Safety Evaluation of Sinusoidal Centerline Rumble Strips

Task 3: Develop Data Collection and Analysis Plan

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INTRODUCTION

The objective of this task is to develop a data collection and analysis plan to assess the safety performance of sinusoidal centerline rumble strips (SCLRS) that were implemented on Montana Department of Transportation (MDT) roadways during 2021. In addition, a data collection and analysis plan to evaluate the safety performance of conventional centerline rumble strips (CLRS) is also described. This document outlines the proposed plan for review by the MDT technical panel.

The remainder of this document is organized into three sections. The first provides a preliminary assessment of sites available for inclusion in this study. The second describes how the analysis database will be created to develop crash modification factors (CMFs) for SCLRS and CLRS. This includes a summary of data currently available from MDT and other sources that may be used in this project. The third section describes the analytical methodology that will be used to estimate the CMFs in the present study.

PRELIMINARY DATA ASSESSMENT

This section provides a preliminary assessment of the sites that may be considered in this study, including a summary of treatment sites (i.e., those with SCLRS and CLRS) and reference group sites (those with no rumble strips). The first subsection describes the sites that have been identified as having SCLRS. The second subsection describes sites that have conventional CLRS. The third subsection describes reference group locations that do not contain rumble strips.

Identification of SCLRS treatment sites

An inventory of sites with SCLRS was provided by MDT for the purpose of this study. This treatment group includes a total of 86 roadway segments comprising a total centerline length of 587.4 miles. The SCLRS are installed on roadway segments across two key areas: Kalispell Division and Missoula Area. In the Kalispell Division, SCLRS are installed along 48 segments consisting of a total of 372.3 miles of roadway (see Table 1 for details). In the Missoula area, SCLRS were installed on 38 segments consisting of a total of 215.1 miles of roadway (see Table 2 for details). The majority of SCLRS were installed during 2021. The lone exceptions were three segments where SCLRS were installed in 2021, along with temporary pavement markings. These three segments were re-striped with standard MDT pavement markings in 2022. A review of these sites revealed that the majority of the SCLRS installation occurs on two-lane rural roadway segments. Note also from Table 1 that two different maximum groove depths were used in the SCLRS installation in Kalispell due to contractor differences. These locations will be considered in a disaggregate analysis to determine if groove depth influences the safety performance of SCLRS.

Table 1. Details of SCLRS Treatment Sites in the Kalispell Division

Site	Route	Beginning reference mile	End reference mile	Length (miles)	Centerline repaired before installing CLRS?	Maximum depth
1	U 6734	0.0	0.5	0.5	No	1/2″
2	S 292	0.5	9.3	8.8	No	1/2″
3	US 2	15.4	29.9	14.5	No	1/2″
4	US 2	36.6	42.5	5.9	Yes	1/2″
5	US 2	42.5	48.5	6.0	No	1/2″
6	US 2	53.8	65.6	11.8	No	1/2″
7	US 2	69.0	81.0	12.0	No	1/2″
8	US 2	81.0	85.0	4.0	Yes	1/2″
9	US 2	85.0	100.0	15.0	No	1/2″
10	US 2	100.0	103.0	3.0	Yes	1/2″
11	US 2	169.0	184.0	15.0	Yes	1/2″
12	US 2	184.0	189.8	5.8	No	1/2″
13**	MT 37	1.0	17.0	16.0	No	1/2″
14	MT 37	62.0	67.0	5.0	No	1/2″
15	S 260	0.0	3.5	3.5	No	1/2″
16	S 482	1.5	6.4	4.9	No	1/2″
17	MT 56	0.0	17.0	17.0	No	1/2″
18	MT 56	31.4	34.0	2.6	No	1/2″
19	MT 35	1.3	23.3	22.0	No	1/2″
20	MT 35	27.7	30.5	2.8	No	1/2″
21	MT 35	32.8	33.6	0.8	No	1/2″
22	MT 35	33.9	40.3	6.4	No	1/2″
23	MT 83	45.8	54.0	8.2	No	1/2″
24	MT 83	54.0	60.8	6.8	No	1/2″
25	MT 83	60.8	70.4	9.6	Yes	1/2″
26	MT 83	72.5	82.5	10.0	No	1/2″
27	S209	0.0	4.9	4.9	No	1/2″
28	S 211	1.0	9.7	8.7	No	1/2″
29	S 354	1.3	12.5	11.2	No	1/2″
30	MT 28	21.2	36.2	15.0	No	1/2″
31	S 352	0.0	5.9	5.9	No	1/2″
32	US 93	61.7	93.0	31.3	No	5/8″
33	US 93	102.0	104.0	2.0	No	5/8″
34	US 93	107.5	110.0	2.5	No	5/8″
35	US 93	123.0	125.0	2.0	No	5/8″
36	US 93	134.0	143.5	9.5	No	5/8″
37	US 93	143.5	149.5	6.0	Yes	5/8″
38	US 93	149.5	158.0	8.5	No	5/8″
39	US 93	158.0	161.0	3.0	Yes	5/8″

Site	Route	Beginning reference mile	End reference mile	Length (miles)	Centerline repaired before installing CLRS?	Maximum depth
40	US 93	161.0	174.0	13.0	No	5/8″
41	US 93	180.0	186.0	6.0	No	5/8″
42	S 503	1.2	8.4	7.2	No	1/2″
43	S 503	8.4	10.5	2.1	Yes	1/2″
44	U6708	0.0	1.2	1.2	No	1/2″
45	S 424	2.1	5.4	3.3	No	1/2″
46	S 424	5.9	13.5	7.6	No	1/2″
47	S 424	13.5	15.8	2.3	Yes	1/2″
48	MT 40	3.3	4.5	1.2	No	1/2″
Total miles in Kalispell Division				**372.3**		

Table 2. Details of SCLRS Treatment Sites in Missoula Area

Site	Route	Beginning reference mile	End reference mile	Length (miles)	Centerline repaired before installing CLRS?	Maximum depth
49	MT200	23.8	29.5	5.7	No	1/2″
50	MT200	46.2	49.0	2.8	No	1/2″
51	MT200	52.0	56.9	4.9	No	1/2″
52	MT200	59.1	70.3	11.2	No	1/2″
53	MT200	72.9	74.0	1.1	No	1/2″
54	MT200	77.0	87.0	10.0	No	1/2″
55	MT200	87.0	90.0	3.0	Yes	1/2″
56	MT200	90.0	98.7	8.7	No	1/2″
57	MT135	0.0	12.9	12.9	No	1/2″
58	US93	44.1	46.0	1.9	No	1/2″
59	US93	37.4	44.1	6.7	Yes	1/2″
60	US93	33.3	37.4	4.1	No	1/2″
61	US93	29.3	32.5	3.2	No	1/2″
62	US93	27.8	29.1	1.3	No	1/2″
63	US93	22.6	26.7	4.1	No	1/2″
64	US93	18.7	22.6	3.9	No	1/2″
65	US93	6.0	17.0	11.0	No	1/2″
66	S212	8.3	17.6	9.3	No	1/2″
67	S474	0.0	3.1	3.1	No	1/2″
68	U8135	3.1	3.9	0.8	No	1/2″
69	S263	4.5	5.5	1.0	No	1/2″
70	U8123	3.5	4.5	1.0	No	1/2″
71	MT83	0.0	4.8	4.8	No	1/2″
72	MT200	32.0	52.5	20.5	No	1/2″
73	U8133	1.0	3.0	2.0	No	1/2″

Site	Route	Beginning reference mile	End reference mile	Length (miles)	Centerline repaired before installing CLRS?	Maximum depth
74	US12	16.2	30.0	13.8	No	1/2″
75	S203	10.1	12.0	1.9	No	1/2″
76	S269	1.4	12.0	10.6	No	1/2″
77	U5301	1.0	1.4	0.4	No	1/2″
78	US93	87.7	90.0	2.3	No	1/2″
79	US93	84.8	85.9	1.1	No	1/2″
80	US93	75.5	82.5	7.0	No	1/2″
81	US93	62.8	68.3	5.5	No	1/2″
82	US93	52.1	62.0	9.9	No	1/2″
83	US93	49.4	51.8	2.4	No	1/2″
84	US93	38.7	45.9	7.2	No	1/2″
85	US93	16.2	23.2	7.0	Yes	1/2″
86	US93	0.0	7.0	7.0	No	1/2″
Total miles in Missoula Area				**215.1**		

Identification of conventional CLRS treatment sites

The research team also obtained roadway inventory data from MDT that included presence of centerline rumble strip information. Based on discussions with the MDT project panel, it is anticipated that there are approximately 3,000 miles of CLRS on state-maintained roadways. The MDT staff has agreed to provide a list of CLRS locations that the Penn State research team will add to other roadway inventory data (e.g., traffic volume, pavement width, etc.) during the data collection process. These sites will be verified using Montana’s Pathweb/Pathview system.

Identification of reference group sites

Once the roadway inventory files are developed, to include locations with SRS and CLRS, those sites that do not contain any rumble strips will serve as a group of reference sites for the proposed CMF development. These sites will serve as comparison sites with which to compare the safety performance of the sites with conventional and sinusoidal centerline rumble strips. These sites will also be verified using Montana’s Pathweb/Pathview system.

DEVELOPMENT OF ANALYSIS DATABASE

The previous section identified locations with SCLRS, conventional CLRS, and no CLRS for consideration in this project. These locations will be integrated into an analysis database for estimation of CMFs in the present study.

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

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

- Corridor ID
- Starting milepost
- Ending milepost
- Segment length
- Unique segment identifier (based on corridor ID and number of the segment along the corridor)
- Year
- Centerline rumble strip type (sinusoidal, conventional, or none)
- Presence of shoulder rumble strips
- Year rumble strip was installed (if applicable)

The MDT has completed an internal project to identify sites with SRS, which are included in the geospatial files that MDT developed for the Penn State research team. In this file, there are approximately 4,800 miles of SRS. The presence of SRS will be verified using Montana's Pathweb/Pathview system, for each analysis year.

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

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

The research team will obtain the above data for the current year (2021), future years (2022 to 2024), and previous years (2018 to 2020). The annual data files will be examined to determine significant changes in the roadway network during the evaluation period. Roadway segments with significant changes will either be updated for the years that the change was made (e.g., if the posted speed limit changed) or removed if the change is significant (e.g., lane addition).

The research team will then supplement the existing information with other characteristics using MDT's Pathweb/Pathview system. When necessary, the Pathweb/Pathview images will be supplemented with Google satellite imagery. The research team will specifically obtain/verify the following features:

- Shoulder type and width: the research team will estimate shoulder type and width using imagery provided in the Pathweb/Pathview system and Google Maps.
- Horizontal alignment: the research team will identify the presence of horizontal curves on individual segments using imagery in the Pathweb system and estimate the radius and length of these curves to include in the analysis database.
- Presence of other safety influencing features: the research team will review Pathweb/Pathview imagery to identify the presence of other safety-influencing features, such as shoulder rumble strips, traffic control devices (e.g., horizontal curve warning signs, stop or signal ahead signs), presence of turn lanes along roadway segments, etc.
- Driveways: conversations with MDT revealed that driveway information in the existing GIS database may not be accurate. Thus, the team will use this as a starting point to verify the number of driveways on individual roadway segments to ensure accuracy in the database.
- Roadside hazard rating: the research team will use Pathweb/Pathview imagery to estimate the roadside hazard rating using the scale developed in Zegeer et al. (1991). In this system, a seven-point categorical scale is used to describe the potential hazards, ranging from 1 (least hazardous) to 7 (most hazardous). A detailed description of roadside design features that "map" to each of the seven RHR categories can be found in Torbic et al. (2009).

Rating = 1

- Wide clear zones greater than or equal to 9 m (30 ft) from the pavement edge line.
- Side slope flatter than 1V:4H (Vertical:Horizontal).
- Recoverable (*meaning: the driver of a vehicle that departs the roadway section should be able to recover the vehicle and steer back onto the roadway*).

Rating = 2

- Clear zone between 6 and 7.5 m (20 and 25 ft) from pavement edge line.
- Side slope about 1V:4H.
- Recoverable.

Rating = 3

- Clear zone about 3 m (10 ft) from the pavement edge line.
- Side slope about 1V:3H or 1V:4H.
- Rough roadside surface.
  Marginally recoverable.

Rating = 4

- Clear zone between 1.5 and 3 m (5 to 10 ft) from pavement edgeline.
- Side slope about 1V:3H or 1V:4H.
- May have guardrail 1.5 to 2 m [5 to 6.5 ft] from pavement edgeline.
- May have exposed trees, poles, or other objects (about 3 m or 10 ft from pavement edgeline).
- Marginally forgiving, but increased chance of a reportable roadside collision.

Rating = 5

- Clear zone between 1.5 and 3 m (5 to 10 ft) from pavement edgeline.
- Side slope about 1V:3H.
- May have guardrail 0 to 1.5 m [0 to 5 ft] from pavement edgeline.
- May have rigid obstacles/embankment within 2 to 3 m (6.5 to 10ft) of pavement edgeline.
- Virtually non-recoverable.

Rating = 6

- Clear zone less than or equal to 1.5 m (5 ft).
- Side slope about 1V:2H.
- No guardrail.
- Exposed rigid obstacles within 0 to 2 m (0 to 6.5 ft) of the pavement edgeline.
- Non-recoverable.

Rating = 7

- Clear zone less than or equal to 1.5 m (5 ft).
- Side slope 1:2 or steeper.
- Cliff or vertical rock cut.
- No guardrail.
- Non-recoverable with high likelihood of severe injuries from roadside collision.

Crash data will also be appended to the analysis database. The research team will request three years of data before and after the installation of SCLRS, as well as for reference group segments. The before period for the SCLRS sites will include the period from 2018 to 2020 (inclusive) whereas the after period will include the period from 2022 to 2024 (inclusive). Since 2021 was the construction year for the SCLRS, the research team will exclude it from the evaluation period.

Various crash frequency measures will be appended to each roadway segment in the analysis database to consider in the CMF development. Based on a review of the sample crash data and associated data dictionary, crash frequencies that are feasible to include in this analysis are:

- Total crash frequency: this represents all crash types and severity levels
    - The research team anticipates excluding collisions with wild animals, domestic animals, and those in work zones/maintenance equipment from total crash frequencies. These are defined by SMS_COLL_TYPE_ID = 954 (wild animals), 957 (domestic animals), and 2054 (work zone/maintenance equipment).
- Fatal + injury (FI) crash frequency: this represents all crash types and severity levels, excluding those with SMS_INJ_SVRTY_ID = 583 ("No apparent injury (property damage only crash)")
- Frequency of following "target" crash types:
    - Single vehicle run-off the road (SVROR): identified as those with SMS_COLL_TYPE_ID = 956 ("Lost Control"), 958 ("Roll Over"), 959 ("Fixed Object")
    - Off-road left: identified using SMS_RDWY_REL_ID = 1019 (outside shoulder left) and SVROR crash codes above
    - Head-on: identified as those with SMS_COLL_TYPE_ID = 953 ("Head On")
    - Sideswipe opposite direction crashes: identified as those with SMS_COLL_TYPE_ID = 947 ("Sideswipe, Opposite Direction")
- Fatal + injury crash frequency of the following "target" crash types:
    - Single vehicle run-off the road (SVROR)
    - Off-road left
    - Head-on
    - Sideswipe opposite direction crashes

CMF DEVELOPMENT

The research team proposes two methods to estimate CMFs as a part of this project. Figure 1 provides a graphical depiction of these approaches. The first is a before-after study to compare the safety performance of roadway segments with SCLRS applied before and after their installation. This will provide a CMF for applying SCLRS to a roadway segment that did not previously have CLRS. The second will be a with-without comparison. This can be used to compare the safety performance of sites with SCLRS to sites without SCLRS but with conventional CLRS installed. It can also be used to compare the safety performance of sites with conventional CLRS installed and sites without CLRS installed. These methods are described in the remainder of this section.

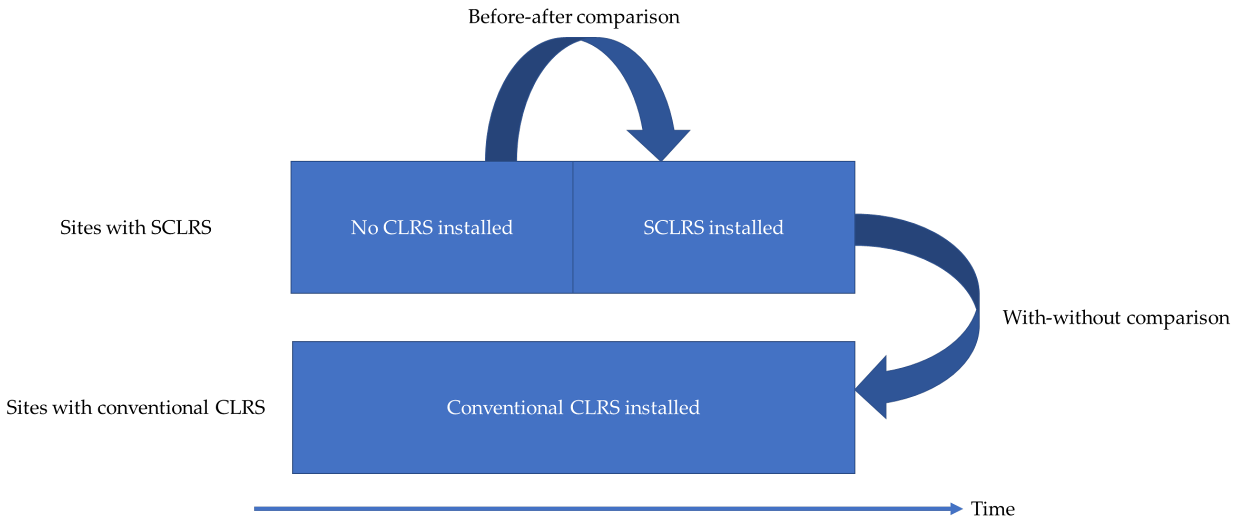

Figure 1. Graphical depiction of analysis approaches

Before-after analysis

To compare safety performance before and after the installation of SCLRS to a site without any CLRS previous installed, the research team proposes to use the EB before-after approach (Hauer, 1997). This is accepted as the state-of-the-art in observational before-after studies in road safety. The proposed EB analysis properly accounts for regression-to-the-mean, differences in traffic volume, and crash trends (time-series effects) between the periods before and after sinusoidal centerline rumble strip installation. The EB approach is comprised of three basic steps, each defined as follows:

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

Step 1: Develop SPF for sites with no SCLRS

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

The research team will consider two methods for the identification of the set of reference group sites. The first will be all sites with similar functional classifications and number of lanes as the treatment sites (e.g., most of the SCLRS in Montana are installed on two-lane rural roads, so two-lane rural roads will be considered in this project). This will be used to maximize the set of reference group sites considered. In the second method, the research team will apply an advanced statistical method (the propensity score matching approach) to identify a subset of reference sites that are as similar as possible to the set of treatment sites with respect to the independent variables considered (e.g., traffic volumes, geometric and roadside design, horizontal curvature, etc.). The propensity scores approach specifically seeks to emulate a randomized experiment that is similar to what would have been done in a clinical trial, in which the treatment and control groups are nearly identical. This is done by estimating a propensity score model that predicts the probability a given site receives treatment based on its features, then "matches" individual treatment sites to sites in the reference group based on these propensity scores. While the result is a new reference group that uses fewer overall sites in the CMF estimation, the reduced reference group minimizes the potential for bias in the CMF estimation that may be caused by the reference and treatment groups being too different. The research team has applied the propensity score approach to estimate the safety effectiveness of horizontal curvature, bus traffic, lane width on urban roads, intersection lighting, intersection forms, and rumble strips (Gooch, 2015; Guadamuz et al., 2020; Li and Donnell, 2020; Sasidharan and Donnell, 2013; Wood et al., 2015).

Data required for SPF development include crash, traffic volume, and geometric data. Negative binomial regression will be used to fit the SPF parameters from the reference group. Other count regression modeling methods, such as panel data models, will be considered, if they offer an improved fit to the data. The general functional form of the negative binomial regression model is:

$$\ln \lambda_i = \beta X_i + \varepsilon_i \tag{1}$$

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

$$Var(\lambda_i) = E(\lambda_i)[1 + \alpha E(\lambda_i)] \tag{2}$$

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

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

$$N_{i,SPF} = AADT_i^{\beta_{AADT}} \times exp\left(\beta_0 + \sum X_{ij}\beta_j\right) \qquad (3)$$

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

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

The expected number of crashes on segment i had no treatment been applied, $N_{i,EB}$, uses an SPF of the type shown in Equation 3 to first estimate the number of crashes that would be expected in each year of the before period at locations with traffic volumes and other characteristics similar to the treatment site being analyzed. An EB adjustment is then applied to the SPF prediction to incorporate reported crash frequency in the prediction of crash frequency at each location. This EB adjustment is shown in Equation 4 (Hauer, 1997).

$$N_{i,EB} = w_i \times N_{i,SPF} + (1 - w_i) \times N_{i,obs} \qquad (4)$$

where $N_{i,EB}$ = predicted crash frequency at location i based on EB adjustment [crashes/year]; w_i = adjustment weight for predicted crash frequency at location i; $N_{i,SPF}$ = predicted crash frequency at location i based on the SPF (e.g., Equation 3) [crashes/year]; and $N_{i,obs}$ = reported or observed crash frequency at location i [crashes/year].

The weight (w_i) used for the EB adjustment for any location i is derived using Equation 5.

$$w_i = \frac{1}{1+\alpha\times\sum_{all\ study\ years} N_{i,SPF}} \qquad (5)$$

Thus, Equations 3, 4, and 5 are used to determine N_{EB}^{before} for the treatment sites in the before period by applying the SPFs generated in Step 1.

The SPF is then used to calculate the predicted crash frequency using the SPF, N_{SPF}^{after}, for all treated sites in the after-period. Finally, the EB method adjusts the expected crash frequency in the after-period, N_{EB}^{after}, and is calculated using Equation 6 and the adjustment factor, γ, from Equation 7.

$$N_{EB}^{after} = N_{EB}^{before} \times \gamma \tag{6}$$

$$\gamma = \frac{\sum_{after\ years} N_{SPF}^{after}}{\sum_{before\ years} N_{SPF}^{before}} \tag{7}$$

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

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

In step 3, an unbiased estimate of the safety effect (θ) of the treatment is obtained using Equations 8 and 9.

$$\theta = \frac{N_{observed}^{after}}{N_{EB}^{after}[1+\frac{Var(N_{EB}^{after})}{N_{EB}^{after^2}}} \tag{8}$$

$$Var\ (N_{EB}^{after}) = \sum_{all\ sites} \gamma^2\ (1-w) N_{EB}^{after} \tag{9}$$

where θ = unbiased estimate of safety effect of the countermeasure; and $N_{observed}^{after}$ = reported or observed crashes during the after-period. Finally, the standard error associated with this safety effect estimate was computed using Equations 10 and 11.

$$Std\ Error\ (\theta) = \sqrt{\theta^2 \left[\frac{\left(\frac{Var\left(N_{observed}^{after}\right)}{N_{observed}^{after^2}}\right)+\left(\frac{Var(N_{EB}^{after})}{N_{EB}^{after^2}}\right)}{\left(1+\frac{Var(N_{EB}^{after})}{N_{EB}^{after^2}}\right)}\right]} \tag{10}$$

$$Var\ (N_{observed}^{after}) = \sum_{all\ sites} N_{EB}^{after} \tag{11}$$

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

CMFs will be estimated using this methodology both with the entire set of reference group sites and the reduced reference group obtained using the propensity score matching procedure. Any differences can be used to determine how much more effective the propensity score matching approach can capture the safety effects associated with sinusoidal centerline rumble strips.

With-without analysis

To compare the safety performance of sites with SCLRS to sites with conventional CLRS, the research team proposes to use the propensity scores-potential outcomes approach (Dehejia and Wahba, 2002). Ideally, this comparison would be done using a randomized experiment in which similar sites are randomly treated with either SCLRS or conventional CLRS. Since this is not possible, the propensity scores-potential outcomes approach seeks to mimic this experimental design. The method uses individual features at a site to calculate its *propensity score*, defined as a measure of the likelihood of that site receiving a specific treatment (Rosenbaum and Rubin, 1983). Sites with and without the treatment are then matched based on their propensity scores, and count regression models are then applied to the matched dataset to quantify the impacts of the treatment.

Propensity score estimation

Propensity scores provide the probability (between 0 and 1) that an entity will receive a treatment and are estimated using the observed characteristics of the entity itself (Holmes, 2013). In this study, a binary logit model will be used to estimate the probability that any segment with CLRS was treated with SCLRS. The prediction for each observation is then stored as the propensity score. The conditional probability of a binary logistic regression is provided in Equation 12, which provides the probability that a road segment will be in a treated condition (SCLRS present, SCLRS=1) (Guo and Fraser, 2010).

$$\boldsymbol{P(SCLRS_i|X_i = x_i) = E(SCLRS_i) = \frac{e^{x_i\beta_i}}{1+e^{x_i\beta_i}}} \tag{12}$$

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

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

$$\boldsymbol{\ln\left(\frac{P}{1-P}\right) = X_i\beta_i} \tag{13}$$

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

The β vector of coefficients can be estimated by maximizing the log-likelihood shown in Equation 14.

$$\boldsymbol{ln[L(\beta)] = \sum_{i=1}^{N} HC_i(x_i\beta_i) - \sum_{i=1}^{N} \ln\left(1 + e^{x_i\beta_i}\right)} \tag{14}$$

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

The propensity score model is estimated using all independent variables that are thought to be associated with rumble strip installation. These variables include segment length, AADT, number of lanes, lane width, shoulder width, posted speed limit, roadside hazard rating, driveway density, and horizontal curvature. Statistical significance is not considered important for the covariates included in the models as propensity score models are used for prediction, and use of parsimonious models (i.e., those with only statistically significant variables) introduce omitted variable bias (Kennedy, 2008).

Propensity Score Matching

In the propensity scores-potential outcomes framework, treated (i.e., those with SCLRS) and untreated sites (i.e., those with conventional CLRS) are matched based on their propensity scores. We propose to use a 1:1 nearest-neighbor (NN) matching algorithm in which each treated site be matched to the untreated site with the closest propensity score within a specified caliper width (10% of the standard deviation of estimated propensity scores) (Holmes, 2013). While 1:1 matching leads to a loss of data from dropping unmatched observations, this is not a concern with a large database, as the matched sample should still be large (Dehejia and Wahba, 2002). Before matching, the set of unmatched sites will be randomly sorted to reduce any bias that might occur. Once an untreated site is matched with a treated site, it will be removed from the database of potential matches so that matching is performed without replacement to maximize the efficiency of the (Dehejia and Wahba, 2002). Unmatched entities (treated or untreated) will be dropped from the analysis.

The effectiveness of the matching procedure at balancing the covariates and reducing selection bias will be assessed using the standardized bias, which quantifies the differences in covariate distribution between the treated and untreated samples. Standardized bias is calculated using Equation 15 (Rosenbaum and Rubin, 1983). Previous studies suggest that matching is effective if the standardized bias for each of the covariates considered in the database is small (usually less than 10 percent) (Austin, 2011), which indicates significant overlap between the treated and untreated dataset. The improvement in the standardized bias between the unmatched and matched data quantifies the improvement in covariate balance provided by matching based on propensity scores.

$$\boldsymbol{St.Bias} = \frac{\mathbf{100}(\bar{x}_T - \bar{x}_{UT})}{\sqrt{\frac{S_T^2 + S_{UT}^2}{2}}} \tag{15}$$

where $\bar{x}_T$ = sample mean of the treated group for a variable x; $\bar{x}_{UT}$ = sample mean of the untreated group for a variable x; S_T^2 = sample variance of the treated group for a variable x; and, S_{UT}^2 = sample variance of the untreated group for a variable x.

CMF Estimation

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

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