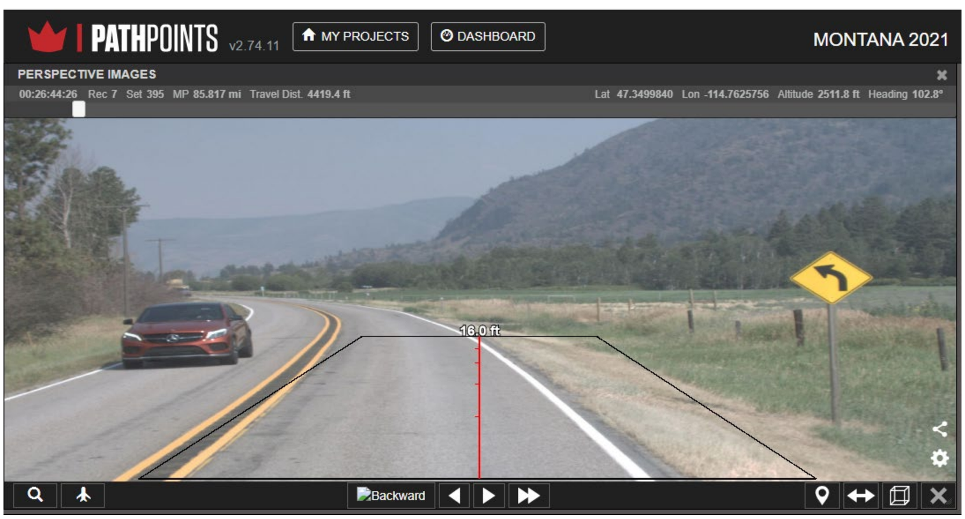


Figure 3. Screen capture of the Pathpoints window showing a horizontal curve warning sign

Source: Google Earth Pro

The Google Earth Pro tool provides high-quality satellite imagery of the roads and built-in functions to measure features to scale. This tool was used to verify the presence of centerline rumble strips and calculate driveway density, which is the number of access points (driveways) within a road segment divided by the length of the segment. The process for extracting this information is explained in Appendix B.

<u>Crash Data</u>

Crash data were appended to the electronic and supplemental data elements to form the safety analysis database used in the present study. Three years of data before and after the installation of SCLRS, as well as for reference group segments, were collected in electronic format. The before period for the SCLRS sites included the period from 2018 to 2020 (inclusive) whereas the after period included the period from 2022 to 2024 (inclusive). Since 2021 was the construction year for the SCLRS, the research team excluded this year from the evaluation period. Various crash frequency measures were appended to each roadway segment in the analysis database to consider in the CMF development. The following crash types, along with the method to identify them in the electronic data files, are summarized below:

- Total crash frequency: this represents all crash types and severity levels
- Fatal + injury (FI) crash frequency: this represents all crash types and severity levels, excluding those defined as “No apparent injury (property damage only crash)”
- Frequency of following “target” crash types:
    - Single vehicle run-off the road (SVROR): identified as those crashes with
        - number.of.vehicles as 1,
        - relation.to.traffic.way as “Separator”, or “Roadside Right” or “Outside Right-Of-Way (Trafficway)”, or “Off Roadway Location Unknown”, or “Roadside Left”
        - first.harmful.event.detail excluding "Animal Domestic", "Animal Wild", "Bridge Overhead Structure", "Cargo/Equipment Loss Or Shift", "Fell/Jumped From Motor Vehicle", "Fire/Explosion", "Pedestrian", "Pedalcycle", "Railway Vehicle (Train Engine)", "Work Zone / Maintenance Equipment", "Other Non-Collision", "Struck By Falling Shifting Cargo", and "Thrown Or Falling Object"
    - Off-road left: identified using
        - number.of.vehicles as 1,
        - relation.to.traffic.way as “Roadside Left”
        - first.harmful.event.detail excluding "Animal Domestic", "Animal Wild", "Bridge Overhead Structure", "Cargo/Equipment Loss Or Shift",

"Fell/Jumped From Motor Vehicle", "Fire/Explosion", "Pedestrian", "Pedalcycle", "Railway Vehicle (Train Engine)", "Work Zone / Maintenance Equipment", "Other Non-Collision", "Struck By Falling Shifting Cargo", and "Thrown Or Falling Object"

  - Head-on: identified as those with collision.type as “Head-on”
  - Sideswipe opposite direction crashes: identified as those with collision.type as “Sideswipe, Opposite Direction”

- Fatal + injury crash frequency of the following “target” crash types:
  - Single vehicle run-off the road (SVROR)
  - Off-road left
  - Head-on
  - Sideswipe opposite direction crashes

CHAPTER 4. ANALYSIS METHODOLOGY

The research team implemented two methods to estimate CMFs for this project. Figure 4 provides a graphical depiction of these approaches. The first is an observational before-after study to compare the safety performance of roadway segments with SCLRS applied before and after their installation. This approach produces a CMF for applying SCLRS to a roadway segment that did not previously have CLRS. The second approach was a with-without comparison, using a causal inference framework. This methodology compares the safety performance of sites with SCLRS to sites without SCLRS but with conventional CLRS installed. It was also used to compare the safety performance of sites with conventional CLRS installed and sites without CLRS installed. These methods are described in the remainder of this chapter.

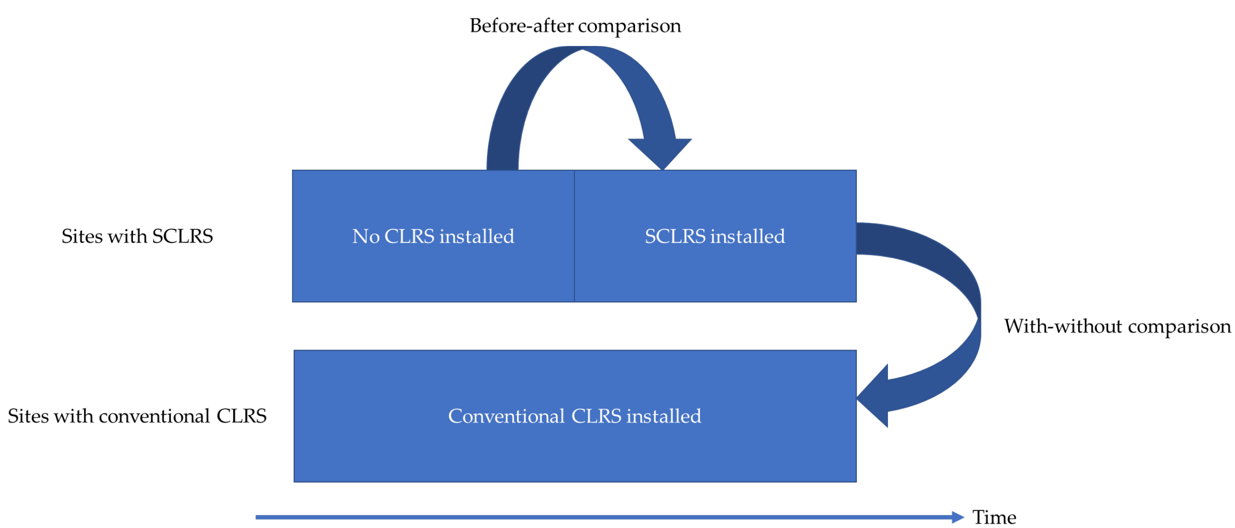


Figure 4. Graphical depiction of analysis approaches

Before-after analysis

To compare safety performance before and after the installation of SCLRS to a site without any CLRS previous installed, the research team used the EB before-after approach (*48*). This is accepted as the state-of-the-art in observational before-after studies in road safety. The EB analysis properly accounts for regression-to-the-mean, differences in traffic volume, and crash trends (time-series effects) between the periods before and after sinusoidal centerline rumble strip installation. The EB approach is comprised of three basic steps, each defined as follows:

- Step 1: Develop a safety performance function (SPF) to predict the safety performance of roadway segments with no SCLRS installed using a group of reference sites without rumble strips.
- Step 2: Apply SPF developed in Step 1 to estimate safety performance at sites with SCLRS in the after period if no SCLRS were installed
- Step 3: Compare the estimated and reported safety performance for sites that have SCLRS installed.

Step 1: Develop SPF for sites with no SCLRS

A reference group was used to account for the effects of traffic volume changes and temporal effects on safety due to the variations in weather, demographics, and crash reporting. This was done through the estimation of a safety performance function (SPF), which relates crash frequency to traffic flow and other relevant factors for a reference group of sites. This enabled simultaneous accounting for temporal and possible regression-to-the-mean effects, as well as those related to changes in traffic volume. The reference group sites were those that did not have centerline rumble strips installed during the evaluation period.

The research team used all sites with similar functional classifications and number of lanes as the treatment sites in this project. Specifically, since SCLRS in Montana are installed on two-lane rural roads, the set of two-lane rural roads were considered as reference sites in this project. This was further subdivided into sites with and without shoulder rumble strips.

Data required for SPF development includes crash, traffic volume, and geometric features. Negative binomial regression was used to fit the SPF parameters from the reference group. The general functional form of the negative binomial regression model is:

$$\ln \lambda_i = \beta X_i + \varepsilon_i \tag{4}$$

where λ_i = expected number of crashes at location i; β = vector of estimable regression parameters; X_i = vector of geometric design, traffic volume, and other site-specific data for location i; and ε_i = gamma-distributed error term. The mean-variance relationship for the negative binomial distribution is:

$$Var(\lambda_i) = E(\lambda_i)[1 + \alpha E(\lambda_i)] \tag{5}$$

where $Var(\lambda_i)$ = variance of reported crashes y occurring at location i; $E(\lambda_i)$ = expected crash frequency at location i; and α = overdispersion parameter.

The research team estimated the SPF using the following functional form, which is used to estimate SPFs in the Highway Safety Manual (HSM 2010):

$$N_{i,SPF} = AADT_i^{\beta_{AADT}} \times e^{(\beta_0 + \sum X_{ij}\beta_j)} \tag{6}$$

where $N_{i,SPF}$ = predicted crash frequency for roadway segment i using an SPF created from the reference group [crashes/year]; β_{AADT} = estimated coefficient for traffic volume; $AADT_i$ = traffic volume on segment i; and β_j = estimated coefficient for other variables X_{ij} that describe segment i.

<u>Step 2: Apply SPF developed in Step 1 to estimate safety performance at sites with SCLRS in the after period if no SCLRS were installed</u>

The expected number of crashes on segment i had no treatment been applied, $N_{i,EB}$, used an SPF of the type shown in Equation 6 to first estimate the number of crashes that would be expected in each year of the before period at locations with traffic volumes and other characteristics similar to the treatment site being analyzed. An EB adjustment was then applied to the SPF prediction to incorporate reported crash frequency in the prediction of crash frequency at each location. This EB adjustment is shown in Equation 7 (*48*).

$$N_{i,EB} = w_i \times N_{i,SPF} + (1 - w_i) \times N_{i,obs} \tag{7}$$

where $N_{i,EB}$ = predicted crash frequency at location i based on EB adjustment [crashes/year]; w_i = adjustment weight for predicted crash frequency at location i; $N_{i,SPF}$ = predicted crash frequency at location i based on the SPF (e.g., Equation 6) [crashes/year]; and $N_{i,obs}$ = reported or observed crash frequency at location i [crashes/year].

The weight (w_i) used for the EB adjustment for any location i is derived using Equation 8.

$$w_i = \frac{1}{1 + \alpha \times \sum_{all\ study\ years} N_{i,SPF}} \tag{8}$$

Thus, Equations 6, 7, and 8 were used to determine N_{EB}^{before} for the treatment sites in the before period by applying the SPFs generated in Step 1.

The SPF was then used to calculate the predicted crash frequency using the SPF, N_{SPF}^{after}, for all treated sites in the after-period. Finally, the EB method adjusted the expected crash frequency in the after-period, N_{EB}^{after}, and was calculated using Equation 9 and the adjustment factor, γ, from Equation 10.

$$N_{EB}^{after} = N_{EB}^{before} \times \gamma \tag{9}$$

$$\gamma = \frac{\sum_{after\ years} N_{SPF}^{after}}{\sum_{before\ years} N_{SPF}^{before}} \quad (10)$$

where γ = adjustment factor for differences in duration and traffic volume between before and after periods; and N_{EB}^{after} = EB adjusted crash frequency predicted during the after-period. This EB adjusted value obtained from Equation 6 provided the expected crash frequency if no treatment was applied. This expected crash frequency was then compared with the reported crash frequency after the treatment was applied to assess the safety effects of the sinusoidal centerline rumble strips.

Step 3: Compare reported and estimated safety performance for sites with SCLRS

In step 3, an unbiased estimate of the safety effect (θ) of the treatment was obtained using Equations 11 and 12.

$$\theta = \frac{N_{observed}^{after}}{N_{EB}^{after}[1+\frac{Var(N_{EB}^{after})}{N_{EB}^{after^2}}} \quad (11)$$

$$Var\ (N_{EB}^{after}) = \sum_{all\ sites} \gamma^2\ (1-w) N_{EB}^{after} \quad (12)$$

where θ = unbiased estimate of safety effect of the countermeasure; and $N_{observed}^{after}$ = reported or observed crashes during the after-period. Finally, the standard error associated with this safety effect estimate was computed using Equations 13 and 14.

$$Std\ Error\ (\theta) = SQRT\left[\theta^2\left[\frac{\frac{Var(N_{observed}{}^{after})}{N_{observed}{}^{after^2}} + \frac{Var(N_{EB}{}^{after})}{N_{EB}{}^{after^2}}}{1+\frac{Var(N_{EB}{}^{after})}{N_{EB}{}^{after^2}}}\right]\right] \quad (13)$$

$$Var\ (N_{observed}^{after}) = \sum_{all\ sites} N_{EB}^{after} \quad (14)$$

The percent change in crashes is 100 $(1-\theta)$; thus, a value of $\theta = 0.70$ with a standard deviation of 0.12 indicates a 30 percent reduction in crashes with a standard deviation of 12%.

With-without analysis

To compare the safety performance of sites with SCLRS to sites with conventional CLRS, the propensity scores-potential outcomes approach (*49*) was used. Ideally, this comparison would be made using a randomized experiment in which similar sites are randomly treated with either SCLRS or conventional CLRS. Since this was not possible, the propensity scores-potential outcomes approach seeks to mimic this experimental design. The method uses individual features at a site to calculate its *propensity score*, defined as a measure of the likelihood of that site receiving a specific treatment (*50*). Sites with and without the treatment are then matched based on their propensity scores, and count regression models are then applied to the matched dataset to quantify the impacts of the treatment.

Propensity score estimation

Propensity scores provide the probability (between 0 and 1) that an entity received a treatment and are estimated using the observed characteristics of the entity itself (*51*). In this study, a binary logit model was used to estimate the probability that any segment with CLRS was treated with SCLRS. The prediction for each observation was stored as the propensity score. The conditional probability of a binary logistic regression is provided in Equation 15, which provides the probability that a road segment will be in a treated condition (SCLRS present, SCLRS=1) (*52*).

$$\boldsymbol{P(SCLRS_i|X_i = x_i) = E(SCLRS_i) = \frac{e^{x_i\beta_i}}{1+e^{x_i\beta_i}}} \quad (15)$$

where $SCLRS$ = presence of a sinusoidal (as opposed to conventional) CLRS [1 if present; 0 otherwise]; X = vector of covariates; i = observation segment number; and, β = vector of estimated coefficients.

This can be derived into the functional form shown in Equation 13. The resulting estimate, P, is considered the propensity score for each road segment observation.

$$\ln(\frac{P}{1-P}) = \boldsymbol{X_i\beta_i} \quad (16)$$

where P = propensity score, probability that $SCLRS = 1$.

The β vector of coefficients can be estimated by maximizing the log-likelihood shown in Equation 17.

$$\boldsymbol{ln[L(\beta)] = \sum_{i=1}^{N} HC_i(x_i\beta_i) - \sum_{i=1}^{N} \ln(1 + e^{x_i\beta_i})} \quad (17)$$

where $L(\beta)$ = log-likelihood of the binary logit.

The propensity score model was estimated using all independent variables that are thought to be associated with rumble strip installation. These variables included segment length, AADT, number of lanes, lane width, shoulder width, posted speed limit, roadside hazard rating, driveway density, and horizontal curvature. Statistical significance was not considered important for the covariates included in the models as propensity score models are used for prediction, and use of parsimonious models (i.e., those with only statistically significant variables) introduce omitted variable bias (*53*).

<u>Propensity Score Matching</u>

In the propensity scores-potential outcomes framework, treated (i.e., those with SCLRS) and untreated sites (i.e., those with conventional CLRS) are matched based on their propensity scores. We implemented a 1:1 nearest-neighbor (NN) matching algorithm in which each treated site was matched to the untreated site with the closest propensity score within a specified caliper width (10% of the standard deviation of estimated propensity scores) (*51*). While 1:1 matching leads to a loss of data from dropping unmatched observations, this is not a concern with a large database, as the matched sample should still be large (*49*). Before matching, the set of unmatched sites was randomly sorted to reduce any bias that might occur. Once an untreated site was matched with a treated site, it was removed from the database of potential matches so that matching was performed without replacement to maximize the efficiency of the (*49*). Unmatched entities (treated or untreated) were dropped from the analysis.

The effectiveness of the matching procedure at balancing the covariates and reducing selection bias was assessed using the standardized bias, which quantified the differences in covariate distribution between the treated and untreated samples. Standardized bias was calculated using Equation 18 (*50*). Previous studies suggest that matching is effective if the standardized bias for each of the covariates considered in the database is small (usually less than 10 percent) (*54*), which indicates significant overlap between the treated and untreated dataset. The improvement in the standardized bias between the unmatched and matched data quantifies the improvement in covariate balance provided by matching based on propensity scores.

$$\boldsymbol{St.Bias} = \frac{\mathbf{100}\ (x_T - x_{UT})}{\sqrt{\left(\frac{S^2{}_T + S^2{}_{UT}}{2}\right)}} \qquad (18)$$

where x_T = sample mean of the treated group for a variable x; x_{UT} = sample mean of the untreated group for a variable x; S_T^2 = sample variance of the treated group for a variable x; and, S_{UT}^2 = sample variance of the untreated group for a variable x.

<u>CMF Estimation</u>

An SPF was developed to estimate crash frequency for the set of matched sites. Negative binomial regression was used, as in the EB before-after framework, since this is the most common model that is used to predict crash frequencies. In this SPF, an indicator variable was used to account for the difference between sites with SCLRS and those with conventional CLRS. This variable provided the resulting CMF estimate, as well as its standard error and statistical significance.

CHAPTER 5. ANALYSIS RESULTS

This chapter of the report includes descriptive statistics of the data collected at the treatment and reference group sites, during the periods before and after SCLRS installation, as well as the CMFs developed for SCLRS and conventional CLRS.

Before Period Data Summary

The final dataset comprised 10,785 roadway segments totaling 7,565.7 miles, of which 490.4 miles were treated sites with sinusoidal centerline rumble strips, and 7075.3 miles were untreated sites without sinusoidal centerline rumble strips. The crash data was merged with the roadway data based on the location information in the crash data. Table 9 provides descriptive summary statistics for the reported annual crash frequencies for all target crash types. The mean and standard deviation of all crash types and severities is relatively consistent from year-to-year in the before period data, among the entire sample.

Table 9. Summary of reported crash frequencies

Description	Year	Mean	Standard Deviation	Minimum	Maximum
Total Crash Frequency	2016	0.355	0.84	0	14
	2017	0.386	0.898	0	13
	2018	0.387	0.905	0	17
	2019	0.357	0.84	0	13
	2020	0.381	0.877	0	11
Fatal and Injury Crash Frequency	2016	0.097	0.344	0	5
	2017	0.092	0.335	0	5
	2018	0.088	0.332	0	5
	2019	0.084	0.319	0	5
	2020	0.093	0.333	0	4
Head On Crash, Total Frequency	2016	0.005	0.071	0	2
	2017	0.005	0.075	0	2
	2018	0.004	0.068	0	2
	2019	0.004	0.065	0	1
	2020	0.005	0.07	0	1
Head On Crash, Fatal and Injury Frequency	2016	0.004	0.061	0	2
	2017	0.004	0.066	0	2
	2018	0.003	0.06	0	2
	2019	0.004	0.06	0	1
	2020	0.004	0.065	0	1
Opposite Direction Sideswipe, Total Frequency	2016	0.008	0.091	0	1
	2017	0.006	0.078	0	1
	2018	0.006	0.08	0	2
	2019	0.006	0.079	0	1
	2020	0.007	0.084	0	2
Opposite Direction Sideswipe, Fatal and Injury Frequency	2016	0.005	0.067	0	1
	2017	0.002	0.048	0	1
	2018	0.003	0.054	0	2
	2019	0.003	0.053	0	1
	2020	0.002	0.042	0	1
Off Road Left, Total Frequency	2016	0.042	0.22	0	4
	2017	0.05	0.242	0	3
	2018	0.045	0.224	0	3
	2019	0.042	0.217	0	3
	2020	0.045	0.226	0	3

Description	Year	Mean	Standard Deviation	Minimum	Maximum
Off Road Left, Fatal and Injury Frequency	2016	0.019	0.142	0	2
	2017	0.02	0.148	0	2
	2018	0.014	0.12	0	2
	2019	0.015	0.127	0	2
	2020	0.018	0.136	0	2
Single Vehicle Run Off Road, Total Frequency	2016	0.104	0.363	0	4
	2017	0.123	0.422	0	8
	2018	0.124	0.411	0	8
	2019	0.111	0.383	0	5
	2020	0.117	0.392	0	6
Single Vehicle Run Off Road, Fatal and Injury Frequency	2016	0.045	0.221	0	4
	2017	0.045	0.223	0	4
	2018	0.039	0.207	0	3
	2019	0.039	0.207	0	4
	2020	0.046	0.225	0	3

Tables 10 and 11 provide descriptive summaries of the continuous variables included in the analysis database. Table 10 shows the average annual daily traffic for the years 2016 to 2020 (inclusive), across the entire sample. Table 11 includes data associated with roadway features, such as cross-section widths, segment length, access and intersection density, posted speed limit, horizontal curve, and vertical gradient information. In Table 11, the features represent data from the year 2022.

Table 12 and 13 present summaries of shoulder rumble strips and other the categorical variables for the before-period. In the final dataset, segments with a posted speed limit of 45 mph or lower were omitted. Where discrepancies in speed limits were found for the same segments across different years in the database, they were manually corrected by verifying the posted speed limit in the Pathpoints videolog.

Table 10. Summary of AADT in the database

Description	Year	Mean	Standard Deviation	Minimum	Maximum
Average Annual Daily Traffic (AADT)	2016	1272.824	1516.047	21	29017
	2017	1270.116	1563.256	21	30978
	2018	1285.397	1553.347	14	31412
	2019	1311.337	1608.791	14	30509
	2020	1242.112	1537.79	1	13837

Table 11. Summary of continuous variables in the dataset

Description	Mean	Standard Deviation	Minimum	Maximum
Surface Width, ft	29.52	5.72	19	74
Segment Length, mi	0.70	0.29	0.1	1
Paved shoulder width, ft	2.68	2.53	0	17
Posted speed limit (mph)	68.13	4.82	50	70
No. of access points per mile	3.86	4.85	0	80
No. of intersections per mile	0.53	1.53	0	40
No. of horizontal curves per mile	1.02	1.91	0	20
Percentage of curve length	12.82	22.3	0	100
Degree of curvature per mile	3.59	10.08	0	256.06
Average gradient (%)	0.60	0.50	0	6.56

Table 12. Summary of shoulder rumble strip presence by year

Shoulder rumble strips	Year	Mileage	Percentage
No rumble strip	2016	5877.9 mi	77.70%
	2017	5860.1 mi	77.50%
	2018	5877.9 mi	77.70%
	2019	5720.4 mi	75.60%
	2020	5535.8 mi	73.20%
Shoulder RS	2016	1687.8 mi	22.30%
	2017	1705.6 mi	22.50%
	2018	1687.8 mi	22.30%
	2019	1845.3 mi	24.40%
	2020	2029.9 mi	26.80%

Table 13. Summary of categorical variables in the dataset

Category	Mileage-yr	Percentage
Functional classification		
Principal Arterial	12184.1	32.21%
Minor Arterial	13014.3	34.40%
Collectors	12580.4	33.26%
Local	49.7	0.13%
Centerline rumble strips		
No centerline rumble strips	22239.5	58.79%
Centerline RS	15589	41.21%
Presence of reverse curve in the roadway segment		
No Reverse Curve	7197.7	95.14%
Reverse Curve	368	4.86%
Presence of compound curve in the roadway segment		
No Compound Curve	7428.3	98.18%
Compound Curve	137.4	1.82%
Presence of curve warning sign in the roadway segment		
No curve warning sign	7266.8	96.05%
Curve warning sign	298.9	3.95%
Posted speed limit (mph)		
50	463.2	1.22%
55	1742.4	4.61%
60	1456.9	3.85%
65	877.7	2.32%
70	33288.3	87.99%

After Period Data Summary

The dataset for this study consisted of 10,785 segments of two-lane, undivided rural roads with posted speed limits greater than 45 mph, representing a total length of 7,565.7 miles. In 2021, sinusoidal centerline rumble strips were installed on 490.4 miles (about 6.5%) of these roads. Thus, for the purposes of this project, the period from 2016 to 2020 (inclusive) is considered the "before" period and the period from 2022 to 2024 (inclusive) is considered the after period.

After period roadway and traffic data obtained from the Montana Department of Transportation (MDT) were merged with the segmented before-period dataset. The additional roadway and traffic variables included the presence of shoulder rumble strips, annual average daily traffic (AADT), and crash counts for the after period (2022–2024). All other roadway attributes—such as surface width, paved shoulder width, and geometric characteristics (e.g., horizontal curve radius, vertical grade)—were assumed to remain unchanged between the before and after periods. The research team confirmed that sites at which sinusoidal rumble strips were installed did not previously have centerline rumble strips during the before period. For certain segments, AADT values were missing for 2023 and 2024. These values were estimated by applying the average annual growth rate to the most recent year of AADT data found in the Montana DOT data files. Crash data for the years 2016–2024 were then merged with the roadway data using crash location information. Table 14 provides descriptive summary statistics of the annual crash frequencies for each target crash type during the before and after periods.

Table 14. Summary of reported crash frequencies

Description	Year	Mean	Standard Deviation	Min	Max	Average for respective before/after period
Total Crash Frequency	2016	0.355	0.84	0	14	0.373
	2017	0.386	0.898	0	13	
	2018	0.387	0.905	0	17	
	2019	0.357	0.84	0	13	
	2020	0.381	0.877	0	11	
	2022	0.369	0.899	0	15	0.355
	2023	0.342	0.849	0	14	
	2024	0.353	0.852	0	13	
Fatal and Injury Crash Frequency	2016	0.097	0.344	0	5	0.091
	2017	0.092	0.335	0	5	
	2018	0.088	0.332	0	5	
	2019	0.084	0.319	0	5	
	2020	0.093	0.333	0	4	
	2022	0.089	0.339	0	5	0.088
	2023	0.086	0.333	0	5	
	2024	0.089	0.331	0	5	
Head On Crash, Total Frequency	2016	0.005	0.071	0	2	0.005
	2017	0.005	0.075	0	2	
	2018	0.004	0.068	0	2	
	2019	0.004	0.065	0	1	
	2020	0.005	0.07	0	1	
	2022	0.005	0.071	0	2	0.005
	2023	0.006	0.08	0	2	
	2024	0.004	0.065	0	1	
Head On Crash, Fatal and Injury Frequency	2016	0.004	0.061	0	2	0.004
	2017	0.004	0.066	0	2	
	2018	0.003	0.06	0	2	
	2019	0.004	0.06	0	1	
	2020	0.004	0.065	0	1	
	2022	0.004	0.06	0	1	0.004
	2023	0.004	0.067	0	1	
	2024	0.003	0.054	0	1	

Description	Year	Mean	Standard Deviation	Min	Max	Average for respective before/after period
Opposite Direction Sideswipe, Total Frequency	2016	0.008	0.091	0	1	0.007
	2017	0.006	0.078	0	1	
	2018	0.006	0.08	0	2	
	2019	0.006	0.079	0	1	
	2020	0.007	0.084	0	2	
	2022	0.007	0.086	0	2	0.007
	2023	0.008	0.092	0	2	
	2024	0.007	0.086	0	3	
Opposite Direction Sideswipe, Fatal and Injury Frequency	2016	0.005	0.067	0	1	0.003
	2017	0.002	0.048	0	1	
	2018	0.003	0.054	0	2	
	2019	0.003	0.053	0	1	
	2020	0.002	0.042	0	1	
	2022	0.003	0.053	0	1	0.003
	2023	0.003	0.058	0	2	
	2024	0.002	0.042	0	1	
Off Road Left, Total Frequency	2016	0.042	0.22	0	4	0.045
	2017	0.05	0.242	0	3	
	2018	0.045	0.224	0	3	
	2019	0.042	0.217	0	3	
	2020	0.045	0.226	0	3	
	2022	0.045	0.228	0	5	0.041
	2023	0.04	0.214	0	3	
	2024	0.039	0.216	0	5	
Off Road Left, Fatal and Injury Frequency	2016	0.019	0.142	0	2	0.017
	2017	0.02	0.148	0	2	
	2018	0.014	0.12	0	2	
	2019	0.015	0.127	0	2	
	2020	0.018	0.136	0	2	
	2022	0.017	0.132	0	2	0.017
	2023	0.016	0.13	0	2	
	2024	0.017	0.133	0	3	

Description	Year	Mean	Standard Deviation	Min	Max	Average for respective before/after period
Single Vehicle Run Off Road, Total Frequency	2016	0.104	0.363	0	4	0.116
	2017	0.123	0.422	0	8	
	2018	0.124	0.411	0	8	
	2019	0.111	0.383	0	5	
	2020	0.117	0.392	0	6	
	2022	0.12	0.417	0	8	0.109
	2023	0.103	0.378	0	8	
	2024	0.103	0.369	0	6	
Single Vehicle Run Off Road, Fatal and Injury Frequency	2016	0.045	0.221	0	4	0.043
	2017	0.045	0.223	0	4	
	2018	0.039	0.207	0	3	
	2019	0.039	0.207	0	4	
	2020	0.046	0.225	0	3	
	2022	0.042	0.215	0	3	0.04
	2023	0.038	0.205	0	3	
	2024	0.04	0.207	0	3	

Tables 15 presents the summary of target crash types separately for sites treated with SCLRS, sites having conventional CLRS, and sites having no CLRS (reference sites). The average crash frequencies for total crash and fatal and injury crashes are higher in the before-period than in the after-period across all three site categories, although the differences are relatively small.

Table 15. Summary of reported crash frequencies for sites treated with SCLRS, conventional CLRS sites, and reference sites

Description	Period	SCLRS sites (N = 6,488)				conventional CLRS sites (N = 36,256)				Reference sites (N = 47,591)			
		Mean	Standard Deviation	Min	Max	Mean	Standard Deviation	Min	Max	Mean	Standard Deviation	Min	Max
Total crash frequency	2016 – 2020	0.853	1.257	0	11	0.438	0.888	0	12	0.326	0.858	0	17
	2022 – 2024	0.823	1.245	0	15	0.396	0.863	0	13	0.250	0.77	0	14
Fatal and injury crash frequency	2016 – 2020	0.196	0.475	0	3	0.103	0.351	0	5	0.081	0.319	0	5
	2022 – 2024	0.189	0.463	0	4	0.093	0.337	0	4	0.068	0.304	0	5
Head-on crash - Total frequency	2016 – 2020	0.010	0.103	0	2	0.006	0.076	0	2	0.004	0.065	0	2
	2022 – 2024	0.009	0.093	0	1	0.006	0.081	0	2	0.004	0.059	0	1
Head-on crash - Fatal and injury frequency	2016 – 2020	0.008	0.091	0	2	0.005	0.069	0	2	0.003	0.057	0	2
	2022 – 2024	0.006	0.078	0	1	0.005	0.068	0	1	0.002	0.049	0	1
Opposite direction sideswipe - Total frequency	2016 – 2020	0.015	0.124	0	2	0.008	0.087	0	2	0.006	0.079	0	2
	2022 – 2024	0.014	0.117	0	1	0.008	0.089	0	2	0.006	0.081	0	3
Opposite direction sideswipe - Fatal and injury frequency	2016 – 2020	0.008	0.094	0	2	0.003	0.051	0	1	0.003	0.055	0	2
	2022 – 2024	0.005	0.073	0	1	0.003	0.053	0	1	0.002	0.046	0	2
Off-road left - Total frequency	2016 – 2020	0.091	0.314	0	3	0.052	0.246	0	4	0.040	0.21	0	3
	2022 – 2024	0.086	0.326	0	5	0.045	0.226	0	3	0.032	0.192	0	5
Off-road left - Fatal and injury frequency	2016 – 2020	0.035	0.195	0	2	0.020	0.143	0	2	0.016	0.129	0	2
	2022 – 2024	0.034	0.190	0	2	0.017	0.132	0	3	0.014	0.12	0	2
Single vehicle run-off-road - Total frequency	2016 – 2020	0.232	0.532	0	4	0.135	0.432	0	8	0.102	0.365	0	5
	2022 – 2024	0.226	0.556	0	5	0.121	0.411	0	8	0.082	0.331	0	6
Single vehicle run-off-road - Fatal and injury frequency	2016 – 2020	0.087	0.306	0	3	0.049	0.231	0	4	0.038	0.206	0	4
	2022 – 2024	0.085	0.304	0	3	0.042	0.214	0	3	0.032	0.186	0	3

Tables 16 and 17 provide descriptive summaries of the AADT and shoulder rumble strip variables indicating their changes during the study period (2016 to 2024). The data indicates increases in the mean values of AADT and mileage of shoulder rumble strips between the before and after periods. Tables 18 and 19 present summaries of the continuous and categorical variables that were assumed to remain constant throughout the study period. For example, the surface width was assumed to remain the same throughout the analysis period.

Table 16. Summary of AADT

Description	Year	Mean	Standard Deviation	Min	Max	Average for before/after period
Average Annual Daily Traffic (AADT)	2016	1272.8	1516.0	21	29017	1276.4
	2017	1270.1	1563.3	21	30978	
	2018	1285.4	1553.3	14	31412	
	2019	1311.3	1608.8	14	30509	
	2020	1242.1	1537.8	1	13837	
	2022	1342.6	1696.1	1	14969	1385.4
	2023	1389.4	1754.5	16	16058	
	2024	1424.2	1799.7	1	15962	

Table 17. Summary of shoulder rumble strip presence by year

Shoulder rumble strips	Year	Mileage	Percentage	Average for before/after period
No rumble strip	2016	5877.9 mi	77.70%	76.34%
	2017	5860.1 mi	77.50%	
	2018	5877.9 mi	77.70%	
	2019	5720.4 mi	75.60%	
	2020	5535.8 mi	73.20%	
	2022	5269.9 mi	69.70%	69.30%
	2023	5221.5 mi	69.00%	
	2024	5233.5 mi	69.20%	
Shoulder RS	2016	1687.8 mi	22.30%	23.66%
	2017	1705.6 mi	22.50%	
	2018	1687.8 mi	22.30%	
	2019	1845.3 mi	24.40%	
	2020	2029.9 mi	26.80%	
	2022	2295.8 mi	30.30%	30.70%
	2023	2344.2 mi	31.00%	
	2024	2332.2 mi	30.80%	

Table 18. Summary of continuous variables in the dataset

Description	Mean	Standard Deviation	Min	Max
Surface Width, ft	29.54	5.72	19	74
Segment Length, mi	0.7	0.29	0.1	1
Paved shoulder width, ft	2.68	2.53	0	17
Posted speed limit, mph	68.04	4.87	50	70
No. of access points per mile	3.86	4.85	0	80
No. of intersections per mile	0.53	1.53	0	40
No. of horizontal curves per mile	1.02	1.91	0	20
Curve proportion, % (ratio of curve length to segment length)	12.82	22.3	0	100
Degree of curvature per mile	3.59	10.08	0	256.06
Average gradient (%)	0.6	0.5	0	6.56

Table 19. Summary of continuous variables in the dataset

Variables	Category	Mileage	Percentage
Functional classification	Principal Arterial	2437.5	32.22%
Functional classification	Minor Arterial	2604.9	34.43%
Functional classification	Collectors	2516	33.26%
Functional classification	Local	7.3	0.10%
Centerline rumble strips	No Rumble Strip	4138.6	54.70%
Centerline rumble strips	Centerline RS	3427.1	45.30%
Sinusoidal centerline rumble strips	No Sinusoidal Rumble Strip	7075.3	93.52%
Sinusoidal centerline rumble strips	Sinusoidal RS	490.4	6.48%
Presence of curve type	Reverse and compound curves [1]	37.1	0.49%
Presence of curve type	Reverse curve only	330.9	4.37%
Presence of curve type	Compound curve only	100.3	1.33%
Presence of curve type	Simple curve	2364.3	31.25%
Presence of curve type	No curve	4733.1	62.56%
Presence of curve warning sign	No curve warning sign	7266.8	96.05%
Presence of curve warning sign	Curve warning sign	298.9	3.95%
Posted speed limit (mph)	50	96.3	1.27%
Posted speed limit (mph)	55	367.9	4.86%
Posted speed limit (mph)	60	342	4.52%
Posted speed limit (mph)	65	357.5	4.73%
Posted speed limit (mph)	70	6402	84.62%

Safety Analysis Results

An Empirical Bayes (EB) observational before-after study methodology was used to estimate the CMF for the sinusoidal centerline rumble strips (SCLRS). A causal inference approach was used to estimate CMFs for conventional centerline rumble strips (CLRS). The crash types considered included the following:

- Total crash frequency (all crash types and severity levels)
- Fatal + injury crash frequency
- Frequency of following "target" crash types:

[1] To identify reverse and compound curves, spacing criteria between successive curves used was 300 ft or less

    - Single vehicle run-off the road
    - Off road left
    - Head-on
    - Sideswipe opposite direction crashes
- Fatal + injury crash frequency of following "target" crash types:
    - Single vehicle run-off the road
    - Off road left
    - Head-on
    - Sideswipe opposite direction crashes

Due to the low number of reported head-on and sideswipe opposite direction crashes, these two crash types were combined for CMF development. Thus, joint CMFs were developed for total head-on and sideswipe opposite direction crashes and for fatal + injury head-on and sideswipe opposite direction crashes.

Sinusoidal Centerline Rumble Strips: EB Evaluation

In the EB evaluation, 490.4 miles of two-lane rural highway segments were treated with SCLRS. Approximately 107.5 miles of these segments also included shoulder rumble strips, both before and after the SCLRS were installed. The reference group, with no centerline rumble strips, contained 3,957.5 miles – approximately 572.8 miles included shoulder rumble strips during the analysis period. The EB evaluation controlled for the presence of shoulder rumble strips by including an indicator variable for their presence in the reference group SPF. The before period was 2016 through 2020 (inclusive) while the after period was 2022 through 2024 (inclusive) – all SCLRS were installed in 2021. The results of the EB evaluation are shown in Table 20 below. An example SPF, with a discussion of how the CMF was derived from the SPF, used in the EB evaluation is shown in Appendix C. All SPFs used in the EB evaluation of SCLRS are shown in Appendix C.

Table 20. shows the CMFs for all SCLRS sites obtained when applying the EB before-after methodology for each of the crash types considered. As shown, the unbiased CMFs for all crash types are less than 1.0. The lone exception was for the single-vehicle run-off-road fatal and injury crash type, which had a CMF 1.071 that was not statistically significant. The total crash, head-on plus opposite direction sideswipe, and head-on opposite direction plus sideswipe fatal plus injury crash types were all statistically significant at the 95^{th}-percentile confidence level. The total crash CMF was 0.925, indicating that SCLRS were associated with a 7.5 percent reduction in total crashes in the present study. The CMFs for head-on plus opposite direction total and head-on plus sideswipe fatal and injury crashes were 0.711 and 0.624, respectively, indicating that SCLRS were associated with a 28.9 percent and 37.6 percent reduction in these crash types, respectively.

The EB analysis was also repeated to include only sites that were treated with SCLRS but did not contain shoulder rumble strips. In this evaluation, the treated sites included 382.9 miles of two-lane rural highway segments with SCLRS and a reference group of 3,384.69 miles of two-lane rural highway segments with no centerline or shoulder rumble strips. The before period was 2016 through 2020 (inclusive) while the after period was 2022 through 2024 (inclusive) – all SCLRS were installed in 2021. The results of this EB evaluation are shown in Table 21 below.

The results are similar to the results shown in Table 20, which considered the application of SCLRS both with and without shoulder rumble strips. As shown in Table 21, the unbiased CMFs for all crash types are less than 1.0, with the exception of the single-vehicle run-off-road fatal and injury crash type and off-road left fatal or injury crash types, which had a CMF 1.104 and 1.006, respectively (both not statistically significant). The fatal plus injury, total head-on plus opposite direction sideswipe, and head-on plus opposite direction fatal plus injury crash types were all statistically significant at the 95th-percentile confidence level.

As noted in Table 6, there were several sites in the Kalispell Division with a SCLRS groove depth of 5/8-inch, which is deeper than the ½-inch groove depth installed at other SCLRS sites. Separate EB analyses were completed to determine if the CMFs associated with various crash types differed for the 5/8-inch relative to the ½-inch groove depth. The results are shown in Tables 22 and 23 for the 5/8-inch groove depth, for sites without and with shoulder rumble strips, respectively. The EB results for sites with the ½-inch groove depth evaluation are shown in Tables 24 and 25, for sites without and with shoulder rumble strips, respectively.

Table 20. Empirical Bayes Results for Sinusoidal Centerline Rumble Strips Before-After Evaluation.

Crash type	Reported crashes in after period	EB estimate in after period	Unbiased CMF	Standard error	Effectiveness	T-stat	95th-percentile CI, Lower	95th-percentile CI, Upper	Remarks
Total crash	2003	2165.151	0.925	0.032	7.5	2.344	0.862	0.988	CMF - statistically significant
Fatal or injury	459	498.237	0.921	0.045	7.9	1.756	0.833	1.009	CMF - not statistically significant
Head-on and opposite direction sideswipe, total	55	77.272	0.711	0.100	28.9	2.890	0.515	0.907	CMF - statistically significant
Head-on and opposite direction sideswipe, fatal or injury	28	44.856	0.624	0.118	37.6	3.186	0.393	0.855	CMF - statistically significant
Single vehicle run-of-road total	550	577.908	0.951	0.045	4.9	1.089	0.863	1.039	CMF - not statistically significant
Single vehicle run-of-road fatal or injury	208	193.964	1.071	0.077	-7.1	-0.922	0.92	1.222	CMF - not statistically significant
Off-road left total	209	222.476	0.938	0.071	6.2	0.873	0.799	1.077	CMF - not statistically significant
Off-road left fatal or injury	83	88.499	0.937	0.105	6.3	0.6	0.731	1.143	CMF - not statistically significant

Table 21. Empirical Bayes Results for Sinusoidal Centerline Rumble Strips Before-After Evaluation (for sites with no shoulder rumble strips).

Crash type	Reported crashes in after period	EB estimate in after period	Unbiased CMF	Standard error	Effectiveness	T value	95th-percentile CI, Lower	95th-percentile CI, Upper	Remarks
Total crash	1426	1521.545	0.937	0.032	6.3	1.969	0.874	1	CMF - Not statistically significant
Fatal or injury	345	387.54	0.889	0.055	11.1	2.018	0.781	0.997	CMF - statistically significant
Head-on and opposite direction sideswipe, total	32	52.908	0.603	0.11	39.7	3.609	0.387	0.819	CMF - statistically significant
Head-on and opposite direction sideswipe, fatal or injury	14	30.254	0.463	0.122	53.7	4.402	0.224	0.702	CMF - statistically significant
Single vehicle run-of-road total	440	481.182	0.913	0.055	8.7	1.582	0.805	1.021	CMF - Not statistically significant
Single vehicle run-of-road fatal or injury	174	157.455	1.104	0.089	-10.4	-1.169	0.93	1.278	CMF - Not statistically significant
Off-road left total	163	183.4	0.888	0.077	11.2	1.455	0.737	1.039	CMF – Not statistically significant
Off-road left fatal or injury	68	67.529	1.006	0.126	-0.6	-0.048	0.759	1.253	CMF - Not statistically significant

Table 22. Empirical Bayes Results for Sinusoidal Centerline Rumble Strips Before-After Evaluation at Sites with 5/8-inch Groove Depth and No Shoulder Rumble Strips.

Treated sites: 53 miles, Treatment applied: 2021

Crash type	Reported crashes in after period	EB estimate in after period	Unbiased CMF	Standard error	Effectiveness	T value	95th-percentile CI, Lower	95th-percentile CI, Upper	Remarks
Total crash	286	326.901	0.874	0.063	12.6	2	0.751	0.997	CMF - statistically significant
Fatal or injury	71	75.112	0.941	0.126	5.9	0.468	0.694	1.188	CMF – Not statistically significant
Head-on and opposite direction sideswipe, total	1	12.37	0.08	0.077	92	11.948	0.000	0.231	CMF - statistically significant
Head-on and opposite direction sideswipe, fatal or injury	1	6.876	0.145	0.145	85.5	5.897	0.000	0.429	CMF - statistically significant
Single vehicle run-of-road total	87	82.182	1.054	0.13	-5.4	-0.415	0.799	1.309	CMF – Not statistically significant
Single vehicle run-of-road fatal or injury	43	27.382	1.561	0.266	-56.1	-2.109	1.04	2.082	CMF - statistically significant
Off-road left total	44	33.068	1.324	0.221	-32.4	-1.466	0.891	1.757	CMF – Not statistically significant
Off-road left fatal or injury	20	13.058	1.522	0.359	-52.2	-1.454	0.818	2.226	CMF – Not statistically significant

Table 23. Empirical Bayes Results for Sinusoidal Centerline Rumble Strips Before-After Evaluation at Sites with 5/8-inch Groove Depth and Shoulder Rumble Strips.

Treated sites: 67.5 miles, Treatment applied: 2021

Crash type	Reported crashes in after period	EB estimate in after period	Unbiased CMF	Standard error	Effectiveness	T value	95th-percentile CI, Lower	95th-percentile CI, Upper	Remarks
Total crash	382	481.45	0.792	0.045	20.8	4.622	0.704	0.88	CMF - statistically significant
Fatal or injury	89	96.912	0.915	0.11	8.5	0.773	0.699	1.131	CMF – Not statistically significant
Head-on and opposite direction sideswipe, total	4	17.418	0.228	0.114	77.2	6.772	0.005	0.451	CMF - statistically significant
Head-on and opposite direction sideswipe, fatal or injury	3	10.125	0.295	0.17	70.5	4.147	0.000	0.628	CMF - statistically significant
Single vehicle run-of-road total	107	103.33	1.033	0.114	-3.3	-0.289	0.81	1.256	CMF – Not statistically significant
Single vehicle run-of-road fatal or injury	49	34.098	1.43	0.226	-43	-1.903	0.987	1.873	CMF – Not statistically significant
Off-road left total	52	41.323	1.252	0.192	-25.2	-1.312	0.876	1.628	CMF – Not statistically significant
Off-road left fatal or injury	21	16.023	1.307	0.295	-30.7	-1.041	0.729	1.885	CMF – Not statistically significant

Table 24. Empirical Bayes Results for Sinusoidal Centerline Rumble Strips Before-After Evaluation at Sites with 1/2-inch Groove Depth and No Shoulder Rumble Strips.

Treated sites: 318.4 miles, Treatment applied: 2021

Crash type	Reported crashes in after period	EB estimate in after period	Unbiased CMF	Standard error	Effectiveness	T value	95th-percentile CI, Lower	95th-percentile CI, Upper	Remarks
Total crash	1140	1194.645	0.954	0.032	4.6	1.438	0.891	1.017	CMF – Not statistically significant
Fatal or injury	274	312.428	0.876	0.055	12.4	2.255	0.768	0.984	CMF - statistically significant
Head-on and opposite direction sideswipe, total	31	40.538	0.762	0.145	23.8	1.641	0.478	1.046	CMF – Not statistically significant
Head-on and opposite direction sideswipe, fatal or injury	13	23.378	0.556	0.155	44.4	2.865	0.252	0.86	CMF - statistically significant
Single vehicle run-of-road, total	353	399.001	0.884	0.055	11.6	2.109	0.776	0.992	CMF - statistically significant
Single vehicle run-of-road, fatal or injury	131	130.073	1.006	0.095	-0.6	-0.063	0.82	1.192	CMF – Not statistically significant
Off-road left, total	119	150.332	0.791	0.077	20.9	2.714	0.64	0.942	CMF - statistically significant
Off-road left, fatal or injury	48	54.471	0.88	0.13	12	0.923	0.625	1.135	CMF – Not statistically significant

Table 25. Empirical Bayes Results for Sinusoidal Centerline Rumble Strips Before-After Evaluation at Sites with 1/2-inch Groove Depth and Shoulder Rumble Strips.

Treated sites: 422.9 miles, Treatment applied: 2021

Crash type	Reported crashes in after period	EB estimate in after period	Unbiased CMF	Standard error	Effectiveness	T value	95th-percentile CI, Lower	95th-percentile CI, Upper	Remarks
Total crash	1621	1683.7	0.963	0.032	3.7	1.156	0.900	1.026	CMF – Not statistically significant
Fatal or injury	370	401.325	0.921	0.055	7.9	1.436	0.813	1.029	CMF – Not statistically significant
Head-on and opposite direction sideswipe, total	51	59.854	0.85	0.126	15	1.19	0.603	1.097	CMF – Not statistically significant
Head-on and opposite direction sideswipe, fatal or injury	25	34.731	0.719	0.145	28.1	1.938	0.435	1.003	CMF – Not statistically significant
Single vehicle run-of-road, total	443	474.578	0.932	0.055	6.8	1.236	0.824	1.04	CMF – Not statistically significant
Single vehicle run-of-road, fatal or injury	159	159.867	0.994	0.084	0.6	0.071	0.829	1.159	CMF – Not statistically significant
Off-road left, total	157	181.153	0.866	0.077	13.4	1.74	0.715	1.017	CMF – Not statistically significant
Off-road left, fatal or injury	62	72.476	0.854	0.11	14.6	1.327	0.638	1.07	CMF – Not statistically significant

The results of the EB evaluation for the SCLRS with 5/8-inch groove depths indicate that the CMFs for total crashes, as well as head-on and opposite direction sideswipe total and head-on and opposite direction sideswipe fatal plus injury crashes are statistically significant at locations with and without shoulder rumble strips (see Tables 22 and 23). However, the mileage of SCLRS sites with a groove depth of 5/8-inch is small (less than 70 miles), and there are fewer than five reported head-on and opposite direction sideswipe crashes for this evaluation at sites with and without shoulder rumble strips, so this finding should be re-evaluated in the future, after additional years of after period data are collected or after installing additional SCLRS sites with a 5/8-inch groove depths. Similarly, the CMF for single-vehicle run-off-road fatal plus injury crashes was statistically significant at site with no shoulder rumble strips.

The results of the EB evaluation for the SCLRS with 1/2-inch groove depths indicate that the CMFs for fatal plus injury crashes, as well as head-on and opposite direction sideswipe fatal plus injury, total single-vehicle run-off-road, and total off-road left crashes are statistically significant at locations without shoulder rumble strips (see Table 24). All of these CMFs are less than 1.0, indicating that the sites with SCLRS are associated with fewer crashes than the reference group sites. All CMFs for the SCLRS sites with ½-inch groove depths are less than 1.0, but none are statistically significant, at locations with shoulder rumble strips, as shown in Table 25.

<u>Centerline Rumble Strips: Causal Inference Framework</u>

As noted in the methodology section, propensity scores were estimated to determine the probability that a two-lane rural roadway segment contained centerline rumble strips as a function of site-specific roadway characteristics. After matching sites with and without centerline rumble strips, a negative binomial regression model was estimated to determine the relationship between various crash types and the presence of conventional centerline rumble strips. In addition, the presence of sinusoidal centerline rumble strips was also included in the potential outcomes model, to develop a comparison to the EB results shown previously. In this analysis, roadway segments that contained shoulder rumble strips during the study period were removed from consideration, to reduce potential confounding effects with the centerline rumble strips.

In this evaluation, the conventional centerline rumble strips were present during 2016 through 2024 – all crashes during the year 2021 were removed from evaluation because the sinusoidal pattern was installed during this year. The sinusoidal pattern was present between 2022 and 2024. The were 40,109 sites (44,597 mile-years) in the analysis file before matching, which included the sites with only centerline rumble strips, sites with only sinusoidal centerline rumble strips, and sites with no rumble strips, all on two-lane rural highways. After matching, 38,492 sites (26,869.5 mile-years) remained in the evaluation. The number and length of conventional and sinusoidal centerline rumble strips in the database, before and after matching, are shown in Table 26 below.

Table 26. Length and Mileage of Centerline Rumble Strips.

Rumble Strip Pattern	Sites (Before Matching)	Mile-years (Before Matching)	Sites (After Matching)	Mile-years (After Matching)
Conventional Centerline	20,516	14,456.4	17,731	12,549.4
Sinusoidal Centerline	1774	1111.9	1515	994.3

The CMFs, including the 95th-percentile range associated with the point estimates for the CMFs, are shown in Table 27 for each crash type, and for each centerline rumble strip pattern. For the purposes of brevity in this task report, the propensity scores model, standardized bias before and after matching, and the potential outcomes model for total crashes is shown in Appendix B.

As shown in Table 27, the CMFs for each crash type for the conventional centerline rumble strips treatment are all less than 1.0. The CMFs for the fatal plus injury, off-road left fatal plus injury, and single-vehicle run-off-road total crash types are all statistically significant at the 95th-percentile confidence level. The CMFs for conventional centerline rumble strips all overlap with the CMFs for SCLRS computed from the EB before-after evaluation results shown in Table 20.

The propensity scores-potential outcomes framework was also used to estimate CMFs for SCLRS, which are also shown in Table 27. These CMFs have 95th-percentile confidence intervals that overlap with the conventional centerline rumble strips CMFs for each crash type. The 95th-percentile confidence intervals around the SCLRS CMFs for each crash type in the propensity scores-potential outcomes framework also overlap with the CMFs for each crash from the EB before-after evaluation results shown in Table 20.

Table 27. Crash Modification Factors for Conventional CLRS and Sinusoidal CLRS from Causal Inference Framework (for sites with no shoulder RS).

Crash Type	CLRS type	CMF	Std Error	95th percentile CI, Lower	95th percentile CI, Upper	Statistically Significant?
Total	Conventional	0.979	0.020	0.9398	1.0182	No
Total	Sinusoidal	1.062	0.042	0.97968	1.14432	No
Fatal plus injury	Conventional	0.878	0.035	0.8094	0.9466	Yes
Fatal plus injury	Sinusoidal	0.974	0.072	0.83288	1.11512	No
Head-on plus sideswipe total	Conventional	0.850	0.098	0.65792	1.04208	No
Head-on plus sideswipe total	Sinusoidal	0.651	0.201	0.25704	1.04496	No
Head-on plus sideswipe fatal plus injury	Conventional	0.792	0.133	0.53132	1.05268	No
Head-on plus sideswipe fatal plus injury	Sinusoidal	0.583	0.280	0.0342	1.1318	No
Off-road left total	Conventional	0.930	0.048	0.83592	1.02408	No
Off-road left total	Sinusoidal	0.890	0.100	0.694	1.086	No
Off-road left fatal plus injury	Conventional	0.949	0.010	0.9294	0.9686	Yes
Off-road left fatal plus injury	Sinusoidal	0.828	0.072	0.68688	0.96912	Yes
Single-vehicle ROR total	Conventional	0.928	0.031	0.86724	0.98876	Yes
Single-vehicle ROR total	Sinusoidal	1.029	0.068	0.89572	1.16228	No
Single-vehicle ROR fatal plus injury	Conventional	0.900	0.047	0.80788	0.99212	Yes
Single-vehicle ROR fatal plus injury	Sinusoidal	0.959	0.097	0.76888	1.14912	No

Note: 95th-percentile confidence interval around CMF point estimate = CMF $\pm$ 1.96*SE

Chapter 6. Benefit-Cost Analysis Results

A simple benefit-cost analysis was performed to understand the impacts of SLCRS as an investment, particularly compared to conventional CLRS. The research team obtained per mile costs of CLRS installation from MDT. Conventional CLRS had an average cost of approximately $1,050 per mile and SCLRS had an average cost of approximately $2,400 per mile. The additional costs associated with the SCLRS were attributable to the need for specialized equipment and tighter construction tolerances required to achieve optimal rumble strip performance (i.e., target groove depth). These requirements reflect the fact that cutting heads experience continual wear and must be replaced more frequently to meet the more stringent specifications associated with SCLRS installation.

These installation costs were converted to an average annual cost assuming a 12-year service life for CLRS (Himes et al., 2017) and a 7% discount rate using the following equation (OMB, n.d.):

$$AC = FC \times \frac{i \times (1+i)^n}{(1+i)^n - 1}$$

where AC is the equivalent annual cost, FC is the fixed cost for installation, i is the discount rate, and n is the service life.

Based on this equation, the annual cost of conventional CLRS is $132.20 and the annual cost for SCLRS is $302.16.

Benefits were computed based on the expected changes in crash frequencies and associated comprehensive crash costs. CMFs were estimated separately for total crash frequency and fatal + injury FI crash frequency. The impact on property damage only (PDO) crashes could be obtained by the difference in total crash frequency and FI crash frequency.

Using reference-site data (i.e., sites without CLRS and without shoulder RS), the research team identified 2,324 fatal-and-injury (FI) crashes and 8,224 property-damage-only (PDO) crashes across 27,077.5 mile-years of two-lane rural roads in Montana. These values correspond to baseline crash rates of 0.0858 FI crashes per mile-year and 0.3037 PDO crashes per mile-year. Applying the crash modification factors (CMFs) for conventional CLRS (0.979 for total crashes and 0.878 for FI crashes) results in an estimated reduction of 0.0105 FI crashes per mile-year and an increase of 0.0023 PDO crashes per mile-year following installation. In contrast, sinusoidal CLRS exhibit CMFs of 0.937 for total crashes and 0.889 for FI crashes, corresponding to an estimated reduction of 0.0095 FI crashes per mile-year and a reduction of 0.0150 PDO crashes per mile-year.

Comprehensive crash costs were obtained to convert these crash savings to monetary units for the benefit-cost analysis (FHWA, 2025). These are provided for individual crash severities in the KABCO scale. To convert these into FI and PDO equivalents, the FHWA crash cost calculator tool (Harmon et al., 2018) was used. Inputs required were crashes by individual severity for the reference sites, as well as individual severity crash costs. These inputs are summarized in Table 29.

Table 28. Inputs to obtained comprehensive crash costs for FI and PDO crashes

Severity level	Percent crash frequency	FHWA crash cost
K	1.91%	$15,988,000
A	3.70%	$1,705,100
B	11.65%	$384,000
C	8.20%	$204,600
O	74.55%	$18,100

The unit crash cost for PDO crashes is directly provided as $18,100, while the estimated cost for fatal-and-injury (FI) crashes was $609,132. Applying these values to the estimated crash reductions associated with conventional and sinusoidal CLRS yields annual crash cost savings of $6,336.75 for conventional CLRS and $6,074.89 for SCLRS.

The benefit–cost ratio (BCR) was computed as the ratio of estimated safety benefits to implementation costs for each CLRS type. The resulting BCRs are 47.93 for conventional CLRS and 20.10 for SCLRS. As expected, these values differ primarily due to higher installation costs associated with SCLRS, given that the underlying CMFs—and thus the magnitude of crash reduction benefits—are comparable between the two treatments.

CHAPTER 7. SUMMARY AND CONCLUSIONS

The purpose of this study was to evaluate the safety effectiveness of SCLRS, and to compare the safety performance of this rumble strip type to conventional CLRS, on two-lane rural highways in Montana. The SCLRS were installed in two areas of Montana in 2021 – an EB before-after evaluation was conducted to evaluate the safety effects of this rumble strip pattern. The installation data of conventional CLRS was unknown in some cases, so a causal inference framework was undertaken to compare the safety performance of this rumble strip pattern. The CMFs developed in the present study, for both the CLRS and SCLRS patterns, are shown in Figure 5, for all crash types considered in the present study.

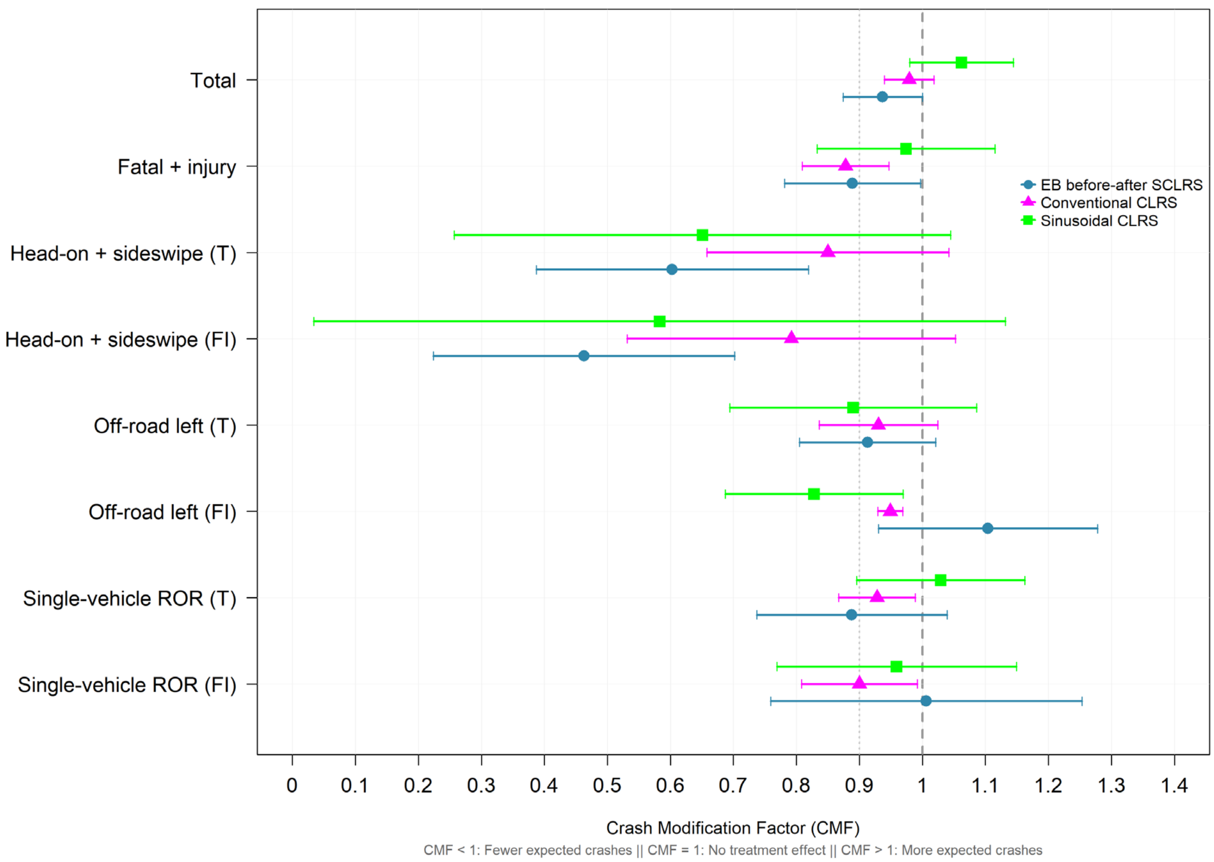


Figure 5. Crash Modification Factors for All Crash Types and Methodologies.

The 95th-percentile confidence intervals among the rumble strips patterns and statistical methodologies overlap for each crash type considered, indicating that the statistical variability around the CMF point estimates is similar for both SCLRS and conventional CLRS in the present study. Both rumble strip patterns are generally associated with fewer expected crashes for all crash types, with a few exceptions for the SCLRS pattern (SVROR fatal plus injury in the EB analysis and total and SVROR total in the causal inference framework), when considering all reference group sites, with and without shoulder rumble strips.

The EB evaluation of SCLRS was also undertaken for sites that did not include shoulder rumble strips during the study period, and the 95th-percentile confidence intervals around the CMFs overlapped with the CMFs when including all reference groups sites in the evaluation (with and without shoulder rumble strips).

The EB evaluation was also undertaken to consider the different groove depth patterns of SCLRS separately. There were fewer than 70 miles of SCLRS installed with the 5/8-inch groove depth, so several crash types had low reported crash frequencies in the after period. Among the crash types with more than 100 reported crashes in the after period, the CMF for total crashes was statistically significant and less than 1.0. In order to further assess how the groove depth affects the safety performance of SCLRS, it is recommended that safety performance at these sites continue to be assessed, or additional sites be installed with the 5/8-inch pattern and the analysis repeated after several years of after period data are available for the evaluation.

A benefit-cost evaluation was completed to determine how the safety effects of SCLRS and conventional CLRS compare relative to their implementation cost. Because the CMFs overlapped between the two rumble strip patterns, and the SCLRS pattern has greater installation costs, the conventional CLRS had higher benefit-cost ratios than SCLRS. However, both patterns have benefit-cost ratios that exceed 1.0.

CHAPTER 8. 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, MN 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.
48. Hauer, E. *Observational Before-After Studies in Road Safety: Estimating the Effect of Highway and Traffic Engineering Measures on Road Safety*. Emerald Group Publishing Limited, Bingley, 1997.
49. Dehejia, R. H., and S. Wahba. Propensity Score-Matching Methods for Nonexperimental Causal Studies. *Review of Economics and Statistics*, Vol. 84, No. 1, 2002, pp. 151–161. https://doi.org/10.1162/003465302317331982.

50. Rosenbaum, P. R., and D. B. Rubin. The Central Role of the Propensity Score in Observational Studies for Causal Effects. *Biometrilca*, Vol. 70, No. 1, 1983, pp. 41–55.
51. Holmes, W. M. *Using Propensity Scores in Quasi-Experimental Designs*. 2013.
52. Guo, C., and M. W. Fraser. *Propensity Score Analysis: Statistical Methods and Applications - Shenyang Guo, Mark W. Fraser - Google Books*. Sage Publications, Inc., Washington DC, 2010.
53. Kennedy, P. *A Guide to Econometrics*. Blackwell Publishing, Malden, MA, 2008.
54. Austin, P. C. An Introduction to Propensity Score Methods for Reducing the Effects of Confounding in Observational Studies. *Multivariate Behavioral Research*, Vol. 46, No. 3, 2011, pp. 399–424. https://doi.org/10.1080/00273171.2011.568786.

APPENDIX A. HORIZONTAL CURVE DATA COLLECTION

The process used to compute horizontal curve information for the present study is described below.

1. Importing Data: GIS shapefiles of each route were imported into AutoCAD Civil 3D. Routes were split into tiny elements approximately 25 ft in length. An example of state route C000060A is shown on the left side of Figure 6. Alternate segments are highlighted with blue dots to indicate the size of the segments relative to the features seen in the background imagery.
2. Change in Bearing Calculation: The absolute value of the change in bearing between consecutive elements was calculated. Elements with negligible differences (e.g., less than 0.1 degrees) were joined. The following distinctions were used:
   - Tangents: Successive elements have no or negligible change in bearing (say, $|\Delta| < 0.1$ degrees).
   - Curves: Successive elements exhibit a non-zero and nearly constant change in bearing.
   - Spirals: Successive elements have non-zero, varying (between 0 to the maximum value for the curves) changes in bearing.

   An illustration of this process of identification is shown in Figure 6.

3. Joining Segments and Identification of PC and PT Locations: Segments with negligible bearing differences were joined to form longer tangents, while keeping the curves and spirals unchanged. This will help identify the Point of Curvature (PC) and Point of Tangency (PT), as shown in Figure 7. These points represent the change going from tangents to curves, or tangents to spirals (if present).

Figure 6. Segments before joining (left) and after joined together (right) based on the change in bearings

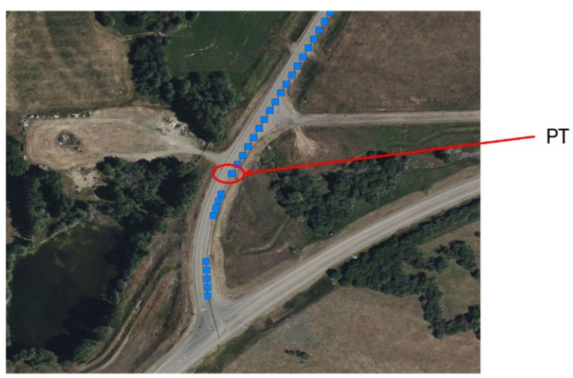
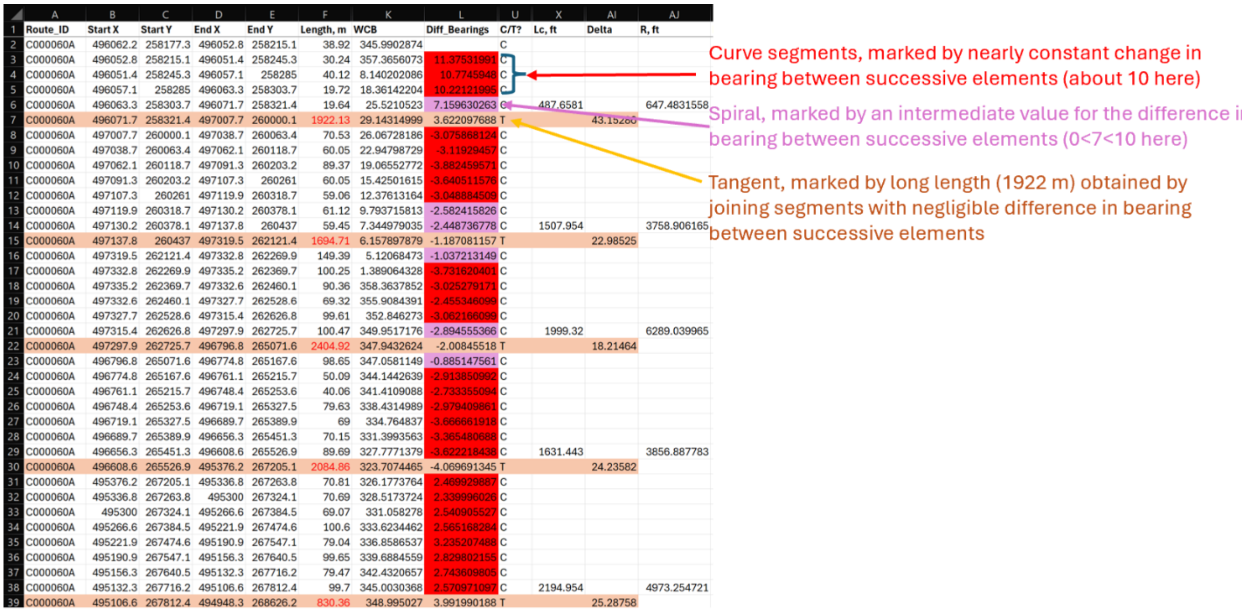


Figure 7. Point of tangency (PT) identified between the curve element and tangent element based on the difference in bearing of successive elements

Figure 8 shows the results in csv format, with column L showing the differences in bearings for consecutive elements. This difference in bearing is used to identify tangents, curves, and spirals. Spirals are generally observed in curves with small radii and short lengths as seen in the first couple of curves for the example shown in Figure 8.



	A	B	C	D	E	F	K	L	U	X	AI	AJ
1	Route_ID	Start X	Start Y	End X	End Y	Length, m	WCB	Diff_Bearings	C/T?	Lc, ft	Delta	R, ft
2	C000060A	496062.2	258177.3	496052.8	258215.1	38.92	345.9902874		C			
3	C000060A	496052.8	258215.1	496051.4	258245.3	30.24	357.3656073	11.37531991	C			
4	C000060A	496051.4	258245.3	496057.1	258285	40.12	8.140202086	10.7745948	C			
5	C000060A	496057.1	258285	496063.3	258303.7	19.72	18.36142204	10.22121995	C			
6	C000060A	496063.3	258303.7	496071.7	258321.4	19.64	25.5210523	7.159630263	C	487.6581		647.4831558
7	C000060A	496071.7	258321.4	497007.7	260000.1	1922.13	29.14314999	3.622097688	T		43.15280	
8	C000060A	497007.7	260000.1	497038.7	260063.4	70.53	26.06728186	-3.075868124	C			
9	C000060A	497038.7	260063.4	497062.1	260118.7	60.05	22.94798729	-3.11929457	C			
10	C000060A	497062.1	260118.7	497091.3	260203.2	89.37	19.06552772	-3.882459571	C			
11	C000060A	497091.3	260203.2	497107.3	260261	60.05	15.42501615	-3.640511576	C			
12	C000060A	497107.3	260261	497119.9	260318.7	59.06	12.37613164	-3.048884509	C			
13	C000060A	497119.9	260318.7	497130.2	260378.1	61.12	9.793715813	-2.582415826	C			
14	C000060A	497130.2	260378.1	497137.8	260437	59.45	7.344979035	-2.448736778	C	1507.954		3758.906165
15	C000060A	497137.8	260437	497319.5	262121.4	1694.71	6.157897879	-1.187081157	T		22.98525	
16	C000060A	497319.5	262121.4	497332.8	262269.9	149.39	5.12068473	-1.037213149	C			
17	C000060A	497332.8	262269.9	497335.2	262369.7	100.25	1.389064328	-3.731620401	C			
18	C000060A	497335.2	262369.7	497332.6	262460.1	90.36	358.3637852	-3.025279171	C			
19	C000060A	497332.6	262460.1	497327.7	262528.6	69.32	355.9084391	-2.455346099	C			
20	C000060A	497327.7	262528.6	497315.4	262626.8	99.61	352.846273	-3.062166099	C			
21	C000060A	497315.4	262626.8	497297.9	262725.7	100.47	349.9517176	-2.894555366	C	1999.32		6289.039965
22	C000060A	497297.9	262725.7	496796.8	265071.6	2404.92	347.9432624	-2.00845518	T		18.21464	
23	C000060A	496796.8	265071.6	496774.8	265167.6	98.65	347.0581149	-0.885147561	C			
24	C000060A	496774.8	265167.6	496761.1	265215.7	50.09	344.1442639	-2.913850992	C			
25	C000060A	496761.1	265215.7	496748.4	265253.6	40.06	341.4109088	-2.733355094	C			
26	C000060A	496748.4	265253.6	496719.1	265327.5	79.63	338.4314989	-2.979409861	C			
27	C000060A	496719.1	265327.5	496689.7	265389.9	69	334.764837	-3.666661918	C			
28	C000060A	496689.7	265389.9	496656.3	265451.3	70.15	331.3993563	-3.365480688	C			
29	C000060A	496656.3	265451.3	496608.6	265526.9	89.69	327.7771379	-3.622218438	C	1631.443		3856.887783
30	C000060A	496608.6	265526.9	495376.2	267205.1	2084.86	323.7074465	-4.069691345	T		24.23582	
31	C000060A	495376.2	267205.1	495336.8	267263.8	70.81	326.1773764	2.469929887	C			
32	C000060A	495336.8	267263.8	495300	267324.1	70.69	328.5173724	2.339996026	C			
33	C000060A	495300	267324.1	495266.6	267384.5	69.07	331.058278	2.540905527	C			
34	C000060A	495266.6	267384.5	495221.9	267474.6	100.6	333.6234462	2.565168284	C			
35	C000060A	495221.9	267474.6	495190.9	267547.1	79.04	336.8586537	3.235207488	C			
36	C000060A	495190.9	267547.1	495156.3	267640.5	99.65	339.6884559	2.829802155	C			
37	C000060A	495156.3	267640.5	495132.3	267716.2	79.47	342.4320657	2.743609805	C			
38	C000060A	495132.3	267716.2	495106.6	267812.4	99.7	345.0030368	2.570971097	C	2194.954		4973.254721
39	C000060A	495106.6	267812.4	494948.3	268626.2	830.36	348.995027	3.991990188	T		25.28758	

Figure 8. Output table calculation that identifies the curve, spiral and tangents based on difference in bearings between successive elements of a route

The deflection angle (Δ_i), for curve 'i', is calculated between the two tangent segments, in order to consider the degree of curvature due to the presence of spirals. The radius of the curve is then calculated by dividing the length of the curve and spirals (if present) by the deflection angle in radians.

$$R_i = \frac{(2 * L_{s,i} + Lc\prime_i)}{\Delta_i} \quad (3)$$

Note that the length of the spirals and the curve will be obtained by adding the length of the segments between PC and PT stations of the curve.

Verification of results: Sample results were validated using images from AutoCAD Civil 3D's Geolocation feature. For example, the radius and curve lengths for the first five curves of route C000060A closely matched actual road geometry, as shown in Figure 9.

Figure 9. Verifying the radius and length of curves for route C000060A using Geolocation feature in Civil3D

Note: If a horizontal curve spans two segments, it should be split and recorded in both segments. In such case, the end point of the curve in the first segment will be assigned as PT for the curve in the first segment and PC for the subsequent segment.

APPENDIX B. ACCESS POINTS AND RUMBLE STRIPS PRESENCE USING GOOGLE EARTH PRO

Google Earth Pro is a free desktop application used to view, analyze, and create geospatial data using 3D terrain and roadway features. For this project, Google Earth Pro is primarily used to collect the number of access points within a roadway section, and also to verify the locations of the presence of rumble strips using Google Street View. The online Google Earth tool can be accessed using the following link: https://www.google.com/earth/about/. The following steps describe the procedure used to gather the access points information.

1. *Convert the coordinates of the mile post locations in DMS format*
   The northing and easting coordinates of the start mileposts for road segments in the provided geodatabase file will be converted to Degrees, Minutes, and Seconds (DMS) format for use in Google Earth. This can be accomplished with a simple R script. The final output will be a comma-separated (.csv) file containing columns for Name, Latitude, and Longitude. It's helpful to create the 'Name' column by combining the route ID with the milepost location corresponding to the latitude and longitude coordinates.

2. *Import the coordinates in Google Earth Pro*
   Once the coordinates are ready, open the Google Earth Pro application and import the coordinates of the mile post locations of the start and end points of the roadway segments. The mile post locations can be represented by pins as shown in **Figure 10**.

Figure 10. Screen capture from the Google Earth Pro interface showing the start and end points of a section, marked by yellow pins, between which the access points can be counted.

3. *Calculate access density*

   Count the number of access points between one set of start and end points. Access density for that roadway segment will be computed as follows:

   Access density, AD (number per mile) = Number of access points / Length of the segment in miles

APPENDIX C. SAFETY PERFORMANCE FUNCTIONS FOR SCLRS EVALUATION

As an example, Table 29 shows the SPF developed for total crash frequency estimated using all reference sites data, including sites with and without shoulder rumble strips. The results show that expected total crash frequency increases with increases in traffic volume, segment length, access density, intersection density, segment gradient and horizontal curvature. Segments wider than 24 feet and with shoulder rumble strips are associated with lower expected crash frequencies.

Table 29. SPF for total crash frequency for reference sites

Variable	Coefficient	Std. error	T-statistic	P-value
Constant	-8.055	0.087	-92.21	<0.001
Natural log of AADT	1.049	0.012	85.87	<0.001
Natural log of segment length	0.923	0.023	39.73	<0.001
Indicator for presence of shoulder rumble strips	-0.194	0.029	-6.57	<0.001
Indicator for roadway width greater than 24 ft	-0.304	0.027	-11.28	<0.001
Access points per mile	0.023	0.006	4.22	<0.001
Intersections per mile	0.025	0.002	12.21	<0.001
Indicator for year = 2017	0.030	0.045	0.66	0.507
Indicator for year = 2018	0.063	0.045	1.40	0.161
Indicator for year = 2019	-0.020	0.046	-0.45	0.656
Indicator for year = 2020	0.073	0.045	1.60	0.109
Indicator for year = 2022	0.019	0.045	0.42	0.677
Indicator for year = 2023	-0.067	0.046	-1.47	0.142
Indicator for year = 2024	-0.038	0.045	-0.84	0.401
Average gradient	0.072	0.023	3.05	0.002
Average degree of curvature per mile	0.015	0.001	18.52	<0.001
Log Likelihood	-21290.1			
AIC	42614.1			
BIC	42761.7			
Overdispersion (θ)	1.824			
Number of Observations	43536			
Root Mean Square Error (RMSE)	0.607			
Mean Absolute Error (MAE)	0.309			
R-squared (Pseudo)	0.367			

Figure 11 provides the associated CURE plot. The plot shows that more than 98% of the observations fall within the 95% confidence interval, which suggests a good fit to the observed data.

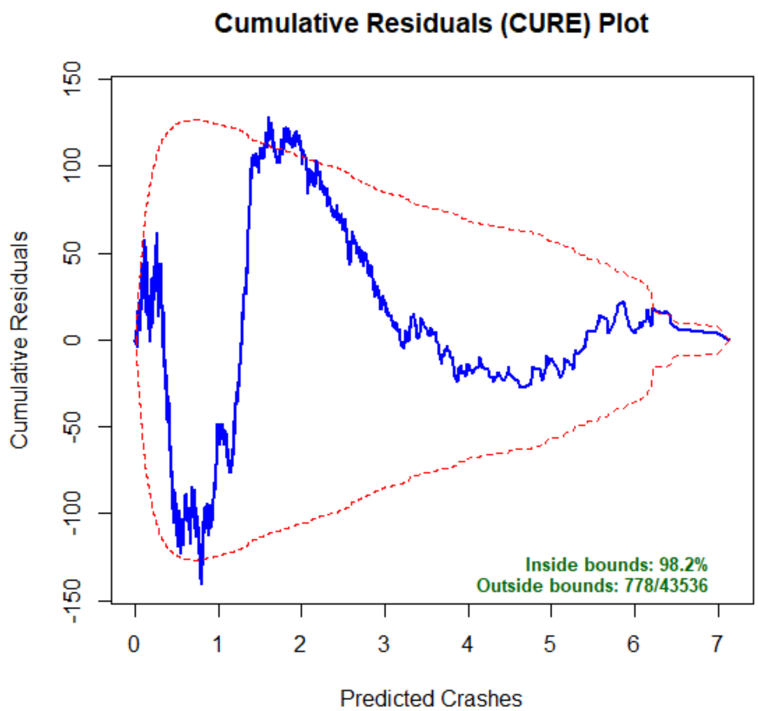


Figure 11. CURE plot for total crash frequency for reference sites

The remainder of Appendix C includes safety performance functions, used in the EB analyses, to develop CMFs for SCLRS. Table 30 through Table 37 provide SPFs for the following crash types at sites that do not include shoulder rumble strips: total crashes, fatal plus injury crashes, total head-on plus opposite direction sideswipe crashes, fatal plus injury head-on plus opposite direction sideswipe crashes, total single-vehicle run-off-road crashes, fatal plus injury single-vehicle run-off road crashes, total off-road left crashes, and fatal plus injury off-road left crashes. Table 30 through Table 45 provide SPFs for the same crash types at all reference group sites, including those with shoulder rumble strips.

Table 30. SPF for total crash frequency for reference sites (excluding sites with SRS)

Variable	**Coefficient**	**Std. Error**	**p-value**
Constant	-8.023	0.094	<0.001
Natural logarithm of AADT	1.045	0.013	<0.001
Natural logarithm of segment length in miles	0.914	0.026	<0.001
Indicator for surface width greater than 24 ft	-0.298	0.027	<0.001
Indicator for presence of intersection	0.112	0.029	<0.001
No. of access points per mile	0.023	0.002	<0.001
Indicator for year = 2017 (Reference year = 2016)	-0.015	0.051	0.762
Indicator for year = 2018 (Reference year = 2016)	0.045	0.05	0.373
Indicator for year = 2019 (Reference year = 2016)	-0.017	0.051	0.738
Indicator for year = 2020 (Reference year = 2016)	0.08	0.051	0.112
Indicator for year = 2022 (Reference year = 2016)	-0.029	0.052	0.57
Indicator for year = 2023 (Reference year = 2016)	-0.111	0.052	0.034
Indicator for year = 2024 (Reference year = 2016)	-0.051	0.051	0.316
Average gradient in %	0.041	0.028	0.139
Average degree of curvature per mile	0.019	0.001	<0.001

Model diagnostics:

Statistic	Value
Log Likelihood	-16700.2
AIC	33432.4
BIC	33568.7
Overdispersion (θ)	1.849
Number of Observations	36928
Root Mean Square Error (RMSE)	0.572
Mean Absolute Error (MAE)	0.282
R-squared (Pseudo)	0.37

Table 31. SPF for fatal plus injury crashes (excluding sites with SRS)

Variable	Coefficient	Std. Error	p-value
Constant	-9.199	0.143	<0.001
Natural logarithm of AADT	1.019	0.021	<0.001
Natural logarithm of segment length in miles	0.93	0.047	<0.001
Indicator for surface width greater than 30 ft	-0.168	0.062	0.007
No. of access points per mile	0.019	0.004	<0.001
Indicator for presence of curve with radius 1000 ft or less	0.562	0.095	<0.001
Average degree of curvature per mile	0.013	0.002	<0.001

Model diagnostics:

Statistic	Value
Log Likelihood	-7285.2
AIC	14586.4
BIC	14654.5
Overdispersion (θ)	2.531
Number of Observations	36928
Root Mean Square Error (RMSE)	0.262
Mean Absolute Error (MAE)	0.103
R-squared (Pseudo)	0.253

Table 32. SPF for total head-on plus opposite direction sideswipe crash frequency (excluding sites with SRS)

Variable	Coefficient	Std. Error	p-value
Constant	-14.224	0.424	<0.001
Natural logarithm of AADT	1.414	0.058	<0.001
Natural logarithm of segment length in miles	1.072	0.129	<0.001
Indicator for presence of intersection	0.22	0.131	0.093
Indicator for presence of reverse or compound curve	0.357	0.197	0.07
Average degree of curvature per mile	0.019	0.004	<0.001

Model diagnostics:

Statistic	Value
Log Likelihood	-1274.7
AIC	2563.3
BIC	2623
Overdispersion (θ)	0.918
Number of Observations	36928
Root Mean Square Error (RMSE)	0.09
Mean Absolute Error (MAE)	0.014
R-squared (Pseudo)	0.294

Table 33. SPF for fatal plus injury head-on plus opposite direction sideswipe crash frequency (excluding sites with SRS)

Variable	Coefficient	Std. Error	p-value
Constant	-15.329	0.578	<0.001
Natural logarithm of AADT	1.495	0.075	<0.001
Natural logarithm of segment length in miles	1.162	0.175	<0.001
Average degree of curvature per mile	0.014	0.007	0.035

Model diagnostics:

Statistic	Value
Log Likelihood	-735.9
AIC	1481.7
BIC	1524.3
Overdispersion (θ)	23.401
Number of Observations	36928
Root Mean Square Error (RMSE)	0.062
Mean Absolute Error (MAE)	0.007
R-squared (Pseudo)	0.261

Table 34. SPF for total single-vehicle run-off-road crash frequency (excluding sites with SRS)

Variable	Coefficient	Std. Error	p-value
Constant	-8.362	0.128	<0.001
Natural logarithm of AADT	0.981	0.018	<0.001
Natural logarithm of segment length in miles	0.871	0.042	<0.001
Indicator for surface width greater than 24 ft	-0.487	0.04	<0.001
Indicator for presence of reverse or compound curve	0.221	0.073	0.002
Indicator for presence of curve with radius 1000 ft or less	0.512	0.088	<0.001
Average degree of curvature per mile	0.011	0.002	<0.001
Average gradient in %	0.095	0.041	0.02

Model diagnostics:

Statistic	Value
Log Likelihood	-9008.4
AIC	18034.7
BIC	18111.4
Overdispersion (θ)	1.511
Number of Observations	36928
Root Mean Square Error (RMSE)	0.309
Mean Absolute Error (MAE)	0.133
R-squared (Pseudo)	0.243

Table 35. SPF for fatal plus injury single-vehicle run-off-road crash frequency (excluding sites with SRS)

Variable	**Coefficient**	**Std. Error**	**p-value**
Constant	-7.423	0.263	<0.001
Natural logarithm of AADT	0.866	0.027	<0.001
Natural logarithm of segment length in miles	0.972	0.071	<0.001
Roadway surface width in ft	-0.052	0.008	<0.001
Indicator for presence of curve with radius 1000 ft or less	0.567	0.129	<0.001
Average degree of curvature per mile	0.011	0.003	<0.001
Average gradient in %	0.198	0.06	0.001

Model diagnostics:

Statistic	Value
Log Likelihood	-4725.7
AIC	9467.5
BIC	9535.6
Overdispersion (θ)	1.805
Number of Observations	36928
Root Mean Square Error (RMSE)	0.184
Mean Absolute Error (MAE)	0.06
R-squared (Pseudo)	0.153

Table 36. SPF for total off-road left crash frequency (excluding sites with SRS)

Variable	Coefficient	Std. Error	p-value
Intercept	-9.215	0.188	<0.001
Natural logarithm of AADT	0.969	0.027	<0.001
Natural logarithm of segment length in miles	0.952	0.067	<0.001
Indicator for surface width greater than 24 ft	-0.383	0.062	<0.001
Indicator for presence of curve with radius 1000 ft or less	0.482	0.134	<0.001
Average degree of curvature per mile	0.009	0.003	0.003
Indicator for presence of curve warning sign	0.493	0.107	<0.001

Model diagnostics:

Statistic	Value
Log Likelihood	-4526.4
AIC	9068.8
BIC	9136.9
Overdispersion (θ)	1.827
Number of Observations	36928
Root Mean Square Error (RMSE)	0.184
Mean Absolute Error (MAE)	0.058
R-squared (Pseudo)	0.19

Table 37. SPF for fatal plus injury off-road left crash frequency (excluding sites with SRS)

Variable	**Coefficient**	**Std. Error**	**p-value**
Intercept	-9.519	0.272	<0.001
Natural logarithm of AADT	0.88	0.04	<0.001
Natural logarithm of segment length in miles	1.104	0.111	<0.001
Average degree of curvature per mile	0.012	0.004	0.002
Paved shoulder width in ft	-0.072	0.027	0.008
Indicator for average absolute gradient greater than 1%	0.36	0.113	0.001

Model diagnostics:

Statistic	Value
Log Likelihood	-2439.3
AIC	4892.7
BIC	4952.3
Overdispersion (θ)	2.148
Number of Observations	36928
Root Mean Square Error (RMSE)	0.119
Mean Absolute Error (MAE)	0.027
R-squared (Pseudo)	0.126

Table 38. SPF for total crash frequency for all reference sites.

Variable	Coefficient	Std. Error	p-value
Constant	-8.055	0.087	<0.001
Natural logarithm of AADT	1.049	0.012	<0.001
Natural logarithm of segment length in miles	0.923	0.023	<0.001
Indicator for presence of shoulder rumble strips	-0.194	0.029	<0.001
Indicator for surface width greater than 24 ft	-0.304	0.027	<0.001
No. of intersections per mile	0.023	0.006	<0.001
No. of access points per mile	0.025	0.002	<0.001
Indicator for year = 2017 (Reference year = 2016)	0.03	0.045	0.507
Indicator for year = 2018 (Reference year = 2016)	0.063	0.045	0.161
Indicator for year = 2019 (Reference year = 2016)	-0.02	0.046	0.656
Indicator for year = 2020 (Reference year = 2016)	0.073	0.045	0.109
Indicator for year = 2022 (Reference year = 2016)	0.019	0.045	0.677
Indicator for year = 2023 (Reference year = 2016)	-0.067	0.046	0.142
Indicator for year = 2024 (Reference year = 2016)	-0.038	0.045	0.401
Average gradient in %	0.072	0.023	0.002
Average degree of curvature per mile	0.015	0.001	<0.001

Model diagnostics:

Statistic	Value
Log Likelihood	-21290.1
AIC	42614.1
BIC	42761.7
Overdispersion (θ)	1.824
Number of Observations	43536
Root Mean Square Error (RMSE)	0.607
Mean Absolute Error (MAE)	0.309
R-squared (Pseudo)	0.367

Table 39. SPF for fatal plus injury crashes for all reference sites

Variable	Coefficient	Std. Error	p-value
Constant	-8.695	0.167	<0.001
Natural logarithm of AADT	1.031	0.02	<0.001
Natural logarithm of segment length in miles	0.912	0.042	<0.001
Indicator for presence of shoulder rumble strips	-0.393	0.059	<0.001
Surface width in ft	-0.027	0.004	<0.001
No. of intersections per mile	0.026	0.01	0.007
No. of access points per mile	0.023	0.003	<0.001
Indicator for presence of curve with radius 1000 ft or less	0.487	0.092	<0.001
Average gradient in %	0.149	0.04	<0.001
Average degree of curvature per mile	0.011	0.002	<0.001

Model diagnostics:

Statistic	Value
Log Likelihood	-8924.5
AIC	17871
BIC	17966.5
Overdispersion (θ)	2.331
Number of Observations	43536
Root Mean Square Error (RMSE)	0.269
Mean Absolute Error (MAE)	0.107
R-squared (Pseudo)	0.246

Table 40. SPF for total head-on plus opposite direction sideswipe crash frequency for all reference sites

Variable	**Coefficient**	**Std. Error**	**p-value**
Constant	-14.315	0.395	<0.001
Natural logarithm of AADT	1.438	0.053	<0.001
Natural logarithm of segment length in miles	1.076	0.111	<0.001
Indicator for surface width greater than 24 ft	-0.167	0.137	0.223
Indicator for intersection density greater than 1	0.248	0.114	0.029
Indicator for average absolute gradient greater than 0.75%	0.245	0.121	0.043
Indicator for presence of shoulder rumble strips	-0.37	0.131	0.005
Average degree of curvature per mile	0.016	0.003	<0.001

Model diagnostics:

Statistic	Value
Log Likelihood	-1684.2
AIC	3386.3
BIC	3464.5
Overdispersion (θ)	1.1
Number of Observations	43536
Root Mean Square Error (RMSE)	0.095
Mean Absolute Error (MAE)	0.016
R-squared (Pseudo)	0.278

Table 41. SPF for fatal plus injury head-on plus opposite direction sideswipe crash frequency for all reference sites

Variable	**Coefficient**	**Std. Error**	**p-value**
Constant	-15.23	0.525	<0.001
Natural logarithm of AADT	1.48	0.068	<0.001
Natural logarithm of segment length in miles	1.242	0.157	<0.001

Model diagnostics:

Statistic	Value
Log Likelihood	-1003.6
AIC	2015.2
BIC	2049.9
Overdispersion (θ)	4.402
Number of Observations	43536
Root Mean Square Error (RMSE)	0.068
Mean Absolute Error (MAE)	0.009
R-squared (Pseudo)	0.251

Table 42. SPF for total single-vehicle run-off-road crash frequency for all reference sites

Variable	Coefficient	Std. Error	p-value
Constant	-8.389	0.133	<0.001
Natural logarithm of AADT	0.96	0.019	<0.001
Natural logarithm of segment length in miles	0.871	0.038	<0.001
Indicator for presence of shoulder rumble strip	-0.565	0.053	<0.001
No. of access points per mile	0.007	0.003	0.041
Indicator for surface width greater than 24 ft	-0.489	0.04	<0.001
Indicator for year = 2017 (Reference year = 2016)	0.132	0.072	0.068
Indicator for year = 2018 (Reference year = 2016)	0.161	0.072	0.026
Indicator for year = 2019 (Reference year = 2016)	0.086	0.073	0.238
Indicator for year = 2020 (Reference year = 2016)	0.177	0.073	0.015
Indicator for year = 2022 (Reference year = 2016)	0.161	0.072	0.026
Indicator for year = 2023 (Reference year = 2016)	0.055	0.073	0.452
Indicator for year = 2024 (Reference year = 2016)	0.028	0.073	0.707
Indicator for presence of curve with radius 1000 ft or less	0.473	0.083	<0.001
Average degree of curvature per mile	0.01	0.002	<0.001
Average gradient in %	0.147	0.036	<0.001
Indicator for presence of curve warning sign	0.411	0.071	<0.001

Model diagnostics:

Statistic	Value
Log Likelihood	-10766.4
AIC	21568.7
BIC	21725
Overdispersion (θ)	1.536
Number of Observations	43536
Root Mean Square Error (RMSE)	0.308
Mean Absolute Error (MAE)	0.134
R-squared (Pseudo)	0.229

Table 43. SPF for fatal plus injury single-vehicle run-off-road crash frequency for all reference sites

Variable	**Coefficient**	**Std. Error**	**p-value**
Constant	-8.363	0.181	<0.001
Natural logarithm of AADT	0.827	0.026	<0.001
Natural logarithm of segment length in miles	0.972	0.064	<0.001
Indicator for presence of shoulder rumble strip	-0.742	0.087	<0.001
Indicator for surface width greater than 24 ft	-0.369	0.061	<0.001
Average degree of curvature per mile	0.01	0.003	<0.001
Indicator for presence of curve with radius 1000 ft or less	0.41	0.126	0.001
Average gradient in %	0.235	0.053	<0.001
Indicator for presence of curve warning sign	0.456	0.104	<0.001

Model diagnostics:

Statistic	Value
Log Likelihood	-5498.3
AIC	11016.6
BIC	11103.4
Overdispersion (θ)	1.775
Number of Observations	43536
Root Mean Square Error (RMSE)	0.181
Mean Absolute Error (MAE)	0.058
R-squared (Pseudo)	0.143

Table 44. SPF for total off-road left crash frequency for all reference sites

Variable	Coefficient	Std. Error	p-value
Intercept	-9.213	0.185	<0.001
Natural logarithm of AADT	0.959	0.026	<0.001
Natural logarithm of segment length in miles	0.941	0.061	<0.001
Indicator for presence of shoulder rumble strip	-0.61	0.081	<0.001
Indicator for surface width greater than 24 ft	-0.385	0.062	<0.001
Indicator for presence of curve with radius 1000 ft or less	0.414	0.13	0.001
Average degree of curvature per mile	0.009	0.003	0.001
Average gradient in %	0.133	0.056	0.017
Indicator for presence of curve warning sign	0.452	0.106	<0.001

Model diagnostics:

Statistic	Value
Log Likelihood	-5417.8
AIC	10855.7
BIC	10942.5
Overdispersion (θ)	1.599
Number of Observations	43536
Root Mean Square Error (RMSE)	0.184
Mean Absolute Error (MAE)	0.058
R-squared (Pseudo)	0.175

Table 45. SPF for fatal plus injury off-road left crash frequency for all reference sites

Variable	**Coefficient**	**Std. Error**	**p-value**
Intercept	-9.102	0.281	<0.001
Natural logarithm of AADT	0.831	0.039	<0.001
Natural logarithm of segment length in miles	1.033	0.098	<0.001
Indicator for presence of shoulder rumble strip	-0.805	0.135	<0.001
Indicator for surface width greater than 24 ft	-0.389	0.091	<0.001
Indicator for percentage of curve length greater than 20	0.683	0.087	<0.001
Indicator for year = 2017 (Reference year = 2016)	-0.202	0.161	0.212
Indicator for year = 2018 (Reference year = 2016)	-0.487	0.175	0.005
Indicator for year = 2019 (Reference year = 2016)	-0.379	0.169	0.025
Indicator for year = 2020 (Reference year = 2016)	-0.02	0.156	0.898
Indicator for year = 2022 (Reference year = 2016)	-0.112	0.158	0.478
Indicator for year = 2023 (Reference year = 2016)	-0.108	0.157	0.491
Indicator for year = 2024 (Reference year = 2016)	-0.1	0.156	0.521
Indicator for average gradient greater than 0.95%	0.354	0.099	<0.001

Model diagnostics:

Statistic	Value
Log Likelihood	-2779.4
AIC	5588.8
BIC	5719
Overdispersion (θ)	3.907
Number of Observations	43536
Root Mean Square Error (RMSE)	0.116
Mean Absolute Error (MAE)	0.026
R-squared (Pseudo)	0.129

APPENDIX D. PROPENSITY SCORES-POTENTIAL OUTCOMES MODELING OUTPUT

Table 46 provides the logistic regression model that was used to obtain propensity scores to match sites with and without centerline rumble strips. Sites with a centerline rumble strip (of any type, traditional or sinusoidal) were modeled a successful outcome in the models, where sites without a centerline rumble strip were modeled as not a success. The results show that roadway segments with higher traffic volumes, wider paved widths, higher speed limits, more access points per mile, higher curvature, the presence of a curve warning sign, larger gradients and designated as a collector, local road, minor arterial or principal arterial are more likely to have centerline rumble strips. Shorter segments and those that have more intersections per mile are less likely to have centerline rumble strips.

Table 46. Logistic regression model to compute propensity of a segment containing a centerline rumble strip

Variable	Coefficient	Std. error	T-statistic	P-value
Constant	-13.80	268	-0.05	0.959
AADT (veh/day)	0.0001	0.000	12.40	<0.00001
Segment length (mi)	-0.0780	0.034	-2.32	0.020
Indicator for roadway width greater than 24 ft	0.00494	0.020	0.25	0.803
Indicator for PSL = 55 mph	-0.40800	0.065	-6.24	<0.00001
Indicator for PSL = 60 mph	1.0200	0.067	15.39	<0.00001
Indicator for PSL = 65 mph	0.5040	0.078	6.45	<0.00001
Indicator for PSL = 70 mph	0.1230	0.059	2.09	0.037
Indicator for year = 2017	0.00496	0.034	0.15	0.885
Indicator for year = 2018	-0.0019	0.034	-0.06	0.956
Indicator for year = 2019	-0.0328	0.035	-0.95	0.343
Indicator for year = 2020	-0.0795	0.035	-2.26	0.024
Indicator for year = 2022	0.2270	0.035	6.48	<0.00001
Indicator for year = 2023	0.1920	0.035	5.45	<0.00001
Indicator for year = 2024	0.1900	0.035	5.41	<0.00001
Access points per mile	0.0221	0.002	11.64	<0.00001
Intersections per mile	-0.0763	0.007	-11.71	<0.00001
Degree of curvature per mile	0.0102	0.001	9.13	<0.00001
Indicator for curve warning sign	0.0831	0.044	1.91	0.056
Indicator for reverse compound curve	0.2570	0.041	6.24	<0.00001
Average gradient	0.1280	0.019	6.70	<0.00001
Indicator for roadway classified as a collector	12.3	268	0.05	0.963
Indicator for roadway classified as a local road	0.0929	274	0.00	1.000
Indicator for roadway classified as a minor arterial	12.6	268	0.05	0.962
Indicator for roadway classified as a principal arterial	13.6	268	0.05	0.960
Indicator for curve present with radius less than 1000 ft	-0.0667	0.054	-1.23	0.221
Log Likelihood	-37685.2			
AIC	75422.4			
BIC	75657.4			
Number of Observations	62399			
McFadden R-squared	0.073			

Figure 12 illustrates the standardized bias of several key variables before and after the matching process, along with the +/- 10 percent bounds that indicate unbiased data. As shown, before matching, traffic volumes exhibited significant bias between sites with and without centerline rumble strips (as indicated by a value of approximately 40 percent) and several other variables are near the +/- 10 percent threshold. However, after matching, the standardized bias of all variables is well within the +/- 10 percent bound.

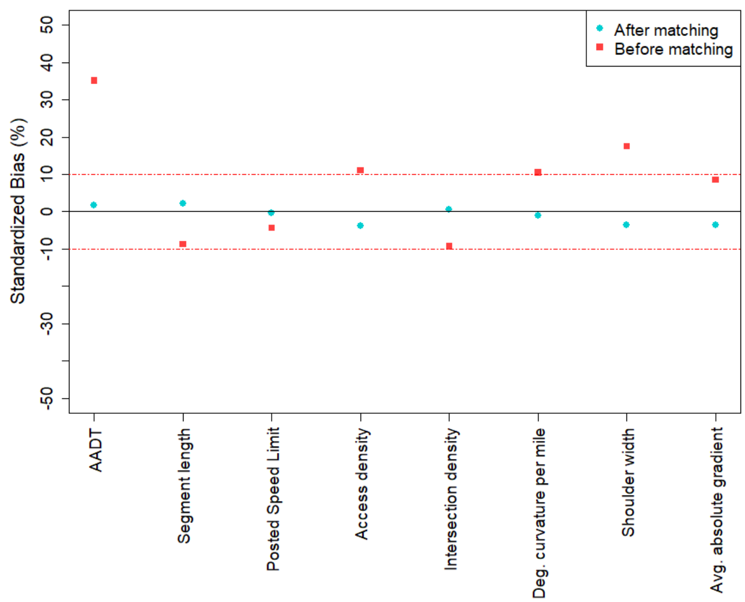


Figure 12. Standardized bias of dataset before and after matching

As an example, Table 47 shows the potential outcomes model for fatal plus injury crash frequency estimated on the matched data. The results show that fatal plus injury crash frequency increases with traffic volume, segment length, access density, segments with the presence of a horizontal curve with a radius of 1000 feet or less, segments with gradients larger than 0.95 percent, and degree of curve per mile. Segments wider than 24 feet are associated with reduced crash frequency. The presence of conventional centerline rumble strips is associated with a decrease in fatal and injury crash frequency. The presence of sinusoidal centerline rumble strips is associated with a decrease in fatal plus injury crash frequency; however, the relationship is not statistically significant.

Table 47. Potential outcomes model on matched data for fatal plus injury crash frequency

Variable	Coefficient	Std.Error	p-value
Constant	-8.328	0.144	<0.001
Natural logarithm of AADT	0.937	0.019	<0.001
Natural logarithm of segment length in miles	0.959	0.036	<0.001
Indicator for surface width greater than 24 ft (1 if present, 0 otherwise)	-0.182	0.037	<0.001
No. of access points per mile	0.018	0.003	<0.001
Indicator for presence of curve with radius of 1000 ft or less (1 if true, 0 otherwise)	0.362	0.074	<0.001
Average gradient in %	0.121	0.036	0.001
Indicator for year = 2017 (Ref. year = 2016)	-0.044	0.061	0.466
Indicator for year = 2018 (Ref. year = 2016)	-0.194	0.063	0.002
Indicator for year = 2019 (Ref. year = 2016)	-0.205	0.064	0.001
Indicator for year = 2020 (Ref. year = 2016)	-0.089	0.063	0.16
Indicator for year = 2022 (Ref. year = 2016)	-0.183	0.066	0.005
Indicator for year = 2023 (Ref. year = 2016)	-0.247	0.067	<0.001
Indicator for year = 2024 (Ref. year = 2016)	-0.218	0.066	0.001
Degree of curvature per mile	0.009	0.002	<0.001
Indicator for presence of conventional CLRS (Ref. = No CLRS)	-0.13	0.035	<0.001
Indicator for presence of sinusoidal CLRS (Ref. = No CLRS)	-0.026	0.072	0.72

Model diagnostics:

Statistic	Value
Log Likelihood	-11576.1
AIC	23188.3
BIC	23342.3
Overdispersion (θ)	2.543
Number of Observations	38492
Root Mean Square Error (RMSE)	0.341
Mean Absolute Error (MAE)	0.169
R-squared (Pseudo)	0.214

The potential outcomes for the following seven crash types are included in Tables 48 through 54: total crashes, total head-on plus opposite direction sideswipe crashes, fatal plus injury head-on plus opposite direction sideswipe crashes, total single-vehicle run-off-road crashes, fatal plus injury single-vehicle run-off road crashes, total off-road left crashes, and fatal plus injury off-road left crashes.

Table 48. Potential outcomes model on matched data for total crash frequency

Variable	Coefficient	Std. error	T-statistic	P-value
Constant	-7.727	0.086	-90.21	<0.001
Natural log of AADT	1.010	0.012	85.27	<0.001
Natural log of segment length	0.958	0.020	48.67	<0.001
Indicator for roadway width greater than 24 ft	-0.155	0.022	-7.03	<0.001
Access points per mile	0.022	0.002	12.93	<0.001
Indicator for year = 2017	0.071	0.036	1.96	0.051
Indicator for year = 2018	0.021	0.036	0.57	0.566
Indicator for year = 2019	-0.045	0.037	-1.22	0.222
Indicator for year = 2020	0.081	0.037	2.19	0.029
Indicator for year = 2022	-0.037	0.038	-0.98	0.328
Indicator for year = 2023	-0.174	0.039	-4.41	<0.001
Indicator for year = 2024	-0.154	0.039	-3.94	<0.001
Intersections per mile	0.038	0.007	5.37	<0.001
Indicator for degree of curvature per mile greater than 3.5	0.336	0.020	16.58	<0.001
Indicated for PSL 55 mph and above	-0.087	0.032	-2.75	0.006
Indicator for arterial roadway	-0.048	0.022	-2.18	0.029
Indicator for average gradient greater than 0.95%	0.090	0.025	3.65	<0.001
Indicator for traditional centerline rumble strips	-0.022	0.020	-1.09	0.276
Indicator for sinusoidal centerline rumble strips	0.060	0.042	1.43	0.152

Model diagnostics:

Statistic	Value
Log Likelihood	-26335.8
AIC	52711.6
BIC	52882.8
Overdispersion (θ)	2.313
Number of Observations	38492
Root Mean Square Error (RMSE)	0.761
Mean Absolute Error (MAE)	0.448
R-squared (Pseudo)	0.362

Table 49. Potential outcomes model on matched data for total head-on and opposite direction sideswipe crash frequency

Variable	Coefficient	Std. Error	p-value
Constant	-14.021	0.431	<0.001
Natural logarithm of AADT	1.384	0.054	<0.001
Natural logarithm of segment length in miles	1.017	0.096	<0.001
Indicator for presence of curve with radius of 1000 ft or less (1 if true, 0 otherwise)	0.513	0.174	0.003
Indicator for degree of curvature per mile greater than 3 (1 if true, 0 otherwise)	0.289	0.102	0.004
Average gradient in %	0.204	0.1	0.042
Indicator for surface width greater than 24 ft (1 if present, 0 otherwise)	-0.211	0.109	0.052
No. of intersections per mile	0.105	0.026	<0.001
Indicator for presence of conventional CLRS (Ref. = No CLRS)	-0.162	0.098	0.098
Indicator for presence of sinusoidal CLRS (Ref. = No CLRS)	-0.429	0.201	0.033

Model diagnostics:

Statistic	Value
Log Likelihood	-2189.3
AIC	4400.6
BIC	4494.7
Overdispersion (θ)	1.707
Number of Observations	38492
Root Mean Square Error (RMSE)	0.115
Mean Absolute Error (MAE)	0.024
R-squared (Pseudo)	0.226

Table 50. Potential outcomes model on matched data for fatal plus injury head-on and opposite direction sideswipe crash frequency

Variable	**Coefficient**	**Std. Error**	**p-value**
Constant	-14.584	0.555	<0.001
Natural logarithm of AADT	1.408	0.07	<0.001
Natural logarithm of segment length in miles	1.141	0.137	<0.001
Indicator for presence of conventional CLRS (Ref. = No CLRS)	-0.241	0.132	0.068
Indicator for presence of sinusoidal CLRS (Ref. = No CLRS)	-0.544	0.28	0.052

Model diagnostics:

Statistic	Value
Log Likelihood	-1304
AIC	2620.1
BIC	2671.4
Overdispersion (θ)	36.815
Number of Observations	38492
Root Mean Square Error (RMSE)	0.082
Mean Absolute Error (MAE)	0.013
R-squared (Pseudo)	0.195

Table 51. Potential outcomes model on matched data for total single-vehicle run-off-road crash frequency

Variable	Coefficient	Std. Error	p-value
Constant	-6.746	0.156	<0.001
Natural logarithm of AADT	0.922	0.017	<0.001
Natural logarithm of segment length in miles	0.947	0.033	<0.001
Indicator for average gradient higher than 1% (1 if true, 0 otherwise)	0.198	0.039	<0.001
Degree of curvature per mile	0.011	0.001	<0.001
Indicator for presence of curve with radius of 1000 ft or less (1 if true, 0 otherwise)	0.477	0.063	<0.001
Indicator for functional classification as principal arterial (1 if true, 0 otherwise)	0.051	0.034	0.134
Surface width in ft	-0.051	0.004	<0.001
Indicator for year = 2017 (Ref. year = 2016)	0.169	0.058	0.003
Indicator for year = 2018 (Ref. year = 2016)	0.116	0.058	0.045
Indicator for year = 2019 (Ref. year = 2016)	0.017	0.06	0.775
Indicator for year = 2020 (Ref. year = 2016)	0.113	0.06	0.057
Indicator for year = 2022 (Ref. year = 2016)	0.068	0.061	0.26
Indicator for year = 2023 (Ref. year = 2016)	-0.047	0.062	0.449
Indicator for year = 2024 (Ref. year = 2016)	-0.123	0.063	0.051
Indicator for presence of conventional CLRS (Ref. = No CLRS)	-0.075	0.031	0.016
Indicator for presence of sinusoidal CLRS (Ref. = No CLRS)	0.028	0.068	0.677

Model diagnostics:

Statistic	Value
Log Likelihood	-14173.9
AIC	28383.9
BIC	28537.9
Overdispersion (θ)	1.476
Number of Observations	38492
Root Mean Square Error (RMSE)	0.413
Mean Absolute Error (MAE)	0.216
R-squared (Pseudo)	0.221

Table 52. Potential outcomes model on matched data for fatal plus injury single-vehicle run-off-road crash frequency

Variable	**Coefficient**	**Std. Error**	**p-value**
Constant	-7.794	0.176	<0.001
Natural logarithm of AADT	0.73	0.025	<0.001
Natural logarithm of segment length in miles	0.959	0.053	<0.001
Indicator for degree of curvature per mile greater than 3.25 (1 if true, 0 otherwise)	0.5	0.051	<0.001
Indicator for average gradient higher than 1% (1 if true, 0 otherwise)	0.205	0.058	<0.001
Indicator for presence of reverse curve (1 if present, 0 otherwise)	0.183	0.077	0.017
Indicator for surface width greater than 30 ft (1 if present, 0 otherwise)	-0.404	0.066	<0.001
Indicator for access points per mile greater than 3 (1 if true, 0 otherwise)	0.112	0.047	0.019
Indicator for presence of conventional CLRS (Ref. = No CLRS)	-0.106	0.047	0.025
Indicator for presence of sinusoidal CLRS (Ref. = No CLRS)	-0.042	0.097	0.663

Model diagnostics:

Statistic	Value
Log Likelihood	-7316.1
AIC	14654.1
BIC	14748.2
Overdispersion (θ)	2.22
Number of Observations	38492
Root Mean Square Error (RMSE)	0.235
Mean Absolute Error (MAE)	0.096
R-squared (Pseudo)	0.132

Table 53. Potential outcomes model on matched data for total off-road left crash frequency

Variable	**Coefficient**	**Std. Error**	**p-value**
Intercept	-9.019	0.192	<0.001
Natural logarithm of AADT	0.906	0.026	<0.001
Natural logarithm of segment length in miles	1.057	0.056	<0.001
Indicator for average gradient higher than 0.95% (1 if true, 0 otherwise)	0.214	0.058	<0.001
Indicator for presence of curve with radius of 1500 ft or less (1 if true, 0 otherwise)	0.672	0.067	<0.001
Degree of curvature per mile	0.007	0.002	0.004
Indicator for surface width greater than 30 ft (1 if present, 0 otherwise)	-0.215	0.062	0.001
Indicator for posted speed limit of 55 mph or less (1 if true, 0 otherwise)	-0.163	0.08	0.043
No. of access points per mile	0.013	0.004	0.002
Indicator for presence of conventional CLRS (Ref. = No CLRS)	-0.073	0.048	0.132
Indicator for presence of sinusoidal CLRS (Ref. = No CLRS)	-0.117	0.1	0.244

Model diagnostics:

Statistic	Value
Log Likelihood	-7136.5
AIC	14297
BIC	14399.7
Overdispersion (θ)	1.321
Number of Observations	38492
Root Mean Square Error (RMSE)	0.242
Mean Absolute Error (MAE)	0.094
R-squared (Pseudo)	0.176

Table 54. Potential outcomes model on matched data for fatal plus injury off-road left crash frequency

Variable	**Coefficient**	**Std. Error**	**p-value**
Intercept	-7.476	0.347	<0.001
Natural logarithm of AADT	0.779	0.039	<0.001
Natural logarithm of segment length in miles	1.164	0.093	<0.001
Indicator for presence of curve warning sign (1 if present, 0 otherwise)	0.465	0.119	<0.001
Indicator for degree of curvature per mile greater than 4 (1 if true, 0 otherwise)	0.359	0.081	<0.001
Indicator for average gradient higher than 1% (1 if true, 0 otherwise)	0.228	0.091	0.012
Surface width in ft	-0.053	0.01	<0.001
Indicator for presence of conventional CLRS (Ref. = No CLRS)	-0.193	0.074	0.01
Indicator for presence of sinusoidal CLRS (Ref. = No CLRS)	-0.157	0.156	0.316

Model diagnostics:

Statistic	Value
Log Likelihood	-3560.8
AIC	7141.7
BIC	7227.3
Overdispersion (θ)	1.776
Number of Observations	38492
Root Mean Square Error (RMSE)	0.146
Mean Absolute Error (MAE)	0.04
R-squared (Pseudo)	0.118