Experiencing the Impact of Centerline Rumble-Strip Installation in Prevention of Head-On and Opposite Sideswipe Collisions in Maine

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EXAMINING THE IMPACT OF CENTERLINE RUMBLE-STRIP INSTALLATION IN PREVENTION OF HEAD-ON AND OPPOSITE SIDEWIME COLLISIONS IN MAINE

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EXAMINING THE IMPACT OF CENTERLINE RUMBLE-STRIP INSTALLATION
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COLLISIONS IN MAINE

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Thesis Advisor: Dr. Mohammadali Shirazi

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Among all traffic collisions, lane departure crashes are the leading type of serious traffic crashes in Maine, comprising 72% of state-wide traffic fatalities. To reduce these crashes, Maine Department of Transportation (MaineDOT) installed shoulder and centerline rumble strips on roadways to prevent lane departure crashes in Maine. With a total installed length of 1503 miles of rumble strips, specifically 511 miles of centerline rumble strips in bidirectional and undivided rural two-lane roadways, there is a need to understand the impact of rumble strips in reducing lane departure crashes. In this thesis, observational before-after studies with two methods: comparison group, and empirical Bayes (EB) comparison group were used to explore the effectiveness of centerline rumble strips in reducing head-on and opposite sideswipe crashes for rural two-lane roadways and compute crash modification factors (CMFs) in Maine. The evaluation investigated the impact of centerline rumble strips on reducing the total and fatal and injury head-on and sideswipe collisions on rural-two lane roadways. The economic benefits of using rumble strips are
also explored by using a benefit-cost analysis. This study finds that the installations of centerline rumble strips are associated with reductions between 28% and 48% of head on and opposite sideswipe collisions on rural two-lane roads. In addition, the rumble strips are a cost-effective countermeasure with the benefits being at least 14 times the costs for the same road facility type.
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CHAPTER 1
INTRODUCTION

According to the definition provided by the Federal Highway Administration (FHWA), a lane-departure crash is a crash that occurs when a vehicle leaves the traveled path, for example, crossing the edge or center line of the road. Lane-departure crashes include head-on, sideswipe (opposite and same direction), went-off-road, and rollover crashes. From these, head-on crashes are the most dangerous type of crash, accounting for 14% of all traffic fatalities and 27% of lane-departure crash fatalities in the U.S. during the period of 2016 to 2018 (Federal Highway Administration - FHWA, 2018).

Maine experiences the highest crash fatality rate among New England states (Bouchard et al., 2020). The majority of these crash fatalities result from lane-departure crashes. In fact, according to crash records from 2010 to 2022, lane departure crashes result in approximately twice (or more) fatalities as other types of crashes each year. Additionally, Maine's lane-departure crashes accounted for approximately 73% of the fatalities, even though only 30% of the total number of crashes in the state were lane departure crashes. Among the lane departure crashes, head-on and opposite sideswipe collisions represented approximately 20% of the total lane departure crashes in the state. Furthermore, according to 2020 crash data, 48% of the crash fatalities in the U.S. occurred in rural areas. In fact, the fatality rate per 100 million vehicles miles travel was 1.7 times higher in rural areas than in urban areas (National Highway Traffic Safety Administration - NHTSA, 2022), and Maine is mainly a rural state where approximately 80% of its roadways are in rural areas (Sawtelle et al., 2023).

1 https://highways.dot.gov/safety/RwD
Maine is unique in many ways. Its location, extreme weather, aging infrastructure, older population, land use, and terrain provide unique features (Islam et al., 2023; Rubin et al., 2022; Sawtelle et al., 2022, 2023). The overall Maine infrastructure received a classification of C (mediocre: requires attention) by the ASCE 2020 Infrastructure Report Card (Bouchard et al., 2020), keeping the same classification since 2008. Specifically, the roadway infrastructure in Maine was classified as D (poor: at risk) in the same report, which has been the same since 2008. In addition, Maine has the oldest population in the United States according to the 2020 US Census, with the largest share (21.8%) of people aged 65 or above, and the second largest share (2.4%) of people aged 85 or above (Caplan & Rabe, 2023). The median age in Maine, in 2020, was 6.8 years higher than the national median of US (Sawtelle et al., 2023). This aging trend in Maine has been evident since the 1990 census (Sawtelle et al., 2023).

Rumble strips are a common and relatively low-cost countermeasure used to prevent lane departure crashes (Himes & McGee, 2016; Smadi & Hawkins, 2016). In fact, the results of a survey sent to the U.S. Department of Transportation (U.S. DOT) of 50 states and 42 of them showed that 98% of the states used rumble strips on the roadway’s centerline and 100% used rumble strips on the shoulders (McGee, 2018). However, the installation and design of rumble strips across states are not uniform (Smadi & Hawkins, 2016). Rumble strips alert drivers about the lane departure through noise and vibration (Himes et al., 2017; Russell & Rys, 2005). Although, centerline and edge rumble strips target different lane-departure crashes. The centerline rumble strips are commonly used in undivided roadways to prevent head-on and opposite-direction sideswipe crashes (Russell & Rys, 2005). On the other hand, edge rumble strips help prevent and reduce run-off-road crashes that may cause rollover or hit fixed objects.
The Maine Department of Transportation (MaineDOT) has installed 1,503 miles of rumble strips across the state roadways as a countermeasure to prevent lane departure crashes. This corresponds to 6%, according to Bouchard et al. (2020), of 23,000 total miles of roadways in the state. It also corresponds to the 17% of the roadway’s mile managed by MaineDOT, which according to Bouchard et al. (2020) are the 37% (8,510 miles) of the total state roadways. The rumble strips were placed either at the centerline (685 miles) or the edge (818 miles) of the roadways. Specifically, the MaineDOT installed 511 miles of centerline rumble strips in bidirectional and undivided rural two-lane roadways. In addition, two types of rumble strips were installed: standard and sinusoidal strips. Sinusoidal rumble strips produced less noise than the standard.

1.1 Problem Statement

The aim of this study is to assess the effectiveness of centerline rumble strips installed in Maine on preventing total and fatal and injury (KABC) head-on and opposite sideswipe collisions on rural two-lane roadways. In this study, the terms fatal and injury crashes and KABC crashes are used interchangeably and refers to the following crash severities defined by the Highway Safety Manual (HSM) (AASHTO, 2010). K: fatal injury, A: incapacitation injury, B: no incapacitating evident injury, and C: possible injury. The effectiveness of the centerline rumble strips is assessed using before-and-after studies with two methods: comparison group, and empirical Bayes (EB) comparison group, to compute crash modification factors (CMFs) and the percentage of change in crash frequency. The results corresponded with the before-and-after study using the EB method is also documented in Appendix B. As part of the before-and-after studies, safety performance functions (SPFs) are estimated for the rural two-lane roadways. In addition, economic analysis is
performed to determine the economic benefits of centerline rumble strip installations on the same roadway type.

1.2 Thesis Outline

The outline of this thesis is as follows. Chapter 2 provides a systematic review of the literature on the effectiveness of rumble strips in reducing lane-departure crashes. Chapter 3 presents the data used in this study and a preliminary analysis of the effectiveness of Maine's rumble strips in reducing lane-departure crashes. Chapter 4 documents the before-and-after study using a comparison group evaluation for centerline rumble strips on rural two-lanes. Chapter 5 documents the before-and-after study using the EB comparison group evaluation for the same facility type. Chapter 6 presents an economic analysis of centerline rumble strip installation considering the benefit-cost ratio. Chapter 7 presents the summary of the findings and recommendations.
CHAPTER 2
LITERATURE REVIEW

This chapter reviews the studies related to the effectiveness of rumble strips in preventing roadway crashes. As discussed, lane-departure crashes are a concern for Maine. Rumble strips use noise and vibration to make drivers aware of lane departure and are a typical countermeasure for mitigating crashes. A high percentage of lane-departure crashes are caused by distracted driving, operating under the influence, or driving fatigued, and vibration and noise help these drivers become aware of departure. Typically, centerline rumble strips are used to help avoid head-on crashes, whereas the edge or shoulder rumble strips are implemented to reduce run-off-road crashes that may result in rollover or hitting fixed objects. Both centerline rumble strips and shoulder rumble strips are useful countermeasures to mitigate lane-departure crashes because of their relatively low cost and the typically high benefit of reducing crashes.

This chapter is organized as follows. First, the effectiveness of centerline rumble strips in reducing crash frequency and severity is discussed. Second, the effectiveness of shoulder rumble strips in decreasing crash frequency and mitigating crash severity was discussed. Third, the effectiveness of the combination of centerline rumble strips and shoulder rumble strips in reducing crash frequency and crash severity is outlined. Finally, the conclusions of the reviewed studies are documented.

2.1 Effectiveness of Centerline Rumble Strips

Persaud et al., (2004) studied the effectiveness of centerline rumble strips installed on rural two-lane undivided roads on different crash types. This study used data from California, Colorado, Delaware, Maryland, Minnesota, Oregon, and Washington, USA. An EB before-and-after study
was developed using 98 treatment sites. Overall, a 12% reduction in the crash frequency was observed on the treated roadways. Frontal and opposing-direction crashes were found to be the most critically affected by the rumble-strip installation and were reduced by 25% during the after period. Overall, a 14% reduction in injury crashes was found on treated roadways. Frontal and opposing crashes had the highest crash severity, although after centerline rumble strip installation, there was a reduction in injury crashes of over 25%.

Sayed et al. (2010) considered both rural two-lane undivided arterials and divided four-lane freeways to analyze the effectiveness of centerline and shoulder rumble strips on crashes in British Columbia, Canada. An EB before-and-after study was conducted to determine the effectiveness of rumble-strip installation. Three years before the treatment and one-to-three years after the treatment crash data were collected for each of the 47 treatment sites. To correct for time-trend effects, 225 comparison segments were considered. These groups have similar attributes and are close to the treated segments. Only arterials received centerline rumble strips treatment. The crash types considered when analyzing centerline rumble strips include head-on or off-road-left crashes. The results indicate a 29.3% reduction in head-on or off-road left crashes on the treated segments. The overall reduction in severe crashes at all the sites was 18%.

Michigan Department of Transportation (Michigan DOT) implemented a rumble-strip installation program from 2008 to 2010. The program installed centerline rumble strips on over 4,000 miles of rural, non-freeway, high-speed roads. The program also installed shoulder rumble strips on some roadways. The program's goal was to mitigate lane-departure crashes. Kay et al. (2015) studied the effectiveness of the rumble-strip installation program performing an EB before-and-after study using crash data from three years before and after treatment. A total of 865 segments treated with centerline rumble strips were analyzed. Overall, a 27.3% reduction in lane-
departure crashes was found on roadways treated with centerline rumble strips. The analysis also included the effectiveness of rumble strips on weather-affected pavement. Wet-pavement crashes were reduced by 53.6% and wintry pavement crashes were reduced by 1.4% on centerline rumble strips-treated roads. Operating-under-the-influence crashes were reduced by 28.9%, and passing-related crashes were reduced by 42.8%. Regarding crash-severity reductions, there was a decrease of 44.2%, 31.3%, 39.8%, and 27.9% for fatal, A-injury, B-injury, and C-injury crashes, respectively.

Dissanayake & Galgamuwa (2017) developed before-and-after studies on lane departure countermeasures, including the centerline rumble strips and shoulder rumble strips, along with other methods. Both two-lane undivided and four-lane divided rural road segments in Kansas are considered. In total, 22,060 tangent and 6,442 curved two-lane undivided rural roadway segments, and 12,065 tangent and 4,095 curved four-lane divided rural roadway segments were considered. Two methods were considered: cross-sectional and case-control. Similar to Kay et al. (2015) centerline rumble strips only for two-lane segments were considered. The cross-sectional and case-control methods determined reductions in lane-departure crashes: There was a 4% and 9% crash reduction in tangent segments and a 6% and 13% reduction in curved segments. The cross-sectional and case-control methods show reductions of 4% and 11% in tangent segments and a 5% and 12% reduction in curved segments, respectively.

Guin et al. (2018) evaluated the effectiveness of centerline rumble strips in reducing lane-departure crashes on two-lane highways in Georgia. Using two years of data before and after the initial installation of the centerline rumble strips for each site and 126 miles of treated roadway, an EB before and after method was used. The overall CMF value for all crashes was 0.58, indicating a 48% reduction in lane-departure crashes after centerline rumble strips installation. The
study also considered the effects of injury or fatal crashes to estimate the impact of severe crashes, although these outcomes proved insignificant due to the small sample size. Noyce & Elango (2004) studied the effectiveness of the centerline rumble strips in Massachusetts. The results found no significant change in the frequency of lane-departure crashes related to the installation of the centerline rumble strips.

2.2 Effectiveness of Shoulder Rumble Strips

Patel et al. (2007) evaluated the effectiveness of shoulder rumble strips on single-vehicle run-off-road crashes in Minnesota. The analysis considered 183 miles of treated rural two-lane roadways. An EB before-and-after method was performed using three to nine years before treatment and three to seven years after treatment crash data. The study period spanned 13 years and the before-and-after periods depended on when the installation was completed for each segment. The results of the analysis showed a 13% reduction in single-vehicle run-off-road crashes and an 18% reduction in single-vehicle run-off-road injury crashes after installing shoulder rumble strips.

Sayed et al. (2010) considered both rural, two-lane, undivided arterials and divided, four-lane freeways to analyze the effectiveness of centerline and shoulder rumble strips on crashes in British Columbia, Canada. A before-and-after study was performed, and the results indicated that shoulder rumble strips reduced run-off-road crashes by 18.4% on freeways and 26.1% on arterials where shoulder rumble strips were installed. The average outcome of severe crashes was reduced by 18%. Cheng et al. (2001) evaluated the effectiveness of shoulder rumble strips on run-off-road crashes on highways in Utah. A total of 186 treated roadways were considered, and the crash rate comparison method was used for analysis. The study found that total crashes were reduced by 33.4% and run-off-road crashes were reduced by 26.9% after installing shoulder rumble strips.
Khan et al. (2015) analyzed the run-off-road crash reduction benefits of shoulder rumble strips on rural two-lane roads. This study used an EB before-and-after analysis method. In total, 178 miles of treated roads in Idaho were considered. Data from three- to six years before and two- to five- years after treatment crash were collected. This study analyzed the impact of volume and segment geometry on the effectiveness of treated segments. The results of the study included a 14% reduction in run-off-road crashes on treated roadways. The effects of geometric features with shoulder rumble strips were also considered. Roadways with moderate curvature were the most effective on roads that also had shoulder rumble strips installed. Shoulder widths of three feet or more were also shown to be more effective when shoulder rumble strips were installed compared to smaller treated-shoulder widths. The annual average daily traffic (AADT) results were not statistically significant in this study.

Park et al. (2014) investigated the effectiveness of crash-reducing countermeasures on rural multi-lane roads in Florida. Countermeasures included shoulder rumble strips, widening shoulder widths, and a combination of the two. The effects of several shoulder widths were considered, and the effects of crash severity, crash frequency, and crash type were analyzed. A total of 60 road segments with shoulder rumble strips and 122 road segments with shoulder rumble strips and shoulder widening were considered. Using an EB before-and-after method, CMFs were developed to compare countermeasures. All the countermeasures showed a decrease in crash frequency, with the combined countermeasure being the most effective. When considering all single-vehicle, run-off road crashes, the combined countermeasure proved to be the most effective for safety. However, when considering injury crashes, widening of the shoulders proved to affect crashes the most. Regarding shoulder width, when considering before-and-after shoulder widening installation
combined with shoulder rumble strips, when the original shoulders were between four- and six-feet wide, the countermeasures had the greatest impact on safety.

Marvin & Clark (2003) evaluated the effectiveness of shoulder rumble strips for single-vehicle lane-departure crashes on Interstates and highways in Montana. The analysis considered three years of crash data before and after shoulder rumble strips installation, and a total of 606 treated miles of roadways. The results of the study include a 14.0% decrease in the crash rate and a 23.5% reduction in the severity rate after the installation of shoulder rumble strips. Other factors were considered, including time of day, visibility, and driver age. Most factors proved to be insignificant in the study, especially for roads other than Interstates. The sample size and reliable data proved to be limitations of this analysis.

Using Kansa data, Dissanayake & Galgamuwa (2017) considered shoulder rumble strips for two- and four-lane road segments. The cross-sectional and case-control method reductions in lane-departure crashes on two-lane segments are: There is a 6% and 15% reduction in tangent segments. There was a 5% reduction using the cross-sectional method for curved segments and a 25% increase using the case-control method for curved segments. The cross-sectional and case-control method reductions in fatal and injury lane-departure crashes on two-lane road segments are: There is a 5% and 10% reduction in the tangent segments, and a 6% and 19% reduction in curved segments. The cross-sectional and case-control method reductions in lane-departure crashes on four-lane segments with paved shoulders more than two feet wide are: there is a 9% and 20% reduction in the tangent segments, and a 16% and 26% reduction in curved segments. The cross-sectional and case-control method reductions in fatal and injury lane-departure crashes on four-lane road segments with paved shoulders more than two feet wide are: There is a 50% and 68% reduction in the tangent segments, and a 69% and 70% reduction in curved segments.
Griffith (1999) evaluated the reduction in single-vehicle, run-off road crashes in Illinois and California after the installation of the shoulder rumble strips. Rural and urban roadways were considered together, and rural roads were considered separately. The results of the before-and-after study showed an 18.3% reduction in all the crashes analyzed. The results also indicate a 13% reduction in injury-related crashes. When considering only the rural segments, there was a 21% reduction in crashes. Wu et al. (2014) evaluated the effectiveness of shoulder rumble strips on single-vehicle, run-off-road crashes. Using two years of before- and after-treatment crash data, a Panel Fixed Effect Analysis approach was considered, and 310 Pennsylvania-treated roadway segments were used. Single-vehicle, run-off-road crashes were reduced by 7% after shoulder rumble strips were installed. The analysis found no impact on crash severity.

Smith & Ivan (2005) studied the effectiveness of shoulder rumble strips installed in Connecticut. The analysis determined whether there was a reduction in single-vehicle, fixed-object crashes and whether any individual roadway factor impacted run-off-road crashes on segments with the installation of shoulder rumble strips. The study used a General Log-linear modeling approach to determine after-effects. Three years before and after treatment, crash data were used. The results indicated a 33% reduction in single-vehicle, fixed-object crashes. The analysis also considered the effects of individual factors. Run-off-road crashes were found to decrease by 48.5% around interchange areas, and run-off-road crashes were found to decrease by 12.8% on roads with speed limits less than 65 mph.

Gårder & Davies (2006) studied the effectiveness of shoulder rumble strips in mitigating runoff-road crashes on Maine rural, interstate highways. This study considered a before-and-after approach that resulted in a 27% reduction in all run-off-road crashes. The study also considered pavement conditions with respect to weather and found that, with dry pavement surfaces, there
was a 43% reduction in run-off-road crashes. The study also found that there was a 58% reduction in sleep-related crashes after the installation of the shoulder rumble strips.

2.3 Effectiveness of combined Centerline and Shoulder Rumble Strips

As discussed, Sayed et al. (2010) considered both rural two-lane undivided arterials and divided four-lane freeways to analyze the effectiveness of centerline rumble strips and shoulder rumble strips on crashes in British Columbia, Canada. When the combination of centerline rumble strips and shoulder rumble strips was analyzed on two-lane undivided arterials, the results of the left run-off road, right run-off road, and head-on crashes indicated a 21.4% reduction in combined crashes. The average outcome of severe crashes decreased by 18%.

Kay et al. (2015) analyzed the safety performance of the rumble-strip installation program set by the Michigan DOT from 2008 to 2010. The majority of roadways only had centerline rumble strips installed; however, shoulder rumble strips were also installed on segments that had over six feet of paved existing shoulders. In total, 384 segments received both treatments, and the results of the combined effect are discussed as follows. Overall, a 32.8% reduction in lane-departure crashes was observed. Wet pavement crashes were reduced by 55.5%, and wintery pavement crashes were reduced by 4.6%. Driving under the influence of crashes decreased by 39.3% and passing-related crashes decreased by 36.5%. Regarding crash-severity reductions, there were decreased by 51.4%, 37.4%, 38.5%, and 35.2% for fatal, A-injury, B-injury, and C-injury crashes, respectively.

Dissanayake & Galgamuwa (2017) studied a combination of centerline rumble strips and shoulder rumble strips for two-lane road segments. The cross-sectional and case-control methods resulted in reductions in lane-departure crashes: There was a 14% and 32% reduction in tangent segments and an 11% and 25% reduction in curved segments. The cross-sectional and case-control
methods resulted in reductions in fatal and injury lane-departure crashes: There was a 6% and 27% reduction in tangent segments, and a 13% and 49% reduction in curved segments.

Lyon et al. (2015) and Persaud et al. (2016) evaluated the effectiveness of centerline rumble strips and shoulder rumble strips installation on roadway crashes in Kentucky, Missouri, and Pennsylvania. Only two-lane, undivided rural roads were considered in this study. An EB before and after method was developed. Different crash types and injury severity crash outcomes were considered in this analysis. Other factors, including the posted speed limit, lane width, and shoulder width, were also considered. All locations showed crash reductions. The CMF values for each crash type evaluated were 0.632, 0.742, and 0.767 for head-on, runoff-road, and sideswipe-opposite-direction crashes, respectively. The overall reduction in lane departure-crashes was 0.733. For all types of crashes, the CMF value was 0.80, and all fatal and injury crashes resulted in a value of 0.771. All CMF values were less than one indicating crash reduction after rumble-strip installation.

2.4 Summary and Conclusions

From the literature reviewed, it is apparent that many states are implementing programs to install various countermeasures to reduce lane-departure crashes. Rumble strips have become a popular countermeasure for reducing these crashes, and many studies have shown a reduction in crashes using before-and-after analyses.

The effectiveness of centerline rumble strips varies, and the reduction in lane-departure crashes ranges from 4% to 48% (Dissanayake & Galgamuwa, 2017; Galgamuwa & Dissanayake, 2019; Guin et al., 2018). Various crash types were evaluated, with reductions of 25% in frontal and opposing directions and 29.3% in head-on collisions (Persaud et al., 2004; Sayed et al., 2010). Kay et al. (2015) found that wet-pavement crashes decreased by 53.6%, wintry pavement crashes
decreased by 28.9%, operating under the influence crashes decreased by 28.9% and crashes involving passing drivers reduced by 42.8% after the installation of centerline rumble strips. Severe crashes were decreased by 4–44.2% (Dissanayake & Galgamuwa, 2017; Galgamuwa & Dissanayake, 2019; Kay et al., 2015).

The effectiveness of shoulder rumble strips also varies; the reduction in total crashes ranges from 6% to 33.4% (Cheng et al., 2001; Dissanayake & Galgamuwa, 2017; Galgamuwa & Dissanayake, 2019). The reduction in single-vehicle, run-off-road crashes ranged from 7% to 26.1% (Sayed et al., 2010; Wu et al., 2014). Injury-related, lane-departure crashes had reductions ranging from 13% to 18% (Griffith, 1999; Patel et al., 2007; Sayed et al., 2010). However, Dissanayake & Galgamuwa (2017) found reductions in injury crashes on four-lane curved roads of as much as 70%. The findings also include a 33% reduction in single-vehicle, fixed-object crashes, a 48.5% reduction in single-vehicle, run-off-road crashes at interchanges, and a reduction of 12.8% on roads with posted speeds of less than 65 mph (Smith & Ivan, 2005). Dry pavements were found to decrease run-off-road crashes by 43%, and sleep-related crashes were found to reduce crashes by 58% (Gårder & Davies, 2006). The effectiveness of the combination of both the centerline rumble strips and shoulder rumble strips also varied across studies. The reduction in lane-departure crashes ranged from 11% to 32.8% (Dissanayake & Galgamuwa, 2017; Galgamuwa & Dissanayake, 2019; Kay et al., 2015). Lyon et al. (2015) found a reduction of head-on, run-off-road, and sideswipe opposite-direction crashes to be 36.8%, 25.8% and 23.3%, respectively. Kay et al. (2015) found wet-pavement crashes reduced by 55.5%, wintery pavement crashes reduced by 4.6%, operating-under-the-influence crashes decreased by 39.3% and crashes occurring due to passing drivers reduced by 36.5%. Severe crashes were reduced by 6–51.4% (Dissanayake & Galgamuwa, 2017; Galgamuwa & Dissanayake, 2019; Kay et al., 2015). Overall, the studies that
evaluated centerline rumble strips or shoulder rumble strips and the combination of the two showed that the combination was a more effective countermeasure and had higher reduction values and lower CMF values (Dissanayake & Galgamuwa, 2017; Galgamuwa & Dissanayake, 2019; Kay et al., 2015).

Although many studies have found that centerline rumble strips and shoulder rumble strips reduce crash frequency and severity, many studies have discussed that a limitation of their research was the sample size. For example, Guin et al. (2018) and Khan et al. (2015) discussed that finding a reduction in injury crashes was not possible with their current sample, as it was too small. Noyce & Elango (2004) found insignificant effects from installing of a centerline rumble strips. Dissanayake & Galgamuwa (2017) also discussed sample size as an issue when considering the effectiveness of rumble strips and combined variables.

Finally, a summary of all studies discussed in this chapter (and the main findings) is shown in Table 1.
<table>
<thead>
<tr>
<th>Author</th>
<th>Location</th>
<th>Crash Type</th>
<th>Facility</th>
<th>Rumble-Strip Type</th>
<th>Modeling Approach</th>
<th>Key Results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maryland, Minnesota, Oregon,</td>
<td>crashes, Lane-departure crashes</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Washington</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sayed et al., (2010)</td>
<td>BC, Canada</td>
<td>Head-on, run-off-road</td>
<td>Rural two-lane undivided arterial, divided</td>
<td>CLRS, shoulder</td>
<td>EB before-and-after study</td>
<td>29.3% reduction in head-on or off-road-left crashes on CLRS segments, 18.4% reduction in run-off-road crashes on shoulder rumble strips segments, 21.4% reduction in all crashes and 18% reduction in severe crashes on roads with both CLRS and shoulder rumble strips.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>four-lane freeways</td>
<td>rumble strips, and combination</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kay et al., (2015)</td>
<td>Michigan</td>
<td>Lane departure</td>
<td>Rural, non-freeway high-speed roads</td>
<td>CLRS, shoulder</td>
<td>EB before-and-after study</td>
<td>27% reduction in all crashes, wet pavement crashes reduced by 53.6%, wintery pavements reduced by 1.4%, OUI crashes reduced by 28.9%, passing related crashes reduced by 43.8% on CLRS segments, 23.8% reduction in all crashes, wet pavement crashes reduced by 55.5%, winter pavement crashes reduced by 4.6%, OUI crashes reduced by 39.3% and passing crashes reduced by 36.5% on roads with both CLRS and shoulder rumble strips.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>rumble strips and combination</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dissanayake and Galgamuwa</td>
<td>Kansas</td>
<td>Lane departure</td>
<td>Rural two-lane undivided and four-lane</td>
<td>CLRS, shoulder</td>
<td>Cross-sectional and case-</td>
<td>4-11% reduction in crashes on tangent CLRS sections, 5-12% reduction on curved CLRS sections, 6-15% reduction on tangent shoulder rumble strips segments, 14-32% reduction on tangent CLRS and shoulder rumble strips segments, 11-25% on curved CLRS and shoulder rumble strips segments.</td>
</tr>
<tr>
<td>(2017); Galgamua and</td>
<td></td>
<td></td>
<td>divided roads</td>
<td>rumble strips and combination</td>
<td>control method</td>
<td></td>
</tr>
<tr>
<td>Dissanayake (2019)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Author</td>
<td>Location</td>
<td>Crash Type</td>
<td>Facility Type</td>
<td>Rumble-Strip Type</td>
<td>Modeling Approach</td>
<td>Key Results</td>
</tr>
<tr>
<td>-----------------</td>
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<td>----------------------------------------</td>
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<td>-------------------</td>
<td>------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Guin et al.,</td>
<td>Georgia</td>
<td>Lane departure</td>
<td>Two-lane highways</td>
<td>CLRS</td>
<td>EB before-and-after study</td>
<td>48% reduction to overall collisions. No significant change to injury-related crashes.</td>
</tr>
<tr>
<td>(2019)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Noyce and Elango</td>
<td>Massachusetts</td>
<td>Lane departure</td>
<td>Two-lane undivided roads</td>
<td>CLRS</td>
<td>Before-and-after study</td>
<td>No significant change.</td>
</tr>
<tr>
<td>(2004)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Patel et al.,</td>
<td>Minnesota</td>
<td>Single-vehicle run-off-road crashes</td>
<td>Rural two-lane roads</td>
<td>shoulder rumble strips</td>
<td>EB before-and-after method</td>
<td>13% reduction in total crashes, 18% reduction in injury crashes.</td>
</tr>
<tr>
<td>(2007)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cheng et al.,</td>
<td>Utah</td>
<td>Run-off-road</td>
<td>Highways</td>
<td>shoulder rumble strips</td>
<td>Accident rate comparison method</td>
<td>33.4% reduction in total crashes, 26.9% reduction in run-off-road crashes.</td>
</tr>
<tr>
<td>(2001)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Khan et al.,</td>
<td>Idaho</td>
<td>Run-off-road</td>
<td>Rural two-lane roads</td>
<td>shoulder rumble strips</td>
<td>EB before-and-after method</td>
<td>14% reduction in crashes.</td>
</tr>
<tr>
<td>(2015)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Park et al.,</td>
<td>Florida</td>
<td>Single-vehicle run-off-road crashes</td>
<td>Rural multi-lane roads</td>
<td>shoulder rumble strips</td>
<td>EB before-and-after method</td>
<td>When original shoulders were paved and between four and six feet, adding shoulder rumble strips proved most significant.</td>
</tr>
<tr>
<td>(2014)</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Marvin and Clark</td>
<td>Montana</td>
<td>Single-vehicle lane-departure crashes</td>
<td>Interstates</td>
<td>shoulder rumble strips</td>
<td>Before-and-after study</td>
<td>14% reduction in crash rate, 23.5% reduction in severity rate.</td>
</tr>
<tr>
<td>(2003)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Griffith</td>
<td>Illinois,</td>
<td>Single-vehicle run-off-road crashes.</td>
<td>Rural and urban freeways.</td>
<td>shoulder rumble strips</td>
<td>Before-and-after study</td>
<td>18.3% reduction in all crashes, 13% reduction in injury crashes, 21% reduction in total rural crashes.</td>
</tr>
<tr>
<td>(1999)</td>
<td>California</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wu et al.,</td>
<td>Pennsylvania</td>
<td>Single-vehicle run-off-road crashes.</td>
<td>Highways, arterials, collectors, local roads</td>
<td>shoulder rumble strips</td>
<td>Panel fixed-effect analysis</td>
<td>7% reduction in crashes. No impact to crash severity.</td>
</tr>
<tr>
<td>(2014)</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Smith and Ivan</td>
<td>Connecticut</td>
<td>Single-vehicle fixed object, Run-off-road</td>
<td>Freeways</td>
<td>shoulder rumble strips</td>
<td>General log-linear approach</td>
<td>33% reduction in single-vehicle fixed-object crashes, run-off road crashes reduced by 48.5% around interchanges, 12.8% reduction in run-off-road crashes on roads with speed limits less than 65 mph.</td>
</tr>
<tr>
<td>(2005)</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Garder and Davies</td>
<td>Maine</td>
<td>Run-off-road</td>
<td>Rural Interstates</td>
<td>shoulder rumble strips</td>
<td>Before-and-after</td>
<td>27% reduction in crashes, dry pavement crashes reduced by 58%.</td>
</tr>
<tr>
<td>(2006)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lyon et al.,</td>
<td>Kentucky,</td>
<td>Head-on, run-off-road, sideswipe-opposite direction.</td>
<td>Two-lane undivided rural roads</td>
<td>Combination of shoulder rumble strips and CLRS</td>
<td>EB before-and-after analysis</td>
<td>Head-on crashes CMF value of 0.632, run-off-road CMF value of 0.742 and sideswipe-opposite direction crashes CMF value of 0.767.</td>
</tr>
<tr>
<td>(2015); Persaud et al., (2016)</td>
<td>Missouri, Pennsylvania</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1 Continued.
CHAPTER 3
DATA DESCRIPTION AND PRELIMINARY ANALYSIS

This chapter documents the description of collected data, as well as a preliminary analysis of the safety effectiveness of rumble strips. This chapter is divided into five sections. Section 3.1 provides an overview of the study area and the data sources used for analysis. Section 3.2 explores lane-departure crashes in Maine. Section 3.3 describes the rumble strips installed in Maine. Section 3.4 presents a naïve before-and-after analysis to evaluate the safety effectiveness of the rumble strips. Finally, Section 3.5 presents the summary and conclusions of the chapter.

3.1 Study Area and Data Collection

This study focuses on rural two-lane roadways in Maine. Data were obtained from two sources: the MaineDOT internal information and the MaineDOT Public Map Viewer\(^2\). Crash records from January 2010 to November 2022, the geometric characteristics of roadways, roadway sections with rumble strips, and roadway curve information were provided by a MaineDOT representative. The crash records for December 2022 were collected from the MaineDOT Public Map Viewer.

All the collected information is geolocated\(^3\). It also contains milepost and route code. This information allowed for merging different datasets. Crashes were matched to roadway segments by comparing the route code and mileposts. The Curve segments, rumble strips, and roadway geometry datasets combined using GIS. For this purpose, new segments were created whenever needed to match the data. This was done because the curve dataset has a different route reference system than roadway geometry and rumble strips.

\(^2\) [https://www.maine.gov/mdot/mapviewer/](https://www.maine.gov/mdot/mapviewer/)
\(^3\) An ESRI file geodatabase was provided by MaineDOT, and shapefile was downloaded from the public map viewer.
In addition to geometric characteristics, the collected roadway dataset also contains information about traffic volume, specifically AADT. However, further computations were needed to obtain the AADT for each year of analysis during the study period of 2010 to 2022. In Maine, only the Interstate highways have a new estimated AADT by traffic counts each year, while for the other facility types of roadways, only certain zones of the state have traffic counts, and the rest use expansion factors. MaineDOT divides the state into three zones, and each year, traffic counts are collected in one zone, while the AADT of the other two zones is estimated using expansion factors by county. To obtain the AADT of each roadway segment for all years of analysis, the expansion factors provided by MaineDOT were used when there were no traffic counts.

3.2 Lane-Departure Crashes in Maine

The total number of reported vehicle crashes in Maine (including all crash types) from January 2010 to December 2022 was 413,817. The most common crash type was rear-ended and sideswipe (32.9%), run off-road (26.4%), intersection movement (16.6%), and deer (14.5%). Regarding lane-departure crashes, the run off-road (26.4%), head-on and opposite sideswipe (2.6%), and rollover (0.6%) collisions constitute approximately 30% of the total crashes in Maine. This is illustrated in Figure 1.

While lane-departure crashes make up around 30% of the total crash count, their severity exceeds that of other crash types. As illustrated in Figure 2, the lane-departure crashes account for around 72.7% of the total vehicle crash-related fatalities between 2010 and 2022. This statistic highlights that, although lane-departure crashes may not be the most frequent type of collisions when compared to other categories, they are the leading cause of fatal collisions in Maine.
Figure 1. The proportion of total crashes by crash type in Maine.

Figure 2. The proportion of fatalities according to the type of crash in Maine.
Examining the aggregated proportion of lane-departure crashes during the entire period of crash records, most of them are run off-road collisions. In fact, looking at the amount of each type of lane-departure crash by year, the recorded run-off road collisions are significantly higher than head-on and opposite sideswipe collisions, and rollovers. Each year, approximately 8,000 run off-road crashes are recorded, whereas the recorded head-on and opposite sideswipe, and rollover crashes are less than 1,000 crashes. This is illustrated in Figure 3.

![Figure 3. Lane-departure crashes in Maine.](image)

### 3.3 Rumble Strips in Maine

As mentioned before, rumble strips can be installed both in the centerline separator of the lanes to deter vehicles from crossing into oncoming traffic and at the edge of the road to prevent vehicles from veering off the road. Moreover, in Maine, two variations of rumble strips - standard and sinusoidal - are deployed, positioned either at the centerline or along the edge of the roadway. Figure 4 shows a
map indicating the locations of the rumble strips. Rumble strips were installed on different facility types, such as Interstates, major collectors, minor arterials, and other principal arterials. It is worth noting that the majority of the edge rumble strips are installed on Interstate highways including I-95. In fact, edge rumble strips were implemented along almost the entire length of the Interstate highway system in Maine.

The installed lengths of the edge rumble strips on the rural two-lanes roadways are presented in Table 2. As noted earlier, the majority of edge rumble strips were installed on Interstates, predominantly of the standard type. Although the year of installation was not recorded for Interstate rumble-strip installations, our anecdotal information suggests that these rumble strips (487 miles) were installed well before 2010. As a result, the Interstate rumble strips are not considered in our analysis. The length of installed edge rumble strips on rural two-lanes on major collectors and minor arterials is less than 1 mile, and on other principal arterials around 12 miles (all installed in 2019). Due to the limited extent of these installations, the evaluation of edge rumble-strip installations is not taken into consideration in the subsequent chapters.

<table>
<thead>
<tr>
<th>Facility Type</th>
<th>Type of Rumble Strip</th>
<th>Standard</th>
<th>Sinusoidal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major Collector</td>
<td>Standard</td>
<td>0</td>
<td>0.7</td>
</tr>
<tr>
<td>Minor Arterial</td>
<td></td>
<td>0</td>
<td>0.2</td>
</tr>
<tr>
<td>Other Principal Arterial</td>
<td></td>
<td>0.7</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0</td>
<td>11.2</td>
</tr>
</tbody>
</table>
Centerline rumble strips have been installed on rural two-lanes major collectors, minor arterials, and other principal arterials. Table 3 presents an overview of the installed lengths categorized by facility type for bidirectional and undivided rural two-lane roadways. Notably, the facility type with the highest number of installations is the ‘other principal arterials’, followed by ‘minor arterials’ and ‘major collectors.’
Table 3. Length of the centerline rumble-strip installations on rural two-lane roads

<table>
<thead>
<tr>
<th>Facility Type</th>
<th>Type of Rumble Strip</th>
<th>2016</th>
<th>2020</th>
<th>2021</th>
<th>2020</th>
<th>2021</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Major Collector</strong></td>
<td>Standard</td>
<td>1.3</td>
<td>0.0</td>
<td>0.0</td>
<td>1.3</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>Sinusoidal</td>
<td>2.9</td>
<td>4.6</td>
<td>7.3</td>
<td>4.6</td>
<td>7.3</td>
</tr>
<tr>
<td></td>
<td>Both</td>
<td>4.2</td>
<td>4.6</td>
<td>7.3</td>
<td>4.6</td>
<td>7.3</td>
</tr>
<tr>
<td><strong>Minor Arterial</strong></td>
<td>Standard</td>
<td>1.3</td>
<td>0.0</td>
<td>0.0</td>
<td>1.3</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>Sinusoidal</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>Both</td>
<td>1.3</td>
<td>0.0</td>
<td>0.0</td>
<td>1.3</td>
<td>0.0</td>
</tr>
<tr>
<td><strong>Other Principal Arterial</strong></td>
<td>Standard</td>
<td>6.9</td>
<td>6.9</td>
<td>6.9</td>
<td>6.9</td>
<td>6.9</td>
</tr>
<tr>
<td></td>
<td>Sinusoidal</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>Both</td>
<td>6.9</td>
<td>6.9</td>
<td>6.9</td>
<td>6.9</td>
<td>6.9</td>
</tr>
</tbody>
</table>

3.4 Naïve Before-and-after Study

An initial assessment of the safety effectiveness of the rumble strips is conducted by comparing the total observed crashes in the three-year period prior to installation with the three years following installation. This approach aligns with a basic before-and-after study design known as ‘native before-and-after analysis.’ To ensure a consistent three-year interval both before and after installation, and considering the limitations posed by the COVID-19 stay-at-home restrictions by changes on traffic volumes and driver behavior (Marshall et al., 2023; Marshall et al., 2023; Shahlaee et al., 2022), only rumble strips installed between 2013 and 2016 are considered for analysis.
For centerline rumble strips installed on rural two-lane bidirectional and undivided roadways, our analysis focuses exclusively on head-on and opposite sideswipe collisions. A naive before-and-after analysis is performed for each individual year of installation and facility type, and the results are presented in Table 4. Overall, centerline rumble strips seem effective in reducing the total number of crashes and fatal and injury crashes, showing a crash reduction of at least 20% in most cases. However, there are still cases where there is no change or an increase in crash frequency. Major collector roads with sinusoidal centerline rumble strips installed in 2016 exhibited a 20% increase in total crashes. Minor arterials with sinusoidal rumble strips installed in 2016 showed an increase of 50% in total crashes and 200% in fatal and injury crashes. However, these results are due to limited installed miles of rumble strips (less than three miles); therefore, the sample size produced biased results (see the installed lengths of the rumble strips are listed in Table 3.)

Additionally, preforming the similar analysis considering only the facility and rumble-strip types (Table 5) and the rumble strips type and installation year (Table 6), a reduction in crash frequency is still present. However, in Table 5, sinusoidal rumble strips on the major collectors and minor arterials show an increase in the crash frequency. In addition, in Table 6, the sinusoidal rumble strips show an increase in the crash frequency; however, as noted regarding the results in Table 3, this is the case when the installed length of the rumble strips is small (less than 3 miles).
Table 4. Naïve before-and-after analysis of centerline rumble strips for rural two-lane roadways by facility and rumble-strip types, and installation year.

<table>
<thead>
<tr>
<th>Type of Rumble Strip</th>
<th>Total Crashes</th>
<th>Fatal/ and Injury (KABC) Crashes</th>
<th>Crash Frequency Change</th>
<th>Crash Frequency Change</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before</td>
<td>After</td>
<td>Before</td>
<td>After</td>
</tr>
<tr>
<td>Major Collector</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td>2</td>
<td>1</td>
<td>-50%</td>
<td>1</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td>5</td>
<td>6</td>
<td>20%</td>
<td>3</td>
</tr>
<tr>
<td>Both</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td>7</td>
<td>7</td>
<td>0%</td>
<td>4</td>
</tr>
<tr>
<td>Minor Arterial</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td>3</td>
<td>1</td>
<td>-67%</td>
<td>2</td>
</tr>
<tr>
<td>2015</td>
<td>28</td>
<td>11</td>
<td>-61%</td>
<td>22</td>
</tr>
<tr>
<td>2016</td>
<td>5</td>
<td>2</td>
<td>-60%</td>
<td>4</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td>2</td>
<td>3</td>
<td>50%</td>
<td>1</td>
</tr>
<tr>
<td>Both</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td>7</td>
<td>5</td>
<td>-29%</td>
<td>5</td>
</tr>
<tr>
<td>Other Principal Arterial</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td>7</td>
<td>5</td>
<td>-29%</td>
<td>7</td>
</tr>
<tr>
<td>2015</td>
<td>16</td>
<td>16</td>
<td>0%</td>
<td>16</td>
</tr>
<tr>
<td>2016</td>
<td>47</td>
<td>27</td>
<td>-43%</td>
<td>47</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td>14</td>
<td>10</td>
<td>-29%</td>
<td>14</td>
</tr>
<tr>
<td>2015</td>
<td>12</td>
<td>7</td>
<td>-42%</td>
<td>12</td>
</tr>
<tr>
<td>2016</td>
<td>16</td>
<td>14</td>
<td>-13%</td>
<td>16</td>
</tr>
<tr>
<td>Both</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td>21</td>
<td>15</td>
<td>-29%</td>
<td>21</td>
</tr>
<tr>
<td>2015</td>
<td>28</td>
<td>23</td>
<td>-18%</td>
<td>28</td>
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<tr>
<td>2016</td>
<td>63</td>
<td>41</td>
<td>-35%</td>
<td>63</td>
</tr>
<tr>
<td>Arterials</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td>10</td>
<td>6</td>
<td>-40%</td>
<td>8</td>
</tr>
<tr>
<td>2015</td>
<td>44</td>
<td>27</td>
<td>-39%</td>
<td>29</td>
</tr>
<tr>
<td>2016</td>
<td>52</td>
<td>29</td>
<td>-44%</td>
<td>34</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td>14</td>
<td>10</td>
<td>-29%</td>
<td>9</td>
</tr>
<tr>
<td>2015</td>
<td>12</td>
<td>7</td>
<td>-42%</td>
<td>9</td>
</tr>
<tr>
<td>2016</td>
<td>18</td>
<td>17</td>
<td>-6%</td>
<td>8</td>
</tr>
<tr>
<td>Both</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td>24</td>
<td>16</td>
<td>-33%</td>
<td>17</td>
</tr>
<tr>
<td>2015</td>
<td>56</td>
<td>34</td>
<td>-39%</td>
<td>38</td>
</tr>
<tr>
<td>2016</td>
<td>70</td>
<td>46</td>
<td>-34%</td>
<td>42</td>
</tr>
</tbody>
</table>

1A negative change in the crash frequency means a reduction in crashes. Hence a positive effectiveness of the rumble strips.
Table 5. Naïve before-and-after study of centerline rumble strips on rural two-lane roadways by facility and rumble strips.

<table>
<thead>
<tr>
<th>Type of Rumble Strip</th>
<th>Total Crashes</th>
<th>Fatal and Injury (KABC) Crashes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before</td>
<td>After</td>
</tr>
<tr>
<td><strong>Major Collector</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Both</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td><strong>Minor Arterial</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>36</td>
<td>14</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Both</td>
<td>38</td>
<td>17</td>
</tr>
<tr>
<td><strong>Other Principal Arterial</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>70</td>
<td>48</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>42</td>
<td>31</td>
</tr>
<tr>
<td>Both</td>
<td>112</td>
<td>79</td>
</tr>
<tr>
<td><strong>Arterials</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>106</td>
<td>62</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>44</td>
<td>34</td>
</tr>
<tr>
<td>Both</td>
<td>150</td>
<td>96</td>
</tr>
</tbody>
</table>

¹A negative change in the crash frequency means a reduction in crashes. Hence a positive effectiveness of the rumble strips.

Table 6. Naïve before-and-after analysis of centerline rumble strips on Maine rural two-lane roadways by rumble-strip type and installation year.

<table>
<thead>
<tr>
<th>Type of Rumble Strip</th>
<th>Total Crashes</th>
<th>Fatal and Injury (KABC) Crashes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before</td>
<td>After</td>
</tr>
<tr>
<td><strong>Standard</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>2015</td>
<td>44</td>
<td>27</td>
</tr>
<tr>
<td>2016</td>
<td>54</td>
<td>30</td>
</tr>
<tr>
<td><strong>Sinusoidal</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td>14</td>
<td>10</td>
</tr>
<tr>
<td>2015</td>
<td>12</td>
<td>7</td>
</tr>
<tr>
<td>2016</td>
<td>23</td>
<td>23</td>
</tr>
<tr>
<td><strong>Both</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td>24</td>
<td>16</td>
</tr>
<tr>
<td>2015</td>
<td>56</td>
<td>34</td>
</tr>
<tr>
<td>2016</td>
<td>77</td>
<td>53</td>
</tr>
</tbody>
</table>

¹A negative change in the crash frequency means a reduction in crashes. Hence a positive effectiveness of the rumble strips.
It is important to note that this preliminary study is merely an exploratory approach and serves as an initial indicator of expected outcomes. Nevertheless, these results do not provide definitive conclusions regarding the safety effectiveness of rumble strips to prevent lane-departure crashes in Maine. To draw more robust and conclusive insights, a meticulously structured and comprehensive study is required. Therefore, in this study, more robust before-and-after studies conducted to evaluate the safety effectiveness of rumble strips. The results of these studies are documented in the subsequent chapters.

3.5 Summary and Conclusions

This chapter described the collected crash data spanning from January 2010 to December 2022 as well as the geometric characteristics and traffic-related information. To facilitate the analysis, these data were meticulously processed through Geographic Information Systems (GIS) for integration and mapping. Additionally, the AADT values for roadways were obtained using traffic counts and expansion factors by county. Edge rumble strips are predominantly installed in Interstates, but there are no records for the year of installation for these rumble strips, precluding the possibility of conducting a before-and-after study to measure their effectiveness. Furthermore, the installed lengths of edge rumble strips in other facility types are insufficient for meaningful analysis. In contrast, centerline rumble strips exhibit more substantial installation lengths. Therefore, the future chapters are focused solely on centerline rumble strips. As an initial step, a preliminary analysis was conducted, suggesting that rumble strips appear to be effective in reducing total and fatal and injury-related lane-departure crashes. However, it is essential to acknowledge that the naïve before-and-after study does not account for the phenomenon of regression to the mean, necessitating more robust methodologies and further in-depth investigation.
CHAPTER 4

BEFORE-AND-AFTER STUDY USING COMPARISON GROUP

This chapter documents the findings of the comparison group before-and-after study. This chapter is divided into four sections. Section 4.1 provides a comprehensive overview of the methodology in two parts. Section 4.1.1 documents the procedure used to select an appropriate comparison group. Section 4.1.2 outlines the steps taken to compute the CMFs. Section 4.2 describes the characteristics of the selected treatment and comparison group. Section 4.3 presents the computed CMFs. Finally, Section 4.4 provides a summary and recommendations.

4.1 Methodology

The before-and-after study with comparison group analysis involves comparing the observed crash frequency of treatment sites with those at untreated sites that share similar characteristics, referred to as the comparison group (Gross et al., 2010). The simple comparison group method is an alternative to more complex methods, such as EB, when a suitable comparison group is available, and the regression-to-the-mean bias is not an issue. Although the latter assumption may not entirely hold in our context, we resort to this method because of data limitations in Maine. That said, Gross et al., (2010) noted that the comparison group approach may account for the regression-to-the-mean bias when the comparison group is selected based on the trends in the observed crash frequency during the before period. We took this into consideration in this study to minimize the adverse effects of the regression-to-the-mean bias.

4.1.1 Comparison Group Selection

The comparison group accounts for changes in causal factors over time (e.g., traffic volume) unrelated to the treatment (Gross et al., 2010; Hauer, 1997). Therefore, the comparison group is a set
of sites that have not received treatment but have similar geometric and operational characteristics to the treated sites. In addition, the comparison group should be selected considering the observed crash frequency during the before period to ensure that the regression-to-the-mean is accounted for. It is important to note that the before-and-after periods for the treatment and comparison group should usually be the same (Gross et al., 2010). Choosing an ideal comparison group is complex. Therefore, Hauer (1997) proposed a method referred to as “test of comparability” or “comparability test” to aid in selecting a suitable comparison group among various alternatives. The comparability test revolves around the fundamental concept that the comparison group is appropriate for analysis if the annual trend of the observed crash frequency is similar in both the treatment and comparison groups during the before period. To conduct this test, a series of sample tests (STs) are computed for each successive pair of years in the before period using Eq. (1).

\[
\text{Sample ST}_i = \frac{\frac{N_{T,i} \cdot N_{C,i+1}}{N_{T,i+1} \cdot N_{C,i}}}{1 + \frac{1}{N_{T,i+1}} + \frac{1}{N_{C,i}}}
\]

where,

- i-th index: year in the before period. If there are n years, then i varies from 1 to n − 1.
- \(N_{T,i}\): total observed crashes in the treatment group in the i-th year of the before period.
- \(N_{C,i}\): total observed crashes in the comparison group in the i-th year of the before period.

From the computed sample tests, the mean, variance, and confidence interval of the sample tests are estimated. If the mean of the computed STs is close to 1 and the confidence interval of the sample STs contains the value 1, the selected sites are suitable to be considered as a comparison group.

4.1.2 Computing the CMF

The comparison group method employs the crash frequency observed in the periods before and after treatment in both the treatment and comparison groups to estimate CMFs. Table 7 summarizes
the data required to compute the CMF using this method. The mentioned data refer to the aggregated crashes over the entire duration of the before-or-after period.

**Table 7. Data needed for the comparison-group before-and-after study.**

<table>
<thead>
<tr>
<th>Period</th>
<th>Treatment Group</th>
<th>Comparison Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>(N_{\text{observed,T,B}}): observed crashes during the before period at the treatment sites.</td>
<td>(N_{\text{observed,C,B}}): observed crashes during the before period at the comparison sites.</td>
</tr>
<tr>
<td>After</td>
<td>(N_{\text{observed,T,A}}): observed crashes during the after period at the treatment sites.</td>
<td>(N_{\text{observed,C,A}}): observed crashes during the before period at the comparison sites.</td>
</tr>
</tbody>
</table>

The expected number of crashes at the treatment sites during the after period is computed using Eq. (2), under the assumption that the treatment has not been implemented.

\[
N_{\text{expected,T,A}} = N_{\text{observed,T,B}} \cdot \frac{N_{\text{observed,C,A}}}{N_{\text{observed,C,B}}}
\]  

(2)

The variance \(N_{\text{expected,T,A}}\) is derived using Eq. (3).

\[
\text{Var}(N_{\text{expected,T,A}}) = N_{\text{expected,T,A}}^2 \left( \frac{1}{N_{\text{observed,T,B}}} + \frac{1}{N_{\text{observed,C,B}}} + \frac{1}{N_{\text{observed,C,A}}} \right)
\]  

(3)

Then, the CMF is estimated using Eq. (4).

\[
\text{CMF} = \frac{N_{\text{observed,T,A}}}{N_{\text{expected,T,A}}} \left( 1 + \frac{\text{Var}(N_{\text{expected,T,A}})}{N_{\text{expected,T,A}}^2} \right)
\]  

(4)

The variance of the CMF is computed using Eq. (5).

\[
\text{Var}(\text{CMF}) = \text{CMF}^2 \left( \frac{1}{N_{\text{observed,T,A}}} + \frac{\text{Var}(N_{\text{expected,T,A}})}{N_{\text{expected,T,A}}^2} \right) \left( 1 + \frac{\text{Var}(N_{\text{expected,T,A}})}{N_{\text{expected,T,A}}^2} \right)^2
\]  

(5)

Eqs. (4) and (5) operate under the assumption that an ideal comparison group is accessible and is employed for the analysis. However, as mentioned previously, selecting an ideal comparison group is often challenging. Consequently, we often rely on a comparability test to select a comparison group.
Consequently, the estimated CMF and its associated variance approximate the true values (Gross et al., 2010).

Finally, the statistical significance of the estimated CMF is assessed by comparing the value $z$ computed using Eq. (6).

$$
z = \left| \frac{1 - \text{CMF}}{\sqrt{\text{Var(CMF)}}} \right| \quad (6)
$$

If $z$ is less than 1.7, there is insufficient evidence to consider the treatment effect as significant at the 90% confidence level. However, if $z$ is greater than or equal to 1.7, the treatment effect is considered significant at the 90% confidence level. Moreover, if $z$ is greater than or equal to 1.96, the treatment effect is considered significant at the 95% confidence level.

### 4.2 Treatment and Comparison Group Sites

The effectiveness of the centerline rumble strips is evaluated for two rural two-lane roadway facility types: minor arterial, and other principal arterial. It is also evaluated for all rural two-lane arterials together. The results for major collectors are excluded given the small sample size. Evaluating centerline rumble strips targeted head-on and opposite sideswipe crashes. Head-on and opposite sideswipe crashes occur when vehicles depart from one lane to the lane in the other direction. Centerline rumble strips may prevent these types of collisions. Head-on or opposite side-swipe collisions can be classified based on the severity of the crashes. Therefore, the CMFs are estimated for both total (including all severities) and fatal and injury collisions (KABC). The effectiveness of the centerline rumble strips is quantified using the CMFs. With the CMF, it is possible to compute the expected change in crash frequency. The safety evaluation is performed using a before-and-after study with the comparison group method described in Section 4.1.

Because head-on and opposite sideswipe are not common crashes, the lack of crashes is a challenge to compute CMFs. To address this issue, four approaches are used to compute the CMFs: 1)
using a single installation year and three years in the before-and-after periods, 2) using a single installation year and five years in the before-and-after periods, 3) using multiple installation years and three years in the before-and-after periods, and 4) using multiple installation years and five years in the before-and-after periods. Subsequently, the significant CMFs with the best comparison group for each analysis were selected.

4.2.1 Treatment Sites

Selecting the treatment sites is based on several factors, including the geometric and roadway characteristics, year of rumble-strip installation, frequency and severity of crashes, and segment length. Considering the geometric and roadway characteristics, the selected sites included rural, two-lane, bidirectional, and undivided segments with centerline rumble strips. For simplicity, only segments with a length greater or equal to 0.01 miles are considered for analysis.

It is common to use a duration of three to five years for the before-and-after period (which corresponds to the four approaches mentioned before.) Collected crash records included collisions between 2010 and 2022. Therefore, to ensure a duration of three years for the before-and-after periods, only rumble strips installed between 2013 and 2019 are used for the analysis, and for five years, only installations between 2015 and 2017 are used. It is important to note that the crashes that occurred in the year of installation are not considered in the analysis; for example, if the rumble strips are installed in 2015, the before period is 2010-2014 and the after period is 2016-2020.

To further refine the analysis, the year with the most installed length of rumble strips and most crashes is selected for the analysis to ensure an adequate sample size. Table 8 shows the length of the centerline rumble-strip installations during 2013-2019 for each individual facility type and the arterials aggregated case (i.e., minor arterials and other principal arterials rural two-lane segments.) Additionally, when considering the two types of rumble strips together in the analysis, it is also
considered to have a balance between the two types. For example, considering both rumble strips in other principal arterials the year with more installed length 2016. However, in 2016, the standard rumble strips are 75% of the total installed length in that year, whereas the sinusoidal type is 25%. But, in 2016, the proportions of the installed rumble strips are: 56% for standard and 44% for sinusoidal. Then, in this case, the year 2016 is preferred for the analysis since the installed length of the two rumble strips is more balanced than in 2017. Although, if the balanced scenario does not show conclusive results, then the unbalanced is also used. It is also noteworthy that, as shown in Table 8, the installed length of the major collector is not sufficient to estimate the CMFs for this facility type. Therefore, a CMF development is not considered for this facility type.
Table 8. Length (in miles) of treatment sites for two-lane rural segments based on facility type.

<table>
<thead>
<tr>
<th>Rumble Strips Year of Installation</th>
<th>Rumble-strip Type</th>
<th>Standard</th>
<th>Sinusoidal</th>
<th>Both</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Major Collector</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2016</td>
<td></td>
<td>1.3</td>
<td>2.9</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>Minor Arterial</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td></td>
<td>6.9</td>
<td>0.0</td>
<td>6.9</td>
</tr>
<tr>
<td>2014</td>
<td></td>
<td>0.0</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>2015</td>
<td></td>
<td>26.9</td>
<td>0.0</td>
<td>26.9</td>
</tr>
<tr>
<td>2016</td>
<td></td>
<td>10.4</td>
<td>6.3</td>
<td>16.7</td>
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<tr>
<td>2017</td>
<td></td>
<td>32.7</td>
<td>9.6</td>
<td>42.3</td>
</tr>
<tr>
<td>2018</td>
<td></td>
<td>0.0</td>
<td>29.4</td>
<td>29.4</td>
</tr>
<tr>
<td>2019</td>
<td></td>
<td>0.0</td>
<td>2.2</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>Other Principal Arterial</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td></td>
<td>10.6</td>
<td>8.6</td>
<td>19.2</td>
</tr>
<tr>
<td>2015</td>
<td></td>
<td>25.8</td>
<td>10.0</td>
<td>35.8</td>
</tr>
<tr>
<td>2016</td>
<td></td>
<td>72.9</td>
<td>24.7</td>
<td>97.6</td>
</tr>
<tr>
<td>2017</td>
<td></td>
<td>28.0</td>
<td>21.5</td>
<td>49.5</td>
</tr>
<tr>
<td>2018</td>
<td></td>
<td>0.0</td>
<td>38.5</td>
<td>38.5</td>
</tr>
<tr>
<td>2019</td>
<td></td>
<td>0.0</td>
<td>8.6</td>
<td>8.6</td>
</tr>
<tr>
<td></td>
<td>Arterials</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td></td>
<td>17.5</td>
<td>8.6</td>
<td>26.1</td>
</tr>
<tr>
<td>2014</td>
<td></td>
<td>0.0</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>2015</td>
<td></td>
<td>52.7</td>
<td>10.0</td>
<td>62.7</td>
</tr>
<tr>
<td>2016</td>
<td></td>
<td>83.3</td>
<td>31.0</td>
<td>114.3</td>
</tr>
<tr>
<td>2017</td>
<td></td>
<td>60.7</td>
<td>31.2</td>
<td>91.9</td>
</tr>
<tr>
<td>2018</td>
<td></td>
<td>0.0</td>
<td>67.9</td>
<td>67.9</td>
</tr>
<tr>
<td>2019</td>
<td></td>
<td>0.0</td>
<td>10.8</td>
<td>10.8</td>
</tr>
</tbody>
</table>

4.2.2 Comparison Group Sites

The comparison group sites are selected by identifying segments with the same geometric characteristics as the treatment sites but without rumble-strip installation. The collected sites are then filtered based on the AADT to ensure that the AADT values of the comparison sites closely matched those of the treatment sites. Specifically, whenever possible, similar sites with an AADT within 5% of treatment sites are selected for analysis; whenever the 5% threshold does not produce an adequate sample, the threshold is changed until suitable samples are found. Finally, the comparability test described in Section 4.1.1 is used to select a suitable comparison group. Table 9 presents the results of comparability tests considering 5 years trend in the before period.
Table 9. Comparability test results.\(^1\)\(^2\)

<table>
<thead>
<tr>
<th>Rumble Strips Type</th>
<th>Total Crashes</th>
<th>Fatal and Injury Crashes (KABC)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SE</td>
</tr>
<tr>
<td>Minor Arterial</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>1.03</td>
<td>0.99</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>0.80</td>
<td>0.07</td>
</tr>
<tr>
<td>Both</td>
<td>1.05</td>
<td>0.98</td>
</tr>
<tr>
<td>Other Principal Arterial</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>0.98</td>
<td>0.23</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>0.77</td>
<td>0.45</td>
</tr>
<tr>
<td>Both</td>
<td>0.93</td>
<td>0.22</td>
</tr>
<tr>
<td>Arterials</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>1.02</td>
<td>0.61</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>0.87</td>
<td>0.35</td>
</tr>
<tr>
<td>Both</td>
<td>1.00</td>
<td>0.51</td>
</tr>
</tbody>
</table>

\(^1\)CMF estimates that are subjectively close to 1 (within 0.9 and 1.1) and showed evidence to be statistically significant at the 5% level are stated in bold.

\(^2\)A duration of 5 years in the before period was considered for evaluating the crash trend in the comparability test.

It is important to note that to compute the comparability test, the observed crash frequency for each year of the before period is necessary, and if it is zero, then the sample test cannot be computed. However, the CMF can still be estimated if the crash frequency aggregated over the before period is not zero. In addition, as shown in Table 8, the installed length of the major collector is not sufficient to estimate the CMFs for this facility type.

4.3 CMF Development

The layout of the study data is assembled after the selection of the treatment and comparison groups, and presented in Tables Table 10 and Table 11. Table 10 presents the selected years of installation and duration of the before and after periods of the study for each facility and rumble strips type, whereas Table 11 presents the descriptive statistics of the data used for the safety evaluation using the comparison group method.

When determining the study layout, certain guidelines are considered, including (1) a preference for analyzing with a single installation year as opposed to multiple, and (2) a preference for...
a shorter time span in the before-and-after periods. Considering these guidelines, the analysis was proceeded in following sequence: (1) using a single installation year with three years of data in the before-and-after periods, (2) using a single installation year with five years of data in the before-and-after periods, (3) using multiple installation years with three years of data in the before-and-after periods, and (4) using multiple installation years and five years of data in the before-and-after periods. Case (1) does not provide conclusive results (see Appendix A), but case (2) does in some analyses. Then, case (3) and (4) are used in the specific cases where case (2) do not provide conclusive results. However, cases of (3) and (4) do not provide conclusive results for these scenarios either. Then, as shown in Table 10, the reported results correspond to single installation year with 5 years of data in the before-and-after periods.

**Table 10. Years of installation and duration of before and after periods used to compute CMFs.**

<table>
<thead>
<tr>
<th>Rumble Strips Type</th>
<th>Total Crashes</th>
<th>Fatal and Injury Crashes (KABC)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Installation Year</td>
<td>Years in Before-and-After Periods</td>
</tr>
<tr>
<td><strong>Minor Arterial</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>2017</td>
<td>5</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>2016</td>
<td>5</td>
</tr>
<tr>
<td>Both</td>
<td>2016</td>
<td>5</td>
</tr>
<tr>
<td><strong>Other Principal Arterial</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>2016</td>
<td>5</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>2016</td>
<td>5</td>
</tr>
<tr>
<td>Both</td>
<td>2016</td>
<td>5</td>
</tr>
<tr>
<td><strong>Arterials</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>2017</td>
<td>5</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>2016</td>
<td>5</td>
</tr>
<tr>
<td>Both</td>
<td>2017</td>
<td>5</td>
</tr>
</tbody>
</table>
Table 11. Statistics of the treatment and comparison groups.

<table>
<thead>
<tr>
<th>Rumble Strips Type</th>
<th>Group Type</th>
<th>Sites(^1)</th>
<th>Miles(^1)</th>
<th>Total Crashes</th>
<th>KABC Crashes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Before</td>
<td>After</td>
</tr>
<tr>
<td><strong>Minor Arterial</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>Treatment</td>
<td>35</td>
<td>22.8</td>
<td>26</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>Comparison</td>
<td>442/319</td>
<td>254.7/166.7</td>
<td>253</td>
<td>296</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>Treatment</td>
<td>4</td>
<td>4.7</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>Comparison</td>
<td>180/289</td>
<td>78.5/149.8</td>
<td>123</td>
<td>115</td>
</tr>
<tr>
<td>Both</td>
<td>Treatment</td>
<td>13</td>
<td>10.8</td>
<td>14</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Comparison</td>
<td>329/375</td>
<td>154.9/195.8</td>
<td>204</td>
<td>213</td>
</tr>
<tr>
<td><strong>Other Principal Arterial</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>Treatment</td>
<td>77</td>
<td>50.7</td>
<td>75</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>Comparison</td>
<td>125/125</td>
<td>47.4</td>
<td>83</td>
<td>72</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>Treatment</td>
<td>23</td>
<td>16.9</td>
<td>24</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td>Comparison</td>
<td>159/62</td>
<td>56.0/22.6</td>
<td>101</td>
<td>86</td>
</tr>
<tr>
<td>Both</td>
<td>Treatment</td>
<td>100</td>
<td>67.6</td>
<td>99</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>Comparison</td>
<td>156</td>
<td>59.2</td>
<td>104</td>
<td>90</td>
</tr>
<tr>
<td><strong>Arterials</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>Treatment</td>
<td>65</td>
<td>43.1</td>
<td>53</td>
<td>36</td>
</tr>
<tr>
<td></td>
<td>Comparison</td>
<td>599/599</td>
<td>303.8</td>
<td>339</td>
<td>388</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>Treatment</td>
<td>27</td>
<td>21.7</td>
<td>29</td>
<td>26</td>
</tr>
<tr>
<td></td>
<td>Comparison</td>
<td>639/170</td>
<td>312.5/64.5</td>
<td>396</td>
<td>398</td>
</tr>
<tr>
<td>Both</td>
<td>Treatment</td>
<td>81</td>
<td>60.8</td>
<td>59</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td>Comparison</td>
<td>686/378</td>
<td>375.5/201.8</td>
<td>383</td>
<td>447</td>
</tr>
</tbody>
</table>

\(^1\)Total/KABC crashes

As expected, the installation of centerline rumble strips overall shows evidence of a reduction in the crash frequency of head-on and opposite sideswipe collisions. Table 12 presents the estimated CMFs and changes in the number of total and fatal and injury crashes by implementing centerline rumble strips on rural two-lane roadway segments in Maine. Only CMFs that are computed with a suitable comparison group and show evidence to be statistically significant at (minimum) 10% levels are considered reliable, and their use is recommended. Those CMFs are noted with a bold font in Table 12. As noted previously, the CMFs of the major collectors could not be estimated. For minor arterials, reliable CMFs are found for standard rumble strips considering total crashes, and for both types of rumble strips considering fatal and injury crashes. CMFs for other principal arterials are reliable for total crashes with standard and both rumble strips, and for fatal and injury crashes with standard rumble...
strips. The combined arterials show reliable CMFs for standard and both rumble strips (total, and fatal and injury crashes.) While computed CMFs for standard rumble strips considering fatal and injury crashes in minor arterials exhibit significance, their utilization is not recommended due to the absence of a suitable comparison group.

### Table 12. Safety effectiveness of centerline rumble strips.

<table>
<thead>
<tr>
<th>Rumble Strips Type</th>
<th>Total Crashes</th>
<th>Fatal and Injury Crashes (KABC)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CMF</td>
<td>SE</td>
</tr>
<tr>
<td><strong>Minor Arterial</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>0.53</td>
<td>0.17</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>0.70</td>
<td>0.39</td>
</tr>
<tr>
<td>Both</td>
<td>0.70</td>
<td>0.27</td>
</tr>
<tr>
<td><strong>Other Principal Arterial</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>0.56</td>
<td>0.14</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>1.01</td>
<td>0.31</td>
</tr>
<tr>
<td>Both</td>
<td>0.68</td>
<td>0.14</td>
</tr>
<tr>
<td><strong>Arterials</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>0.58</td>
<td>0.13</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>0.86</td>
<td>0.23</td>
</tr>
<tr>
<td>Both</td>
<td>0.72</td>
<td>0.14</td>
</tr>
</tbody>
</table>

1CMF estimates that were computed using a suitable comparison group and showed evidence of being statistically significant at least at the 10% level are stated in bold.
2A negative change (-) shows a reduction. A positive change (+) shows an increase.
*Although it is significant, the comparison group was considered not suitable.

### 4.4 Summary and Recommendations

This chapter examined the effectiveness of rumble-strip installation in preventing lane-departure crashes for rural two-lane roadways in Maine using a comparison group before-and-after study. The methodology involved selecting an appropriate comparison group based on the observed crash frequency during the before period. Comparability tests for the comparison groups were performed to find suitable comparison groups and address the issue of the regression to the mean to some degree. The results show evidence in some combinations of facilities and rumble strips that the installation of centerline rumble strips is effective in reducing lane-departure crashes. However, not all
the estimated CMFs show evidence of statistical significance; therefore, only some are recommended for use:

- Minor arterial roadways with standard rumble strips for total crashes (47% reduction).
- Minor arterial roadways with both types of rumble strips for fatal and injury (KABC) crashes (44% reduction).
- Other principal arterial roadways with standard rumble strips for total and fatal and injury (KABC) crashes (44% reduction).
- Other principal arterial roadways with both types of rumble strips for total crashes (32% reduction).
- Arterials roadways with standard rumble strips for total crashes (42% reduction).
- Arterials roadways with standard rumble strips for fatal and injury (KABC) crashes (28% reduction).
- Arterials roadways with both types of rumble strips for total and fatal and injury crashes (54% reduction).
- Arterials roadways with both types of rumble strips for fatal and injury (KABC) crashes (35% reduction).
CHAPTER 5
BEFORE-AND-AFTER STUDY USING EMPIRICAL BAYES COMPARISON GROUP

This chapter documents the findings of the EB comparison group before-and-after study. This chapter is divided into five sections. Section 5.1 provides a comprehensive overview of the methodology in three parts. Section 5.1.1 documents the procedure used to select treatment and comparison groups. Section 5.1.2 outlines the steps taken to compute the CMFs. Section 5.1.3 documents the procedure used to fit SPFs. Section 5.2 describes the characteristics of the selected treatment and the comparison groups. Section 5.3 presents the computed SPFs. Section 5.4 presents the computed CMFs. Finally, Section 5.5 provides the chapter summary and recommendations.

5.1 Methodology

The before-and-after study with EB comparison group is a mix between the EB method (see Appendix B regarding the EB method) and the comparison group. The EB comparison group method addresses the challenge of regression to the mean by using SPFs to predict crashes in the post-treatment period for both the treatment and comparison groups. As explained by Hauer (1997), before-and-after studies are based on a comparison between what would have been the safety of an entity in the period after the countermeasure if no countermeasures had been installed, and the safety after the countermeasure installation. Therefore, timeframe plays a vital role in before-and-after studies. Two crucial periods must be defined: the time prior to the installation of the countermeasure, called the before period, and the time after the installation of the countermeasure, called the after period. A before-and-after study compares the following: $N_{\text{observed}_A}$: observed crash frequency in the after period at sites with the countermeasure, and $N_{\text{expected}_A}$: expected crash frequency in the after period at the sites with the countermeasure if the countermeasure has not been installed. The subsequent subsections
delineate the procedures entailed in before-and-after studies using the EB comparison group methodology.

5.1.1 Treatment and Comparison Group Selection

According to the recommendations of the HSM (AASHTO, 2010), at least 10–20 sites are required in the treatment and comparison groups. In addition, the comparison group should have a minimum of 650 aggregated crashes. Furthermore, it is a usual practice to use before and after periods of three to five years. However, the periods before and after installation do not need to have the same duration. It is important to note that this method may underestimate the safety effectiveness of treatments. This is because the method is unable to use sites with an observed crash frequency of zero (0) in the before or after period. For example, a site that experiences zero crashes in the defined period after treatment implementation is not considered in this method. Likewise, if a site has experienced zero crashes in the before period, it again is not considered for the safety evaluation.

5.1.2 Computing the CMF

The EB comparison group method employs the crash frequency observed and predicted in the periods before and after treatment in both the treatment and comparison groups to estimate CMFs. Table 7 summarizes the crash data required to compute the CMF using this method. The mentioned data refer to the aggregated crashes over the entire duration of the before- or after-period. It is noteworthy that the predicted average crash frequency is presented as an input. However, to compute the prediction, it is necessary to use SPFs. The section 5.3 describes the procedure for fitting the SPFs.
Table 13. Crash data needed for the EB comparison-group before-and-after study.

<table>
<thead>
<tr>
<th>Group</th>
<th>Before Period</th>
<th>After Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment</td>
<td>$N^i_{\text{observed},T,B}$: observed crashes during the before period at the i-th treatment site.</td>
<td>$N^i_{\text{observed},T,A}$: observed crashes during the after period at the i-th treatment site.</td>
</tr>
<tr>
<td></td>
<td>$N^i_{\text{predicted},T,B}$: predicted crashes during the before period at the i-th treatment site.</td>
<td>$N^i_{\text{predicted},T,A}$: predicted crashes during the after period at the i-th treatment site.</td>
</tr>
<tr>
<td>Comparison</td>
<td>$N^j_{\text{observed},T,B}$: observed crashes during the before period at the j-th comparison site.</td>
<td>$N^j_{\text{observed},C,A}$: observed crashes during the after period at the j-th comparison site.</td>
</tr>
<tr>
<td></td>
<td>$N^j_{\text{predicted},T,B}$: predicted crashes during the before period at the j-th comparison site.</td>
<td>$N^j_{\text{predicted},C,A}$: predicted crashes during the after period at the j-th comparison site.</td>
</tr>
</tbody>
</table>

Additionally, the duration of the before and after periods for the treatment and comparison groups is required.

$Y_{T,B}$: duration of the before period for the treatment group.

$Y_{T,A}$: duration of the after period for the treatment group.

$Y_{C,B}$: duration of the before period for the comparison group.

$Y_{C,A}$: duration of the after period for the comparison group.

To account for changes in traffic volumes and durations of the before period, the adjustment factor for each combination of treatment and comparison sites, $Adj_{B}^{ij}$, is computed using Eq. (7), and for the after period, the adjustment factor, $Adj_{A}^{ij}$, is computed using Eq. (8).

$$Adj_{B}^{ij} = \frac{N^i_{\text{predicted},T,B}}{N^j_{\text{predicted},C,B}} \cdot \frac{Y_{T,B}}{Y_{C,B}}$$ \hspace{1cm} (7)

$$Adj_{A}^{ij} = \frac{N^i_{\text{predicted},T,A}}{N^j_{\text{predicted},C,A}} \cdot \frac{Y_{T,A}}{Y_{C,A}}$$ \hspace{1cm} (8)

Then, the expected average crash frequency for each comparison site in the before period is computed using Eq. (9), and for the after period with Eq. (10)

$$N^j_{\text{expected},C,B} = \sum_{i} (N^i_{\text{predicted},C,B} \cdot Adj_{B}^{ij})$$ \hspace{1cm} (9)
\[ \text{adjusted} = \sum_{j} (N_{\text{predicted},C,A} \cdot \text{Adj}_{A,j}) \]  

The total expected average crash frequency of the comparison group for each treatment site in the before period is computed using Eq. (11) and for the after period using Eq. (12).

\[ \text{total expected} = \sum_{j} (N_{\text{expected},C,B}) \]  

\[ \text{total expected} = \sum_{j} (N_{\text{expected},C,A}) \]  

For each treatment site the comparison ratio \( r_{i,C} \) is computed using Eq. (13).

\[ r_{i,C} = \frac{N_{\text{total expected},C,A}}{N_{\text{total expected},C,B}} \]  

The expected crash frequency for each treatment site in the after period, if no treatment has been installed, \( N_{\text{expected,T,A}} \), is computed as shown in Eq. (14).

\[ N_{\text{expected,T,A}} = N_{\text{observed,T,B}} \cdot r_{i,C} \]  

Subsequently, by comparing the observed and expected crashes, the CMF for each treatment site is computed using Eq. (15). The natural logarithm of the CMF is then calculated using Eq. (16).

\[ \text{CMF} = \frac{N_{\text{expected,T,A}}}{N_{\text{observed,T,A}}} \]  

\[ R = \ln(\text{CMF}) \]  

The weight of each treatment site is computed using Eq. (17).

\[ w = \frac{1}{(R_{\text{se}})^2} \]  

Where,

\[ (R_{\text{se}})^2 = \frac{1}{N_{\text{observed,T,B}}} + \frac{1}{N_{\text{observed,T,A}}} + \frac{1}{N_{\text{total expected,C,B}}} + \frac{1}{N_{\text{total expected,C,A}}} \]
The weighted average natural logarithm of CMF is computed using Eq. (19), and exponentiated to obtain the actual CMF as Eq. (20). The standard error of CMF is given by Eq. (21).

\[ R = \frac{\sum_i (w^i \cdot R^i)}{\sum_i w^i} \]  

(19)

\[ \text{CMF} = \exp(R) \]  

(20)

\[ \text{SE} = \frac{\text{CMF}}{\sqrt{\sum_i w^i}} \]  

(21)

Once the CMF is known, it is possible to find the safety effectiveness (in percentage) of the treatment using Eq. (22).

\[ \text{Safety effectiveness(\%)} = (1 - \text{CMF}) \cdot 100 \]  

(22)

Finally, to assess the statistical significance of CMF, the test statistic \( z \) shown in Eq. (23) must be computed. If \( z \) is less than 1.7, there is insufficient evidence to consider the treatment effect as significant at the 90% confidence level. However, if \( z \) is greater than or equal to 1.7, the treatment effect is considered significant at the 90% confidence level. Moreover, if \( z \) is greater than or equal to 1.96, the treatment effect is considered significant at the 95% confidence level.

\[ z = \left| \frac{1 - \text{CMF}}{\text{SE}} \right| \]  

(23)

5.1.3 Developing Safety Performance Functions

Over-dispersed crash data is a common issue that can be addressed using a NB model. The NB model can be described as a combination of independent Bernoulli trials (Hilbe, 2011). The probability density function (PDF) of the NB distribution is given in Eq (24).

\[ \text{NB}(p_i, \phi) \equiv \frac{\Gamma(y_i + \phi)}{\Gamma(y_i + 1) \times \Gamma(\phi)} (p_i)^y (1 - p_i)\phi; \quad \phi, p > 0 \]  

(24)

Where,

\( y_i \): observed number crashes at the i-th site.
\( p_i \): event probability at the i-th site.

\( \Phi \): inverse over-dispersion parameter \((1/\theta)\).

The parameter \( p_i \) can be defined by the following equation as a function of the long-term mean response value at the i-th site \((\mu_i)\) and the inverse over-dispersion parameter \((\phi)\).

\[
p_i = \frac{\mu_i}{\mu_i + \phi}
\]  

(25)

Therefore, Eq. (25) can be rewritten as:

\[
\text{NB} (\mu_i, \phi) \equiv P(y_i | \mu_i, \phi) = \frac{\Gamma(y_i + \phi)}{\Gamma(y_i + 1) \times \Gamma(\phi)} \left( \frac{\mu_i}{\mu_i + \phi} \right)^y \left( \frac{\phi}{\mu_i + \phi} \right)^\phi ; \phi, \mu > 0
\]  

(26)

Where,

\( y_i \): observed number crashes at the i-th site.

\( \mu \): long-term mean of crashes at the i-th site.

\( \phi \): inverse over-dispersion parameter.

Then, a regression analysis using the NB model is used to predict the number of crashes based on a set of variables, such as AADT, segment length, shoulder width, etc. A log-linear function was assumed to develop the SPFs, as shown in Eq (27):

\[
\ln(\mu_i) = \beta_0 + \sum_{j=1}^{m} \beta_j x_{ij}
\]  

(27)

Where:

\( \mu_i \): long-term mean of crashes at the i-th site.

\( \beta_{ij} \): regression coefficient for the j-th variable.

\( x_{ij} \): value of the j-th variable for the i-th site.

\( m \): number of independent variables.
Once the NB model is fitted, parameter $\phi$, known as the inverse dispersion parameter, is recorded, and used in the CMF development.

5.2 Treatment and Comparison Group

The effectiveness of the centerline rumble strips is evaluated for two rural two-lane roadway facility types: minor arterial, and other principal arterial. It is also evaluated for all two-lane arterials together. As noted earlier, the major collectors are not included in analysis due to small sample size. Evaluation of centerline rumble strips targeted head-on and opposite sideswipe crashes. Head-on and opposite sideswipe crashes occur when vehicles depart from one lane to the lane in the other direction. Centerline rumble strips may prevent these types of collisions. Head-on or side-swipe collisions can be classified based on the severity of the crashes. Therefore, the CMFs are estimated for both total (including all severities) and fatal and injury collisions (KABC). The effectiveness of the centerline rumble strips is quantified using the CMFs. Knowing the CMF, it is possible to compute the expected change in crash frequency. Note that the safety evaluation performed in chapter 4 used before-and-after studies with the simple comparison group method. This section uses the EB and comparison group to estimate the CMFs.

5.2.1 Selecting the Treatment and Comparison Groups

The selection of the treatment sites is based on several factors, including the geometric and roadway characteristics, year of rumble-strip installation, frequency and severity of crashes, and segment length. Considering the geometric and roadway characteristics, the selected sites included rural, two-lane, bidirectional, and undivided segments with centerline rumble strips. For simplicity, only segments with a length greater or equal to 0.1 miles are considered for analysis. The standard practice is to use a timeframe of three to five years for the before-and-after period. The collected data include crash records from 2010 to 2022. Consequently, the analysis only considers rumble strips
installed between 2015 and 2019, for a duration of five years prior to the installation and three years after the installation. In this case, three years in the after period are selected to be able to consider installed rumble strips in 2018, since this is the year with most installations of sinusoidal rumble strips. The crashes that occurred in the year of installation are not included in the analysis; for example, if the rumble strips are installed in 2015, the before period is 2010-2014 and the after period is 2016-2019.

Trying to overcome the limitation of the method, which does not allow the consideration of sites with zero observed crashes, different years of rumble-strip installation are considered. This allowed us to increase the number of sites. For example, if a facility type has rumble-strip installations in 2016 and 2017, the sites with installed treatment in those years are considered together in the treatment group. Table 8 shows the length of the centerline rumble-strip installations for each individual facility type and the arterials aggregated case (i.e., minor arterials and other principal arterials rural two-lane segments.)

The comparison group sites are selected by identifying segments with the same geometric characteristics as the treatment sites but without rumble-strip installation. The collected sites are then filtered based on the AADT to ensure that the AADT values of the comparison sites closely matched those of the treatment sites. Whenever possible, sites similar to an AADT within 5% of the treatment sites are selected for analysis. The layout of the study is presented in Table 14, Table 15, and Table 16. Table 14 shows the years of treatment installation, the AADT slack used to select the comparison group, and the duration of the before and after periods. Table 15 and Table 16 present the number of sites in the treatment and comparison groups as well as the observed crash frequency and predicted crash frequency in the before and after periods. Table 15 focuses on total crashes and Table 16 focuses on fatal and injury crashes.
Table 14. Installation and duration of the before and after periods used to compute CMFs.

<table>
<thead>
<tr>
<th>Rumble Strips Type</th>
<th>Installation Year</th>
<th>AADT Slack</th>
<th>Number of Years Before Period</th>
<th>AADT Slack</th>
<th>Number of Years After Period</th>
<th>Installation Year</th>
<th>AADT Slack</th>
<th>Number of Years Before Period</th>
<th>AADT Slack</th>
<th>Number of Years After Period</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Minor Arterial</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Other Principal Arterial</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>2015, 2016, 2017</td>
<td>10%</td>
<td>5</td>
<td>3</td>
<td>2015, 2016, 2017</td>
<td>5%</td>
<td>5</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Both</td>
<td>2016, 2017, 2018</td>
<td>10%</td>
<td>5</td>
<td>3</td>
<td>2016, 2017, 2018</td>
<td>5%</td>
<td>5</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Arterials</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>2016, 2017</td>
<td>45%</td>
<td>5</td>
<td>3</td>
<td>2016, 2017</td>
<td>30%</td>
<td>5</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Both</td>
<td>2016, 2017</td>
<td>25%</td>
<td>5</td>
<td>3</td>
<td>2016, 2017</td>
<td>30%</td>
<td>5</td>
<td>3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 15. Summary of treatment and comparison sites used for the study of total crashes.

<table>
<thead>
<tr>
<th>Rumble Strips Type</th>
<th>Treatment group</th>
<th>Comparison Group1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed Crashes</td>
<td>Predicted Crashes</td>
</tr>
<tr>
<td></td>
<td>Sites Before</td>
<td>After</td>
</tr>
<tr>
<td><strong>Minor Arterial</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>10</td>
<td>16</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>Both</td>
<td>9</td>
<td>15</td>
</tr>
<tr>
<td><strong>Other Principal Arterial</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>25</td>
<td>49</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>Both</td>
<td>27</td>
<td>49</td>
</tr>
<tr>
<td><strong>Arterials</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>35</td>
<td>65</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>11</td>
<td>17</td>
</tr>
<tr>
<td>Both</td>
<td>31</td>
<td>56</td>
</tr>
</tbody>
</table>

1Note: as shown in the layout of the study, the before period is 5 years, and the after period 3 years.
Table 16. Summary of treatment and comparison sites used for study of fatal and injury crashes.

<table>
<thead>
<tr>
<th>Rumble Strips Type</th>
<th>Treatment group</th>
<th>Comparison Group¹</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed Crashes Before</td>
<td>After</td>
</tr>
<tr>
<td>Minor Arterial</td>
<td>4 6 5 2.3 1.4 58</td>
<td>89 68 34.9 21.7</td>
</tr>
<tr>
<td>Standard</td>
<td>2 5 3 1.6 1.0 36</td>
<td>51 43 19.9 12.4</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>4 7 5 2.8 1.7 62</td>
<td>85 72 34.1 21.2</td>
</tr>
<tr>
<td>Both</td>
<td>11 21 13 7.4 4.6 17</td>
<td>20 18 5.9 3.7</td>
</tr>
<tr>
<td>Other Principal Arterial</td>
<td>5 5 6 3.1 1.9 11</td>
<td>14 11 4.7 2.9</td>
</tr>
<tr>
<td>Standard</td>
<td>16 26 19 10.5 6.5 17</td>
<td>20 18 5.9 3.7</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>15 27 18 9.7 6.0 93</td>
<td>134 105 49.6 30.8</td>
</tr>
<tr>
<td>Both</td>
<td>2 4 3 1.7 1.0 59</td>
<td>83 65 31.6 19.6</td>
</tr>
<tr>
<td>Arterials</td>
<td>14 24 16 9.4 5.9 66</td>
<td>92 73 34.8 21.6</td>
</tr>
<tr>
<td>Standard</td>
<td>2 4 3 1.7 1.0 59</td>
<td>83 65 31.6 19.6</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>14 24 16 9.4 5.9 66</td>
<td>92 73 34.8 21.6</td>
</tr>
<tr>
<td>Both</td>
<td>5 6 7 3.1 1.9 11</td>
<td>14 11 4.7 2.9</td>
</tr>
<tr>
<td>Other Principal Arterial</td>
<td>5 5 6 3.1 1.9 11</td>
<td>14 11 4.7 2.9</td>
</tr>
<tr>
<td>Standard</td>
<td>16 26 19 10.5 6.5 17</td>
<td>20 18 5.9 3.7</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>15 27 18 9.7 6.0 93</td>
<td>134 105 49.6 30.8</td>
</tr>
<tr>
<td>Both</td>
<td>2 4 3 1.7 1.0 59</td>
<td>83 65 31.6 19.6</td>
</tr>
<tr>
<td>Arterials</td>
<td>14 24 16 9.4 5.9 66</td>
<td>92 73 34.8 21.6</td>
</tr>
</tbody>
</table>

¹Note: as shown in the layout of the study, the before period is 5 years, and the after period 3 years.

5.3 Safety Performance Functions

SPFs are developed for all arterials (minor arterials and other principal arterials) and rural two-lane roadways (major collectors, minor arterials, and other principal arterials), considering total and fatal and injury crashes. The SPFs are developed using the NB2 regression model. In all SPFs, the length of the roadway section, in miles, and the number of years (i.e., ten years) are included as an offset. Different variables related to the geometric characteristics and traffic of roadways are tested. These variables include but not limited to,

- Average annual daily traffic (AADT)
- Speed limit
- Left shoulder width (in feet)
- Right shoulder width (in feet)
- Average shoulder width (in feet)
- Lane width (in feet)
- Total width (in feet)
- Curve presence (1: yes, 0: no)
- Left turn lane count.

The shoulder widths (left and right) are correlated. Therefore, each of them is included in a different model. The average shoulder width is calculated and tested as a variable to account for both variables. The SPF models are presented in Table 17. In that table, the regression coefficients, standard errors, and p-values are provided. The table also includes an estimation of the inverse dispersion parameter for the NB model. All SPF models predict the number of head-on and opposite sideswipe collisions per year per mile of targeted cash.

It is worth mentioning that the first objective was to obtain the SPFs for each facility type. However, the number of crashes is insufficient, resulting in an estimated inverse dispersion parameter that showed no statistical significance. This makes the SPFs unreliable. Subsequently, to improve the SPFs, different rural-two-lane facility types are aggregated. This increases the amount of data used in the estimation and improves the SPFs. So, Table 17 present to cases: SPF fitted considering arterial rural two-lane roadways (minor arterial and other principal arterial), and SPF fitted considering rural two-lane roadways (major collector, minor arterial and other principal arterial). In both cases SPFs for total and fatal and injury crashes are fitted.
Table 17. SPFs fitted with 10 years of cross-sectional data.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Total Crashes</th>
<th>Fatal and Injury (KABC) Crashes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Arterials</td>
<td>Aggregated</td>
</tr>
<tr>
<td>Constant</td>
<td>-12.312***</td>
<td>-11.479***</td>
</tr>
<tr>
<td></td>
<td>(0.525)</td>
<td>(0.254)</td>
</tr>
<tr>
<td>Ln(AADT)</td>
<td>1.165***</td>
<td>1.082***</td>
</tr>
<tr>
<td></td>
<td>(0.061)</td>
<td>(0.031)</td>
</tr>
<tr>
<td>Curve presence</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No</td>
<td>Base</td>
<td>Base</td>
</tr>
<tr>
<td></td>
<td>0.397***</td>
<td>0.345***</td>
</tr>
<tr>
<td></td>
<td>(0.075)</td>
<td>(0.048)</td>
</tr>
<tr>
<td>Yes</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Base</td>
<td>Base</td>
</tr>
<tr>
<td></td>
<td>1,838</td>
<td>6,538</td>
</tr>
<tr>
<td>Road segments</td>
<td>815</td>
<td>2,092</td>
</tr>
<tr>
<td>Crashes</td>
<td>2,747.1</td>
<td>8,030.1</td>
</tr>
<tr>
<td>AIC</td>
<td>2,769.2</td>
<td>8,057.2</td>
</tr>
<tr>
<td>BIC</td>
<td>-1,369.5</td>
<td>-4,011.0</td>
</tr>
<tr>
<td>Log likelihood</td>
<td>7.622***</td>
<td>3.763***</td>
</tr>
<tr>
<td>Inverse dispersion Parameter</td>
<td>(3.485)</td>
<td>(0.713)</td>
</tr>
</tbody>
</table>

Note: *p<0.1; **p<0.05; ***p<0.01

5.4 CMF Development

Considering the SPFs in Table 17 and the EB comparison group study mentioned previously, the CMFs for different types of rumble strips (standard and sinusoidal) were calculated. When considering total crashes, the SPF fitted for arterial two-lane roadways was used. However, when considering fatal and injury (KABC) crashes the SPF fitted for rural two-lanes aggregated in was used since the one fitted for arterials was not reliable. Table 18 displays the computed CMFs and their safety effectiveness in head-on and opposite sideswipe crashes resulting from the implementation of centerline rumble strips. This table provides results for both total and fatal and injury crashes. However, since the total length of the major collectors with installed centerline rumble strips between 2015 and 2016 was approximately 4 miles, it was not possible to compute the CMFs. Nevertheless, only CMF computed for standard rumble strips in other principal arterials considering total crashes, showed evidence to be statistically significant. The results are presented in Table 18.
Table 18. Safety effectiveness of centerline rumble strips on head-on and sideswipe crashes in rural two-lanes roadways with multiple years of installation and five years period.

<table>
<thead>
<tr>
<th>Rumble Strips Type</th>
<th>Total Crashes CMF</th>
<th>SE</th>
<th>Crash Frequency Change (^\text{21})</th>
<th>Z-Test</th>
<th>Fatal and Injury Crashes (KABC) CMF</th>
<th>SE</th>
<th>Crash Frequency Change (^\text{2})</th>
<th>Z-Test</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Minor Arterial</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>0.96</td>
<td>0.38</td>
<td>-4%</td>
<td>0.11</td>
<td>0.94</td>
<td>0.58</td>
<td>-6%</td>
<td>0.10</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>0.78</td>
<td>0.42</td>
<td>-22%</td>
<td>0.52</td>
<td>0.58</td>
<td>0.43</td>
<td>-42%</td>
<td>0.98</td>
</tr>
<tr>
<td>Both</td>
<td>0.79</td>
<td>0.33</td>
<td>-21%</td>
<td>0.64</td>
<td>0.74</td>
<td>0.44</td>
<td>-26%</td>
<td>0.59</td>
</tr>
<tr>
<td><strong>Other Principal Arterial</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>0.67</td>
<td>0.16</td>
<td>-33%</td>
<td>2.06</td>
<td>0.63</td>
<td>0.23</td>
<td>-37%</td>
<td>1.61</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>1.30</td>
<td>0.64</td>
<td>30%</td>
<td>0.47</td>
<td>1.34</td>
<td>0.84</td>
<td>34%</td>
<td>0.40</td>
</tr>
<tr>
<td>Both</td>
<td>0.73</td>
<td>0.17</td>
<td>-27%</td>
<td>1.59</td>
<td>0.75</td>
<td>0.23</td>
<td>-25%</td>
<td>1.09</td>
</tr>
<tr>
<td><strong>Arterials</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>0.76</td>
<td>0.16</td>
<td>-24%</td>
<td>1.50</td>
<td>0.73</td>
<td>0.23</td>
<td>-27%</td>
<td>1.17</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>1.04</td>
<td>0.38</td>
<td>4%</td>
<td>0.11</td>
<td>0.82</td>
<td>0.63</td>
<td>-37%</td>
<td>0.29</td>
</tr>
<tr>
<td>Both</td>
<td>0.81</td>
<td>0.18</td>
<td>-19%</td>
<td>1.06</td>
<td>0.73</td>
<td>0.24</td>
<td>-27%</td>
<td>1.13</td>
</tr>
</tbody>
</table>

\(^1\) CMF estimates that were computed using a suitable comparison group and showed evidence of being statistically significant at least at the 10% level are stated in bold.

\(^2\) A negative change (-) shows a reduction. A positive change (+) shows an increase.

5.5 Summary and Recommendations

This chapter examined the effectiveness of rumble-strip installation in preventing lane-departure crashes in Maine’s rural two-lane roadways using an EB comparison group before-and-after study. The methodology involved comparing the observed and predicted crash frequency of a group of sites where the treatment has been installed and a group of comparison sites with similar characteristics but without the treatment. This method requires considerably more data than the comparison group and EB before-and-after studies for which the use of this method resulted in only one CMF with evidence of statistical significance, and it is recommended for use:

- Other principal arterial roadways with standard rumble strips for total crashes (33% reduction).
CHAPTER 6
ECONOMIC ANALYSIS

This chapter documents the findings of an economic analysis for installation of rumble strips. This chapter is divided into three sections. Section 6.1 provides an overview of the proposed method. Section 6.2 presents the results of the study. Section 6.3 presents the summary and conclusions.

6.1 Methodology

The economic analysis is performed by computing the benefit-cost ratio considering the roadway sections without the installation of rumble strips and the CMFs computed in Chapter 4. Chapter 4 presents significant CMFs for standard centerline rumble strips on rural, bidirectional, undivided, two-lane roadways targeting head-on and opposite sideswipe collisions. It is noteworthy that significant CMFs are found for the facility types: minor arterial segments, other principal arterial segments, and all arterial segments together. Thus, the economic analysis focuses on these scenarios.

The benefits are assumed to be savings on the crash cost if rumble strips are installed. To estimate the savings, the total crash cost should first be computed and then converted to savings multiplying by (1-CMF). However, to use the same units, the savings are converted to USD per mile per year, dividing by the number of miles and years considered in the crash counts. The cost is considered as the rumble-strip installation cost per mile divided by the number of years of service life. With this, the benefit-cost ratio (BC) is computed using Eq. (28).

\[
BC = \frac{(\text{Crash cost per mile per year}) \cdot (1 - \text{CMF})}{\text{(Cost of installation per mile per year)}}
\] (28)

6.2 Benefit-Cost Ratio

The total crash cost is estimated using the value of unit crash cost per severity for the state of Maine. This information was provided by the Federal Highway Administration (Harmon et al., 2018). The total crash cost by severity is computed by multiplying the cost of a crash by the number of crashes.
Then, the total cost by severity is computed by summing over all costs. The total cost of head-on and opposite sideswipe collisions on rural two-lane roadways is listed in Table 19. Knowing the total crash cost, the number of years (10 years, from 2010 to 2019), the length of the roadway sections used in the estimation, and the CMF, the cost is converted to savings per mile per year. The number of miles and the countermeasure effectiveness (1-CMFs) are shown in Table 20.

### Table 19. Estimation of total crash cost of head-on and sideswipe collisions for rural two-lane roadways in Maine

<table>
<thead>
<tr>
<th>Crash Severity</th>
<th>Unit Crash Cost</th>
<th>Number of Crashes</th>
<th>Total Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Minor Arterial</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>$304,400</td>
<td>62</td>
<td>$18,872,800</td>
</tr>
<tr>
<td>B</td>
<td>$111,200</td>
<td>114</td>
<td>$12,676,800</td>
</tr>
<tr>
<td>C</td>
<td>$62,700</td>
<td>206</td>
<td>$12,916,200</td>
</tr>
<tr>
<td>K</td>
<td>$5,740,100</td>
<td>29</td>
<td>$166,462,900</td>
</tr>
<tr>
<td>PDO</td>
<td>$10,100</td>
<td>853</td>
<td>$8,615,300</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>$219,544,000</strong></td>
</tr>
<tr>
<td><strong>Other Principal Arterial</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>$304,400</td>
<td>39</td>
<td>$11,871,600</td>
</tr>
<tr>
<td>B</td>
<td>$111,200</td>
<td>59</td>
<td>$6,560,800</td>
</tr>
<tr>
<td>C</td>
<td>$62,700</td>
<td>111</td>
<td>$6,959,700</td>
</tr>
<tr>
<td>K</td>
<td>$5,740,100</td>
<td>4</td>
<td>$22,960,400</td>
</tr>
<tr>
<td>PDO</td>
<td>$10,100</td>
<td>469</td>
<td>$4,736,900</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>$53,089,400</strong></td>
</tr>
<tr>
<td><strong>Arterials</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>$304,400</td>
<td>101</td>
<td>$30,744,400</td>
</tr>
<tr>
<td>B</td>
<td>$111,200</td>
<td>173</td>
<td>$19,237,600</td>
</tr>
<tr>
<td>C</td>
<td>$62,700</td>
<td>317</td>
<td>$19,875,900</td>
</tr>
<tr>
<td>K</td>
<td>$5,740,100</td>
<td>33</td>
<td>$189,423,300</td>
</tr>
<tr>
<td>PDO</td>
<td>$10,100</td>
<td>1322</td>
<td>$13,352,200</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>$272,633,400</strong></td>
</tr>
</tbody>
</table>

### Table 20. Number of miles and (1-CMFs) used in the savings estimation.

<table>
<thead>
<tr>
<th>Facility Type</th>
<th>Roadway Miles</th>
<th>(1-CMF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minor Arterial</td>
<td>720.52</td>
<td>0.47</td>
</tr>
<tr>
<td>Other Principal Arterial</td>
<td>324.75</td>
<td>0.44</td>
</tr>
<tr>
<td>Arterials</td>
<td>1045.27</td>
<td>0.42</td>
</tr>
</tbody>
</table>
The cost of rumble-strip installation per mile, as provided by the Maine Department of Transportation (MaineDOT), is $3,500 per mile. A study on the safety effectiveness of centerline plus rumble strips on two-lane rural roads by Persaud et al. (2016) reported that the service life of rumble strips in Missouri and Kentucky is 7–10 years and 12–15 years, respectively. To ensure a conservative estimate, we considered the 7-year service life as the lowest service life applicable to rumble strips in Maine. The results of the analysis, accounting for this assumption, are shown in Table 21. Even under the assumption of the shortest service life, the minimum benefit-cost ratio remains at 14.4 (for other principal arterials), confirming the cost-effectiveness of the treatment. Furthermore, the analysis is extended by considering a rumble-strip service life of 10 years, which is assumed to be the highest service life of rumble strips in Maine. The results of the analysis, taking this assumption into account as presented in Table 22. Both scenarios suggest that treatment is cost-effective for all facility types. Under the assumption of a higher service life, the minimum benefit-cost ratio remains at 20.6 (for other principal arterials), confirming the cost-effectiveness of the treatment.

<table>
<thead>
<tr>
<th>Table 21. Benefit-cost ratio estimation considering a rumble strips service life of 7 years.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total Crash Cost</strong></td>
</tr>
<tr>
<td>----------------------</td>
</tr>
<tr>
<td><strong>Minor Arterial</strong></td>
</tr>
<tr>
<td><strong>Other Principal Arterial</strong></td>
</tr>
<tr>
<td><strong>Arterials</strong></td>
</tr>
</tbody>
</table>
Table 22. Benefit-cost ratio estimation considering a rumble-strip service life of 10 years.

<table>
<thead>
<tr>
<th></th>
<th>Total Crash Cost</th>
<th>Crash Cost per Mile</th>
<th>Crash Cost per Mile per Year</th>
<th>Benefit</th>
<th>Rumble-Strip Cost per Mile per Year</th>
<th>Benefit-Cost Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minor Arterial</td>
<td>$219,544,000</td>
<td>$304,702</td>
<td>$30,470</td>
<td>$14,321</td>
<td>$350</td>
<td>40.9</td>
</tr>
<tr>
<td>Other Principal Arterial</td>
<td>$53,089,400</td>
<td>$163,476</td>
<td>$16,348</td>
<td>$7,193</td>
<td>$350</td>
<td>20.6</td>
</tr>
<tr>
<td>Arterials</td>
<td>$27,263,340</td>
<td>$260,825</td>
<td>$26,082</td>
<td>$10,950</td>
<td>$350</td>
<td>31.3</td>
</tr>
</tbody>
</table>

6.3 Summary and Conclusions

In this chapter, a comprehensive analysis conducted to determine the benefit-cost ratio of implementing rumble strips as a safety measure to mitigate head-on and opposite sideswipe collisions on rural two-lane roadways. The economic benefits were evaluated by quantifying the potential savings in crash-related expenses that would result from the installation of rumble strips and compared these benefits to the associated installation costs. The findings indicated that the installation of rumble strips is a highly cost-effective approach for analyzed facilities. Even when factoring in the most conservative estimates for service life and cost, the benefits outweigh the costs by a significant margin, with a ratio of nearly 14 to 1.
CHAPTER 7
SUMMARY AND RECOMMENDATIONS

The aim of this study was to assess the impact of sinusoidal and standard centerline rumble strips on the frequency of head-on and opposite sideswipe crashes in Maine’s rural two-lane roadways using a before-and-after studies. Two methods were used: comparison group (Chapter 4), and EB comparison group (Chapter 5). The results of the EB before-and-after study was also documented in Appendix B. The study analyzed 12 years of crash records and roadway segment information provided by the MaineDOT considering total and fatal and injury (KABC) crashes.

The comparison group method considers the aggregated crashes of all treatment/comparison sites during the entire duration of the before and after periods; the duration of the before and periods must be the same. However, this method does not necessarily address the regression to the mean phenomena. To overcome this limitation, a suitable comparison group was selected. The selection of a suitable comparison group is based on selection of sites with similar geometric and traffic characteristics and yearly crash trend in the period prior to the installation of the countermeasure, in this case, rumble strips. The selection of similar geometric and traffic characteristics is easier than that of a similar crash trend. A comparability test was performed for this purpose. It is worth mentioning again that for this method to address the regression to the mean (to some degree), a suitable comparison group must be used. However, this method requires less data than EB and EB comparison group.

The EB method addresses the regression to the mean; it is not restricted to having the same duration in the before and after periods, and it is considered one of the most robust before-and-after studies. It addresses the regression to the mean predicting the number crash frequency if no countermeasure is installed using the SPF. It also considers the dispersion of the data using the dispersion parameter obtained from the SPF. However, this requires more data because the analysis is
not performed with aggregated crashes but with crashes per section per year. In addition, SPFs are necessary; if SPFs are not available, data for fitting them are also necessary. This increases the data requirements, because fitting reliable SPFs requires much more data than 5 years of crashes.

The EB comparison group method is a combination of the comparison group and EB methods. It is also a method that requires additional data. It can also underestimate the effect of the countermeasure of analysis, in this case the rumble strips, since it cannot consider sites that experienced zero crashes either in the before or after period. This method also addresses the regression to mean and requires SPFs. However, this method does not explicitly require the dispersion parameter. The comparison group did not require a comparability test because the crash trends are considered in the SPF. However, the comparison group must have geometric and traffic characteristics that are similar to those of the treatment group. This method is not restricted to before and after periods to have the same duration.

Estimating the effects of centerline rumble strips was challenging due to the type of crash that it impacts. Despite being one of the most serious types of crash, it is one of the less frequent types of lane-departure collisions. This created the challenge of lack of data. In addition, the stay-at-home restrictions of 2020 also restricted the data available for the study because they disrupted the normal traffic characteristics, and this effect was not possible to capture in the SPFs with the available data. One way to overcome this is to use comparison group-based methods, because both the treatment and comparison groups are affected in the same way.

This study found the percentage change in the crash frequency for a specific combination of roadway facilities and types of rumble strips. Most of the effects were estimated using the comparison group method; however, there are also results from the EB comparison group method. All the reliable CMFs are presented in Table 23.
Table 23. Safety effectiveness of centerline rumble strips for rural two-lane roadways.

<table>
<thead>
<tr>
<th>Rumble Strip Type</th>
<th>Crash Severity</th>
<th>Method</th>
<th>CMF</th>
<th>SE</th>
<th>Crash Frequency Change</th>
<th>Z-Test</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Minor Arterial</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>All Crashes</td>
<td>Comparison group</td>
<td>0.53</td>
<td>0.17</td>
<td>-47%</td>
<td>2.82</td>
</tr>
<tr>
<td>Both</td>
<td>Fatal and injury</td>
<td>Comparison group</td>
<td>0.56</td>
<td>0.24</td>
<td>-44%</td>
<td>1.81</td>
</tr>
<tr>
<td><strong>Other Principal Arterials</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>All Crashes</td>
<td>Comparison group</td>
<td>0.56</td>
<td>0.14</td>
<td>-44%</td>
<td>3.16</td>
</tr>
<tr>
<td>Standard</td>
<td>All Crashes</td>
<td>EB comparison group</td>
<td>0.67</td>
<td>0.16</td>
<td>-33%</td>
<td>2.06</td>
</tr>
<tr>
<td>Standard</td>
<td>Fatal and injury</td>
<td>Comparison group</td>
<td>0.52</td>
<td>0.17</td>
<td>-48%</td>
<td>2.84</td>
</tr>
<tr>
<td>Both</td>
<td>All Crashes</td>
<td>Comparison group</td>
<td>0.68</td>
<td>0.14</td>
<td>-32%</td>
<td>2.23</td>
</tr>
<tr>
<td><strong>Arterials</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>All Crashes</td>
<td>Comparison group</td>
<td>0.58</td>
<td>0.13</td>
<td>-42%</td>
<td>3.26</td>
</tr>
<tr>
<td>Standard</td>
<td>Fatal and injury</td>
<td>Comparison group</td>
<td>0.46</td>
<td>0.13</td>
<td>-54%</td>
<td>4.10</td>
</tr>
<tr>
<td>Both</td>
<td>All Crashes</td>
<td>Comparison group</td>
<td>0.72</td>
<td>0.14</td>
<td>-28%</td>
<td>1.91</td>
</tr>
<tr>
<td>Both</td>
<td>Fatal and injury</td>
<td>Comparison group</td>
<td>0.65</td>
<td>0.17</td>
<td>-35%</td>
<td>2.06</td>
</tr>
</tbody>
</table>

1A negative change (−) shows a reduction. A positive change (+) shows an increase.

The specific changes in the crash frequency due to rumble strip installation computed with the comparison group method are listed below.

- Standard centerline rumble strips installed in minor arterials reduced the total crash frequency of head-on and opposite sideswipe collisions by 47%.
- Standard and sinusoidal centerline rumble strips in minor arterials reduced the fatal and injury crash frequency of head-on and opposite sideswipe collisions by 44%.
- Standard centerline rumble strips installed in other principal arterials reduced the total crash frequency of head-on and opposite sideswipe collisions by 44%.
- Standard centerline rumble strips installed in other principal arterials reduced the fatal and injury crash frequency of head-on and opposite sideswipe collisions by 48%.
- Standard and sinusoidal centerline rumble strips in other principal arterials reduced the total crash frequency of head-on and opposite sideswipe collisions by 32%.
- Standard centerline rumble strips installed in arterial roadways reduced the total crash frequency of head-on and opposite sideswipe collisions by 42%.
• Standard centerline rumble strips installed in arterial roadways reduced the fatal and injury crash frequency of head-on and opposite sideswipe collisions by 54%.

• Standard and sinusoidal centerline rumble strips installed in arterial roadways reduced the total crash frequency of head-on and opposite sideswipe collisions by 28%.

• Standard and sinusoidal centerline rumble strips installed in arterial roadways reduced the fatal and injury crash frequency of head-on and opposite sideswipe collisions by 35%.

The specific changes in the crash frequency due to rumble strip installation computed with the EB comparison group method are listed below.

• Standard centerline rumble strips installed in other principal arterials reduced the total crash frequency of head-on and opposite sideswipe collisions by 33%.

Likewise, the economic benefits in installation of centerline rumble strips on rural two-lanes was assessed by computing the potential savings in expenses associated with and compared that with the cost of installation. The research suggests that the installation of rumble strips is a highly cost-effective solution for the analyzed facilities. Even when considering the most conservative estimates for service life and cost, the benefits exceed the costs by a considerable margin, with a ratio of nearly 14 to 1.

Finally, it is worth posting out that an additional effective countermeasure for reducing head-on crashes is the consideration of cable barriers. Qawasmeh & Eustace (2021) conducted a systematic review of the cable barriers effectiveness in preventing cross median crashes. Examining data from 12 states, they found a reduction range of 50% to 96% in total crashes, and 42% to 93% considering fatal and serious injuries. However, it is important to note that the cable barrier reduces the lane departure collisions, but the cars still impact the barrier, however, as shown by Zou et al. (2014) hitting a barrier is associated with a lower risk of injury, specifically for cable barriers the odds of injury reduced between 78% and 85%.
BIBLIOGRAPHY


APPENDICES

APPENDIX A: COMPUTED CMFs WITH A SINGLE INSTALLATION YEAR AND 3 YEARS OF BEFORE-AND-AFTER PERIODS

This section presents the results of the comparability test and CMFs computed with the comparison group method using a 3-year duration for the before and after periods.

Table A-1. Comparability test results.

<table>
<thead>
<tr>
<th>Rumble Strips Type</th>
<th>Total Crashes</th>
<th>Fatal and Injury Crashes (KABC)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lower 95%</td>
<td>Upper 95%</td>
</tr>
<tr>
<td></td>
<td>SE CL</td>
<td>CMF SE CL</td>
</tr>
<tr>
<td>Minor Arterial</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>2017</td>
<td>0.77 0.54 -0.3 1.83 35%</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>2018</td>
<td>0.47 0.36 -0.23 1.18 5%</td>
</tr>
<tr>
<td>Both</td>
<td>2017</td>
<td>0.77 0.54 -0.28 1.82 35%</td>
</tr>
<tr>
<td>Other Principal Arterial</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>2016</td>
<td>0.87 0.34 0.21 1.535 1%</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>2018</td>
<td>0.76 0.43 -0.07 1.60 1%</td>
</tr>
<tr>
<td>Both</td>
<td>2017</td>
<td>0.97 0.44 0.10 1.83 5%</td>
</tr>
<tr>
<td>Arterials</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>2017</td>
<td>0.80 0.23 0.35 1.25 35%</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>2018</td>
<td>0.62 0.25 0.13 1.10 25%</td>
</tr>
<tr>
<td>Both</td>
<td>2017</td>
<td>0.86 0.15 0.57 1.16 35%</td>
</tr>
</tbody>
</table>

Note: CMF estimates that are subjectively close to 1 (within 0.9 and 1.1) and showed evidence to be statistically significant at the 5% level are stated in bold.
Table A-2. Safety effectiveness of centerline rumble strips.

<table>
<thead>
<tr>
<th>Rumble Strips Type</th>
<th>Total Crashes</th>
<th>Fatal and Injury Crashes (KABC)</th>
<th>Z-Test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Year</td>
<td>CMF</td>
<td>SE</td>
</tr>
<tr>
<td><strong>Minor Arterial</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>2017</td>
<td>0.31</td>
<td>0.13</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>2018</td>
<td>0.55</td>
<td>0.22</td>
</tr>
<tr>
<td>Both</td>
<td>2017</td>
<td>0.33</td>
<td>0.14</td>
</tr>
<tr>
<td><strong>Other Principal Arterial</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>2016</td>
<td>0.69</td>
<td>0.20</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>2018</td>
<td>0.31</td>
<td>0.16</td>
</tr>
<tr>
<td>Both</td>
<td>2017</td>
<td>0.99</td>
<td>0.35</td>
</tr>
<tr>
<td><strong>Arterials</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>2017</td>
<td>0.52</td>
<td>0.15</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>2018</td>
<td>0.44</td>
<td>0.15</td>
</tr>
<tr>
<td>Both</td>
<td>2017</td>
<td>0.60</td>
<td>0.16</td>
</tr>
</tbody>
</table>

1 CMF estimates that were computed using a suitable comparison group and showed evidence of being statistically significant at least at the 10% level are stated in bold.

2 A negative change (-) shows a reduction. A positive change (+) shows an increase.
APPENDIX B: BEFORE-AND-AFTER STUDY WITH EMPIRICAL BAYES

This appendix documents the findings of the EB before-and-after study. This chapter is divided into five sections. Section B.1 provides a comprehensive overview of the methodology in three parts. Section B.1.1 documents the general scope of the EB before-after studies. Section B.1.2 outlines the steps taken to compute the CMFs. Section B.1.3 documents how to estimate the SPF. Section B.2 describes the selection of the treatment sites used in the study. Sections B.3 and B.4 present the estimated and computed CMFs, respectively. Finally, Section B.5 provides a summary of the study and recommendations.

B.1 Methodology

The EB method for before-and-after studies accounts for the issue of regression to the mean and stands as one of the most reliable methods for estimating CMFs and quantifying the safety effectiveness of countermeasures. The subsequent subsections delineate the procedures entailed in before-and-after studies using the EB methodology.

B.1.1 Before-After Studies with EB

This method uses SPFs to account for the regression to the mean issue by weighting the observed crash frequency with the average crash frequency predicted using the SPF (AASHTO, 2010). The HSM (AASHTO, 2010). also states that safety evaluation using the EB method requires at least 10 to 20 treatment sites and three to five years of crash records in the before and after periods. However, the safety evaluation can still be performed with fewer sites or years, but the results are less likely to show evidence of statistical significance.

B.1.2 Computing CMFs

In the context of the EB before-and-after study, the CMF and the percentage of safety improvement are derived by applying Eq. (29), and Eq. (30).
CMF = \sum_i \frac{N_{\text{observed},A}}{\sum_i N_{\text{expected},A}} \frac{\text{Var} \left[ \sum_i N_{\text{expected},A} \right]}{(\sum_i N_{\text{expected},A})^2} 

\Delta \text{safety} = (1 - \text{CMF}) \times 100 

Furthermore, the variance of CMF is computed using Eq. (31).

\text{Var}(\text{CMF}) = \frac{\text{CMF}^2 \times \left( \frac{1}{N_{\text{observed},A}} + \frac{\text{Var} \left[ \sum_i N_{\text{expected},A} \right]}{(\sum_i N_{\text{expected},A})^2} \right)}{1 + \frac{\text{Var} \left[ \sum_i N_{\text{expected},A} \right]}{(\sum_i N_{\text{expected},A})^2}} 

The variable \( N_{\text{expected},A} \) is found using Eq. (32).

\[ N_{\text{expected},A} = N_{\text{expected},B} \times \frac{N_{\text{predicted},A}}{N_{\text{predicted},B}} \]

Where,

\( N_{\text{expected},B} \): the expected number of crashes in the before period at the i-th site with treatment.

\( N_{\text{predicted},B} \): the predicted number of crashes in the before period at the i-th site with treatment.

\( N_{\text{predicted},A} \): the predicted number of crashes in the after period at the i-th site with treatment.

The predictions of \( N_{\text{predicted},B} \) and \( N_{\text{predicted},A} \) are computed using SPFs. In this study, SPFs were developed using the data collected in Maine. To estimate the number of crashes expected in the before period at the sites with the countermeasure \( N_{\text{expected},B} \), the EB method is applied using Eq. (33) and Eq. (34).

\[ N_{\text{expected},B} = w_{i,B} \times N_{\text{predicted},B} + (1 - w_{i,B}) \times N_{\text{observed},B} \]

\[ w_{i,B} = \frac{1}{1 + \frac{\text{Var}[N_{\text{predicted},B}]}{E[N_{\text{predicted},B}]} \times \frac{1}{N_{\text{predicted},B}}} \]

Where,

\( N_{\text{observed},B} \): the number of crashes observed in the before period at the i-th treated site.
\( N_{\text{predicted},B}^i \) : the number of crashes predicted in the before period at the i-th treated site.

\( w_{i,B} \) : the weight for the i-th site.

The expected value (\( E[N_{\text{predicted},B}^i] \)) and variance (\( \text{Var}[N_{\text{predicted},B}^i] \)) of the predicted number of crashes in the before period depend on the model used to develop the SPFs. In this case, a negative binomial (NB) model was chosen. Subsequently, the weight presented in Eq. (34) is equivalent to Eq. (35).

\[
 w_{i,B} = \frac{1}{1 + (\theta \times \sum N_{\text{predicted},B}^i)}
\]  

(35)

Where,

\( \theta \) : the dispersion parameter of the NB model.

To estimate the expected number of crashes in the after period (\( N_{\text{expected},A}^i \)), changes in different factors, such as the traffic volume, from the before to the after period must be considered. Accounting for these changes is accomplished with the ratio of SPF prediction in the after and before periods as shown in Eq. (36).

\[
 N_{\text{expected},A}^i = N_{\text{expected},B}^i \times \frac{N_{\text{predicted},A}^i}{N_{\text{predicted},B}^i}
\]  

(36)

Where,

\( N_{\text{expected},B}^i \): number of expected crashes in the before period at the i-th treated site.

\( N_{\text{predicted},A}^i \): number of predicted crashes in the after period at the i-th treated site.

\( N_{\text{predicted},B}^i \): number of predicted crashes in the before period at the i-th treated site.

**B.2 Treatment Sites**

This study focuses on the rural two-lane roadways in Maine. The data include information on roadway elements (including rumble-strip information) and crash records. The rumble-strip data include variables such as length, unique element identification, type of rumble-strip (standard or
sinusoidal), rumble-strip location (centerline, left edge, or right edge), and year of installation. Crash records have data from January 2010 to December 2022, containing information such as the type of crash, unique crash identification, type of crash, date, hour, injuries, and location. Information on the crash data was combined with rumble-strip data to create a final database for the study. This contains information about the crash and rumble strips of the element where the crash occurred. Because head-on crashes are uncommon, different years of installation were considered for each combination facility and rumble-strip type to increase the number of sites and crashes. The treatment sites were then selected considering the geometric and roadway characteristics, year of rumble-strip installation, and segment length. Considering the geometric and roadway characteristics, the selected sites included rural, two-lane, bidirectional, and undivided segments with centerline rumble strips. Only the segments with lengths greater than or equal to 0.1 miles were considered for analysis.

Typically, before-and-after studies employ durations ranging from three to five years for analysis. The duration of the before and after period does not necessarily have to match. In this study, the choice of the 'before' and 'after' period durations is guided by the availability of crash records spanning from 2010 to 2022. Additionally, it is imperative to acknowledge the unique impact of stay-at-home order restrictions resulting from the COVID-19 pandemic in 2020 on traffic volumes and driver behavior (Marshall, Shirazi, & Ivan, 2023; Marshall, Shirazi, Shahlae, et al., 2023; Shahlae et al., 2022). Consequently, crash records from 2020 onwards are excluded from analysis. This limitation led to considering the year 2016 as the most recent installation year that three years ‘after’ data is readily available. Furthermore, to increase the robustness of analysis, a five-year duration is also chosen for the 'before' period. Thus, only rumble-strip installations occurring in 2015 and 2016 are considered for analysis, with a 'before' period of five years and an 'after' period of three years. The layout of the study is presented in Tables B-1, B-2, and B-3. Table B-1 lists the selected years of installation and the
durations of the before and after periods. In some cases, for example, with minor arterials, standard rumble strips were installed in 2015 and 2016; therefore, both years are considered, but sinusoidal rumble strips were installed only in 2016. When evaluating both types of rumble strips together, only 2016 is used because the installation of both types occurred in that year. Tables B-2 and B-3 and summarizes the number of sites, miles, and crashes used for each case for total and fatal and injury (KABC) crashes, respectively.

Table B-1. Installation years and duration of the before and after periods used to compute CMFs.

<table>
<thead>
<tr>
<th>Rumble Strips Type</th>
<th>Total Crashes</th>
<th>Fatal and Injury Crashes (KABC)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Installation Year</td>
<td>Years in Before Period</td>
</tr>
<tr>
<td><strong>Minor Arterial</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>2015, 2016</td>
<td>5</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>2016</td>
<td>5</td>
</tr>
<tr>
<td>Both</td>
<td>2016</td>
<td>5</td>
</tr>
<tr>
<td><strong>Other Principal Arterial</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>2015, 2016</td>
<td>5</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>2015, 2016</td>
<td>5</td>
</tr>
<tr>
<td>Both</td>
<td>2015, 2016</td>
<td>5</td>
</tr>
<tr>
<td><strong>Arterials</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>2015, 2016</td>
<td>5</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>2016</td>
<td>5</td>
</tr>
<tr>
<td>Both</td>
<td>2016</td>
<td>5</td>
</tr>
</tbody>
</table>
Table B-2. Summary of treatment sites used for the safety effectiveness of centerline rumble strips considering total crashes.

<table>
<thead>
<tr>
<th>Rumble Strips Type</th>
<th>Sites</th>
<th>Miles</th>
<th>Observed Crashes Before</th>
<th>Observed Crashes After</th>
<th>Predicted Crashes Before</th>
<th>Predicted Crashes After</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Minor Arterial</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>40</td>
<td>25.2</td>
<td>49</td>
<td>13</td>
<td>23.7</td>
<td>15.0</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>4</td>
<td>4.7</td>
<td>5</td>
<td>3</td>
<td>2.9</td>
<td>1.8</td>
</tr>
<tr>
<td>Both</td>
<td>13</td>
<td>10.8</td>
<td>14</td>
<td>5</td>
<td>8.16</td>
<td>5.1</td>
</tr>
<tr>
<td><strong>Other Principal Arterial</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>117</td>
<td>66.4</td>
<td>105</td>
<td>43</td>
<td>41.9</td>
<td>43.2</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>35</td>
<td>23.4</td>
<td>42</td>
<td>21</td>
<td>25.5</td>
<td>15.9</td>
</tr>
<tr>
<td>Both</td>
<td>152</td>
<td>89.8</td>
<td>147</td>
<td>64</td>
<td>94.9</td>
<td>59.2</td>
</tr>
<tr>
<td><strong>Arterials</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>157</td>
<td>91.5</td>
<td>154</td>
<td>56</td>
<td>93.1</td>
<td>58.3</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>27</td>
<td>21.7</td>
<td>29</td>
<td>17</td>
<td>19.3</td>
<td>12.0</td>
</tr>
<tr>
<td>Both</td>
<td>196</td>
<td>119.7</td>
<td>201</td>
<td>80</td>
<td>121.6</td>
<td>76.0</td>
</tr>
</tbody>
</table>

Table B-3. Summary of treatment sites used for the safety effectiveness of centerline rumble strips considering fatal and injury (KABC) crashes.

<table>
<thead>
<tr>
<th>Rumble Strips Type</th>
<th>Sites</th>
<th>Miles</th>
<th>Observed Crashes Before</th>
<th>Observed Crashes After</th>
<th>Predicted Crashes Before</th>
<th>Predicted Crashes After</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Minor Arterial</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>40</td>
<td>25.2</td>
<td>38</td>
<td>7</td>
<td>13.4</td>
<td>8.4</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>4</td>
<td>4.7</td>
<td>4</td>
<td>3</td>
<td>1.7</td>
<td>1.0</td>
</tr>
<tr>
<td>Both</td>
<td>13</td>
<td>10.8</td>
<td>12</td>
<td>4</td>
<td>4.7</td>
<td>2.9</td>
</tr>
<tr>
<td><strong>Other Principal Arterial</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>117</td>
<td>66.4</td>
<td>63</td>
<td>26</td>
<td>38.6</td>
<td>24.0</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>35</td>
<td>23.4</td>
<td>24</td>
<td>14</td>
<td>14.2</td>
<td>8.8</td>
</tr>
<tr>
<td>Both</td>
<td>152</td>
<td>89.8</td>
<td>87</td>
<td>40</td>
<td>52.8</td>
<td>32.8</td>
</tr>
<tr>
<td><strong>Arterials</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>157</td>
<td>91.5</td>
<td>101</td>
<td>33</td>
<td>51.2</td>
<td>32.5</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>27</td>
<td>21.7</td>
<td>15</td>
<td>11</td>
<td>10.9</td>
<td>6.7</td>
</tr>
<tr>
<td>Both</td>
<td>196</td>
<td>119.7</td>
<td>129</td>
<td>50</td>
<td>67.9</td>
<td>42.3</td>
</tr>
</tbody>
</table>

B.3 CMF Development

The implementation of a countermeasure, such as rumble strips, is anticipated to influence the trend in crash occurrences. CMFs serve as a metric for assessing the effectiveness of safety treatments, illustrating the extent to which the countermeasure, like rumble strips, alters the frequency of crashes. In other words, when the CMF is known, it facilitates the determination of the countermeasure's safety
effectiveness in terms of crash reduction. Using the SPFs presented in chapter 5.3 and the EB before-and-after study noted earlier, the CMFs for different rumble-strip types (standard and sinusoidal) are computed. Table B-4 presents the CMFs and safety effectiveness of centerline rumble strips in reduction of head-on and opposite sideswipe crashes. The total length of the major collectors with installed centerline rumble strips between 2015 and 2016 is too small (~4 miles) to compute the CMFs. Therefore, no results are presented. However, reliable CMFs were obtained for standard and both types of rumble strips considering total and fatal and injury (KABC) crashes on arterials. Also, for standard rumble strips considering fatal and injury (KABC) crashes on minor arterials. Table B-4 presents the results.

Table B-4. Safety effectiveness of centerline rumble strips on head-on and sideswipe crashes in rural two-lane roadways with multiple years of installation and a five-year period.

<table>
<thead>
<tr>
<th>Rumble Strips Type</th>
<th>Total Crashes</th>
<th>Fatal and Injury Crashes (KABC)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CMF</td>
<td>SE</td>
</tr>
<tr>
<td><strong>Minor Arterial</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>0.80</td>
<td>0.23</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>1.47</td>
<td>0.93</td>
</tr>
<tr>
<td>Both</td>
<td>0.93</td>
<td>0.43</td>
</tr>
<tr>
<td><strong>Other Principal Arterial</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>0.94</td>
<td>0.15</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>1.27</td>
<td>0.29</td>
</tr>
<tr>
<td>Both</td>
<td>1.07</td>
<td>0.14</td>
</tr>
<tr>
<td><strong>Arterials</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard</td>
<td>0.94</td>
<td>0.13</td>
</tr>
<tr>
<td>Sinusoidal</td>
<td>1.38</td>
<td>0.35</td>
</tr>
<tr>
<td>Both</td>
<td>1.03</td>
<td>0.12</td>
</tr>
</tbody>
</table>

1CMF estimates that showed evidence of being statistically significant at least at the 10% level are stated in bold.
2A negative change (-) shows a reduction. A positive change (+) shows an increase.

B.4 Summary and Conclusions

This appendix documented the CMFs and the percentage of change in safety upon installation of centerline rumble strips on rural two-lanes in Maine using the EB before-and-after study. SPFs were
fitted, and CMFs were computed for total and fatal and injury head-on and opposite sideswipe collisions considering multiple years of rumble-strip installation. The study found inconclusive results since none of the CMFs showed evidence of statistical significance. The use of the CMFs presented in this chapter is not recommended.
APPENDIX C: CODE FOR COMPARISON GROUP BEFORE-AND-AFTER STUDY

The section presents a sample Python code of the developed functions for the comparison group before-and-after evaluation. In each case, only the core part of the code is shown, that is, excluding data entry and manipulation.

Function to prepare the treatment group data.

```python
def prepare_treatment_data(df_data, treatment_query, crash_count):
    """Prepares treatment data for analysis.
    Parameters:
    -----------
    - df_data (pd.DataFrame): The input DataFrame containing the raw data.
    - treatment_query (str): The query string to filter the data for the treatment group.
    - crash_count (str): The column name representing crash counts.
    Returns:
    -------
    - df_treatment (pd.DataFrame): The DataFrame containing the filtered treatment data.
    - obs_treat_before (int): The sum of crash counts for the treatment group before the treatment.
    - obs_treat_after (int): The sum of crash counts for the treatment group after the treatment.
    """

    # Study data
    df_treatment = (df_data
                    .query(treatment_query)
                    .reset_index(drop=True))

    # Aggregate crash counts
    obs_treat_before = (df_treatment
                         .query("BEFORE_AFTER_5Y == 'Before'")
                         [crash_count].sum())

    obs_treat_after = (df_treatment
                        .query("BEFORE_AFTER_5Y == 'After'")
                        [crash_count].sum())
    return(df_treatment, obs_treat_before, obs_treat_after)
```


Function to prepare the comparison group data.

def prepare_comparison_data(
    df_data,
    df_treatment,
    slack,
    comparison_query,
    crash_count,
    years_before,
    years_after
):
    """Prepares the comparison group data for analysis.

Parameters:
------------
- df_data (pd.DataFrame): The input DataFrame containing the raw data.
- df_treatment (pd.DataFrame): The DataFrame containing the filtered treatment data.
- slack (float): The slack value for AADT range comparison.
- comparison_query (str): The query string to filter the data for the comparison group.
- crash_count (str): The column name representing crash counts.
- years_before (list): The list of years for the period before treatment.
- years_after (list): The list of years for the period after treatment.

Returns:
--------
- df_comparison (pd.DataFrame): The DataFrame containing the filtered comparison data.
- obs_comp_before (int): The sum of crash counts for the comparison group before the treatment.
- obs_comp_after (int): The sum of crash counts for the comparison group after the treatment.
""

# Comparison roads data
df_comparison_roads = (df_data
                      .query(comparison_query)
                      .drop_duplicates(subset=['ID_NS'])
                      .reset_index(drop=True)
                      )

# Subset unique AADT values in the treatment group
df_treatment_aadt = (df_treatment
                      .drop_duplicates(subset=['AADT_EF_2016'])
                      .reset_index(drop=True)
                      )

# Initialize an empty list to store the rows of df2 that meet the condition
selected_rows = []

# Iterate through each row in df2
for index, row_comparison in df_comparison_roads.iterrows():
    aadt_comparison = row_comparison['AADT_EF_2016']

    # Check if aadt_df2 is within any range in df1
    for _, row_treatment in df_treatment_aadt.iterrows():
        min_range = (1-slack) * row_treatment['AADT_EF_2016']
        max_range = (1+slack) * row_treatment['AADT_EF_2016']
if min_range <= aadt_comparison <= max_range:
    selected_rows.append(row_comparison)
    break

# Create a DataFrame from the selected rows
subset_comparison = pd.DataFrame(selected_rows)

# Filter unique road ID
subset_comparison_id = subset_comparison['ID_NS'].unique()

# Subset the comparison groupd data
df_comparison = (df_data
    .query(comparison_query)
    .query("ID_NS in @subset_comparison_id")
    .reset_index(drop=True)
)

# Aggregate crash counts
obs_comp_before = (df_comparison
    .query("CRASH_YEAR in @years_before")
    [crash_count].sum()
)

obs_comp_after = (df_comparison
    .query("CRASH_YEAR in @years_after")
    [crash_count].sum()
)

return(df_comparison, obs_comp_before, obs_comp_after)

Function to prepare the data for the comparability test.

def prepare_comparability_test_data(df_treatment,
    df_comparison,
    years,
    crash_count_col
):
    """ Prepares data for the comparability test.

    Parameters:
    """
    - df_treatment (pd.DataFrame): The DataFrame containing the filtered treatment data.
    - df_comparison (pd.DataFrame): The DataFrame containing the filtered comparison data.
    - years (list): The list of years for the analysis.
    - crash_count_col (str): The column name representing crash counts.

    Returns:
    """
    - df_crash_data (pd.DataFrame): The DataFrame containing crash data for the comparability test.

    # Subset crash data in study population
crash_data_study = (
    df_treatment
    # Filter for before crashes
    .query('BEFORE_AFTER_5Y == "Before"')
    # Summarize the crashes by year
    .groupby(['CRASH_YEAR'], as_index=False)[crash_count_col].sum()
)

# Subset crash data in comparison group
crash_data_compa = (
    df_comparison
    # Summarize the crashes by year
    .groupby(['CRASH_YEAR'], as_index=False)[crash_count_col].sum()
)

# Create the dataframe for the comparability test
df_crash_data = pd.DataFrame(years, columns=['YEAR'])

# Add the crashes in the study population to the dataframe
df_crash_data['TREATMENT'] = (
    df_crash_data['YEAR']
    .map(crash_data_study.set_index('CRASH_YEAR')[crash_count_col])
)

# Add the crashes in the reference population to the dataframe
df_crash_data['COMPARISON'] = (
    df_crash_data['YEAR']
    .map(crash_data_compa.set_index('CRASH_YEAR')[crash_count_col])
)

return df_crash_data

def comparability_test(df_crash_trend):
    """Conducts the comparability test of the treatment and comparison groups.

    Parameters:
    - df_crash_trend (pd.DataFrame): The DataFrame containing crash trends for
      the comparability test. It is the output of the function
      'prepare_comparability_test_data'.

    Returns:
    - mean (float): The mean of the sample CMF.
    - se (float): The standard error of the sample CMF.
    - lower_limit (float): The lower limit of the confidence interval for the
      sample CMF.
    - upper_limit (float): The upper limit of the confidence interval for the
      sample CMF.
    """

df_crash_trend['SAMPLE_CMF'] = np.NAN
for i in range(len(df_crash_trend) - 1):
    df_crash_trend.loc[i, 'SAMPLE_CMF'] = (
        (df_crash_trend.loc[i, 'TREATMENT'] * 
         df_crash_trend.loc[i+1, 'COMPARISON']) / 
        (df_crash_trend.loc[i+1, 'TREATMENT'] * 
         df_crash_trend.loc[i, 'COMPARISON']) 
    ) / 
    (1 + 
     (1/df_crash_trend.loc[i+1, 'TREATMENT']) + 
     (1/df_crash_trend.loc[i, 'COMPARISON']) 
    )

mean = df_crash_trend['SAMPLE_CMF'].mean()
se = df_crash_trend['SAMPLE_CMF'].std()

lower_limit = mean - 1.96*se
upper_limit = mean + 1.96*se

return(mean, se, lower_limit, upper_limit)

Function to compute the CMF.

def cmf_comp_group2(
    obs_treat_before,
    obs_treat_after,
    obs_comp_before,
    obs_comp_after
):
    """Computes the Crash Modification Factor (CMF) and its standard error for the comparison group.

Parameters:
-----------
- obs_treat_before (int): The sum of crash counts for the treatment group before the treatment.
- obs_treat_after (int): The sum of crash counts for the treatment group after the treatment.
- obs_comp_before (int): The sum of crash counts for the comparison group before the treatment.
- obs_comp_after (int): The sum of crash counts for the comparison group after the treatment.

Returns:
--------
- cmf (float): The Crash Modification Factor for the comparison group.

80
# Expected crash counts in the treatment group after the treatment
expect_treat_after = obs_treat_before * (obs_comp_after/obs_comp_before)

# Variance of the expected crash counts in the treatment group after
# the treatment
var_expect_treat_after =
    expect_treat_after**2
    * ((1/obs_treat_before) + (1/obs_comp_before) + (1/obs_comp_after))

# Crash modification factor - CMF
cmf =
    (obs_treat_after/expect_treat_after) / 
    (1 + (var_expect_treat_after/expect_treat_after**2))

# CMF variance
var_cmf =
    (cmf**2) * 
    ( 
        (1/obs_treat_after) + 
        (var_expect_treat_after/expect_treat_after**2) 
    ) / 
    (1 + (var_expect_treat_after/expect_treat_after**2))**2

# CMF standard error
se_cmf = np.sqrt(var_cmf)

return (cmf,se_cmf)
APPENDIX D: CODE FOR EMPIRICAL BAYES BEFORE-AND-AFTER STUDY

The section presents a sample Python code of the developed functions for the EB before-and-after evaluation. In each case, only the core part of the code is shown, that is, excluding data entry and manipulation.

---

### Function to prepare the data.

```python
    """Prepare data for input in function `compute_eb_cmf()`.

    This function takes a (tidy) data frame with road segments and crashes and
    then manipulates it to create a data frame in the format required by the
    function that computes the CMFs with the empirical bayes method
    (`compute_eb_cmf()`)

    Parameters
    ----------
    df : pd.DataFrame
        Data frame with road segments and crashes. Each row corresponds to a
        road segment and crashes. Different crashes are in the same road segment
        are in different rows.
    crash_count : str
        Name of the column with the crash counts.
    spf : function
        Safety performance function to predict crashes.
    dispersion_param : float
        Dispersion parameter associated to the SPF.
    n_years_before : int
        Number of years to study before the treatment.
    n_years_after : int
        Number of years to study after the treatment.

    Returns
    -------
    df_eb : pd.DataFrame
        Data frame with road segments and crashes in the format required by the
        function `compute_eb_cmf()`.
    """

    # 1.0 Unique road segments
    # -----------------------------------------------
    df_eb = (df
    # df
```

---
# Drop duplicated segments
.drop_duplicates(subset=['ID_NS'])
# Keep only the columns of interest
.loc[:, 'ID_NS']
# Copy in a new data frame
.copy()

# 2.0 Aggregate observed crashes
# -------------------------------------------------------------------------------------------------

## 2.1 Subset before crashes
df_before = df.query('BEFORE_AFTER_5Y in ['Before', 'No Crash']].copy()

## 2.2 Aggregate crashes in the before period
df_temp_before = (  
df_before  
# Group roads by segmente id  
.groupby(['ID_NS'], as_index=False)  
# Aggregate crashes counts (total and kabc) by road segment  
[[[crash_count]].sum()  
# Rename columns  
.rename(columns={crash_count: "OBSERVED_BEFORE"})
)

## 2.3 Merge unique roads and aggregated crashes
df_eb = pd.merge(  
df_eb,  
df_temp_before,  
how='left',  
on='ID_NS'  
)

de[df_temp_before]

## 2.4 Fill missing values with 0 in crash count columns
df_eb.loc[:, 'OBSERVED_BEFORE'] = (  
df_eb.loc[:, 'OBSERVED_BEFORE'].fillna(value=0)
)

## 2.5 Subset after crashes
df_after = df.query('BEFORE_AFTER_3Y in ['After', 'No Crash']].copy()

## 2.6 Aggregate crashes in the after period
df_temp_after = (  
df_after  
# Group roads by segmente id  
.groupby(['ID_NS'], as_index=False)  
# Aggregate crashes counts (total and kabc) by road segment  
[[[crash_count]].sum()  
# Rename columns
rename(columns={\'crash_count\': \"OBSERVED_AFTER\")
}

## 2.7 Merge unique roads and aggregated crashes

\n```python
df_eb = pd.merge(  
    df_eb,  
    df_temp_after,  
    how='left',  
    on='ID_NS'
)
```

del(df_temp_after)

## 2.8 Fill missing values with 0 in crash count columns

\n```python
df_eb.loc[:, \'OBSERVED_AFTER\'] = (  
    df_eb.loc[:, \'OBSERVED_AFTER\'].fillna(value=0)
)
```

# 3.0 Predict crashes in the before period

## 3.1 Years in the before period

\n```python
years_before = np.arange(  
    start = np.min(df_before[\'RS_YEAR_INSTALL\'].astype(int)) - n_years_before,  
    stop = np.max(df_before[\'RS_YEAR_INSTALL\'].astype(int)),  
    step = 1
)
```

## 3.2 Subset unique roads

\n```python
df_temp_before = df.drop_duplicates(subset=[\'ID_NS\']).copy()
```

## 3.3 Predict crashes in the before period

\n```python
for year in years_before:  
    df_temp_before[year] = spf(  
        df_temp_before,  
        year  
    )
```

## 3.4 Aggregate predicted crashes in the before period

\n```python
df_temp_before[\'PREDICTED_BEFORE\'] = (  
    df_temp_before.loc[:, years_before]  
    .sum(axis=1)
)
```

## 3.5 Merge unique roads and aggregated crashes

\n```python
df_eb = pd.merge(  
    df_eb,  
    df_temp_before[['ID_NS', 'PREDICTED_BEFORE']],  
    how='left',  
    on='ID_NS'
)
```
# 4.0 Predict crashes in the after period

## 4.1 Years in the after period

```python
years_after = np.arange(
    start = np.min(df_after['RS_YEAR_INSTALL'].astype(int))+1,
    stop = np.max(df_after['RS_YEAR_INSTALL'].astype(int))+1+n_years_after,
    step =1
)
```

## 4.2 Subset unique roads

```python
df_temp_after = df.drop_duplicates(subset=['ID_NS']).copy()
```

## 4.3 Predict crashes in the after period

```python
for year in years_after:
df_temp_after[year] = spf(
    df_temp_after,
    year
)
```

## 4.4 Aggregate predicted crashes in the before period

```python
df_temp_after['PREDICTED_AFTER'] = (  
df_temp_after.loc[:, years_after].sum(axis=1)  
)
```

## 4.5 Merge unique roads and aggregated crashes

```python
df_eb = pd.merge(
    df_eb,
    df_temp_after[['ID_NS', 'PREDICTED_AFTER']],
    how='left',
    on='ID_NS'
)
```

# 5.0 Add dispersion parameter

```python
df_eb['DISPERSION'] = dispersion_param
```

return df_eb

---

**Function to compute the CMF.**

```python
def compute_eb_cmf(
    df: pd.DataFrame,
) -> tuple[pd.DataFrame, float, float, float]:
    """Compute crash modification factor (CMF) using the empirical Bayes""
```
This function computes the CMF using the empirical Bayes method. It follows the procedure of the Highway Safety Manual 2010 presented in appendix 9A.

**Parameters**

```
df : pandas.DataFrame
    Dataframe with the site id and the aggregated crash frequency in the before and after periods. The columns must be named: "OBSERVED_BEFORE", "OBSERVED_AFTER", "PREDICTED_BEFORE", "PREDICTED_AFTER", and "DISPERSION".
```

**Returns**

```
df : pandas.DataFrame
    Dataframe with the results of the calculation steps.

cmf : float
    Unbiased overall CMF

safety_effectiveness : float
    Unbiased overall safety effectiveness as decimal (not percentage)

std_error_cmf : float
    Standar error of the unbiased overall CMF (and safety effectiveness)
```

**Notes**

The steps 1 and 3 are not included in this function. The results of these steps correspond to the columns "PREDICTED_BEFORE" and "PREDICTED_AFTER" that are input of this function.

```
# Step 2 - Compute the expected crash frequency in the before period
# for each site
# -----------------------------------------------

## 2.1 Compute the weight for each site

```python
df['WEIGHT'] = (1 / (1 + df['DISPERSION'] * df['PREDICTED_BEFORE']))
```

## 2.2 Compute the crash frequency for each site

```python
df['EXPECTED_BEFORE'] = (df['WEIGHT'] * df['PREDICTED_BEFORE']
+ (1-df['WEIGHT']) * df['OBSERVED_BEFORE'])
```

# Step 4 - Compute the adjustment factor for each site

```
df['ADJUST_FACTOR'] = (df['PREDICTED_AFTER'] / df['PREDICTED_BEFORE'])
```

# Step 5 - Compute expected crash frequency in the after period

# for each site
# Step 6 - Compute an estimated CMF (odds ratio) for each site
#-----------------------------------------------

df["CMF"] = (df['OBSERVED_AFTER'] / df['EXPECTED_AFTER'])

# Step 7 - Compute the safety effectiveness for each site
#-----------------------------------------------

df["SAFETY_EFFECTIVENESS"] = (1 - df["CMF"])

# Step 8 - Compute the overall CMF
#-----------------------------------------------

cmf_biased = (np.sum(df['OBSERVED_AFTER']) / np.sum(df['EXPECTED_AFTER']))

# Step 9 - Compute the overall unbiased CMF
#-----------------------------------------------

## 9.1 Compute the variance of expected crashes in the after period
var_expected_after = np.sum((df["ADJUST_FACTOR"]**2) * df["EXPECTED_BEFORE"] * (1 - df["WEIGHT"]))

## 9.2 Compute the average unbiased CMF

cmf = (cmf_biased / (1 + (var_expected_after / df["EXPECTED_AFTER"].sum()**2)))

# Step 10 - Compute the overall unbiased safety effectiveness
#-----------------------------------------------

safety_effectiveness = 1-cmf

# Step 11 - Compute the variance of the unbiased CMF
#-----------------------------------------------
variance_cmf = (
    (cmf_biased**2
     * (1/df['OBSERVED_AFTER'].sum())
     + (var_expected_after / np.sum(df['EXPECTED_AFTER'])**2)
     )
    )
    / (1 + (var_expected_after / np.sum(df['EXPECTED_AFTER'])**2))

# Step 12 - Compute the standard error of the CMF#
# --------------------------------------------------
std_error_cmf = np.sqrt(variance_cmf)

# Step 13 - Compute the standard error of the safety effectiveness#
# --------------------------------------------------------------

# std_error_safety_effectiveness = std_error_cmf

return df, cmf, safety_effectiveness, std_error_cmf
The section presents a sample Python code of the developed functions for the comparison group EB before-and-after evaluation. In each case, only the core part of the code is shown, that is, excluding data entry and manipulation.

**Function to predict the crashes in the before period for the treatment group.**

```python
def predict_before(df_before, spf, n_years):
    
    """Predict crashes in the before period.
    This function predicts crashes in the before period using a specified SPF.
    
    Parameters
    ----------
    df_before : pandas.DataFrame
        DataFrame containing information for the before period.
        It must have columns "RS_YEAR_INSTALL", "ID_NS".
    spf : function
        A function that takes two arguments: df (DataFrame) and year (int),
        and returns a DataFrame with crash predictions for the specified year.
    n_years : int
        Number of years in the before period.
    
    Returns
    -------
    pandas.DataFrame
        DataFrame with predicted crashes in the before period.
        It includes columns: "ID_NS", "RS_YEAR_INSTALL", <years_before>,
        "CRASH_SUM".
        <years_before> represent individual years in the before period.
    """
    
    # Years in the before period
    years_before = np.arange(  
        start = np.min(df_before.query("RS_YEAR_INSTALL !=0")["RS_YEAR_INSTALL"]).astype(int))-n_years,  
        stop = np.max(df_before["RS_YEAR_INSTALL"]).astype(int)),  
        step = 1  
    )
    
    # Empty dataframe to store the predicted crashes in the before period
    df_pred_before = pd.DataFrame(  
        # number of rows
        index = range(  
            len(df_before.index)
        )
    )
```
# Add id to the predicted crashes data frame
df_pred_before['ID_NS'] = df_before['ID_NS']

# Predict the crashes in the before period
for i, val in enumerate(years_before):
    # Iterate over each year in the before period
    # Predict the crashes in each site in each period
    df_pred_before.loc[:,val] = spf(df_before, val)

# Add year of installation to the predicted crashes data frame
df_pred_before['RS_YEAR_INSTALL'] = df_before['RS_YEAR_INSTALL']

# Tidy the predicted crashes data frame
df_pred_before = pd.melt(
    df_pred_before,
    id_vars=['ID_NS', 'RS_YEAR_INSTALL'],
    var_name='CRASH_YEAR',
    value_name='CRASH_PRED'
)

# Fill in zeros for the years outside the period of analysis
df_pred_before['CRASH_PRED'] = np.where(
    # Condition fro zero values
    df_pred_before['CRASH_YEAR'] <
    (df_pred_before['RS_YEAR_INSTALL'].astype(int)-n_years),
    # Value if true
    0,
    # Value if false
    df_pred_before['CRASH_PRED']
)

df_pred_before['CRASH_PRED'] = np.where(
    # Condition fro zero values
    df_pred_before['CRASH_YEAR'] >=
    df_pred_before['RS_YEAR_INSTALL'].astype(int),
    # Value if true
    0,
    # Value if false
    df_pred_before['CRASH_PRED']
)

# Un-tidy the predicted crashes data frame
df_pred_before = df_pred_before.pivot(
    index='ID_NS',
    columns='CRASH_YEAR',
    values='CRASH_PRED'
).reset_index(drop=False)
# Sum predicted crashes in the before period
df_pred_before["CRASH_SUM"] = (  
df_pred_before[years_before]  
 .sum(axis=1)  
)

return(df_pred_before)

Function to predict crashes in the after period for the treatment group.
def predict_after(df_after, spf, n_years):

    """Predict crashes in the after period.  
This function predicts crashes in the after period using a specified SPF.  

Parameters  
----------  
df_after : pandas.DataFrame  
    DataFrame containing information for the after period.  
    It must have columns "RS_YEAR_INSTALL", "ID_NS".  
spf : function  
    A function that takes two arguments: df (DataFrame) and year (int),  
    and returns a DataFrame with crash predictions for the specified year.  
n_years : int  
    Number of years in the after period.

Returns  
--------  
pandas.DataFrame  
    DataFrame with predicted crashes in the after period.  
    It includes columns: "ID_NS", "RS_YEAR_INSTALL", <years_after>,  
    "CRASH_SUM".  
    <years_after> represent individual years in the after period.
    """

    # Years in the after period  
    years_after = np.arange(  
        start = np.min(df_after.query("RS_YEAR_INSTALL !=0")  
    )["RS_YEAR_INSTALL"].astype(int))+1,  
    stop = np.max(df_after["RS_YEAR_INSTALL"].astype(int))+n_years+1,  
    step =1  
    )

    # Empty dataframe to store the predicted crashes in the after period  
df_pred_after = pd.DataFrame(  
        # number of rows  
        index=range(  
            len(df_after.index)  
        ),  
        # columns  
        columns = [year for year in years_after],
# Add id to the predicted crashes data frame
df_pred_after['ID_NS'] = df_after['ID_NS']

# Predict the crashes in the after period
for i, val in enumerate(years_after):
    # Iterate over each year in the after period
    # Predict the crashes in each site in each period
    df_pred_after.loc[:, val] = spf(df_after, val)

# Add year of installation to the predicted crashes data frame
df_pred_after['RS_YEAR_INSTALL'] = df_after['RS_YEAR_INSTALL']

# Tidy the predicted crashes data frame
df_pred_after = pd.melt(
    df_pred_after,
    id_vars=['ID_NS', 'RS_YEAR_INSTALL'],
    var_name='CRASH_YEAR',
    value_name='CRASH_PRED'
)

# Fill in zeros for the years outside the period of analysis
df_pred_after['CRASH_PRED'] = np.where(
    # Condition fro zero values
    df_pred_after['CRASH_YEAR'] > (df_pred_after['RS_YEAR_INSTALL'].astype(int)+n_years),
    # Value if true
    0,
    # Value if false
    df_pred_after['CRASH_PRED']
)

df_pred_after['CRASH_PRED'] = np.where(
    # Condition fro zero values
    df_pred_after['CRASH_YEAR'] <= df_pred_after['RS_YEAR_INSTALL'].astype(int),
    # Value if true
    0,
    # Value if false
    df_pred_after['CRASH_PRED']
)

# Un-tidy the predicted crashes data frame
df_pred_after = df_pred_after.pivot(
    index='ID_NS',
    columns='CRASH_YEAR',
    values='CRASH_PRED'
).reset_index(drop=False)

# Sum predicted crashes in the before period
df_pred_after['CRASH_SUM'] = (}
Function to predict crashes in the comparison group.

```python
def predict_comp(df, spf, years):
    """Predict crashes in the comparison group for a specified period.
    This function predicts crashes for a specified period using a specified SPF.
    Parameters
    ----------
    df : pandas.DataFrame
        DataFrame containing information for the specified period.
        It must have the column "ID_NS" as the unique id of the road segment.
    spf : function
        A function that takes two arguments: df (DataFrame) and year (int),
        and returns a DataFrame with crash predictions for the specified year.
    years : list of int
        List of years to predict crashes for.
    Returns
    -------
    pandas.DataFrame
        DataFrame with predicted crashes for the specified years.
        It includes columns: "ID_NS", <years>, "CRASH_SUM".
        <years> represent individual years in the specified period.
    """

    # Empty dataframe to store the predicted crashes in the after period
    df_pred = pd.DataFrame(
        # number of rows
        index=len(df.index),
        # columns
        columns=[year for year in years],
    )

    # Add the ID
    df_pred['ID_NS'] = df['ID_NS']

    # Predict the crashes in the after period
    for i, val in enumerate(years):
        # Iterate over each year in the after period
        # Predict the crashes in each site in each period
        df_pred.loc[:, val] = spf(df, val)
```

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# Sum predicted crashes in the before period
df_pred["CRASH_SUM"] = (  
df_pred[years]  
.sum(axis=1)  
)

return(df_pred)

Function to prepare the data for the treatment group.

def agregate_crashes_treatment(df, crash_count, spf, n_years_before, n_years_after):

    # Create data frame to store the results
df_data = pd.DataFrame()  
df_data['ID_NS'] = df['ID_NS'].unique()

    # Observed crashes
    # -----------------

    # Count observed crashes in the before period
    df_temp = (  
df  
    .query('BEFORE_AFTER_5Y == "Before"')  
    .groupby(['ID_NS'], as_index=False)[crash_count].sum()  
    )

    # Populate observed crashes at treatment sites in the before period
    df_data['OBS_BEFORE'] = (  
df_data['ID_NS']  
    .map(df_temp.set_index('ID_NS')[crash_count])
    )

    # Count observed crashes in the after period
    df_temp = (  
df  
    .query('BEFORE_AFTER_3Y == "After"')  
    .groupby(['ID_NS'], as_index=False)[crash_count].sum()  
    )

    # Populate observed crashes at treatment sites in the before period
    df_data['OBS_AFTER'] = (  
df_data['ID_NS']  
    .map(df_temp.set_index('ID_NS')[crash_count])
    )

    # Predicted crashes
    # -----------------

    # Predict crashes in the before period
    df_temp = predict_before(  
        # data frame filtered with only the unique road segments  
        df_before = (  
        )  
    )
df
    .drop_duplicates(subset=['ID_NS'])
    .reset_index(drop=True)
),

# safety performance functions
spf = spf,
# number of years in the before period
n_years=n_years_before
)

# Populate predicted crashes at treatment sites in the before period
df_data['PRED_BEFORE'] = (
df_data['ID_NS']
    .map(df_temp.set_index('ID_NS')['CRASH_SUM'])
)

# Predict crashes in the after period
df_temp = predict_after(
    # data frame filtered with only the unique road segments
df_after = (df
        .drop_duplicates(subset=['ID_NS'])
        .reset_index(drop=True)
),

# safety performance function
spf = spf,
# number of years in after period
n_years=n_years_after
)

# Populate predicted crashes at treatment sites in the before period
df_data['PRED_AFTER'] = (
df_data['ID_NS']
    .map(df_temp.set_index('ID_NS')['CRASH_SUM'])
)

return(df_data)

Function to prepare the data for the comparison group.

def agregate_crashes_comparison(
df, aadt_list, year, slack, crash_count, years_before, years_after, spf):
    """Aggregate crash data for treatment sites."""
Parameters
----------
df : pandas.DataFrame
    DataFrame containing crash data.
aadt_list : list of int
    List of AADT values to filter the comparison group.
slack : float
    Percentage of slack to apply to the AADT values.

crash_count : str
    Name of the column containing crash counts.
years_before : list of int
    List of years in the before period.
years_after : list of int
    List of years in the after period.
spf : function
    A function that takes two arguments: df (DataFrame) and year (int),
    and returns a DataFrame with crash predictions for the specified year.

Returns
-------
pandas.DataFrame
    DataFrame with aggregated crash data for treatment sites.
    It includes columns: "ID_NS", "OBS_BEFORE", "OBS_AFTER", "PRED_BEFORE", 
    "PRED_AFTER".

Notes
-----
This function aggregates crash data for treatment sites, including observed 
and predicted crashes.

Examples
--------
>>> df = ... 
>>> crash_count = 'CRASH_COUNT' 
>>> query_treatment = 'TREATMENT == "Yes"' 
>>> def spf(df, year): 
...     # Define spf function logic 
...     return df_predictions 
>>> aggregate_crashes_treatment(df, crash_count, query_treatment, spf) 

# Initialize an empty list to store the rows of df2 that meet the condition
selected_rows = []

# Iterate through each row in df2
for index, row in df.iterrows():
    aadt_comparison = row[f'AADT_EF_{year}']

    # Check if aadt_df2 is within any range in df1
    for aadt in aadt_list:
        min_range = (1-slack) * aadt 
        max_range = (1+slack) * aadt
if min_range <= aadt_comparison <= max_range:
    selected_rows.append(row)

break

# Create a DataFrame from the selected rows
df = pd.DataFrame(selected_rows)

# Create data frame to store the results
df_data = pd.DataFrame()
df_data['ID_NS'] = df['ID_NS'].unique()

# Observed crashes
# ----------------
# Count observed crashes in the before period
df_temp = (df
    .query('CRASH_YEAR in @years_before')
    .groupby(['ID_NS'], as_index=False)[crash_count]
    .sum()
)

# Populate observed crashes at treatment sites in the before period
df_data['OBS_BEFORE'] = (df_data['ID_NS']
    .map(df_temp.set_index('ID_NS')[crash_count])
)

# Count observed crashes in the after period
df_temp = (df
    .query('CRASH_YEAR in @years_after')
    .groupby(['ID_NS'], as_index=False)[crash_count]
    .sum()
)

# Populate observed crashes at treatment sites in the before period
df_data['OBS_AFTER'] = (df_data['ID_NS']
    .map(df_temp.set_index('ID_NS')[crash_count])
)

# Predicted crashes
# -----------------
# Predict crashes in the before period
df_temp = predict_comp(
    # data frame filtered with only the unique road segments
    df = (df
        .drop_duplicates(subset=['ID_NS']))
Function to compute the CMF.

```python
def compute_cmf_comparison_group_eb(df_treatment, df_comparison, n_treatment_before, n_treatment_after, n_comparison_before, n_comparison_after):
    
    """ Compute CMF with empirical Bayes comparison group method. 

    This function computes the Crash Modification Factor (CMF) and its Standard Error (SE) using the empirical Bayes comparison group method.

    Parameters:
    df_treatment (DataFrame): Data for treatment sites.

    df_data['PRED_BEFORE'] = (df_data['ID_NS'].map(df_temp.set_index('ID_NS')['CRASH_SUM']))
    
    # Predict crashes in the after period
    df_temp = predict_comp(
        # data frame filtered with only the unique road segments
        df = (
            df
            .drop_duplicates(subset=['ID_NS'])
            .reset_index(drop=True)
        ),
        # safety performance function
        spf = spf,
        # years in after period
        years = years_after
    )
    
    df_data['PRED_AFTER'] = (df_data['ID_NS'].map(df_temp.set_index('ID_NS')['CRASH_SUM']))
    
    return df_data
```

df_comparison (DataFrame): Data for comparison sites.
n_treatment_before (int): Number of years before in the treatment sites.

n_treatment_after (int): Number of years after in the treatment site.

n_comparison_before (int): Number of years before in the comparison sites.

n_comparison_after (int): Number of years after in the comparison sites.

Returns:

tuple: A tuple containing:
- CMF (float): The Crash Modification Factor.
- SE_CMF (float): The Standard Error of the CMF.

```
# Step 3a - before adjustment factor comparison sites
adj_factor_before = np.matmul(
    df_comparison[['PRED_BEFORE']].to_numpy()**-1,
    np.transpose(df_treatment[['PRED_BEFORE']].to_numpy())
)* (n_treatment_before/n_comparison_before)

# Step 3b - after adjustment factor comparison sites
adj_factor_after = np.matmul(
    df_comparison[['PRED_AFTER']].to_numpy()**-1,
    np.transpose(df_treatment[['PRED_AFTER']].to_numpy())
)* (n_treatment_after/n_comparison_after)

# Step 4a - before expected average crash frequency for comparison sites
expected_before = np.multiply(
    df_comparison[['OBS_BEFORE']].to_numpy(),
    adj_factor_before)

# Step 4b - after expected average crash frequency for comparison sites
expected_after = np.multiply(
    df_comparison[['OBS_AFTER']].to_numpy(),
    adj_factor_after)

# Step 5 - total expected comparison-group crash frequency before
# total_expected_before = expected_before.sum(axis=0)
total_expected_before = np.nansum(expected_before, axis=0)

# Step 6 - total expected comparison-group crash frequency after
# total_expected_after = expected_after.sum(axis=0)
total_expected_after = np.nansum(expected_after, axis=0)

# Step 7 - comparison ratio (r) for each treatment site
r = total_expected_after/total_expected_before

# Step 8 - expected average crash frequency for treatment sites
# in the after period, had no treatment been implemented
expected_treatment_after = df_treatment['OBS_BEFORE'].to_numpy() * r

# Step 9 - cmf for each site
cmfs = np.where(
    # Condition: denomitar diferent than 0
    expected_treatment_after != 0,
    # If true: compute the cmf
    df_treatment['OBS_AFTER'] / expected_treatment_after,
    # If false: fill with nan
    np.nan
)

# Convert CMF = 0 to nan to avoid indeterminations in Ln(cmf)
cmfs[cmfs==0] = np.nan

# Step 10 - ln(cmfs)
ln_cmfs = np.log(cmfs)

# Handle inf values
# ln_cmfs[np.isinf(ln_cmfs)] = np.nan

# Step 11 - weight for each site
sqr_se_ln_cmfs = np.where(df_treatment['OBS_BEFORE'] != 0, 1/df_treatment['OBS_BEFORE'], np.nan) + np.where(df_treatment['OBS_AFTER'] != 0, 1/df_treatment['OBS_AFTER'], np.nan) + np.where(total_expected_before != 0, 1/total_expected_before, np.nan) + np.where(total_expected_after != 0, 1/total_expected_after, np.nan)

w = 1/sqr_se_ln_cmfs

# Step 12 - Ln(CMF) - weighted average ln cmf for treatment sites
ln_CMF = np.nansum(w*ln_cmfs)/np.nansum(w)

# Step 13 - CMF
CMF = np.exp(ln_CMF)

# Step 14 - safety effectivenes

# Step 15 - SE
SE_CMF = CMF/np.sqrt(np.nansum(w))

return(CMF, SE_CMF)
Jhan Kevin Gil Marin was born and raised in Medellin, Colombia on November 5, 1996. He graduated from High School at I.E. INEM Jose Felix de Restrepo in 2013. He attended the Universidad Nacional de Colombia and graduated in 2021 with a bachelor’s degree in civil engineering. Then he began his Master of Science in Civil Engineering at the University of Maine in the Spring 2022 session. After receiving his degree, Jhan plans to do a PhD. Jhan is a candidate for the Master of Science degree in Civil Engineering from the University of Maine in December 2023.