DEPARTMENT OF TRANSPORTATION

Rectangular Rumble Strip Safety Evaluation

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HDR

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16. Abstract (Limit: 250 words)

This evaluation determined the change in crash frequency, type or severity associated with longitudinal rectangular rumble strips on rural two-lane undivided and rural four-lane divided Minnesota roadways constructed between 2012 and 2018. Crash Modification Factors (CMFs) were estimated using cross-sectional analysis to compare crash experience of locations with (i.e., centerline only, centerline + shoulder, or shoulder only) and without rectangular rumble strips. The cross-sectional analysis matched sites with and without 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 1,200 miles of treated (i.e., centerline only, centerline + shoulder, or shoulder only) and untreated sites on rural two-lane roads and approximately 35 miles of treated (i.e., shoulder rumble strips) and untreated sites on rural four-lane divided roads. On rural two-lane undivided roads, the CMF for centerline + shoulder rumble strips was 0.73 for all crashes; shoulder only rumble strips had a CMF of 0.68 for all crashes. For single vehicle run-off-the-road crashes on rural two-lane highways, the CMF for rumble strips on the centerline + shoulder was 0.68; the CMF for shoulder only rumble strips was 0.76. The CMF for head-on, or opposite direction sideswipe crashes on rural two-lane roads with centerline and shoulder rumble strips was 0.64. On rural four-lane divided roads, the CMF for shoulder rumble strips for all crashes was 0.66 and 0.40 for single vehicle run-off-the-road crashes.

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RECTANGULAR RUMBLE STRIP SAFETY EVALUATION

FINAL REPORT

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ACRONYMS AND ABBREVIATIONS

Acronym	Meaning
AADT	annual average daily traffic
AIC	Akaike information criterion
CMF	Crash Modification Factor
CRSP	County Road Safety Plan
DSP	District Safety Plan
FHWA	Federal Highway Administration
GIS	Geographic information system
HOSSOD	head-on/sideswipe-opposite-direction
KA	fatal or serious injury crashes
LRS	Linear Referencing System
MnDOT	Minnesota Department of Transportation
MVMT	Million Vehicle Miles Travelled
NB	negative binomial
NCHRP	National Cooperative Highway Research Program
SPF	safety performance functions
SVROR	single vehicle run-off-the-road
TAMS	Transportation Asset Management System
TIS	Transportation Information System
TOT	total

EXECUTIVE SUMMARY

Between 2008 and 2012 in Minnesota, 1,850 crashes resulted in fatalities and serious injuries due to vehicles departing from 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 may be placed along the outside edge of the traffic lane or along the centerline of an undivided roadway.

In 2011, MnDOT implemented a rumble strip policy requiring new centerline and shoulder rumble strips, where sufficient shoulder is present, on rural roads with posted speed limits of 55 miles per hour or higher. The objective of this evaluation was to determine the safety effect of rumble strips on Minnesota roads from 2012 to 2018. Specifically, Crash Modification Factors (CMFs) based on Minnesota only data were estimated for rectangular rumble strips as follows:

- Rumble strip types:
  - centerline only,
  - shoulder only, and
  - centerline + shoulder rumble strips
- Road types:
  - rural undivided two-lane, and
  - rural divided four-lane segments
- Crash types:
  - single vehicle run-off-the-road (SVROR), and
  - head-on/sideswipe-opposite-direction (HOSSOD) crashes
- Crash severities:
  - total (TOT), and
  - fatal or serious injury crashes (also referred to as KA crashes)

Pedestrian and bicyclist crashes were also investigated; however, there was an insufficient number of crash observations on which to conduct a statistical evaluation.

Where a sufficient sample size was available, CMFs were estimated using a cross-sectional analysis, matching sites with and without 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 1,200 miles of treated (i.e., centerline only, centerline + shoulder, or shoulder only) and untreated sites on rural two-lane roads and approximately 35 miles of treated (i.e., shoulder rumble strips) and untreated sites on rural four-lane divided roads.

The results show that, in general, shoulder rectangular rumble strips reduce crashes for both two-lane undivided and four-lane divided rural roadways. Shoulder rumble strips appear to be especially effective on rural four-lane roadways, particularly for SVROR crash types. Specifically:

- Rural two-lane roads with shoulder rectangular rumble strips have:
  - 32 percent fewer TOT crashes than comparable facilities without rectangular rumble strips; and

    - 24 percent fewer SVROR crashes than comparable facilities without rectangular rumble strips.
- Rural two-lane undivided roadways with centerline and shoulder rectangular rumble strips have on average:
    - 27 percent fewer TOT crashes than comparable facilities without rectangular rumble strips;
    - 32 percent fewer SVROR crashes than comparable facilities without rumble strips; and
    - 36 percent fewer HOSSOD crashes than comparable facilities without rumble strips.
- Rural four-lane divided roadways with shoulder rectangular rumble strips have, on average,
    - 34 percent fewer TOT crashes than comparable facilities without rumble strips; and
    - 60 percent fewer SVROR crashes than comparable facilities without rumble strips.

Future research on rectangular rumble strips should focus on identifying the means to confirm type (i.e., rectangular or sinusoidal), dates and exact locations (e.g., route identifier, beginning and end points, etc.) of when and where rumble strips are first installed on a roadway segment. With clarity as to when the effect of rumble strips can start to be measured, the size of the pool of eligible treatment sites that could be evaluated in the future will increase substantially.

CHAPTER 1: BACKGROUND

Between 2008 and 2012 in Minnesota, 1,850 crashes resulted in fatalities and serious injuries due to vehicles departing from the roadway.[1] The majority of these crashes occurred on rural roads and were often associated with driver drowsiness, distractions, or intoxication.[2] 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 may 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) shows that centerline rumble strips on rural two-lane roads reduced total crashes by 9 percent and head-on/sideswipe-opposite-direction (HOSSOD) crashes by 39 percent.

In 2011, MnDOT implemented a rumble strip policy requiring new centerline and shoulder rumble strips, where sufficient shoulder is 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 is to determine the safety effect of installing longitudinal rectangular rumble strips on Minnesota roads from 2012 to 2018. The safety effect is 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. The safety effectiveness of sinusoidal rumble strips was initially evaluated; however, sample sizes of road segments with sinusoidal rumble strips were too small to provide reliable estimates of safety effectiveness. A summary of the statistical evaluation of sinusoidal rumble strips is in a memorandum from HDR to MnDOT, dated January 2020.

For the purpose of this study, and for determining the safety effectiveness of rectangular 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 + shoulder rumble strips
- Road types:
    - rural undivided two-lane, and
    - rural divided four-lane segments
- Crash types:
    - single vehicle run-off-the-road (SVROR), and

[1] Rumble Strips and Strips. Minnesota Department of Transportation. 2020. https://www.dot.state.mn.us/trafficeng/safety/rumble/index.html

[2] Ibid.

    - HOSSOD crashes
- Crash severities:
    - total (TOT), and
    - fatal or serious injury crashes (also referred to as KA crashes)[3]

Pedestrian and bicyclist crashes were also investigated; however, there were not enough crash observations on which to conduct a statistical evaluation. Appendix A: of this report tabulates counts of observed pedestrian and bicyclist crashes by rumble strip location.

HDR chose the cross-sectional analysis approach with treatment and nontreatment sites to estimate the CMFs for rectangular rumble strips as information confirming the first installation date for a rectangular rumble strip was not available. The data provided no indication on whether the 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 rectangular rumble strip was implemented could not be discerned.

This evaluation included three steps that are described in the following chapters:

1. Reviewing existing literature on the safety effectiveness of rectangular 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

[3] *Manual on Classification of Motor Vehicle Traffic Accidents*. American National Standards Institute. August 2007. https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/07D16

CHAPTER 2: LITERATURE REVIEW

HDR conducted a literature review pertaining to the safety effectiveness of longitudinal rumble strips using information from Guidance for the Design and Application of Shoulder and Centerline Rumble Strips (National Cooperative Highway Research Program [NCHRP] Report 641) and the Federal Highway Administration (FHWA) CMF Clearinghouse (accessed December 2019).[4,5] MnDOT has studied the safety effectiveness of centerline rumble strips and concluded that the rumble strips reduce crashes on rural two-lane roads by 9 percent for total crashes and 12 percent for fatal and injury crashes.[6]

NCHRP Report 641: Guidance for the Design and Application of Shoulder and Centerline Rumble Strips, included a literature review and original research about rumble strips. The literature review summarized research conducted in Minnesota, which found shoulder rumble strip on rural two-lane highways reduced:

- SVROR total crashes by 13 percent, and
- SVROR injury crashes by 18 percent.

It also showed that centerline rumble strips on rural two-lane highways reduced:

- all crashes (all types) by 42 percent, and
- fatal or serious injury crashes by 73 percent (all crash types).

The work included original research that was conducted in many states, including Minnesota. This research found that shoulder rumble strips on rural freeways reduce:

- SVROR crashes by 11 percent (all severities), and
- fatal or all injury crashes by 16 percent.

On rural two-lane roads, shoulder rumble strips reduce:

- SVROR total crashes by 15 percent and
- fatal or all injury crashes by 29 percent.

Many CMFs exist on the CMF Clearinghouse for installing rumble strips. After filtering out transverse rumble strips – which are designed to serve a different function (i.e., speed management) - CMFs applicable to angle and rear-end crashes, and only including CMFs from studies with high ratings for study design (i.e., four or five star), the Clearinghouse returned a total of 232 CMFs in the “rumble strip” search query. The CMFs have varying applications such as tangent versus horizontal sections, installing rumble strips together with wider edge line striping, and installing shoulder rumble strips at varying distances offset from edge line striping.

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[4] Crash Modification Factors Clearinghouse. Federal Highway Administration. December 2019. http://www.cmfclearinghouse.org/

[5] *Guidance for the Design and Application of Shoulder and Centerline Rumble Strips (Report 641).* National Cooperative Highway Research Program. 2009. https://www.nap.edu/download/14323#

[6] *Rumble Strips and Stripes*. Minnesota Department of Transportation. 2019. https://www.dot.state.mn.us/trafficeng/safety/rumble/index.html

The CMFs presented in Table 1 are an average of CMFs from similar applications studied in this rumble strip evaluation. Installing centerline and shoulder rumble strips together on rural two-lane undivided roads is expected to reduce total crashes by 28 percent, while shoulder rumble strips exclusively are expected to reduce fatal and all injury crashes by 26 percent.

Table 1: Published CMFs for Research on Rumble Strips on Rural Two-Lane Undivided Roads (FHWA CMF Clearinghouse)

Countermeasure Description	Number of CMFs (Total Crashes)	Average CMF (Total Crashes)	Range of CMFs (Total Crashes)	Number of CMFs (Fatal and All Injury)	Average CMF (Fatal and All Injury)	Range of CMFs (Fatal and All Injury)
Install Shoulder Rumble Strips	23	0.84	0.53-1.40	8	0.74	0.53-1.05
Install Centerline Rumble Strips	34	0.75	0.33-1.04	9	0.76	0.55-1.04
Install Centerline and Shoulder Rumble Strips	28	0.72	0.44-1.02	4	0.79	0.56-1.02

The CMFs presented in Table 2 show CMFs on rural two-lane undivided highways, similar to Table 1, but only for CMFs that included Minnesota test sites in the study sample. No CMFs were available for installing centerline and shoulder rumble strips together. Compared to all CMFs shown in Table 1, the CMFs that included Minnesota sites are relatively equivalent.

Table 2: Published CMFs for Research on Rumble Strips on Rural Two-Lane Undivided Highways (Studies Using Minnesota Site Data)

Countermeasure Description	Number of CMFs (Total Crashes)	Average CMF (Total Crashes)	Range of CMFs (Total Crashes	Number of CMFs (Fatal and All Injury)	Average CMF (Fatal and All Injury)	Range of CMFs (Fatal and All Injury)
Install Shoulder Rumble Strips	15	0.86	0.53-1.18	6	0.74	0.53-1.05
Install Centerline Rumble Strips	11	0.75	0.51-0.96	5	0.73	0.55-0.91

CHAPTER 3: DATA COMPILATION AND DATABASE DEVELOPMENT

Steps needed for development of the relational database are shown in **Error! Reference source not found.**. Data was inspected for inconsistencies and anomalies such as missing route identifiers and gaps in roadway attribute data (Step 1). Data collected prior to 2016 was geospatially referenced using MnDOT's Transportation Information System (TIS), while data collected from 2016 to date are referenced by MnDOT's new Linear Referencing System (LRS). To be relatable, data from the two systems were spatially joined using geographic information system (GIS) software (Step 2). Finally, associated roadway, crash, traffic volume, and intersection data are related to the segments with rumble strips (i.e., treatment) and segments with no rumble strip (i.e., nontreatment), 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 B:.

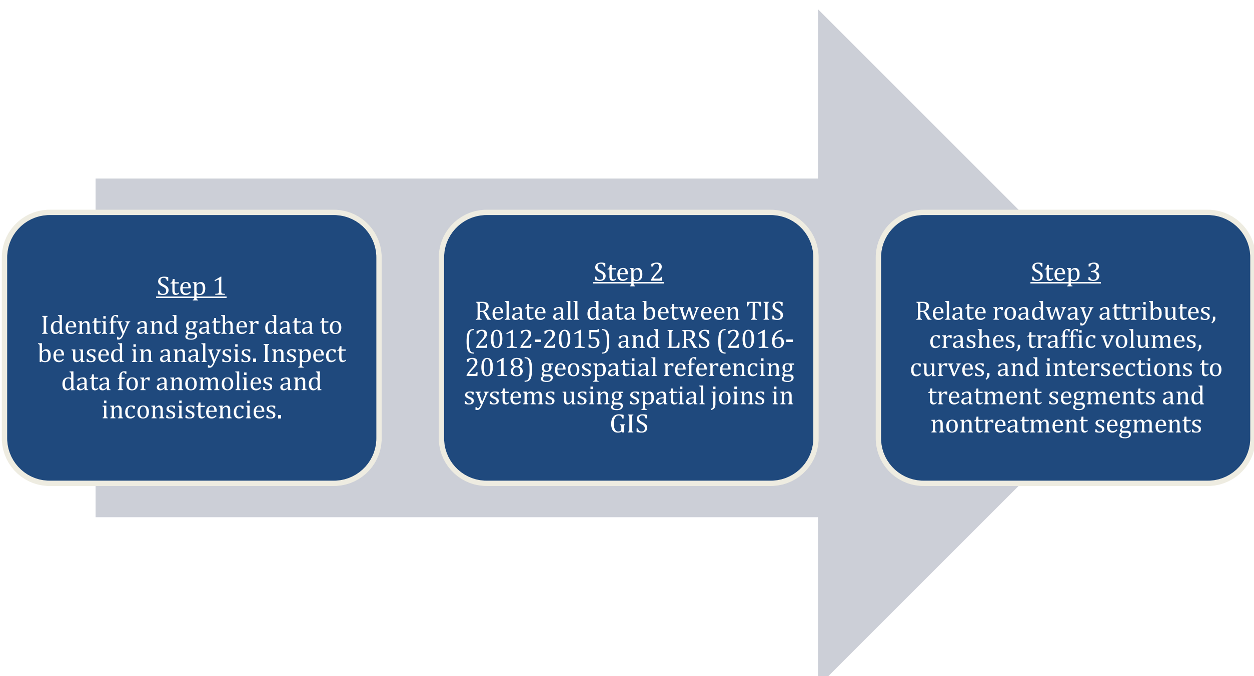

Figure 1: Database Development Approach

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. HDR applied this type of analysis to estimate the safety effectiveness of rumble strips relative to comparable sites without rumble strips. The estimated coefficients from the SPFs associated with the rectangular rumble strips can then be used to derive the CMFs.

Separate SPFs were developed for each roadway and crash type and severity of interest based on crash data on all treatment and nontreatment sites. The dependent variable used in the model specification are the crash frequencies of the crash types and severities of interest. The independent variables included in the models are site characteristics that can affect the outcome such as whether or not the site has a rumble strip installed, site length, annual average daily traffic (AADT), shoulder widths, shoulder types, lane widths, degree of curvature, number of intersections, and types of intersections.

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 rectangular rumble strip variables.

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 2012 to 2018 analysis period. Sites with rectangular-only rumble strips installed from 2012 to 2018 were included in the study. Therefore, a rectangular rumble strip site can have up to 7 years of crash data depending on the 'best-guess' installation date. Each site-year is considered an observation in the cross-sectional study, which allows for quantification of site variability across years.

The data provided included the letting dates of the rumble strip projects. It was assumed that the installations of the rumble strip projects were completed 6 months after the letting date. Information prior to the assumed completion date was not included in the analysis. Also, it could not be determined if any sinusoidal rumble strips were implemented onto the sites with rectangular rumble strips after 2016. As the potential likelihood of this occurrence is extremely low, it was assumed that no sinusoidal rumble strip improvements were done on these sites over the analysis period.

4.1.3 Selecting Treatment and Nontreatment 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 nontreatment sites. **Error! Reference source not found.** shows an illustrative example of how a treatment site was established for analysis.

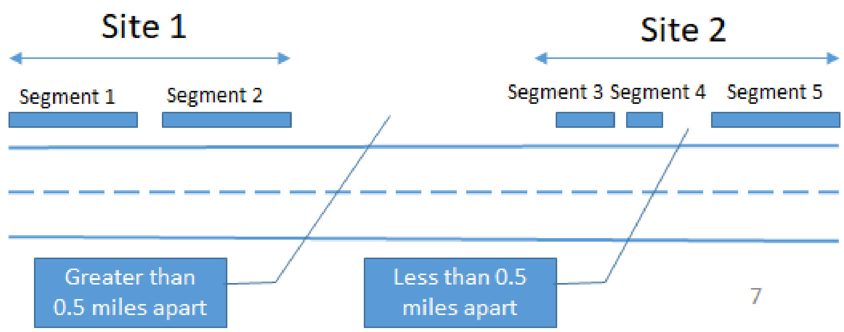

Figure 2: Illustrative Example of how Sites were Determined for Analysis

After the treatment sites were established, the data was 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, degree of curvature, the left and right shoulder widths, surface widths, the percentage that the shoulders were paved or unpaved, and the percentage of the various intersection categories present on a site.

The treatment and nontreatment sites were matched to account for unobserved variation in the data. The data were analyzed using matched-pair comparisons, which involves one-to-one matching of treatment sites to nontreatment sites. Pairs of sites were selected such that their characteristics are similar except that one site in the pair has the treatment and the other does not. The paired sites in the analytical dataset belonged to the same time period, roadway type, and construction district of Minnesota and also shared similar site length and AADT. The paired sites also shared similar roadway attributes where possible. Details as to how nontreatment sites were matched to treatment sites are in 0. The information from treatment sites and their paired nontreatment sites was combined to finalize the analytical file.

Table 3 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 3: 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 (2012 – 2018)
Treatment type indicators	No rumble strip; rectangular centerline rumble strip; rectangular shoulder rumble strip; rectangular centerline and shoulder rumble strip
Year	Year (2012 – 2018)
AADT	AADT
Location Reference Variables	Length; beginning mile post; ending mile post
Crash Totals	TOT; TOT KA; SVROR; SVROR KA; HOSSOD; HOSSOD KA
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
TOT = Total

4.1.4 SPF Development

The 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 model forms were developed for each combination of crash type, crash severity, and roadway type of interest.

The models included indicator variables to identify the effects of the various rectangular rumble strip types (e.g., centerline, shoulder, or both). All of 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 rectangular rumble strip types on crash rates. Only the independent variables that were found to be statistically significant were included in the final models.

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

- Degree of curvature
- Number of curves
- Right shoulder average width (in feet)
- Roadway average width (in feet)
- Percentage of left shoulder that is paved
- Percentage of right shoulder that is paved
- Whether or not there is an intersection
- Number of intersections
- Percentage of intersection type (four-way, three-way)
- Percentage of intersection lighting system (CRSP, DSP, TAMS)

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.

Refer to the tables in Appendix D: for a detailed output of the regression results for each combination of crash type, crash severity, and roadway type. These tables present the estimates of the regression coefficients, the upper and lower 95 percent confidence limits of the model estimates, and the p-values.

4.2 DESCRIPTIVE STATISTICS

Table 4 and Table 5 summarize the number of observations by site type in the cross-sectional analysis for rural two-lane undivided roadways and rural four-lane divided roadways, respectively. The rural four-lane divided roadways contain no centerline rumble strips.

The crash statistics for the crash severities (all and KA) on rural two-lane undivided roadways are summarized by site type in Table 6, Table 7, and Table 8 for TOT, SVROR, and HOSSOD crash types, respectively. The crash statistics for the crash severities (all and KA) on rural four-lane divided roadways are summarized by site type in

Table 9, Table 10, and Table 11 for TOT, SVROR, and HOSSOD crash types, respectively. The tables display the crash frequencies and rates. The frequency of KA crashes are generally very low across all categories. The rural four-lane divided roadway does not have sufficient crash data for HOSSOD crash types to conduct a cross-sectional analysis.

Table 4: Summary of Site Observations by Site Type for Rural Two-lane Undivided Roadways

Site Type	Number of Sites	Length (mi)	Number of Site Years	Mile-Years
No Rumble Strip	104	603.47	500	2,921.48
Rectangular-Centerline + Shoulder	44	40.88	218	1,052.37
Rectangular-Centerline	10	205.54	60	245.87
Rectangular-Shoulder	50	373.79	222	1,710.59

Site Type	Number of Sites	Length (mi)	Number of Site Years	Mile-Years
Total	**208**	**1,223.68**	**1000**	**5,930.31**

Table 5: Summary of Site Observations by Site Type for Rural Four-lane Divided Roadways

Site Type	Number of Sites	Length (mi)	Number of Site Years	Mile-Years
No Rumble Strip	7	15.87	24	73.25
Rectangular-Shoulder	7	16.94	24	78.14
Total	**14**	**32.80**	**48**	**151.39**

Table 6: Crash Statistics for All Crash Types by Site Type for Rural Two-Lane Undivided Roadways

Site Type	TOT Crash Frequency	TOT Crash Rates (per MVMT)	TOT KA Crash Frequency	TOT KA Crash Rates (per MVMT)
No Rumble Strip	1,036	0.24	42	0.01
Rectangular-Centerline + Shoulder	367	0.47	28	0.04
Rectangular-Centerline	61	1.72	3	0.08
Rectangular-Shoulder	322	0.31	23	0.02

Table 7: Crash Statistics for SVROR Crash Types by Site Type for Rural Two-Lane Undivided Roadways

Site Type	SVROR Crash Frequency	SVROR Crash Rates (per MVMT)	SVROR KA Crash Frequency	SVROR KA Crash Rates (per MVMT)
No Rumble Strip	388	0.09	18	0.00
Rectangular-Centerline + Shoulder	138	0.18	7	0.01
Rectangular-Centerline	25	0.71	1	0.03
Rectangular-Shoulder	150	0.14	7	0.01

Table 8: Crash Statistics for HOSSOD Crash Types by Site Type for Rural Two-Lane Undivided Roadways

Site Type	HOSSOD Crash Frequency	HOSSOD Crash Rates (per MVMT)	HOSSOD KA Crash Frequency	HOSSOD KA Crash Rates (per MVMT)
No Rumble Strip	70	0.02	12	0.003
Rectangular-Centerline + Shoulder	29	0.04	7	0.01
Rectangular-Centerline	5	0.14	1	0.03

Site Type	HOSSOD Crash Frequency	HOSSOD Crash Rates (per MVMT)	HOSSOD KA Crash Frequency	HOSSOD KA Crash Rates (per MVMT)
Rectangular-Shoulder	27	0.03	11	0.01

Table 9: Crash Statistics for All Crash Types by Site Type for Rural Four-Lane Divided Roadways

Site Type	TOT Crash Frequency	TOT Crash Rates (per MVMT)	TOT KA Crash Frequency	TOT KA Crash Rates (per MVMT)
No Rumble Strip	141	9.19	4	0.26
Rectangular-Shoulder	110	5.65	3	0.15

Table 10: Crash Statistics for SVROR Crash Types by Site Type for Rural Four-Lane Divided Roadways

Site Type	SVROR Crash Frequency	SVROR Crash Rates (per MVMT)	SVROR KA Crash Frequency	SVROR KA Crash Rates (per MVMT)
No Rumble Strip	80	5.21	2	0.13
Rectangular-Shoulder	63	3.24	1	0.05

Table 11: Crash Statistics for HOSSOD Crash Types by Site Type for Rural Four-Lane Divided Roadways

Site Type	HOSSOD Crash Frequency	HOSSOD Crash Rates (per MVMT)	HOSSOD KA Crash Frequency	HOSSOD KA Crash Rates (per MVMT)
No Rumble Strip	2	0.13	0	0
Rectangular-Shoulder	1	0.05	0	0

4.3 RESULTS

Based on the results of this comprehensive evaluation, calculated CMFs that showed statistically significant results with p-values of .05 or less are presented in this section. The CMFs for all crash severities of rectangular rumble strip types (centerline + shoulder, shoulder) on rural two-lane undivided roadways are displayed for the TOT, SVROR, and HOSSOD crash types in Table 12, Table 13, and Table 14, respectively. The CMFs for all crash severities of only centerline + shoulder rectangular rumble strips for HOSSOD crash types are in Table 14. The CMFs for all crash severities of shoulder rectangular rumble strips on rural four-lane divided roadways are displayed by crash type in Table 15. The tables display the average CMFs and their ranges, estimated from the models' coefficients.

No statistically significant benefits were observed for rectangular rumble strips for KA crashes regardless of roadway or crash type. It was not possible to ascertain any significant effects of this type due to the extremely low frequencies of KA crashes in the sites under study. The limited KA crash counts make it more difficult to mathematically rule out the role that random chance might have played and obtain clear, significant results.

Centerline rectangular rumble strips on rural two-lane undivided roadways had no statistically significant improvements across all crash types. Again, given previously established research on the effectiveness of centerline rumble strips, this result could be due to the small sample sizes of this treatment type compared to the sample sizes used for the other treatment types. The mile-years data for the centerline rectangular rumble strips sample is approximately 20 percent the size of the mile-years for the other rectangular rumble strip treatment types.

Appendix E: contains the CMFs (and their associated ranges) for all crashes and KA crashes by applicable rumble strip types for rural two-lane undivided roadways and rural four-lane divided roadways. Descriptions as to the level of statistical significance (from statistically significant at the 0.001 significance level to not significant) are provided for each outcome using a color coding scheme.

No HOSSOD crash type results for rural four-lane divided roadways are provided as there was no crash data for these sites.

Shoulder rectangular rumble strips on rural two-lane undivided roadways, on average, had 32 percent fewer TOT crashes (varies from 20 to 42 percent fewer). On average there were 24 percent fewer SVROR crashes with a range of 4 to 39 percent fewer. No significant effects were identified for HOSSOD crash types for shoulder rectangular rumble strips on rural two-lane undivided roadways.

Centerline and shoulder rectangular rumble strips on rural two-lane undivided roadways, on average had 27 percent fewer TOT crashes with a range of 14 to 38 percent. There were 32 and 36 percent fewer SVROR and HOSSOD crashes, respectively. The change in SVROR crashes could range from 13 to 47 percent fewer, while the difference in HOSSOD crashes can range from 1 to 60 percent fewer. The potential range in the difference of crashes for HOSSOD crashes types is greater because there are less occurrences of these events for these sites.

On rural four-lane divided roads, on average there were 34 percent fewer TOT crash types at locations with shoulder rectangular rumble strips, and on average 60 percent fewer SVROR crash types. The difference in TOT crash types can range from 5 to 55 percent, while the difference in SVROR crashes ranges from 17 to 82 percent.

In general, shoulder rectangular rumble strips reduce crashes for both two-lane undivided and four-lane divided rural roadways. Shoulder rumble strips appear to be especially effective on rural four-lane roadways, particularly for SVROR crash types. Rectangular centerline and shoulder rumble strips also reduce crashes for rural two-lane undivided roadways. Rural two-lane roadways that include both shoulder and centerline rectangular rumble strips are more effective at reducing SVROR and HOSSOD crash types than roadways that include only shoulder rectangular rumble strips.

Table 12: Rectangular Rumble Strip CMFs for Total Crashes on Rural Two-Lane Undivided Roadways

Rectangular Rumble Strip Location	Average CMF (Total Crashes)	Range of CMFs (Total Crashes)
Centerline + shoulder	0.73	0.62 - 0.86
Shoulder	0.68	0.58 - 0.80

Table 13: Rectangular Rumble Strip CMFs for SVROR Crash Types on Rural Two-Lane Undivided Roadways

Rectangular Rumble Strip Location	Average CMF (Total Crashes)	Range of CMFs (Total Crashes)
Centerline + shoulder	0.68	0.53 - 0.87
Shoulder	0.76	0.61 - 0.96

Table 14: Rectangular Rumble Strip CMFs for HOSSOD Crash Types on Rural Two-Lane Undivided Roadways

Rectangular Rumble Strip Location	Average CMF (Total Crashes)	Range of CMFs (Total Crashes)
Centerline + shoulder	0.64	0.40 – 0.99

Table 15: Rectangular Shoulder Rumble Strip CMFs by Crash Type for Rural Four-Lane Divided Roadways

Crash Type	Average CMF (Total Crashes)	Range of CMFs (Total Crashes)
All	0.66	0.45 – 0.95
SVROR	0.40	0.18 – 0.83

CHAPTER 5: SUMMARY OF FINDINGS AND RECOMMENDATIONS

HDR's analysis of rural two-lane undivided and rural four-lane divided roadways shows that roads with rectangular rumble strips have fewer crashes in total and fewer KA crashes relative to comparable roadways that do not have rectangular rumble strips.

The CMFs estimated from this study are consistent with estimates and ranges from the FHWA CMF Clearinghouse record. One example of this finding is that the average of the CMFs from the FHWA Clearinghouse for all crashes recorded on rural two-lane undivided roadways for rumble strips located on shoulder sections of the roadway is 0.84 (Table 1) and 0.86 (Table 2) when only studies that included Minnesota are analyzed. HDR's average CMF estimate for similar road segments with rumble strips on the shoulder is 0.68 with a range of 0.58 to 0.80 (Table 12)

In summary, the estimated differences in all crashes by rumble strip placement, road type, and crash type are as follows:

- Rural two-lane roads with shoulder rectangular rumble strips on average have 32 percent fewer TOT crashes
  - The average difference in SVROR crashes types is 24 percent fewer
- Rural two-lane undivided roadways with centerline and shoulder rectangular rumble strips, on average, have 27 percent fewer TOT crashes
  - The average difference in crashes for SVROR and HOSSOD crash types is 32 and 36 percent, respectively
- Rural four-lane divided roadways with shoulder rectangular rumble strips have, on average, 34 percent fewer TOT crashes
  - The average difference in SVROR crash types is higher at 60 percent.

Due to low incidences of KA crashes over the study period (2012 to 2018), estimates of CMFs for this level of crash severity were not statistically significant and imply no notable improvement of the safety effectiveness of rectangular rumble strips. In addition, estimates of CMFs for only centerline sections of rural two-lane undivided roadways were not statistically significant. HDR believes this particular outcome was probably related to the lower mileage of centerline sections relative to total miles of other rectangular rumble strips over the study period.

Results of this analysis reaffirm the safety effectiveness of rectangular rumble strips from the perspective of reducing all crashes for rural two-lane undivided roadways and for rural four-lane divided roadways.

Future research on rectangular rumble strips should focus on identifying the means to confirm dates and exact locations (e.g., route identifier, beginning and end points, etc.) of when and where rumble strips are first installed on a roadway segment. It is important to have larger sample sizes to fairly assess the effectiveness of road safety treatments. With clarity as to when the effect of rumble strips can start to be measured, the size of the pool of eligible treatment sites that could be evaluated in the future will increase substantially.

APPENDIX A: TOTAL PEDESTRIAN AND BICYCLIST CRASHES ON RUMBLE STRIP TREATMENT SITES, 2012-2018

Pedestrian and bicyclist related crashes from 2012 to 2018 on the rumble strip segments from the primary data are shown in Table A-1 and Table A-2. Due to the low crash frequency, a cross-sectional statistics analysis would not have been appropriate for understanding accurately, the impacts which these countermeasures may have had on bicycle and pedestrian safety.

Table A-1. Total Pedestrian Crashes on Rumble Strip Treatment Sites, 2012-2018

Road Type	Centerline Rumble Strips Only	Shoulder Rumble Strips Only	Centerline and Shoulder Rumble Strips
Rural undivided two-lane	2	1	3
Rural divided four-lane	0	6	0

Table A-2. Total Bicyclist Crashes on Rumble Strip Treatment Sites, 2012-2018

Road Type	Centerline Rumble Strips Only	Shoulder Rumble Strips Only	Centerline and Shoulder Rumble Strips
Rural undivided two-lane	0	0	1
Rural divided four-lane	0	0	0

APPENDIX B: DATA SOURCES, COMPILATION AND DATABASE DEVELOPMENT

B.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.[7] The data used is statewide for the years 2012 to 2018. 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 B-1 shows a summary of the data sources and their corresponding example data, file types, years available, and geospatial referencing systems.

Table B-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)	2012-2014 & 2016-2018	TIS (2009-2014) & LRS (2016-2018)
Rumble Strip Projects	State project number, bid item, installation route	Excel (.xlsx)	2012-2018	TIS
Rumble Strip LiDAR	Location of rumble strips	Excel (.xlsx)	2017-2018	Latitude/Longitude
Crashes	Crash severity, crash date	GIS (.shp)	2012-2018	LRS
Traffic Volumes (AADT)	AADT, year	GIS (.shp) & Excel for 2012-2017 (.xlsx)	2012-2018	LRS
Curves	Curve radius, length	GIS (.shp)	Assumed to be constant 2012-2018	TIS
Intersections	Number of approaches, traffic control type	GIS (.shp)	2014 (Assumed to be constant for 2012-2018)	TIS

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

B.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 B-2 shows the main steps, organized by source, to prepare the data and major assumptions made prior to importing into the database.

Table B-2. Roadway Data Preparation and Assumptions

Data Source	Preparation and Assumptions
Roadway Data	No data available for 2015. Data from 2014 used for 2015.
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) in: 2012 roadway data (297 segments) 2013 roadway data (376,690 segments) 2014 roadway data (376,690 segments)
Roadway Data	Gaps were found in roadway attribute data. For instance, on route ID 300000060, no attribute data exists from milepost 77.901 and 85.543. 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 (110 bid items)
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 GIS to the 2012 roadway network (TIS system). Where there are divided highways, route reference points vary slightly (due to slightly different lengths on each side of the highway) and the GIS output had a few overlapping segments. This overlap was purged in Excel.
Crash Data	51 crashes removed from data due to location on non-trafficway segments (e.g. parking lot crashes) (see email correspondence from Eric DeVoe, 7/22/2019)
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.

Data Source	Preparation and Assumptions
Traffic Volume Data	AADT GIS linework originally in LRS referencing system and spatially linked to 2012 roadway network to get data in TIS system. Where there are divided highways, route reference points vary slightly (due to slightly different lengths on each side of the highway) and the GIS output had a few overlapping segments. This overlap was purged in Excel.
Curve and Intersection Data	Data only available for one year. Curves and intersections assumed to be constant throughout analysis period.

B.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 nontreatment segments. Data for curves and intersections were linked to the treatment segments and nontreatment segments assumed to be constant throughout the analysis period.

Finally, subsequent installations of different types of rumble strips on treatment segments were tracked. For instance, several shoulder only rumble strip segments in 2012 had centerline rumble strips installed within the same segment in later years. These later centerline rumble strip installations were related as control variables from the year of installation to the end of the analysis period.

APPENDIX C: ONE-TO-ONE MATCH OF TREATMENT TO NONTREATMENT SITES

The matching procedure involved two stages resulting in a one-to-one match of treatment sites to nontreatment sites. The first stage matches the treatment site to multiple nontreatment sites. The second stage selects one nontreatment site for each treatment.

In the first stage of the matching procedure, the nontreatment sites were matched to the treatment sites by site length, AADT, roadway type, construction district, and time period. If the ratios between the two sites for the AADT and length were greater than 0.85, then it was considered a match. The roadway segments with no rumble strips from the primary data were used to produce nontreatment sites. The rule for creating nontreatment sites was similar to that of creating treatment sites. That is, the adjacent segments are less than 0.5 mile apart and belong to the same route, road type, and construction district. Every possible permutation of continuous roadway segments was generated and compared to each treatment site. If the above criteria were met, then the permutation of roadways segments was considered a nontreatment site that matched the treatment site. The treatment sites were therefore matched to multiple sets of nontreatment sites.

In the second stage of the matching procedure, the data for all matched nontreatment sites were aggregated by site and year in the same manner as the treatment sites. The similarity of the other site characteristics (e.g., roadway attributes, curves, and intersections) were accessed between the nontreatment and treatment sites using ratios. Each nontreatment site within each comparison group was ranked based on the ratio. The closer the ratio was to 1, the greater the rank. The nontreatment site with the highest rank was selected for each comparison group. If the selected nontreatment site overlapped with a nontreatment site in another comparison group that had a better rank, then the next ranked nontreatment site was selected in that group. This verified that no sites overlapped with one another to avoid double counting in the data. Not every treatment site could be matched to a nontreatment site and were removed from the analysis. The treatment sites that remained were paired to exactly one nontreatment site.

APPENDIX D: MODEL REGRESSION OUTPUT

In Table D-1 through Table D-10, the symbols in the significance column have the following definitions:

*** = Statistically Significant at 0.001 level of significance

** = Statistically Significant at 0.01 level of significance

* = Statistically Significant at 0.05 level of significance

. = Statistically Significant at 0.1 level of significance

blank = not significant

Table D-1: Negative Binomial Model Output for TOT Crashes on Rural Two-Lane Undivided Roadways

Independent Variables	Coefficient	Lower CL	Upper CL	p-value	Sig.
(Intercept)	-8.2	-8.7	-7.8	<0.001	***
Rectangular Rumble Strip - Centerline	-0.082	-0.4	0.22	0.6	
Rectangular Rumble Strip - Centerline + Shoulder	-0.31	-0.48	-0.15	<0.001	***
Rectangular Rumble Strip - Shoulder	-0.38	-0.54	-0.22	<0.001	***
Curvature	0.024	-0.0023	0.049	0.06	.
Average of right shoulder width (ft.)	-0.023	-0.045	-0.00094	0.04	*
Includes Intersection(s)	-3.6	-7.1	-0.45	0.04	*
IntersectionType=Four-way (%)	3	-0.2	6.5	0.09	.
IntersectionType=Four-way, Three-way (%)	4.9	1.4	8.7	0.009	**
IntersectionType=Three-way (%)	3.4	0.26	6.9	0.05	*
offset(log(Vehicle Miles Travelled))	1				

Table D-2: Poisson Model Output for TOT KA Crashes on Rural Two-Lane Undivided Roadways

Independent Variables	Coefficient	Lower CL	Upper CL	p-value	Sig.
(Intercept)	-12	-13	-11	<0.001	***
Rectangular Rumble Strip - Centerline	0.17	-1.3	1.2	0.8	
Rectangular Rumble Strip - Centerline + Shoulder	0.23	-0.28	0.72	0.4	
Rectangular Rumble Strip - Shoulder	0.2	-0.33	0.71	0.4	
Curvature	0.049	-0.035	0.11	0.2	
Average of right shoulder width (ft.)	0.012	-0.06	0.086	0.8	
offset(log(Vehicle Miles Travelled))	1				

Table D-3: Negative Binomial Model Output for SVROR Crashes on Rural Two-Lane Undivided Roadways

Independent Variables	Coefficient	Lower CL	Upper CL	p-value	Sig.
(Intercept)	-7.4	-8.2	-6.6	<0.001	***
Rectangular Rumble Strip - Centerline	-0.14	-0.62	0.3	0.6	
Rectangular Rumble Strip - Centerline + Shoulder	-0.39	-0.64	-0.14	0.003	**
Rectangular Rumble Strip - Shoulder	-0.27	-0.5	-0.037	0.03	*
Average Roadway width (ft.)	-0.051	-0.068	-0.034	<0.001	***
Intersection LightingSystem=CRSP (%)	-0.54	-1.1	0.02	0.07	.
Intersection LightingSystem=CRSP, DSP (%)	-0.6	-19	14	0.9	
Intersection LightingSystem=DSP (%)	3.1	0.026	6.1	0.05	*
Intersection LightingSystem=TAMS (%)	-1.1	-2.1	-0.19	0.03	*
offset(log(Vehicle Miles Travelled))	1				

Table D-4: Negative Binomial Model Output for SVROR KA Crashes on Rural Two-Lane Undivided Roadways

Independent Variables	Coefficient	Lower CL	Upper CL	p-value	Sig.
(Intercept)	-9	-11	-6.6	<0.001	***
Rectangular Rumble Strip - Centerline	-0.44	-3.3	1.2	0.7	
Rectangular Rumble Strip - Centerline + Shoulder	-0.22	-1.2	0.62	0.6	
Rectangular Rumble Strip - Shoulder	-0.39	-1.4	0.46	0.4	
Average Roadway width (ft.)	-0.11	-0.19	-0.04	0.007	**
offset(log(Vehicle Miles Travelled))	1				

Table D-5: Poisson Model Output for HOSSOD Crashes on Rural Two-Lane Undivided Roadways

Independent Variables	Coefficient	Lower CL	Upper CL	p-value	Sig.
(Intercept)	-12	-12	-11	<0.001	***
Rectangular Rumble Strip - Centerline	0.15	-0.93	1	0.8	
Rectangular Rumble Strip - Centerline + Shoulder	-0.45	-0.92	-0.0022	0.05	*
Rectangular Rumble Strip - Shoulder	-0.041	-0.52	0.42	0.9	
Right shoulder width (ft.)	0.069	0.0012	0.14	0.05	*
Number of Curves	0.054	0.021	0.086	0.001	***
Number of Intersections	-0.033	-0.057	-0.01	0.005	**
offset(log(Vehicle Miles Travelled))	1				

Table D-6: Poisson Model Output for HOSSOD KA Crashes on Rural Two-Lane Undivided Roadways

Independent Variables	Coefficient	Lower CL	Upper CL	p-value	Sig.
(Intercept)	-15	-17	-13	<0.001	***
Rectangular Rumble Strip - Centerline	0.5	-2.4	2.2	0.6	
Rectangular Rumble Strip - Centerline + Shoulder	-0.005	-1	0.91	1	
Rectangular Rumble Strip - Shoulder	0.81	-0.034	1.6	0.06	.
Average Roadway width (ft.)	0.055	-0.0065	0.11	0.07	.
offset(log(Vehicle Miles Travelled))	1				

Table D-7: Negative Binomial Model Output for TOT Crashes on Rural Four-Lane Divided Roadways

Independent Variables	Coefficient	Lower CL	Upper CL	p-value	Sig.
(Intercept)	-8	-9.1	-7	<0.001	***
Rectangular Rumble Strip - Shoulder	-0.42	-0.79	-0.049	0.05	*
Paved left shoulder (%)	0.84	0.076	1.7	0.07	.
Paved right shoulder (%)	-1.2	-2.5	0.15	0.1	
offset(log(Vehicle Miles Travelled))	1				

Table D-8: Poisson Model Output for TOT KA Crashes on Rural Four Lane Divided Roadways

Independent Variables	Coefficient	Lower CL	Upper CL	p-value	Sig.
(Intercept)	-14	-17	-11	<0.001	***
Rectangular Rumble Strip - Shoulder	0.15	-2.3	2.2	0.9	
Curvature	0.17	-0.5	0.98	0.7	
Includes Intersection(s)	1.3	-2	4.7	0.4	
offset(log(Vehicle Miles Travelled))	1				

Table D-9: Negative Binomial Model Output for SVROR Crashes on Rural Four-Lane Divided Roadways

Independent Variables	Coefficient	Lower CL	Upper CL	p-value	Sig.
(Intercept)	-8.7	-9.4	-8	<0.001	***
Rectangular Rumble Strip - Shoulder	-0.92	-1.7	-0.19	0.02	*
Curvature	0.25	0.017	0.5	0.04	*
Includes Intersection(s)	-0.87	-1.8	-0.02	0.06	.
offset(log(Vehicle Miles Travelled))	1				

Table D-10: Poisson Model Output for SVROR KA Crashes on Rural Four-Lane Divided Roadways

Independent Variables	Coefficient	Lower CL	Upper CL	p-value	Sig.
(Intercept)	-12	-16	-8.7	<0.001	***
Rectangular Rumble Strip - Shoulder	-1.9	-6.6	2.1	0.4	
Curvature	0.17	-1.1	1.7	0.8	
Includes Intersection(s)	-1.4	-7	3.4	0.6	
offset(log(Vehicle Miles Travelled))	1				

APPENDIX E: CMF STUDY ESTIMATES AND RANGES

In Table E-1 through Table E-4, the symbols in the significance column have the following definitions:

*** = Statistically Significant at 0.001 level of significance

** = Statistically Significant at 0.01 level of significance

* = Statistically Significant at 0.05 level of significance

. = Statistically Significant at 0.1 level of significance

blank = not significant

Table E-1: Rectangular Rumble Strip CMFs for All Crash Types, Total and KA Crashes on Rural Two-Lane Undivided Roadways (Statistically significant and not significant)

Rectangular Rumble Strip Location	Average CMF (Total Crashes)	Range of CMFs (Total Crashes)	Total Crash Sig.	Average CMF (KA Crashes)	Range of CMFs (KA Crashes)	KA Crash Sig.
Centerline + shoulder	0.73	0.62 - 0.86	***	1.3	0.76 - 2.1	
Centerline	0.92	0.67 - 1.2		1.2	0.27 - 3.3	
Shoulder	0.68	0.58 - 0.80	***	1.2	0.72 - 2.0	

Table E-2: Rectangular Rumble Strip CMFs for SVROR Crash Types, Total and KA Crashes on Rural Two-Lane Undivided Roadways

Rectangular Rumble Strip Location	Average CMF (Total Crashes)	Range of CMFs (Total Crashes)	Total Crash Sig.	Average CMF (KA Crashes)	Range of CMFs (KA Crashes)	KA Crash Sig.
Centerline + shoulder	0.68	0.53 - 0.87	**	0.80	(0.30 - 1.9)	
Centerline	0.87	0.54 - 1.3		0.64	0.04 - 3.3	
Shoulder	0.76	0.61 - 0.96	**	0.68	0.25 - 1.6	

Table E-3: Rectangular Rumble Strip CMFs for HOSSOD Crash Types, Total and KA Crashes on Rural Two-Lane Undivided Roadways

Rectangular Rumble Strip Location	Average CMF (Total Crashes)	Range of CMFs (Total Crashes)	Total Crash Sig.	Average CMF (KA Crashes)	Range of CMFs (KA Crashes)	KA Crash Sig.
Centerline + shoulder	0.64	0.40 – 1.0	*	1.0	0.37 - 2.5	
Centerline	1.2	0.39 - 2.8		0.96	0.59 - 1.5	
Shoulder	0.96	0.59 - 1.5		2.2	1.0 - 5.0	.

Table E-4: Rectangular Shoulder Rumble Strip CMFs by Crash Type for Total and KA Crashes for Rural Four-Lane Divided Roadways

Crash Type	Average CMF (Total Crashes)	Range of CMFs (Total Crashes)	Total Crash Sig.	Average CMF (KA Crashes)	Range of CMFs (KA Crashes)	KA Crash Sig.
All	0.66	0.45 – 0.95	*	1.2	0.10 - 9.0	
SVROR	0.40	0.18 – 0.83	*	0.15	0.0014 - 8.2	