DEPARTMENT OF TRANSPORTATION

Sinusoidal Rumble Strips Safety Evaluation

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16. Abstract (Limit: 250 words)

This evaluation determined the change in crash frequency, type or severity associated with longitudinal sinusoidal rumble strips on rural two-lane undivided Minnesota roadways constructed between 2018 and 2022. Crash modification factors (CMFs) were estimated using cross-sectional analysis to compare crash experience of locations with sinusoidal rumble strips (i.e., centerline only, centerline and shoulder, or shoulder only) compared to roads with rectangular rumble strips. The cross-sectional analysis matched sites with sinusoidal and rectangular rumble strips using matched-pair comparisons. Negative binomial (NB) or Poisson log-linear regression models were used to model the crashes at all treatment and non-treatment sites. There was a total of approximately 327 miles of treated (i.e., centerline only, centerline and shoulder, or shoulder only sinusoidal rumble strips) and approximately 302 miles of untreated (i.e., centerline only, centerline and shoulder, or shoulder only rectangular rumble strips) on rural two-lane divided roads. Overall, the results of the models indicated no significant differences in crash rates between rural two-lane undivided roads with sinusoidal rumble strips, and rural two-lane undivided roads with rectangular rumble strips.

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Sinusoidal Rumble Strips Safety Evaluation

Final Report

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Executive Summary

Between 2018 and 2022 in Minnesota, 3,860 crashes resulted in fatalities and serious injuries due to vehicles departing the roadway. The majority of these crashes occurred on rural roads and were often associated with driver drowsiness, distractions, or intoxication. Rumble strips can improve driver safety by providing a tactile and audible response when contacted to alert drivers who inadvertently depart from the traffic lane. Rumble strips can be placed along the outside edge of the traffic lane or along the centerline of an undivided roadway. Previous research by the Minnesota Department of Transportation (MnDOT) showed that shoulder rectangular rumble strips on rural two-lane roads reduced total crashes by 32 percent and single vehicle run-off-road (SVROR) crashes by 24 percent (https://www.dot.state.mn.us/trafficeng/safety/reportspubl.html).

In 2011, MnDOT implemented a rumble strip policy requiring new centerline and shoulder rumble strips, where sufficient shoulder was present, on rural roads with posted speed limits of 55 miles per hour or higher. The total mileage of rumble strips throughout the state has significantly increased since the original implementation of the policy.

The objective of this evaluation was to determine the safety effect of installing longitudinal sinusoidal rumble strips on Minnesota roads from 2018 to 2022. However, during the development of the analytical dataset for this study, it was noted that there was a limited number of reference sites with no rumble strips installed. As a result, the comparison shifted from a traditional cross-sectional design comparing roads with rumble strips to those without, to a study on the relative efficacy of sinusoidal rumble strips compared to rectangular rumble strips, which were recently studied.

To determine the safety effectiveness of sinusoidal rumble strips, crash modification factors (CMFs) were computed for the following rumble strip types, road types, crash types, and crash severities:

- Rumble strip types:
  - Centerline only,
  - Shoulder only, and
  - Centerline and shoulder rumble strips
- Road types:
  - Rural undivided two-lane
- Crash types:
  - Total (any type or severity)
  - Run-off-road, and
  - Head-on crashes
- Crash severities:
  - Fatal or serious injury crashes (also referred to as KA crashes)

CMFs are estimated using negative binomial and Poisson models. Where there is sufficient sample size and variation in the data, the impact of the placement of the sinusoidal rumble strip (shoulder, centerline, or both) is assessed relative to the same placement of rectangular rumble strips.

Overall, the analysis does not detect statistically significant differences in the crash rates for rural two-lane undivided roads with sinusoidal rumble strips and those with rectangular rumble strips.

Chapter 1: Background

Between 2018 and 2022 in Minnesota, 3,860 crashes resulted in fatalities and serious injuries due to vehicles departing the roadway. The majority of these crashes occurred on rural roads and were often associated with driver drowsiness, distractions, or intoxication. Rumble strips can improve driver safety by providing a tactile and audible response when contacted to alert drivers who may be inadvertently departing from the traffic lane. Rumble strips can be placed along the outside edge of the traffic lane or along the centerline of an undivided roadway. Previous research by the Minnesota Department of Transportation (MnDOT) showed that shoulder rectangular rumble strips on rural two-lane roads reduced total crashes by 32 percent and single vehicle run-off-road (SVROR) crashes by 24 percent (https://www.dot.state.mn.us/trafficeng/safety/reportspubl.html).

In 2011, MnDOT implemented a rumble strip policy requiring new centerline and shoulder rumble strips, where sufficient shoulder was present, on rural roads with posted speed limits of 55 miles per hour or higher. The total mileage of rumble strips throughout the state has significantly increased since the original implementation of the policy. In contrast to traditional rumble strips, which grind each notch into the pavement leaving edges, sinusoidal rumble strips (also known as mumble strips) use a wave pattern ground into the pavement that lessens the external noise produced when vehicles drive across them (https://www.dot.state.mn.us/trafficeng/safety/rumble/index.html).

The objective of this evaluation was to determine the safety effect of installing longitudinal sinusoidal rumble strips on Minnesota roads from 2018 to 2022. The safety effect was documented in the form of a crash modification factor (CMF). A CMF is a multiplicative factor used to specify a change in crash frequency or severity that can be associated with the treatment under consideration (i.e., rumble strips). CMFs are expressed as a decimal. A CMF less than 1.0 indicates the treatment would reduce crashes. A CMF greater than 1.0 indicates an expected increase in crashes. Subtracting the CMF from 1.0 and multiplying the result by 100 provides practitioners with an estimate of the percentage crash reduction. During the development of the analytical dataset, it was noted that that there was a limited number of reference sites with no rumble strips installed. Furthermore, on video log review of the initial control sites, a large proportion of roadways that were identified as having no rumble strips had some rumble strips (sinusoidal or rectangular) installed. As a result, the comparison shifted from a traditional cross-sectional design comparing roads with rumble strips to those without, to a study on the relative efficacy of sinusoidal rumble strips compared to rectangular rumble strips.

The null hypothesis of the models presented in this study is that there is no difference in crash rates between roads with sinusoidal rumble strips, and those with rectangular rumble strips (which are known to be effective at improving safety outcomes), and the alternative hypothesis is that sites with sinusoidal rumble strips have more or fewer crashes than roads with rectangular rumble strips.

For the purpose of this study and for determining the safety effectiveness of sinusoidal rumble strips, CMFs are computed for the following rumble strip types, road types, crash types, and crash severities:

- Rumble strip types:
    - Centerline only,
    - Shoulder only, and
    - Centerline and shoulder rumble strips
- Road types:
    - Rural undivided two-lane
- Crash types:
    - Total (any type or severity)
    - Run-off-road, and
    - Head-on crashes
- Crash severities:
    - Fatal or serious injury crashes (also referred to as KA crashes)

As a result of data limitations, crash types and severities are assessed individually, and distinctions between rumble strip types are only made for models of total and run-off-road crashes.

The research team chose the cross-sectional analysis approach with sinusoidal rumble strip treatment and reference rectangular rumble strip sites to estimate the CMFs for sinusoidal rumble strips, as information regarding the presence of rumble strips prior to first installation date for the sinusoidal rumble strips was not available. The data provided no indication on whether a rumble strip was being installed at a site that never had a rumble strip or if a pre-existing rumble strip was being updated. Therefore, traditional approaches, empirical-Bayes, and the before-after analysis, could not be applied because information for the period before a sinusoidal rumble strip was implemented could not be discerned.

This evaluation included three steps described in the following chapters:

1. Reviewing existing literature on the safety effectiveness of sinusoidal rumble strips and reviewing published CMFs from a federally maintained national database
2. Identifying data required for this evaluation and then gathering and compiling the data in a relational database
3. Performing a statistical analysis on the rumble strip and related roadway, traffic volume, and crash data, including activities to build an analytical file suitable for the statistical analysis

Chapter 2: Literature Review

A compendium of work has been done evaluating sound levels experienced both inside and outside a vehicle traversing sinusoidal rumble strips, but none has been completed evaluating safety improvements or crash modification factors (CMFs).

Montana DOT and Pennsylvania State University are collaborating on ongoing research evaluating CMFs for sinusoidal rumble strips using an Empirical Bayes observational before-after study design comparing crash frequency with the original conventional centerline rumble strips to crash frequency with the sinusoidal centerline rumble strips installed in 2021 (https://www.mdt.mt.gov/research/projects/sclrs-safety-eval.aspx). According to their study proposal, analysis results will be disaggregated by season (fall, winter, spring, summer) and roadway features (i.e., horizontal curvature), and CMFs will be developed for total crash frequency, KA crash frequency, and frequency of single vehicle run-off the road, off road left, head on, and sideswipe opposite direction crashes. Data collection for this study will be completed in 2025 and no results are currently available.

Chapter 3: Data Compilation and Database Development

Two key steps are needed for development of the relational database are shown in Figure 1. Data were inspected for inconsistencies and anomalies such as missing route identifiers and gaps in roadway attribute data (Step 1). For this study, MnDOT provided a table with the location (route and reference point) and date constructed for sinusoidal rumble strips. After the sinusoidal rumble strip locations were spatially located on the Linear Referencing System (LRS) network, the actual start and stop limits of the sinusoidal rumble strip locations were verified using the MnDOT video log system and adjustments were made to location as needed. Rectangular rumble strip sites were identified using a GIS layer provided by MnDOT. MnDOT converted a 2017 and 2018 lidar scan into a GIS file, and rectangular rumble strip sites were identified from this file and assumed to exist from 2017/18 through 2022. Step 2 involved associating roadway data from 2018 to 2022 from MnDOT's LRS to sinusoidal and rectangular sites. Finally, associated crash, traffic volume, and intersection data are related to the segments with sinusoidal rumble strips (i.e., treatment) and segments with rectangular rumble strips (i.e., reference), and compiled within a SQL server relational database. Details as to the methods, challenges, and assumptions in the database development can be found in Appendix A.

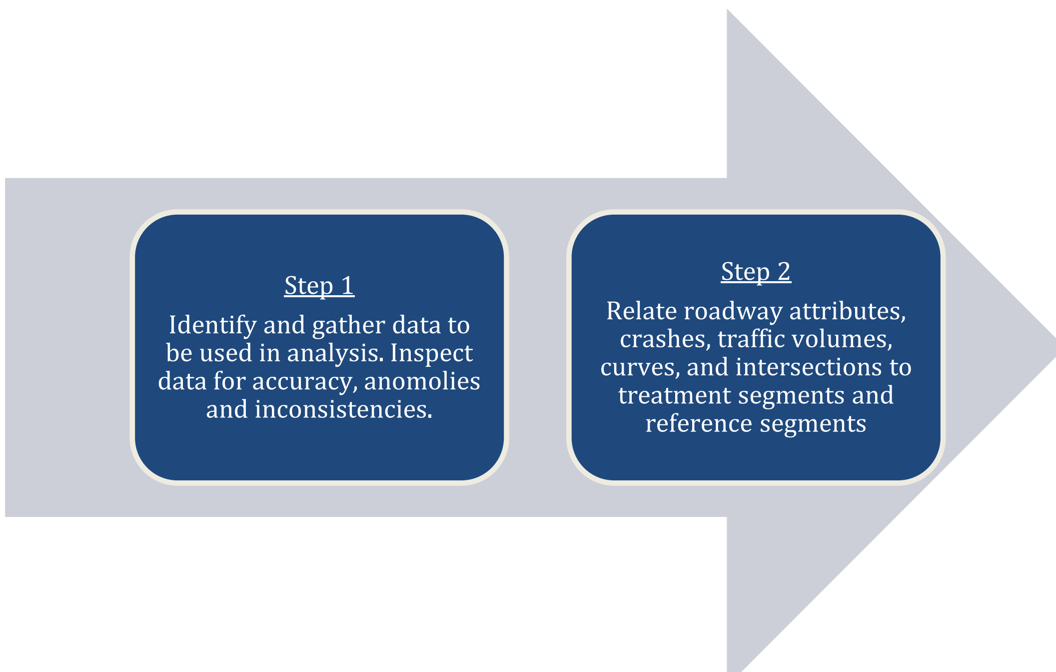

Figure 1: Database Development Approach

Chapter 4: Statistical Analysis

4.1 Method

4.1.1 Cross-sectional Analysis to Estimate Safety Performance Functions

A cross-sectional analysis compares the crash experience of locations with and without some feature (of interest) and then attributes the difference in safety to that feature. This method typically involves the estimation of multiple variable linear regression models referred to as safety performance functions (SPFs) that include sites with and without the treatment. The SPFs are mathematical equations that relate crash frequency with site characteristics. The research team applied this type of analysis to estimate the safety effectiveness of sinusoidal rumble strips relative to comparable sites with rectangular rumble strips, which have known CMFs. The estimated coefficients from the SPFs associated with the sinusoidal rumble strips relative to rectangular rumble strips can then be used to derive implied sinusoidal CMFs relative to roads without any rumble strips.

Separate SPFs were developed for each crash type and severity of interest based on crash data on all treatment and reference sites. The dependent variable used in the model specification are the crash frequencies of the crash types and severities of interest. The independent variables considered for inclusion in the models are site characteristics that can affect the outcome (crash counts), such as the type of rumble strip, rumble strip placement, vehicle miles traveled, shoulder lane presence, number of curves, the degree of curvature, the number of intersections, the posted speed, and the construction district, and the functional class of the road.

Because crashes are counts, special types of regression models often used in road safety analyses are the Poisson and negative binomial (NB) regression models. The choice of using either the Poisson or the NB regression models depends on the variability of the data. To translate the coefficients from the model into practical measures of safety (for example, CMFs), one only needs to take the exponent of the coefficients associated to the sinusoidal rumble strip variables. Where feasible, the regression models' treatment effects were differentiated by the placement of the rumble strip on the shoulder, centerline, or both locations. To estimate these effects, interaction terms were included in the model. For these models, the main effects and interactions of interest must be summed before taking the exponent.

4.1.2 Analytical Dataset

A suitable dataset of cross-sectional data, referred to as the analytical dataset, was developed for modeling. The analytical dataset is made up of crash data and site characteristics (i.e., AADT, curvature, shoulder widths, intersections, etc.) for each site over the 2018 to 2022 analysis period. Sites with sinusoidal rumble strips installed from 2018 to 2022 and reference or control sites with rectangular rumble strips installed at some point before 2018 were included in the study. Therefore, a sinusoidal rumble strip site can have up to 4 years of crash data depending on the installation date for sinusoidal rumble strips. Rectangular rumble strips were in place in 2017 or 2018 and were assumed to remain in place through 2022. Each site-year was considered an observation in the cross-sectional study, which allowed for quantification of site variability across years.

4.1.3 Selecting Treatment and Reference Sites

The treatment sites were selected to be independent from each other. This means that the frequency of crashes from one site would not cause the frequency of crashes in another site to be more or less likely. To achieve this, the distance from each treatment site was greater than 0.5 mile. Also, any site shorter than 0.5 mile was removed from the analysis. The treatment sites were selected based on sufficient data characteristics and the availability of comparison reference sites. Figure 2 shows an illustrative example of how a treatment site was established for analysis.

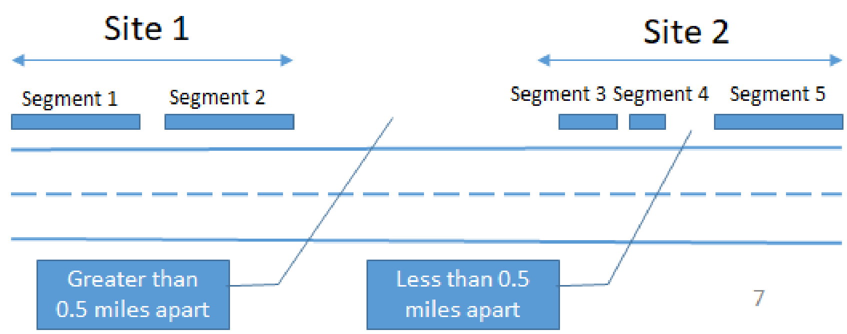

Figure 2: Illustrative Example of how Sites were Determined for Analysis

After the treatment sites were established, the data were aggregated for each treatment site and year. Adjacent segments with different roadway attributes were combined into a single site by using a weighted average calculated for each site based on the length of each segment. The roadway attributes that were weighted include the AADT, the left and right shoulder widths, surface widths, and the percentage that the shoulders were paved or unpaved.

The treatment and reference sites were then matched to produce a balanced dataset for statistical analysis. The purpose of matching is to avoid introducing bias to the estimates of the impact of sinusoidal rumble strips that may result from imbalances on road characteristics. Using the analytical dataset, treatment and reference sites were collapsed across to a site-level dataset that included characteristics considered for matching (AADT across all years, site length, the proportion of the site in a municipal boundary, the number of curves and intersections, the construction district of the site, the traveling surface width, the functional class, and the placement of the rumble strip). For variables where values differ across years, the average across all years or the initial value were used as appropriate. For example, sites were matched based on average AADT across all years, whereas the construction district was determined based on the first value observed for the site.

The data were matched using optimal pair matching based on road characteristics. The matching implementation required exact matches on the placement of the rumble strips and the functional class of the road. This means that within all possible matches (based on sites with the same functional class and presence of a shoulder or centerline rumble strip), the best matches were selected based on the similarity of relevant characteristics. Prior to matching, continuous variables were standardized, and the variables that determine exposure (site length and AADT) were given additional weight. Pairs of sites were selected such that their characteristics are similar except that one site in the pair is a treatment site (with sinusoidal rumble strips) and the other is a reference site (with rectangular rumble strips). Details as to how reference sites were matched to treatment sites, as well as the effectiveness of the matching are available in Appendix B. Next, the dataset was filtered such that only years after the sinusoidal rumble strip was installed were included for both the treatment sites and their matched control sites. That is, if a treatment site had a sinusoidal rumble strip installed in 2020, both that site and the matched reference were filtered to only include data from 2021 and 2022. The finalized analytical dataset includes only these matched site-years. Table 1 displays the variables in the analytical file used for analysis. A summary of the information contained in the analytical file is provided in the descriptive statistics section.

Table 1: Analytical File Variables

Variable Type	Variables
Unit of Analysis	Site ID; route number; construction district; roadway type (rural two-lane undivided, rural four-lane divided); installation year (2018 – 2022)
Treatment type indicators	Sinusoidal centerline rumble strip; sinusoidal shoulder rumble strip; sinusoidal centerline and shoulder rumble strip; rectangular centerline rumble strip; rectangular shoulder rumble strip; rectangular centerline and shoulder rumble strip
Year	Year (2018 – 2022)
AADT	AADT
Location Reference Variables	Length; beginning mile post; ending mile post
Crash Totals	Total; Total KA; Total Run-off-Road; Total Head-On
Roadway attribute	Right/Left paved shoulder width; right/left unpaved shoulder width; surface width; percentage of right/left paved shoulder; percentage of right/left unpaved shoulder
Curves	Number of curves; degree of curvature

Intersection	Number of intersections; intersection type (four-way, four-way and three-way, roundabout, three-way); lighting (no, unknown, yes); lighting system (CRSP, DSP, TAMS); percentage of intersection types, percentage of lighting, percentage of lighting system

Notes: AADT = Annual average daily traffic
CRSP = County Road Safety Plan
DSP = District Safety Plan
HOSSOD = Head-on/sideswipe-opposite-direction
KA = Fatal or serious injury crashes
SVROR = Single vehicle run-off-the-road
TAMS = Transportation Asset Management System

4.1.4 SPF Development

NB or Poisson log-linear regression models were used, where appropriate, to model the crash counts of all treatment and nontreatment sites. SPFs based on these models were developed for the crash types and severities of interest. Poisson models were estimated for head-on and KA crashes in a subset of the analytical dataset in which both treatment and reference sites had rumble strips on the centerline and the shoulder. This adjustment was made due to non-convergence in the NB models, and when using Poisson models in the full data. The non-convergence is a result of sparse crash counts for these categories, and preliminary data analysis revealed that KA crashes were more likely to occur on roads with both shoulder and centerline rumble strips.

In the NB models, interaction terms were included in the models for placement of the rumble strip (shoulder or centerline) in order to refine the comparison between treatment and reference sites (such that, for example, shoulder only sinusoidal sites were not compared to centerline only rectangular sites). The use of interaction terms also allowed treatment effects to be recovered for specific placements of the rumble strips (shoulder, centerline, or both).

For the Poisson models, only a main treatment effect was estimated. This is because the indicator variables for the placement of the rumble strips (centerline or shoulder) are the same across all observations when the data is restricted to only sites with rumble strips on both the centerline and the shoulder.

All the independent variables of interest included in the analytical dataset were incorporated in the models to determine the best possible SPFs for estimating the effectiveness of the various sinusoidal rumble strip types on crash rates. Only the independent variables that were found to be statistically significant were included in the final models with the rumble strip treatment indicators and interaction terms.

The following independent variables were found to be statistically significant from the various models that were developed:

- Construction district,
- Functional class,
- Average angle of curves on site,
- Presence of a paved shoulder on the right side,
- Number of intersections

To avoid over-fitting the models with too many independent variables, the Akaike information criterion (AIC), was used. The smaller the AIC, the better the model fit. The AICs of the different models, including different combinations of independent variables were compared. The independent variables were selected based on the model with the smallest AIC and the significance level of the independent characteristics.

Refer to the tables in Appendix C for a detailed output of the regression results for the crash type and severities of interest. These tables present the estimates of the regression coefficients, the upper and lower 95 percent confidence limits of the model estimates, the p-values, and the exponentiated coefficients.

4.2 Descriptive Statistics

Table 2 summarizes the number of observations by rumble strip type and placement in the cross-sectional analysis. In this table, "Length (mi)" refers to the total site lengths in the final year of analysis, whereas mile-years is the sum of site lengths across all years. The crash counts by severity and type examined are summarized in Table 3.

Table 2: Summary of Observations by Site Type

Rumble Strip Type	Rumble Strip Placement	Number of Sites	Length (mi)	Number of Site-Years	Mile-Years
Rectangular	Shoulder	25	84	32	264
Rectangular	Centerline	6	14	16	40
Rectangular	Both	11	204	69	594
Rectangular	**Total**	**42**	**302**	**117**	**899**
Sinusoidal	Shoulder	25	90	32	270
Sinusoidal	Centerline	6	25	16	68
Sinusoidal	Both	11	211	69	609
Sinusoidal	**Total**	**42**	**327**	**117**	**946**
Total		**84**	**629**	**234**	**1,845**

Table 3: Crash Counts by Site Type

Rumble Strip Type	Rumble Strip Placement	Total Crashes	Run-off-Road Crashes	Head-on Crashes	Fatal and Serious Injury Crashes
Rectangular	Shoulder	36	21	1	1
Rectangular	Centerline	14	8	1	1
Rectangular	Both	235	105	16	20
Rectangular	**Total**	**285**	**134**	**18**	**22**
Sinusoidal	Shoulder	55	27	7	6
Sinusoidal	Centerline	32	12	0	2
Sinusoidal	Both	288	125	25	22
Sinusoidal	**Total**	**375**	**164**	**32**	**30**
Total		**660**	**298**	**50**	**52**

4.3 Results

The estimates from the NB models (for total crashes and run-off-road crashes) and the Poisson models (for head-on and KA crashes) are reported in Appendix C.

In interpreting the CMFs, it is important to recall that the comparison is between sinusoidal rumble strips and rectangular rumble strips, rather than between sinusoidal rumble strips and no rumble strips. This means that the (insignificant) CMFs reported are for the treatment effect of changing the rumble strip on a specific placement from rectangular to sinusoidal. As a hypothetical example, if the CMF for shoulder rumble strips on run-off-road crashes (1.12) were significant, it would imply that switching from rectangular rumble strips on the shoulder to sinusoidal rumble strips on the shoulder would increase run-off-road crashes by 12%.

Additional care should be taken in interpreting the CMFs for head-on and KA crashes reported in Table 5. These CMFs were estimated from a subset of the analytical data which included only roadways with rumble strips on both the centerline and shoulder. For example, if the CMF for head-on crashes (1.46) were significant, it would imply that switching from rectangular on both sides of the road to sinusoidal on both sides of the road would result in a 46% increase in head-on crashes. However, as discussed above, given the lack of statistical significance, the CMFs reported below should not be used to make inferences about how changes in the rumble strip type would affect crashes. Rather, the main conclusion of the study is that there is no evidence of any differences in crash rates between rural two-lane undivided roads with sinusoidal rumble strips when compared to equivalent roads with rectangular rumble strips.

Table 4 and Table 5 respectively report the exponentiated coefficients from the models, which are the CMFs relative to rectangular rumble strips. Based on the results of this evaluation, calculated CMFs (relative to roads with rectangular rumble strip) were not statistically significant. This indicates that the null hypothesis of no difference between the effectiveness of rectangular and sinusoidal rumble strips at reducing crashes on rural two-lane undivided roads cannot be rejected. While the point estimates of CMFs are generally greater than one, indicating a trend towards higher crash counts on roads with sinusoidal rumble strips, the estimates are imprecise. Consequently, for coefficient of interest, the lower-bound of the 95% confidence interval is below one, while the upper-bound is above one. However, the confidence interval remains large for all coefficients estimated. For example, consider the 95% confidence interval for shoulder sinusoidal rumble strips on total crashes. The lower bound of the two coefficients estimated to produce this result implies a CMF relative to rectangular rumble strips of $e^{(-0.344\ -0.463)} = 0.44$, and the upper bound would imply a CMF of $e^{(0.957\ +0.488)} = 4.24$. This is much weaker evidence of no effect for sinusoidal CMFs than if the confidence interval implied a range of 0.94 and 1.09 with no statistical significance. Given these results, there is insufficient evidence to conclude that sinusoidal rumble strips are less (or more) effective than rectangular rumble strips.

In interpreting the CMFs, it is important to recall that the comparison is between sinusoidal rumble strips and rectangular rumble strips, rather than between sinusoidal rumble strips and no rumble strips. This means that the (insignificant) CMFs reported are for the treatment effect of changing the rumble strip on a specific placement from rectangular to sinusoidal. As a hypothetical example, if the CMF for shoulder rumble strips on run-off-road crashes (1.12) were significant, it would imply that switching from rectangular rumble strips on the shoulder to sinusoidal rumble strips on the shoulder would increase run-off-road crashes by 12%.

Additional care should be taken in interpreting the CMFs for head-on and KA crashes reported in Table 5. These CMFs were estimated from a subset of the analytical data which included only roadways with rumble strips on both the centerline and shoulder. For example, if the CMF for head-on crashes (1.46) were significant, it would imply that switching from rectangular on both sides of the road to sinusoidal on both sides of the road would result in a 46% increase in head-on crashes. However, as discussed above, given the lack of statistical significance, the CMFs reported below should not be used to make inferences about how changes in the rumble strip type would affect crashes. Rather, the main conclusion of the study is that there is no evidence of any differences in crash rates between rural two-lane undivided roads with sinusoidal rumble strips when compared to equivalent roads with rectangular rumble strips.

Table 4: Sinusoidal Rumble Strip CMFs, Total and Run-off-Road Crashes (by Rumble Strip Placement)

Rumble Strip Placement	Crash Type	CMF (Relative to Rectangular)	Significance Level
Shoulder	Total (All Crashes)	1.37	Not statistically significant
Centerline	Total (All Crashes)	1.34	Not statistically significant
Both	Total (All Crashes)	1.36	Not statistically significant
Shoulder	Run-off-Road Crashes	1.19	Not statistically significant
Centerline	Run-off-Road Crashes	0.84	Not statistically significant
Both	Run-off-Road Crashes	1.37	Not statistically significant

Table 5: Sinusoidal Rumble Strip CMFs for Head-on and KA Crashes (Any Placement)

Rumble Strip Placement	Crash Type	CMF (Relative to Rectangular)	Significance Level
Any	Head-on Crashes	1.46	Not statistically significant
Any	KA Crashes	1.38	Not statistically significant

Chapter 5: Conclusions

The analysis of rural two-lane undivided roadways does not find evidence that roads with sinusoidal rumble strips have more (or fewer) crashes relative to comparable roadways with rectangular rumble strips. This should not be interpreted as strong evidence that there is no difference between sinusoidal and rectangular rumble strips in terms of crash prevention. Although the sample size exceeds the CMF Clearinghouse guidelines for miles/sites and crashes observed, the CMFs are estimated with low precision (https://www.cmfclearinghouse.org/sqr.php). Overall, the point estimates of the treatment effects range from a 16% decrease in run-off-road crashes for sinusoidal centerline rumble strips to a 46% increase in head-on crashes, although no effect can reject the null hypothesis of no difference from rectangular rumble strips at any reasonable confidence level. In summary, the study provides no evidence that sinusoidal rumble strips are better or worse at preventing crashes than rectangular rumble strips. Further research is needed to understand the impact of sinusoidal rumble strips on road safety, as well as the relative performance of sinusoidal rumble strips to rectangular rumble strips.

Additional research into the impact of sinusoidal rumble strips could include before-after analysis of sinusoidal rumble strips relative to either roads with no rumble strips or roads with rectangular rumble strips. Such an analysis would require the identification of the pre-treatment condition for the five years preceding the current sinusoidal rumble strip sites. A cross-sectional analysis could also be considered where crash rates on sinusoidal road segments could be compared to crash rates on comparable road segments with no rumble strips. However, another data extraction logic approach would need to be explored that could correctly confirm roads without rumble strips. Given MnDOT's 2011 rumble strip policy, which has led to extensive use of longitudinal rumble strips on state highways, an alternative is to partner with counties that have implemented or are willing to implement sinusoidal rumble strips on their paved roads. Since many counties have not used rumble strips as extensively as MnDOT, there are sufficient road segments to establish treatment and reference groups for a before-after or cross-sectional study.

The ideal analysis of sinusoidal rumble strips would involve stratified random assignment to treatment, with the installation of sinusoidal rumble strips being randomized among roads with similar risk factors or pre-treatment crash rates. However, this experimental design is costly in that it involves installing rumble strips along some roadways that already have low crash rates. Furthermore, there is a potential safety cost to any treatment plan that includes random assignment, as it requires delaying the installation of rumble strips on roadways that have high crash rates. For this reason, such an experimental design would only be appropriate for a comparison of the relative impact of sinusoidal rumble strips to other types of rumble strips (such that all roadways with high crash rates receive some sort of rumble strip).

Appendix A: Data Sources, Compilation and Database Development

A.1 Data Sources

Roadway attribute data, crash data, project data, and traffic volume data required for this evaluation are identified and gathered in accordance with the project Master Data Collection Plan.[1] The data used is statewide for the years 2018 to 2022. The data sources used in this evaluation are as follows:

- Rumble strip project data (e.g., project installation date, overall project limits)
- Rumble strip LiDAR data (e.g., location and type of rumble strips)
- Crash data (e.g., crash severity, crash type, crash date)
- Roadway attribute data (e.g., lane widths, shoulder widths)
- Traffic volume data (e.g., average number of vehicles per day, year of data collection)
- Curve data (e.g., curve radius, curve length)
- Intersection data (e.g., number of approaches, traffic control type)

Table A-1 shows a summary of the data sources and their corresponding example data, file types, years available, and geospatial referencing systems.

Table A-1. Data Sources and Descriptions

Data Source	Example Data	File Type	Years Available	Geospatial Referencing System
Roadway	Shoulder width, lane width, area type	GIS (.shp) &Text File for attributes (.txt)	2018-2022	LRS (2018-2023)
Sinusoidal Rumble Strip Projects	District, installation route, installation year	Excel (.xlsx)	2018-2022	Highway mile point
Rectangular Rumble Strip LiDAR	Location and placement of rectangular rumble strips	GIS (.shp)	2017-2018 but assumed to be constant 2018-2022	LRS
Crashes	Crash severity, crash date, crash type	Excel (.csv)	2018-2022	LRS
Traffic Volumes (AADT)	AADT, year	GIS (.shp)	2018-2022	LRS
Curves	Curve radius, length	GIS (.shp)	Assumed to be constant 2018-2022	LRS

[1] *MnDOT Master Data Collection Plan, Minnesota DOT Traffic Safety Evaluation.* MnDOT, 2019.

Data Source	Example Data	File Type	Years Available	Geospatial Referencing System
Intersections	Number of approaches, traffic control type	GIS (.shp)	2021 (Assumed to be constant for 2018-2022)	LRS

A.2 Data Preparation and Assumptions

Prior to incorporating the data into the SQL Server database, the raw data was inspected for consistency and completeness and purged of erroneous data. For instance, several bid items in the rumble strip project data lacked the necessary route identifiers and/or beginning and ending points needed for geospatial referencing and therefore were not included in the final dataset. Certain assumptions were also needed regarding the data, for instance, applying a growth rate for AADT data not available for certain years. Table A-2 shows the main steps, organized by source, to prepare the data and major assumptions made prior to importing into the database.

Table A-2. Roadway Data Preparation and Assumptions

Data Source	Preparation and Assumptions
Roadway Data	Only used attribute data in increasing route direction (i.e., "-I")
Roadway Data	Removed true zero-length segments (i.e., beginning point equal to ending point)
Roadway Data	Gaps were found in roadway attribute data. Road segments without attribute data were not included in this analysis.
Rumble Strip Project Data	Bid items with blank routes and/or blank beginning and end points removed
Rumble Strip LiDAR Data	Shoulder rumble strips were always assumed to be on both sides of the road. After checking visually in GIS and reading the MnDOT rumble strip policy, it was assumed universally that if a road segment has shoulder rumble strips on one side of the road, the road segment has shoulder rumble strips on both sides of the road. Over long stretches of road, this assumption holds true.
Rumble Strip LiDAR Data	LiDAR linework did not originally have route references. LiDAR linework was spatially joined in SQL to the 2018 roadway network (LRS system).
Traffic Volume Data	Many segments missing AADT for certain years. Linear interpolation was used for missing values where two or more values for other years existed, otherwise applied the MnDOT standard 1.2% growth rate for missing values where only one year was available.
Traffic Volume Data	AADT GIS linework originally in LRS referencing system and spatially linked to roadway network

Data Source	Preparation and Assumptions
Curve and Intersection Data	Data only available for one year. Curves and intersections assumed to be constant throughout analysis period.

A.3 Database Development

All data were related in SQL Server using the roadway attribute data as the base using the route identifier, beginning/ending mile points, and year of installation/data collection. Traffic volume and crash data for years following rumble strip installation were linked to the treatment segments and reference segments. Data for curves and intersections were linked to the treatment segments and reference segments assumed to be constant throughout the analysis period.

Appendix B: One-to-One Match of Treatment to Reference Sites

B.1 Overview of Matching Methodology

Matching of treatment and control sites was done in R using the MatchIt package.[2] Matches were selected using optimal pair to minimize the total Euclidean distance between scaled variables of interest (with length and AADT scaled up by a factor of 5 to receive more weight in the matching algorithm). Table B-1 reports the variables and methods used in matching. Of 929 eligible control sites, 132 and were matched to 132 (of 138) eligible treatment sites, leaving 6 unmatched treatment sites due to the requirement that matches share exact rumble strip placements and functional class. Of these 132 matched sites, only those with 75% similarity between treatment and matched control in AADT and length were kept. This led to 42 pairs of treatment and control variables in the final analytical dataset.

Table B- 1. Matching Specification

Variable	Matching Method	Scale/Weight
Length	Euclidean Distance	5
AADT	Euclidean Distance	5
Percent in Municipal Boundary	Euclidean Distance	1
Travel Surface Width	Euclidean Distance	1
Posted Speed	Euclidean Distance	1
Number of Curves	Euclidean Distance	1
Number of Intersections	Euclidean Distance	1
Functional Class	Exact	-
Construction District	Euclidean Distance (Categorical)	1
Rumble Strip on Shoulder	Exact	-
Rumble Strip on Centerline	Exact	-

B.2 Matching Impact

To assess the impact of matching, the distribution of treatment and reference characteristics before and after matching were assessed. Table B-2 presents percentiles of the exposure variables (length and AADT), as well as the total crashes prior to matching for all two-lane undivided treatment and control on which complete data is available, and Table B-3 presents the corresponding values from the matched and filtered analytical datasets.

[2] *MatchIt Documentation.* Noah Greifer, 2023. https://cran.r-project.org/web/packages/MatchIt/vignettes/MatchIt.html.

Table B- 2. Distribution of Key Variables in Rural Two-Lane Undivided Roads, Pre-Matching

Group Variable/ Percentile	Treatment AADT	Reference AADT	Treatment Length	Reference Length	Treatment Crashes (annual)	Reference Crashes (annual)
5	280	380	1	0	-	-
10	493	620	1	0	-	-
25	1,072	1,200	4	1	-	-
50	1,860	2,450	7	2	1	-
75	4,054	4,542	12	5	3	1
90	6,957	8,900	16	9	8	4
95	8,528	15,300	21	12	11	6

Table B- 3. Distribution of Key Variables in Rural Two-Lane Undivided Roads, Post-Matching

Group Variable / Percentile	Treatment AADT	Reference AADT	Treatment Length	Reference Length	Treatment Crashes (annual)	Reference Crashes (annual)
5	488	460	2	2	-	-
10	797	774	3	2	-	-
25	1,257	1,212	4	4	1	1
50	1,745	1,879	7	7	3	2
75	4,101	3,951	12	11	6	5
90	7,084	6,300	15	15	11	9
95	7,777	6,852	17	16	15	10

Overall, the matching and filtering compresses the distribution of AADT in both treatment and control sites. For reference sites, the matching shifts the distribution of lengths right, whereas the treatment site length distribution is compressed. Crashes are an outcome variable and were not considered in the matching. However, by increasing the similarity of observable independent roadway characteristics in the analytical dataset, the matching procedure makes the distributions of crashes more similar between treatment and reference sites.

Appendix C: Model Regression Output

C.1 Interpreting Poisson and Negative Binomial Models

Poisson and NB models use a log link function. The log link function transforms the linear combination of predictors in a generalized linear model to ensure that the response variable's expected values remain positive.

The NB models (for total and run-off-road crashes) are in the following form:

$$E[Y] = exp(b_0 + b_1 Sinusoidal + b_2 Centerline + b_3 (Treat \times Shoulder) + b_4 (Treat \times Centerline) + \boldsymbol{X\beta} + ln(VMT))$$

Where Y is the outcome of interest, $Sinusoidal$ is an indicator for having sinusoidal (rather than rectangular) rumble strip, $Centerline$ is an indicator for having a rumble strip on the centerline, $\boldsymbol{X}$ is a vector of other covariates included, and VMT is vehicle-miles traveled. The coefficient on $ln(VMT)$ is fixed at one, allowing the outcome to be adjusted by vehicle-miles traveled (and allowing the interpretation of exponentiated coefficients in terms of crash rates.

Based on the conditional expectation function above, the CMFs of interest relative to rectangular rumble strips are recovered from:

- Shoulder sinusoidal $= e^{(b_1+b_3)}$
- Centerline sinusoidal $= e^{(b_1+b_4)}$
- Both sinusoidal $= e^{(b_1+b_3+b_4)}$

The Poisson models have the form:

$$E[Y] = exp(a_0 + a_1 Sinusoidal + \boldsymbol{X\alpha} + ln(VMT))$$

With the same variable interpretations. The exponentiated coefficient e^{a_1} is the CMF of interest, representing the impact of switching from both location placements of rectangular rumble strips to both location placements of sinusoidal rumble strips.

C.2 Regression Results

The following tables present the NB and Poisson models for the main results of the study.

Table C- 1. Total/All Crashes, Negative Binomial Model

	B	95% CI Lower Limit	95% CI Upper Limit	p-value	Exp(B)
(Intercept)	-10.1	-10.7	-9.58	<0.001	0.0000402
Sinusoidal	0.306	-0.344	0.957	0.356	1.36
Centerline	0.364	-0.0296	0.758	0.0699	1.44
Treatment x Shoulder	0.0124	-0.463	0.488	0.959	1.01
Treatment x Centerline	-0.0107	-0.517	0.495	0.967	0.989
Construction District = Willmar	-0.113	-0.371	0.144	0.389	0.893
Construction District = Detroit Lakes	-0.385	-0.672	-0.0972	0.00871	0.681
Construction District = Brainerd	-0.0619	-0.398	0.274	0.718	0.940
Construction District = Bemidji	-0.875	-2.33	0.578	0.238	0.417
Construction District = Duluth	0.0132	-0.279	0.305	0.929	1.01
# Intersections	0.130	0.0309	0.230	0.0102	1.14
Average Curvature	-0.0235	-0.0454	-0.00164	0.0351	0.977
Left Shoulder Width	-1.05	-2.49	0.381	0.150	0.348
(Negative binomial)	0.0476	0.00984	0.231		

Table C- 2. Run-off-Road Crashes, Negative Binomial Model

	B	95% CI Lower Limit	95% CI Upper Limit	p-value	Exp(B)
(Intercept)	-9.72	-10.4	-8.99	<0.001	0.0000601
Sinusoidal	-0.323	-1.48	0.838	0.586	0.724
Centerline	0.0926	-0.488	0.673	0.755	1.10
Treatment x Shoulder	0.497	-0.463	1.46	0.311	1.64
Treatment x Centerline	0.143	-0.637	0.923	0.719	1.15
Functional Class = Principal Arterial	-0.121	-0.524	0.282	0.556	0.886
Functional Class = Other	1.03	0.0965	1.96	0.0305	2.80
Construction District = Willmar	-0.0710	-0.543	0.401	0.768	0.931
Construction District = Detroit Lakes	-0.536	-1.03	-0.0438	0.0328	0.585
Construction District = Brainerd	-0.124	-0.715	0.466	0.680	0.883
Construction District = Bemidji	-0.588	-2.27	1.09	0.493	0.556
Construction District = Duluth	0.117	-0.358	0.593	0.629	1.12
Metro, Mankato, Rochester	0[a]				1.00
Average Curvature	-0.0432	-0.0782	-0.00817	0.0156	0.958
Right Shoulder Width	-0.0762	-0.135	-0.0175	0.0110	0.927
(Negative binomial)	0.301	0.139	0.652		

Table C- 3. Head-on Crashes, Poisson Model

	B	95% CI Lower Limit	95% CI Upper Limit	p-value	Exp(B)
(Intercept)	-14.3	-15.6	-12.9	<0.001	0.000000643
Sinusoidal	0.375	-0.414	1.16	0.351	1.46
Functional Class = Principal Arterial	1.34	0.463	2.22	0.00278	3.83
Construction District = Willmar	0.0527	-0.970	1.08	0.920	1.05
Construction District = Detroit Lakes	-0.0215	-1.14	1.10	0.970	0.979
Construction District = Brainerd	0.142	-1.15	1.44	0.830	1.15
Construction District = Duluth	1.63	0.375	2.88	0.0108	5.08
Average Curvature	0.124	0.0281	0.220	0.0113	1.13

Table C- 4. KA Crashes, Poisson Model

	B	95% CI Lower Limit	95% CI Upper Limit	p-value	Exp(B)
(Intercept)	-11.9	-12.5	-11.2	<0.001	0.00000708
Sinusoidal	0.323	-0.408	1.05	0.387	1.38
Construction District					
Construction District = Willmar	-0.222	-1.00	0.559	0.578	0.801
Construction District = Detroit Lakes	-1.59	-3.08	-0.0891	0.0378	0.205
Construction District = Brainerd	0.242	-0.717	1.20	0.621	1.27
Construction District = Duluth	-0.224	-1.26	0.807	0.670	0.799

Appendix D: CMF Study Estimates

D.1 CMF Estimates

The table below summarizes the CMFs relative to rectangular rumble strips estimated in this study.

Table D-1. CMF Summary

Rumble Strip Placement	Crash Type	CMF (Relative to Rectangular)	Significance Level
Shoulder	Total (All Crashes)	1.37	Not statistically significant
Centerline	Total (All Crashes)	1.34	Not statistically significant
Both	Total (All Crashes)	1.36	Not statistically significant
Shoulder	Run-off-Road Crashes	1.19	Not statistically significant
Centerline	Run-off-Road Crashes	0.84	Not statistically significant
Both	Run-off-Road Crashes	1.37	Not statistically significant
Any	Head-on Crashes	1.46	Not statistically significant
Any	KA Crashes	1.38	Not statistically significant