Safety Effectiveness of Non-Freeway Sinusoidal Shoulder Corrugations

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16. Abstract

Sinusoidal rumble strips were designed to alleviate noise concerns by reducing roadside noise for residents, while maintaining adequate levels of in-vehicle noise and vibration. However, while research has shown that traditional rumble strip designs are effective towards reducing lane departure crashes, the safety performance of the sinusoidal rumble strip design remains unproven. Additionally, it is not well understood how the various corrugation designs impact bicyclist stability and comfort. Research was conducted to evaluate the effectiveness of sinusoidal shoulder corrugations as a traffic safety strategy, considering noise and vibration, stability and comfort for bicyclists, and traffic crashes. Five primary tasks were conducted, which included: (1) a field evaluation of roadside noise and in-vehicle noise and vibration produced by sinusoidal shoulder corrugations compared to traditional shoulder corrugations; (2) a field evaluation of bicyclist comfort, stability, and vibration when contacting sinusoidal vs. traditional corrugations; (3) an online nationwide survey of bicyclists' perceptions and experiences with rumble strips; (4) a survey of motorcyclists traveling in Michigan to determine their perceptions and experiences with rumble strips; (5) a safety performance analysis to develop crash modification factors for sinusoidal shoulder rumble strips. Overall, it was concluded that sinusoidal shoulder corrugations effectively reduce roadside noise compared to traditional corrugations without compromising the level of in-vehicle noise or vibration necessary to alert drivers. At 55 mph, the sinusoidal corrugations generated roadside noise levels that were 2.4 decibels lower than the traditional corrugations, regardless of vehicle type. At 65 mph, the sinusoidal corrugations generated roadside noise levels that were 4.8 dBA and 8.8 dBA lower than the traditional corrugations when contacted by a minivan and snowplow truck, respectively. The results of the safety performance analysis show that installation of sinusoidal shoulder corrugations reduced total crashes by 8.3 percent and single vehicle lane departure crashes by 29.6 percent. In contrast, results from the bicycle field study indicated that riders preferred the traditional corrugation design over the sinusoidal design, due to the lower comfort and reduced controllability experienced when traversing sinusoidal corrugations. This finding was supported by the vibration measurements, as the sinusoidal corrugations produced greater vibration at the bicycle handlebar than the traditional design. However, both the bicyclist field study and the nationwide bicyclist survey found that bicyclists value a smooth and debris-free shoulder of at least 3-ft in width as the most important aspect towards ensuring comfort, stability, and overall safety. Motorcyclists were in general agreement with bicyclists in that debris on the pavement surface represents greater safety concern than rumble strips, as motorcyclists generally do not experience significant safety or control issues when encountering rumble strips. Collectively, the results suggest that continued use of sinusoidal shoulder corrugations in noise-sensitive environments is warranted, although additional design considerations, such as including regular gaps in the corrugations and/or placing the corrugations on the edge line, should be considered along highways utilized by bicyclists.

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EXECUTIVE SUMMARY

Lane departure crashes commonly occur on high-speed rural highways and represent more than 30 percent of all traffic fatalities and serious injuries in Michigan. Longitudinal rumble strips are a relatively low-cost countermeasure intended to reduce lane departure crashes. The Michigan Department of Transportation (MDOT) has been a pioneer in rumble strip implementation, which notably included systemwide implementation of centerline rumble strips and broad implementation of shoulder rumble strips on rural non-freeway highways occurring between 2008 and 2010. This implementation has contributed to a steady decline in the rate of lane departure crashes over the past two decades. Regardless, the presence of rumble strips on highways leads to potentially adverse effects, including increased roadside noise levels and potential bicycle instability, particularly when utilized on highway shoulders.

Research Problem

Sinusoidal rumble strips were designed to alleviate noise concerns by reducing roadside noise for residents, while maintaining adequate levels of in-vehicle noise and vibration. However, the safety performance of sinusoidal rumble strips remains unproven, and it is not well understood how the various corrugation designs impact bicyclist stability and comfort. Since 2020, several hundred miles of sinusoidal shoulder rumble strips have been installed on rural state highways throughout Michigan. The majority of these installations occurred on roadways where no shoulder or edge line rumble strips previously existed. This afforded a unique opportunity to evaluate the safety effectiveness of the sinusoidal design, in addition to noise and vibration produced during vehicle contact and comfort and stability for bicyclists. Examples of traditional and sinusoidal shoulder rumble strip corrugations are depicted in the figure below.

Traditional Rectangular (left) and Sinusoidal (right) Shoulder Corrugations

Study Design

Research was conducted to evaluate the effectiveness of sinusoidal shoulder corrugations as a traffic safety strategy, considering noise and vibration, stability and comfort for bicyclists, and traffic crashes. Five primary tasks were conducted to address the research objectives, which are summarized as follows:

- A field study was conducted to evaluate the differences in roadside noise and in-vehicle noise and vibration produced by sinusoidal rumble strips compared to traditional rumble strip designs for various vehicle types (minivan and plow truck) and speeds (55 and 65 mph).
- A second field study was conducted to evaluate the impacts of sinusoidal rumble strips on bicyclist comfort and stability compared to traditional rumble strip designs.
- A nationwide survey of bicyclists was conducted to obtain broader insights into cyclists' perceptions and experiences with rumble strips across the United States.
- A survey of motorcyclists traveling in Michigan was conducted to determine motorcyclists' perceptions and experiences with rumble strips.
- A safety performance analysis was performed to develop crash modification factors (CMF) for sinusoidal shoulder rumble strips.

Synthesis of the findings from these tasks allowed for development of recommendations for future rumble strip design and implementation, which will help inform subsequent changes to policy and standards.

Summary of Findings

Noise and Vibration

The noise results confirm that traditional rumble strips produce higher roadside noise than the sinusoidal design, particularly at 65 mph and especially for the truck. At 55 mph, the traditional corrugations generated 2.4 dBA greater roadside noise than the sinusoidal design for both the minivan and the snowplow truck. However, at 65 mph, the traditional corrugations generated 4.8 dBA and 8.8 dBA more noise than the sinusoidal corrugations for the minivan and snowplow truck, respectively.

Both corrugation designs produced sufficient in-vehicle noise (i.e., greater than 3 dBA) to alert drivers in the minivan, which is consistent with the findings from prior research. However, the in-vehicle noise produced by the sinusoidal design was insufficient to alert drivers in the snowplow truck, particularly at 55 mph. These differences are likely due to differences in tire width, cabin noise insulation, and suspension characteristics between the two types of vehicles.

Turning to the vibration results, both sinusoidal and traditional corrugations produced considerable (5.5 to 13.0 dB) vibration at the steering column in the lateral (X) and longitudinal (Y) directions, while vertical (Z) vibration was much less pronounced (2.5 to 5.4 dB). The snowplow truck generally experienced less vibration during contact with the corrugations compared to the minivan, likely due to dampening caused by the greater weight and more robust suspension system of the truck. The amount of vibration generated by the corrugations was generally unaffected by speed. There was no statistical association between the depth (3/8 inch or 1/2 inch) or width (8 inch or 12 inch) of the corrugations and noise or vibration. Pavement type (hot mix asphalt or chipseal) was also not found to meaningfully affect corrugation noise or vibration.

Bicyclist Considerations

Results from the bicyclist field study indicated that riders preferred the traditional rumble strip design over the sinusoidal design across nearly all evaluated conditions. Riders reported lower comfort and reduced controllability when traversing sinusoidal rumble strips, a finding that was supported by the vibration measurements. The sinusoidal design produced greater vibration than the traditional design across each of the bicycle frame materials (carbon fiber, aluminum, steel, and titanium), speeds, and tire pressures. These objective vibration measurements aligned closely with riders' subjective responses, reinforcing the conclusion that sinusoidal rumble strips impose greater physical disturbance on bicyclists than traditional designs under the conditions evaluated.

The nationwide bicyclist survey indicated that bicyclists give high priority to a smooth, debris-free shoulder surface of adequate usable width to ensure safety and comfort while cycling on the shoulder. Rumble strip design characteristics, such as corrugation depth, width, and gap configuration were assigned lower relative importance by bicyclists. In addition, perceived risk while riding on roadway shoulders was primarily associated with surface conditions and visibility constraints, with sand and gravel, shoulder pavement corrugation, and limited sight distance cited most frequently. As for risks associated with drivers, distracted driving and insufficient lateral clearance during passing maneuvers were considered high risk factors when cycling on the shoulder. These results suggest that maintaining clear, continuous shoulder space and minimizing surface irregularities may play a central role in bicyclist comfort and perceived safety on roadways where rumble strips are present. Prior negative experiences with rumble strips, such as being forced into the travel lane or experiencing loss of bicycle control, were strongly associated with both route-planning and route avoidance decisions.

Motorcyclist Considerations

The results of the motorcyclist survey suggest that motorcyclists generally do not experience significant safety or control issues when riding over shoulder rumble strips. When properly designed and installed, shoulder rumble strips appear to provide useful warning benefits while posing minimal risk to riders. Debris, such as sand or gravel on the pavement surface, was considered to be a far greater safety concern for motorcyclists than rumble strips.

Safety Performance

The safety performance analysis demonstrated measurable safety benefits associated with the installation of sinusoidal corrugations on the shoulder of two-lane rural highways that previously did not have shoulder corrugations. For total crashes, a CMF of 0.917 was estimated, corresponding to an 8.3 percent reduction in crashes at treated sites. Lane departure crashes—the primary target crash type for shoulder rumble strips—experienced substantial reductions after installation of the sinusoidal shoulder rumble strips. A CMF of 0.712 was estimated for total lane departure crashes, corresponding to a 28.8 percent reduction. For lane departure crashes involving only single vehicles, the CMF was 0.704, indicating a 29.6 percent reduction. Overall, the magnitude of the crash reductions observed in this study are consistent with the extensive prior research on the safety performance of traditional rumble strips, in addition to the limited prior research on sinusoidal rumble strips.

Conclusions

Overall, it was concluded that sinusoidal shoulder corrugations can effectively reduce roadside noise compared to traditional corrugations without compromising the level of in-vehicle noise or vibration that is necessary to alert drivers, particularly for passenger vehicles. While the in-vehicle noise produced during contact with the sinusoidal corrugations was insufficient to alert drivers in the snowplow truck at 55 mph, adequate levels of steering column vibration did occur. In terms of safety performance, the results of the safety performance analysis suggest that sinusoidal shoulder rumble strips provide meaningful crash reductions, including an 8.3 percent reduction in total crashes and a 29.6 percent reduction in single vehicle lane departure crashes, while addressing community noise concerns associated with traditional corrugation designs.

In contrast, results from the bicycle field study indicated that riders preferred the traditional rumble strip design over the sinusoidal design. Riders reported lower comfort and reduced controllability when traversing sinusoidal rumble strips. This finding was supported by vibration measurements, as the sinusoidal corrugations produced greater vibration than the traditional design across each of the tested bicycle frame materials, speeds, and tire pressures. However, both the bicyclist field study and the nationwide bicyclist survey found that bicyclists value a smooth and debris-free shoulder of at least 3-ft in width as the most important aspect towards ensuring comfort, stability, and overall safety. Motorcyclists were in general agreement with bicyclists in that debris on the pavement surface represents a greater safety concern than rumble strips, as motorcyclists generally do not experience significant safety or control issues when encountering rumble strips.

Implementation Recommendations for Sinusoidal Shoulder Rumble Strips

From a policy and implementation perspective, these results support the continued deployment of sinusoidal shoulder rumble strips as an effective and context-sensitive countermeasure for reducing lane departure crashes on rural two-lane roadways. To that end, the continued use of sinusoidal shoulder corrugations in noise-sensitive environments is recommended. Examples of appropriate environments would include residential areas, schools, hospitals, offices, and other noise-sensitive areas.

In terms of corrugation dimensions, although no meaningful differences in noise or vibrations were observed between the different corrugation depths or widths, 3/8-inch corrugation depths are preferred in areas frequented by bicyclists. Furthermore, a corrugation width of 8 inches placed at the edge line would help ensure an adequate usable paved shoulder for bicyclists, which the nationwide survey of bicyclists suggested should be a minimum width of 3-feet, smooth, and free of debris. Additionally, due to the considerable comfort and stability issues faced by bicyclists when traversing over sinusoidal corrugations, adequate gaps in the rumble strips should be provided. The inclusion of warning signage for rumble strips, particularly in construction zones where motorcyclists are shifted onto the shoulder, may further enhance awareness and comfort for motorcyclists. While this research provided substantial evidence of the noise, vibration, and safety effects of sinusoidal shoulder rumble strips, future research should explore alternative corrugation designs that can meet the noise and vibration objectives, while providing a more comfortable and controlled experience for bicyclists.

1. INTRODUCTION AND BACKGROUND

1.1 Introduction

According to the Federal Highway Administration (FHWA), more than half of all traffic fatalities in the United States result from crashes involving departure from the travel lane, with approximately two thirds of these crashes occurring in rural areas [*1*]. Nearly 500,000 lane departure crashes occurred within Michigan from 2013 to 2022 [*2*]. These crashes resulted in 4,367 fatalities and 19,509 serious injuries, which represented more than 30 percent of all traffic fatalities and serious injuries in Michigan, while comprising less than 20 percent of all crashes [*2*]. Consistent with the Michigan Department of Transportation's (MDOT) commitment to the *Safe System Approach* [*3*], the identification and implementation of innovative strategies to reduce lane departure crashes has represented a core component of the state's highway safety efforts to achieve the ultimate *Towards Zero Deaths* vision [*4*]. In fact, roadway engineering strategies to reduce these potentially severe crashes have been emphasized by Michigan's *Strategic Highway Safety Plan* [*5*] and the *Traffic Safety Engineering Action Team* [*6*] since their inception in 2006.

Longitudinal rumble strips are a relatively low-cost countermeasure intended to reduce lane departure crashes and have been shown to provide cost-benefit ratios of greater than 100 to 1 [*7*]. Longitudinal rumble strips "are milled or raised elements on the pavement intended to alert drivers through vibration and sound that their vehicles have left the travel lane" and have long been recognized by the FHWA as a proven safety countermeasure [*8*]. MDOT has been a pioneer in rumble strip implementation, which notably included 5,400 miles of centerline rumble strips (CLRS) and 1,700 miles of shoulder rumble strips (SRS) installed on rural highways statewide between 2008 and 2010 [*9*]. This system-wide implementation has contributed to a steady decline in the rate of fatal and serious injury lane departure crashes over the past two decades (Figure 1).

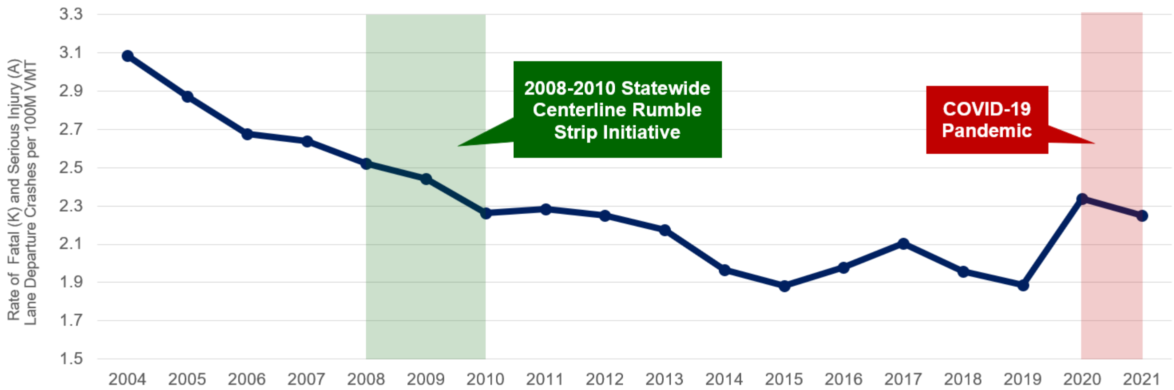

Figure 1. Fatal and Serious Injury Lane Departure Crash Rate per 100M VMT in Michigan 2004-2021 [2]

Despite this focus on roadway departure crashes, there remains additional opportunities to accelerate progress towards the state's highway safety goals through continued implementation of innovative engineering treatments. This includes seeking opportunities to expand the use of longitudinal rumble strip treatments along Michigan's high-speed non-freeway network, such as along shoulders of rural highways that did not previously possess shoulder rumble strips.

Prior research has consistently demonstrated that longitudinal rumble strip treatments can provide safety performance benefits [*10*], including an evaluation of the MDOT 2008-2010 CLRS trunkline non-freeway initiative conducted by the research team [*11,12*]. However, the noise created by traditional rumble strips can be disruptive to adjacent residents or businesses [*13-17*]. Several adverse health effects have been associated with long-term exposure to road noise, including sleeping disorders, annoyance, learning problems, hypertension and ischemic heart disease [*18-20*]. Additionally, prior work has also demonstrated that the use of longitudinal rumble strip treatments may impact bicycle safety and comfort depending on the configuration [*11,13*]. Thus, alternative rumble strip designs that mitigate such concerns may offer the potential to be installed on previously untreated sections of rural non-freeways in Michigan.

Sinusoidal rumble strips, which are also referred to as "mumble strips" [*21*], represent one potential alternative that has been implemented by roadway agencies across the United States. Sinusoidal rumble strips were initially investigated in Europe as early as 2007 [*22*] and were designed with a sine wave pattern as a means to maintain adequate interior noise and vibration levels to alert drivers while reducing exterior noise [*21*]. A profile comparison between traditional corrugations and a sinusoidal corrugation design is shown in Figure 2.

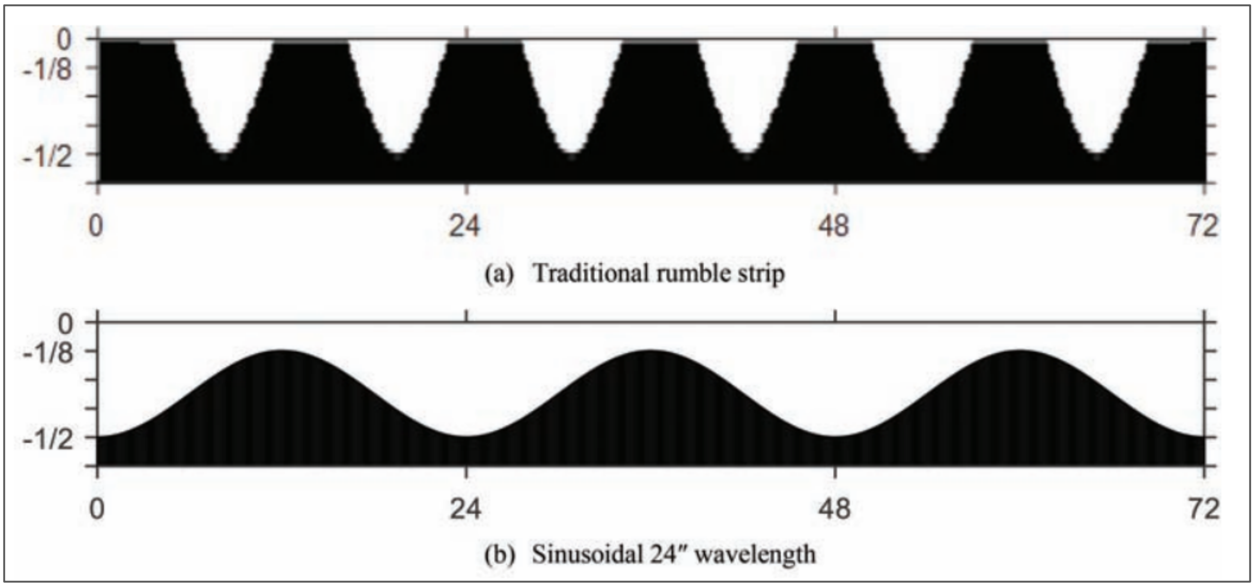

Figure 2. Example of Traditional and Sinusoidal Rumble Strip Profiles [*21*]

1.2 Sinusoidal Rumble Strips in Michigan

Recently, MDOT has installed various configurations of sinusoidal shoulder and centerline corrugations on rural trunkline highways throughout Michigan. MDOT specifies that sinusoidal rumble strip corrugations have a continuous profile, created by periodically depressing the milling head into the pavement to a depth ranging from 1/16 to 1/2 inch, with a wavelength of 14 inches [*23*]. Sinusoidal shoulder corrugations are typically 12-inches wide, while narrower 8-inch wide corrugations are used at the edge line, which allows for installation on shoulders that are narrower than would be allowed for traditional corrugations. Traditional rumble strips are milled to a depth of 1/2 inch, width of 12 inches, and corrugated length of 7 inches, with a 5-inch uncut gap between corrugations. MDOT's typical dimensions for non-freeway shoulder corrugations are displayed in Figure 3 [*23*]. Examples of the two types of shoulder corrugations are displayed in Figure 4.

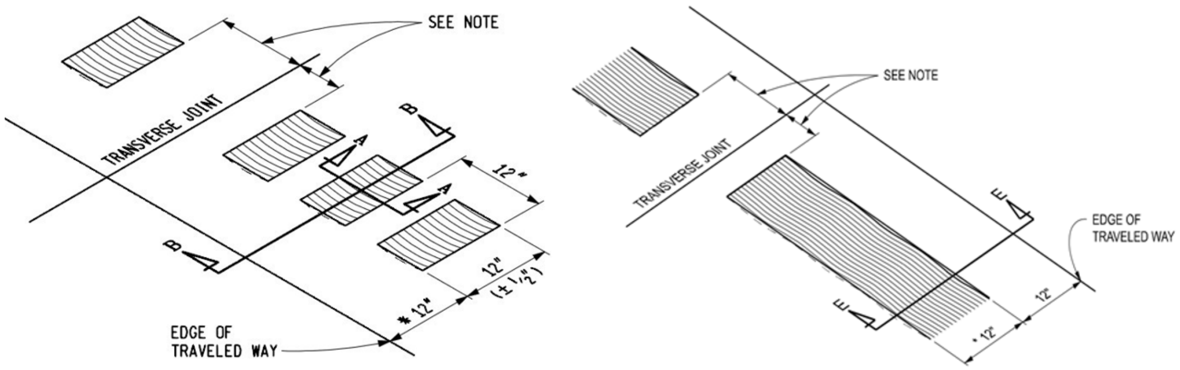

Figure 3. MDOT Typical Dimensions for Traditional Rectangular (left) and Sinusoidal (right) Non-Freeway Shoulder Corrugations (R-112-J) [*23*]

Figure 4. Traditional Rectangular (left) and Sinusoidal (right) Shoulder Corrugations

Implementation of sinusoidal shoulder rumble strips began on state trunkline highways in Michigan's upper peninsula in summer of 2018 [*24*]. Shortly thereafter, MDOT published Design Advisory 2021-04 in October 2021 [*25*] which specified sinusoidal corrugations as the standard for non-freeway SRS as shown in Standard Plan R-112-J *Shoulder and Centerline Corrugations* (Figure 3) [*23*] and Section 6.05.11 of the MDOT *Road Design Manual* [*26*]. This design guidance for sinusoidal rumble strips is summarized below:

- Non-freeway SRS shall be sinusoidal corrugations and implemented along all rural two-lane, four-lane, and divided 55 mph trunkline roadways where the paved shoulder is at least six feet wide.
- Non-freeway CLRS should be traditional corrugations and used along all rural two-lane and four-lane 55 mph trunkline roadways where the paved lane and shoulder width beyond the corrugation is greater than 13 feet. However, sinusoidal corrugations may be used where there is a history of noise complaints related to existing CLRS installations, relatively high volumes of passing maneuvers are expected, or specific maintenance concerns are present.
- Sinusoidal CLRS or SRS may be used along non-freeway roadways beyond those scenarios outlined above when safety considerations outweigh concerns related to road noise or bicycle accommodation. This provides flexibility to install longitudinal rumble strip treatments in scenarios where less than six feet of paved shoulder is available in coordination with MDOT's non-motorized program staff.
- While traditional corrugations remain the standard for freeway facilities, sinusoidal corrugations may be used consistent with an evaluation of adjacent land use.

Between 2018 and 2025, more than 1,100 miles of sinusoidal shoulder corrugations had been installed on two-lane highways across Michigan, nearly all of which were added along corridors that were previously without shoulder corrugations. This level of implementation placed MDOT in an excellent position to evaluate the safety performance aspects of sinusoidal shoulder corrugations.

1.3 Research Problem

Although traditional rumble strips are generally understood to provide safety benefits, their presence on highways also leads to several potentially adverse effects, including potential bicycle instability and increased roadside noise levels. Sinusoidal rumble strips were designed to alleviate noise concerns by reducing roadside noise for residents, while maintaining adequate levels of in-vehicle noise and vibration. However, while research has shown that traditional rumble strips are effective towards reducing lane departure crashes, the safety performance of sinusoidal rumble strips remains unproven. Thus, questions remain as to whether the sinusoidal rumble strip design results in safety performance benefits that compare favorably to traditional rumble strip designs. Additionally, it is not well understood how the various corrugation designs impact bicyclist stability and comfort. Research is needed to provide a better understanding of the effects of the sinusoidal rumble strip designs, including noise and vibration, bicyclist stability and comfort, and lane departure crashes. These outcomes will help guide future rumble strip design and implementation and help inform subsequent changes to policy and standards.

1.4 Research Objectives

Research was conducted to evaluate the effectiveness of sinusoidal shoulder corrugations as a traffic safety strategy, considering noise and vibration, stability and comfort for bicyclists, and traffic crashes. The specific objectives of the research were as follows:

1. Identify and synthesize best practices related to the use of sinusoidal rumble strips.
2. Evaluate the differences in roadside noise and in-vehicle noise and vibration produced by sinusoidal rumble strips compared to traditional rumble strip designs across various speeds and vehicle types.
3. Evaluate the impacts of sinusoidal rumble strips on bicyclist comfort and stability compared to traditional rumble strip designs.
4. Analyze the impact of sinusoidal shoulder rumble strips on safety performance, including development of crash modification factors (CMFs) for sinusoidal shoulder rumble strips.

The outcomes of the research include a series of analytical tools (including CMFs), design recommendations, and promotion materials to support the continued expansion of longitudinal rumble strip treatments along Michigan's rural non-freeway network.

1.5 Report Outline

This report documents all work performed to achieve the study objectives. The chapters are organized as follows:

- Chapter 1: Introduction and Background
- Chapter 2: Literature Review
- Chapter 3: Field Evaluation of Noise and Vibration
- Chapter 4: Field Evaluation of Bicyclist Comfort and Stability
- Chapter 5: Nationwide Bicyclist Survey
- Chapter 6: Motorcyclist Survey
- Chapter 7: Safety Performance Analysis and CMF Development
- Chapter 8: Conclusions and Implementation Recommendations

2. LITERATURE REVIEW

This chapter provides a review of the extant literature pertaining to noise and vibration associated with sinusoidal rumble strips, the safety implications of rumble strip designs, and the effects of rumble strips on bicyclists and motorcyclists. As of 2025, at least 23 states have implemented sinusoidal rumble strips. Seven of these states have evaluated sinusoidal rumble strips via noise and vibration studies, while six states have initiated safety performance studies to estimate CMFs for sinusoidal rumble strips. Figure 5 provides a map depicting installations and evaluations of sinusoidal rumble strips in the United States as of 2025.

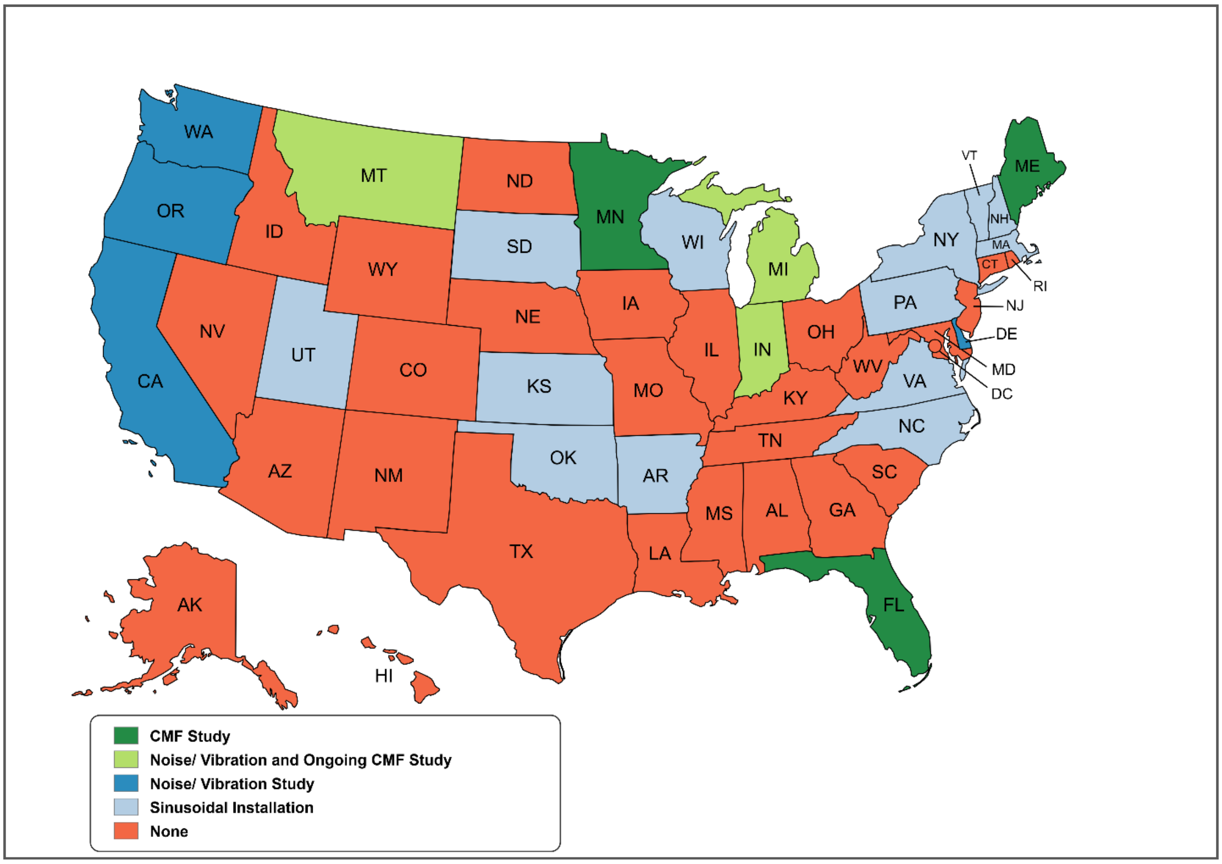

Figure 5. Installation and Evaluation of Sinusoidal Rumble Strips as of 2025

2.1 Evaluation of Noise and Vibration Produced by Sinusoidal Rumble Strips

Sinusoidal rumble strip corrugations are designed to maintain interior noise and vibration levels, while at the same time reducing the amount of exterior noise compared to traditional corrugation designs. In 2009, research sponsored by the California Department of Transportation (Caltrans) focused on developing an optimized sinusoidal rumble strip design aimed at minimizing exterior noise while maintaining or enhancing interior noise and vibration levels. The proposed design featured a wavelength of (14 inches) and a peak-to-peak amplitude of (0.3125 inches). This design was suggested based on the interaction between tire geometry and vehicle dynamics. Field tests conducted in northern California during 2012 and 2015 demonstrated the effectiveness of the design in reducing noise levels compared to traditional rumble strips. Specifically, exterior noise decreased by an average of 6.2 dB across three different passenger vehicles and by 3.2 dB for a dump truck. Additionally, the design, now patented by Caltrans, showed interior noise and vibration differences exceeding 13 dB, with results within 1 dB of traditional rumble strips [*21*].

In a 2016 study that was funded by the Minnesota Department of Transportation (MnDOT), six different sinusoidal rumble strip designs were evaluated on a test track along with four additional designs in a real-world setting. The rumble strips were constructed with a consistent 14-inch wavelength, while the depth and perpendicular width varied. The findings indicated that shallower rumble strips produced lower exterior noise levels, although the interior noise levels in pickup trucks and heavy vehicles might not have been adequate with the shallower designs. Based on evaluations involving bicycles and motorcycles, a 14-inch strip was favored over two parallel 8-inch strips. For passenger vehicles, the sinusoidal rumble strips increased interior noise levels by at least 12 dB across all designs, while the increase in exterior noise remained under 7 dB compared to off strip events [*13*].

In another study conducted in Indiana in 2018, researchers evaluated sinusoidal rumble strips with three different wavelengths while maintaining a constant depth and perpendicular width. The findings revealed that the longer wavelengths of 18 inches and 24 inches did not produce sufficient interior sound levels to effectively alert drivers. In contrast, the 12-inch wavelength demonstrated a balance, significantly increasing interior noise levels while keeping exterior noise levels lower. Specifically, the 12-inch design reduced roadside noise by 5 to 11 dB compared to traditional rumble strips and increased interior noise levels by 4 to 12 dB relative to baseline road noise. These results were obtained using six different vehicle types, including a passenger car and a semi-truck, driving 50 mph while striking the rumble strips [*27*].

A 2019 study conducted for the Oregon Department of Transportation (ODOT) evaluated the noise and vibration performance of sinusoidal rumble strips. This study compared a sinusoidal design with a wavelength of 16 inches to a traditional rectangular rumble strip, using three vehicle types: a passenger car, a minivan, and a heavy vehicle. The sinusoidal rumble strip had a greater width but was shallower than the traditional strip. Results indicated that, for the passenger car and minivan, exterior noise was lower when using the sinusoidal design compared to the traditional rumble strips. Interior noise levels were also lower with the sinusoidal strip for both the passenger car and minivan. The heavy vehicle, equipped with dual tires, did not produce significant exterior or interior noise when striking the traditional rumble strip. However, the wider sinusoidal design generated a sufficient interior alert for heavy vehicles, with a 6.8 dB increase, suggesting that a wider strip may be more suitable for heavy vehicles. In terms of exterior noise, the passenger car experienced a 5.4 dB increase with the rectangular strip and a 3.1 dB increase with the sinusoidal strip. For the minivan, the traditional strip caused a 4.6 dB increase, while the sinusoidal strip resulted in a 0.2 dB decrease. The heavy vehicle showed a 2.2 dB increase with the traditional strip and a 5.7 dB increase with the wider sinusoidal strip [*17*].

In another recent study that was conducted as part of *NCHRP 15-68 (01) Report: Effective Low-Noise Rumble Strips* and detailed in NCHRP Report 1107, a measurement program was conducted to establish recommended methods for evaluating the noise and vibration performance of various rumble strip designs. Measurements were performed on both shoulder and non-shoulder rumble strips using eight different vehicles, ranging from small compact cars to a large SUVs at 45 and 60 (mph) striking speeds. Two different rumble strip designs were evaluated to analyze the impact on driver feedback and the resulting interior and exterior noise. The first design featured traditional rectangular strips, while the second utilized a continuous sinusoidal profile. This study mainly focused on recommending standard procedures for measuring noise and vibration on rumble strips for practitioners and researchers. Findings of this study showed that sinusoidal strips will create less exterior noise in comparison to traditional strips, while they can create enough interior noise (i.e., greater than 6 dB from baseline) to alert drivers. They also recommend measuring interior noise level close to the driver's ear location and measuring vibration at the seat track location and with the steering column as a secondary option [*28,29*].

Another study, sponsored by the Montana Department of Transportation (MDT), aimed to assess whether sinusoidal centerline rumble strips (SCLRS) produce lower exterior noise levels at noise-sensitive locations along Montana roadways compared to traditional centerline rumble strips (CLRS). This project evaluated four different SCLRS designs against CLRS at various striking speeds (30, 50, and 70 mph). The findings indicated that SCLRS designs are quieter than traditional CLRS, with the difference becoming more noticeable at higher speeds. The SCLRS produced lower exterior noise levels, reducing noise by up to 4.4 dBA at 30 mph, 9.2 dBA at 50 mph, and 13.2 dBA at 70 mph striking speeds for passenger vehicles [*16*].

The Delaware Department of Transportation (DelDOT) assessed the exterior noise generated by edge line sinusoidal rumble strips at four study sites along two state routes. The results indicated that the impact noise from sinusoidal rumble strips was not noticeable at distances of 50, 150, 250, and 400 feet from the edge line [*15*].

The Washington State Department of Transportation (WSDOT) conducted research to evaluate the internal and external acoustical performance of sinusoidal rumble strip designs. The results showed that sinusoidal rumble strips had the lowest overall exterior sound levels and exhibited flatter, less “spikey” 1/3 octave bands in the lower frequencies. The increase in interior noise levels for sinusoidal rumble strips ranged from 7 dBA to 13 dBA, exceeding the recommended level of 6 dBA specified in *NCHRP Report 641* [*14*].

Other studies conducted in Kentucky, Florida, and Oregon have confirmed that sinusoidal rumble strips effectively reduce exterior noise while still producing enough interior noise to alert drivers when they leave their travel lane. Along with previously reviewed research, these studies demonstrate that sinusoidal rumble strips serve as a viable alternative to traditional rectangular rumble strips, offering noise reduction benefits without compromising their warning function [*30,31,32*]. Table 1 summarizes the key research documents reviewed in this section that focused on noise and vibration evaluations of sinusoidal rumble strips.

2.2 Safety Performance of Traditional Rumble Strips

Extensive research has been completed that has evaluated the safety performance of traditional rumble strip designs. The first group of studies focused on centerline rumble strips, which sought to assess the effectiveness of this type of corrugation in reducing roadway departure crashes. FHWA defines a roadway departure crash as a crash “which occurs after a vehicle crosses an edge line or a centerline or otherwise leaves the traveled way” [*33*]. The safety effectiveness of CLRS for two-lane two-way highways in adverse winter weather conditions and under different winter maintenance levels was evaluated in Wyoming. By applying the before-after empirical Bayes (EB) method and developing safety performance functions (SPFs), the study found that CLRS contributed to a crash reduction of 25 percent to 68 percent on the analyzed routes. Additionally, higher levels of winter maintenance were associated with greater CLRS effectiveness [*34*].

A Michigan DOT evaluation assessed the safety impacts of a statewide CLRS installation program carried out by MDOT between 2008 and 2010. The study used the EB method to assess the effectiveness of CLRS installed on 4,077 miles of two-lane, two-way highways. Results showed that CLRS reduced target cross-centerline crashes by 27.3 percent, and this reduction increased to 32.8 percent when CLRS were combined with shoulder rumble strips (SRS). Additionally, the study provided valuable insights into identifying and addressing target (cross-centerline) lane departure crashes for use in rumble strip safety performance evaluation [*35*].

Table 1. Reviewed Noise and Vibration Evaluations of Sinusoidal Rumble Strips

Study Title	Summary
Traffic Noise at Rumble Strips – Denmark (2007) [*22*]	Pass-by noise levels conducted in Denmark for various rumble strip designs, which included sinusoidal, “cylinder-segment”, and rectangular. Sinusoidal rumble strips provided the lowest increase in noise level (0.5 to 1.0 dB), with the rectangular-shaped strips producing the highest increase (3 to 7 dB).
Sinusoidal Rumble Strip Design Optimization Study – Minnesota DOT (2016) [*13*]	Four potential sinusoidal configurations (all with 14-inch wavelengths) were compared to Minnesota’s traditional rumble strip design, via evaluation of external and internal noise levels. While all four potential sinusoidal configurations resulted in less external noise levels than the current standard for passenger cars, depths of 1/2 in. gave superior performance for pickups.
Assessment of Alternative Sinusoidal Rumble Strip Construction – Indiana DOT (2018) [*27*]	Compared three different sinusoidal designs to traditional milled rumble strips by collecting vibration data, internal and external noise data, as well as retro reflectivity information. All three sinusoidal designs generated less external noise than the conventional design, interior noise was similar, and retro-reflectivity met minimum standards one year after installation. Wavelengths of 12 inches provided balance between interior and exterior noise levels.
Design and Acoustic Evaluation of Sinusoidal Mumble Strips vs. Conventional Ground-In Rumble Strips – CALTRANS (2018) [*21*]	Compared noise generated by sinusoidal vs. conventional rumble strips. The sinusoidal design generated lower high-frequency exterior noise levels while providing generally the same or greater interior noise levels.
New Rumble Strip Designs to Reduce Roadside Noise & Promote Safety – WSDOT (2018) [*14*]	Evaluated noise levels from a series of new rumble strip designs. Sinusoidal rumble strips were found to be the highest performing design given the lower exterior noise levels and within the acceptable range for interior noise.
Rumble Strip Wayside Noise Study Experimental Project – Montana DOT (2019) [*16*]	Compared roadside noise for four potential sinusoidal CLRS designs to the current traditional CLRS design. Noise levels during contact with the current design exceeded each of the sinusoidal designs at speeds of 30, 50 or 70 mph.
Quantifying the Performance of Low-Noise Rumble Strips – Oregon DOT (2019) [*17*]	Study conducted in Oregon evaluated sinusoidal CLRS as an alternative to the conventional rounded design. Exterior noise levels were lower with the sinusoidal CLRS for a passenger car and a van but were higher for heavy vehicles. Interior noise levels were sufficient to create a noticeable alert.
NCHRP Research Report 1107: Effective Low-Noise Rumble Strips – National Academies of Science (2024) [*29*]	Tests using eight vehicles at 45 and 60 mph compared noise and vibration performance of traditional rounded strips to sinusoidal strips. Results showed that sinusoidal strips reduce exterior noise while maintaining sufficient interior noise (>6 dB) to alert drivers. The study also recommended standard measurement procedures, including assessing interior noise near the driver’s ear and vibration at the seat track and steering column.
Rumble Strip and Sinusoidal (Mumble) Strip Noise Study along SR-16 and SR-20 – Delaware DOT (2019) [*15*]	Study conducted in Delaware to investigate sinusoidal rumble strips installed along two state routes. The study noted that the differences in external noise created by vehicles passing over the mumble strips compared to regular road noise should typically not be perceptible from distances 50 feet or greater.
Evaluation of Alternative Rumble Strip Designs – Kentucky Transportation Cabinet (2020) [*30*]	While this study conducted in Kentucky did not include a new field evaluation of sinusoidal rumble strips, the authors conducted a detailed literature review and an assessment of current practices. The prior work reviewed in the study has generally shown that alternative designs (such as sinusoidal rumble strips) can provide increased interior noise and vibration with less exterior noise.
Effect of Rumble Strip Profiles on Noise Levels – Florida DOT (2020) [*31*]	Study conducted in Florida which investigated noise levels for a range of rumble strip profiles. The work demonstrated that sinusoidal rumble strips (as well as raised audible rumble strips) were associated with an increase in internal noise levels without a discernible increase in external noise levels.
Rumble Strip Design Analysis to Contribute to Low Exterior Noise Using Finite Element Modeling – Oregon DOT (2022) [*32*]	Study sponsored by the Oregon DOT to evaluate a range of rumble strip designs, including 21 sinusoidal designs, via finite element modeling. The simulation results were in general agreement with prior field evaluations and sinusoidal designs produced lower noise output than traditional designs.

The Virginia Department of Transportation (VDOT) evaluated the safety impact of CLRS on rural two-lane highways, particularly focusing on roadway curves. The findings indicated that curves designed for speeds of 55 mph or less experienced a 25 percent reduction in total crashes, with a 42 percent decrease in head-on, opposite-direction sideswipe, fixed-object, and off-road crashes. For straight road segments, total crashes decreased by 37 percent, while fatal and injury crashes saw a 46 percent reduction. When considering all road segments, the overall reduction in total crashes was 0.93, and for head-on and opposite-direction sideswipe crashes, the reductions were 0.93 and 0.65 for both total crashes and fatal or injury crashes, respectively [*36*]. Research conducted by the Washington DOT (WSDOT), demonstrated that CLRS decreased total lane-departure crashes by 34.9 percent and reduced fatal and injury crashes by 37.7 percent. For cross-centerline crashes, reductions of 44.6 percent for total crashes and 48.6 percent for fatal and injury crashes were observed [*37*].

In addition to research on centerline rumble strips, other evaluations have specifically examined shoulder rumble strips (SRS) and their effects on target crashes. An EB study examining run-off-road (ROR) crashes on two-lane rural highways in Minnesota found that the installation of SRS led to a 13 percent reduction in all ROR crashes and an 18 percent reduction in ROR crashes involving injury [*38*]. Another study in Idaho assessed the impact of SRS on reducing ROR crashes across three types of roadways: two-lane rural highways, four-lane rural highways, and rural freeways. The study analyzed all ROR crashes, severe ROR crashes, and truck-related ROR crashes using comparison groups and EB methods for before-and-after evaluations. In cases where sufficient control data wasn't available, a simpler naïve before-after analysis was applied. For two-lane rural highways, SRS installation reduced all ROR crashes by 15 percent and severe ROR crashes by 74 percent, with greater benefits on roads with mild to moderate curves. On rural freeways, all ROR crashes decreased by 29 percent, and severe crashes dropped by 67 percent, with the difference reflecting a higher occurrence of minor crashes in these areas. Four-lane rural highways experienced a 60 percent reduction in all ROR crashes and a 45 percent reduction in severe crashes. Truck-related ROR crashes across all rural highways also declined significantly, with reductions ranging from 42 percent to 62 percent [*39*].

NCHRP Report 641 provides a comprehensive study on both CLRS and SRS safety effectiveness. It was found that the installation of CLRS on rural two-lane roadways led to reductions in total crashes, fatal and injury crashes, target crashes (head-on and opposite-direction sideswipe), and fatal and injury target crashes of 9 percent, 12 percent, 30 percent, and 44 percent, respectively. On urban two-lane roadways, CLRS reduced total target crashes and fatal and injury target crashes by 40 percent and 64 percent, respectively. SRS were found to reduce total ROR crashes by 15 percent and fatal and injury ROR crashes by 29 percent [*40*].

Many safety performance evaluations of rumble strips have included development of crash modification factors (CMFs), which are multiplicative factors reflecting safety performance impact associated with the treatment. The Minnesota DOT's *Rectangular Rumble Strip Safety Evaluation* report [*10*] included a comprehensive review of the CMFs specific to conventional (i.e., non-sinusoidal) longitudinal rumble strips from the FHWA's *CMF Clearinghouse* [*41*]. Table 2 is adapted from the MnDOT report and lists the CMFs for rural two-lane highways from the *CMF Clearinghouse* for CLRS only, SRS only, and CLRS plus SRS. Table 2 demonstrates that the use of conventional longitudinal rumble strips on the centerline and/or shoulder provides consistent reductions in crashes and injuries along rural two-lane highways.

Table 2. Summary of CMFs for Conventional Longitudinal Rumble Strips on Two-Lane Rural Highways [*10*]

Installation Configuration	Fatal and Injury Crashes			Total Crashes		
	Number of CMFs	Average CMF	Range of CMFs	Number of CMFs	Average CMF	Range of CMFs
CLRS only	9	0.76	0.55 – 1.04	34	0.75	0.33 – 1.04
SRS only	8	0.74	0.53 – 1.05	23	0.84	0.53 – 1.40
CLRS + SRS	4	0.79	0.56 – 1.02	28	0.72	0.44 – 1.02

2.3 Safety Performance of Sinusoidal Rumble Strips

While the safety performance impacts of traditional rumble strip designs have been researched extensively, few safety performance analyses of sinusoidal rumble strips have been completed at the time of this report, although several projects are ongoing. A recent Florida study assessed the safety impacts of sinusoidal edge line rumble strips on rural two-lane and multi-lane roadways. Using the EB method, the study found a 30 percent reduction in total lane departure crashes on rural two-lane roads with edge line sinusoidal rumble strips. On multi-lane highways, sinusoidal rumble strips were associated with a 61 percent reduction in lane departure crashes, though this finding was not statistically significant [*42*].

A recent study sponsored by the Minnesota DOT examined the safety effectiveness of sinusoidal rumble strips on rural two-lane undivided roadways built between 2018 and 2022. CMFs were estimated through a cross-sectional analysis comparing crash rates at locations with sinusoidal rumble strips (centerline only, centerline and shoulder, or shoulder only) to those with rectangular rumble strips. The analysis used matched-pair comparisons to align sites with similar characteristics. The results indicated no significant differences in crash rates between rural two-lane undivided roads with sinusoidal rumble strips and those with rectangular rumble strips [*43*].

A recent study in Maine evaluated the impact of sinusoidal and traditional centerline rumble strips on lane departure crashes along rural two-lane roads using the EB before-and-after method. The results indicated a CMF of 0.78 for total crashes and 0.58 for fatal and injury crashes on minor arterial roads with sinusoidal centerlines. In contrast, principal arterial roads showed a CMF of 1.30 for total crashes and 1.34 for fatal and injury crashes. A key limitation of the study was the insufficient data and small sample size, which rendered the CMFs for sinusoidal designs statistically insignificant. The authors highlighted that the limited crash data constrained the statistical significance of the findings, emphasizing the need for future studies with larger datasets [*44*]. Table 3 summarizes the completed research projects that focused on safety evaluation of sinusoidal rumble strip designs.

Table 3. Selected Completed Sinusoidal Rumble Strip Safety Evaluations

Study	Summary
Florida DOT: Evaluating the safety effectiveness of edge line sinusoidal rumble strips on lane departure crashes prevention (2024) [*42*]	Evaluating the safety impacts of edge line sinusoidal rumble strips on rural two-lane and multi-lane roadways. Using the empirical Bayes (EB) method, the study found a 30% reduction in total lane departure crashes on rural two-lane roads with these rumble strips. In multilane highways 61% reduction were observed, though the result was not statistically significant.
Minnesota DOT: Sinusoidal Rumble Strips Safety Evaluation (2023) [*43*]	Examined the safety effectiveness of sinusoidal rumble strips on rural two-lane undivided roadways built between 2018 and 2022. Crash modification factors (CMFs) were estimated through a cross-sectional analysis comparing crash rates at locations with sinusoidal rumble strips (centerline only, centerline and shoulder, or shoulder only). The results indicated no significant differences in crash rates between sinusoidal rumble strips and those with traditional rumble strips.
Maine DOT: Examining the Impact of Centerline Rumble-Strip Installation in Prevention of Head-On and Opposite Sideswipe Collisions in Maine (2023) [*44*]	Safety performance evaluation of Maine's sinusoidal centerline rumble strip installations which began in 2018. The Empirical Bayes (EB) observational before-and-after method is utilized. CMFs were developed for sinusoidal CLRS but the results were not statistically significant due to insufficient data and small sample size.

2.4 Effect of Rumble Strips on Bicyclists

Bicyclists may face challenges navigating rumble strips, especially when the strips are designed to target motor vehicle drivers. A National Park Service study found that as rumble strips become longer and deeper, they cause greater discomfort and make it more difficult for bicyclists to maintain control while crossing them [*45*]. A Kansas DOT study surveyed bicyclists and found their primary concern with rumble strips is the limited shoulder space available for safe travel. When it came to crossing rumble strips, 70 percent of the 23 participants favored or somewhat favored "football-shaped" designs over rectangular ones [*46*]. A study conducted in Maine investigated whether rumble strips pose any safety risks to bicyclists. The findings revealed that participants considered the rumble strips, which were milled circular strips measuring 7 in long and 1/2 in deep and narrower rectangular strips of the same depth, to be annoying but not hazardous [*47*]. A related study conducted in Arizona examined the feasibility of adding gaps in rumble strip patterns to allow bicyclists to cross safely and specifically aimed to determine the optimal gap size needed for safe exits without striking the strips. The researchers found that providing gaps of approximately 12 ft at intervals of 40 to 60 ft ensures optimal safety for bicyclists [*48*]. Research conducted in California and Pennsylvania examined how shoulder rumble strips affect bicyclist safety and comfort. The California study identified 5/16 in as the optimal depth for bicyclists, while the PennDOT study found that depths between 1/4 to 3/8 in were considered acceptable, with 1/4 in being the most preferred [*49,50*]. In summary, bicyclists' primary concern is to ensure that rumble strips are designed and installed in a way that supports safe travel for cyclists. Key factors include sufficient space between the rumble strip and the shoulder edge, appropriately spaced gaps for crossing, and a depth ranging from 0.25 to 0.4 in.

2.5 Effect of Rumble Strips on Motorcyclists

The FHWA examined how rumble strips impact motorcyclists, revealing that raised pavement markers and rumble strip bars can become slippery in wet conditions. However, milled centerline rumble strips were not found to create safety concerns, as riders crossing the strips showed no noticeable changes in steering, braking, or throttle control. Handling issues were only found to occur when the rider was unaware of the rumble strips. Installation of warning signs such as "Centerline Rumble Strips Ahead" were recommended to improve awareness [*51*]. A Minnesota DOT study surveyed motorcyclists and found that they preferred rumble strips with a width of 14 in and a maximum depth of 3/8 in. The findings also highlighted concerns about raised strips and tapered edges, with riders favoring a straight-edge design instead [*13*]. A study in Sweden interviewed motorcyclists about their experience driving over longitudinal rumble strips that were 0.375 in deep. The riders had no concerns about the design or its impact on driving and also noted that the rumble strips felt less noticeable at higher speeds [*52*]. Research conducted in the United Kingdom assessed motorcycle safety with their optimal sinusoidal "rippleprint" rumble strip, which had a depth of 0.3 in and a wavelength of 13.8 in. Motorcycles traveling between 20 to 40 mph experienced some vibration in the handlebars, but no loss of control was reported. Braking performance was comparable to that on a flat surface. At higher speeds, 50 and 60 mph, motorcyclists did not report any handling issues either [*53*]. In summary, motorcyclists can generally cross milled rumble strips without issue, although raised strips or lack of awareness of centerline rumble strips may cause some challenges. A maximum depth of 0.375 inch was recommended to ensure optimal stability for motorcyclists.

3. FIELD EVALUATION OF NOISE AND VIBRATION

A field study was performed to assess the potential of sinusoidal corrugations as an alternative to traditional designs for non-freeway shoulder applications. The primary objective of this field study was to determine if the sinusoidal design provides adequate in-vehicle noise and vibration to effectively alert drivers, while simultaneously minimizing roadside noise. To test this hypothesis, noise and vibration data were collected at rural highway sites in Michigan.

3.1 Methodology

NCHRP Report 1107: *Effective Low-Noise Rumble Strips* outlines recommended procedures for evaluating the noise and vibration performance of rumble strip designs [*29*]. While most previous field studies on rumble strip noise and vibration have focused on data from a single vehicle type, running speed, or rumble strip design, the current study expands on this body of work by including multiple vehicle types, running speeds, and rumble strip designs to assess the influence of these factors on generated noise and vibration levels. The findings will seek to determine if the sinusoidal design provides adequate in-vehicle noise and vibration to effectively alert drivers within the tested vehicle types and at typical travel speeds, while simultaneously minimizing roadside noise impacts for nearby residents.

3.1.1 Site Selection

Six two-lane rural highway locations in Michigan were selected for the field evaluation. The sites, which are displayed in Figure 6, were selected due to low traffic volumes, adequate roadsides for data collection, and proximity to each other, while providing diversity in the rumble strip design characteristics. Each location included an asphalt pavement surface for both the travel lanes and shoulders. Sinusoidal shoulder corrugations existed at four of the locations, while the remaining two locations included traditional shoulder corrugations. The site details are provided in Table 4. Figure 8 displays the shoulder corrugations present at each site.

Table 4. Noise and Vibration Study Site Characteristics

Site	Location	Corrugation Type	Corrugation Dimensions in Inches (Width, Depth, Offset from Edge of Travel Lane)
Site 1	M-134, West of Cedarville	Sinusoidal	W: 8, D: 0.375, O: 0
Site 2	M-123, South of Trout Lake	Sinusoidal	W: 12, D: 0.375, O: 8
Site 3	M-134, East of Cedarville	Traditional	W: 12, D: 0.5, O: 18
Site 4	M-28, East of M-123	Sinusoidal	W: 12, D: 0.5, O: 6
Site 5	M-66, North of Maple Grove	Sinusoidal	W: 12, D: 0.375, O: 18
Site 6	M-66, South of Maple Grove	Traditional	W: 12, D: 0.375, O: 18

Note that while MDOT’s specification calls for a depth of 0.5 inches for non-freeway shoulder corrugations, a 0.125-inch variance in corrugation depth is allowed. Thus, all sites were within the allowable depth specification.

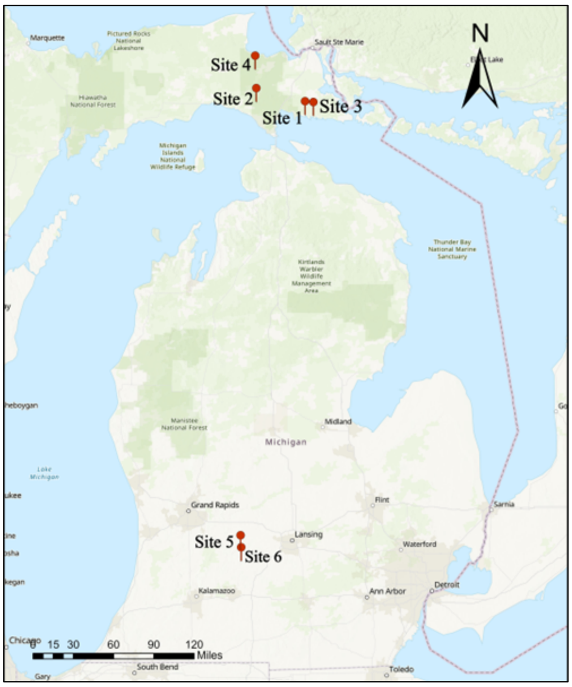

Figure 6. Locations for Field Evaluation of Shoulder Rumble Strip Noise and Vibration

3.1.2 Test Vehicles

Two vehicles were utilized during the data collection, including a 2023 Chrysler Pacifica minivan and a 2021 Western Star W4900SF snowplow truck owned by MDOT, which are shown in Figure 7. The inclusion of a snowplow truck represents an addition to the vehicle types tested, as the *NCHRP 1107* study evaluated a variety of passenger vehicles, including a minivan, but did not include a heavy truck. The minivan was equipped with 245/50R20 tires, while the snowplow truck used 385/65R22.5 tires in the front and dual 12R22.5 H/16PLY tires in the rear. To ensure consistency during testing, tire pressure was maintained to the manufacturer specification of 30 psi for the minivan and 110 psi for the snowplow truck.

Figure 7. Test Vehicles: Minivan (Left) and MDOT Snowplow Truck (Right)

Figure 8. Shoulder Corrugations Present at Each Noise and Vibration Data Collection Site

3.1.3 Controlled Pass-By Procedure

Controlled pass-bys were conducted with the two test vehicles on and off the shoulder corrugations at each test site at speeds of 55 and 65 mph. These speeds were selected as they represent the statutory speed limits for rural state non-freeway highways in Michigan. Speeds were controlled using the vehicle's cruise control. The quality of each pass-by, specifically, whether the vehicle remained entirely on or off the rumble strips, was verified by a roadside observer. Potential interference from other vehicles was also evaluated during this process. Runs that did not meet the established criteria or were disrupted by traffic or other noise sources were repeated as necessary.

For the minivan, two clean passes (without disruptions or nearby traffic) were recorded and averaged for each test condition. For the snowplow truck, only a single clean pass was collected due to time constraints. To obtain baseline pavement noise and vibration measurements at each site, a series of pass-bys were also made for each vehicle at each speed while driving in the travel lane as close as possible to the corrugations without making contact. In total, 48 data points (6 sites x 2 vehicles x 2 speeds x 2 types of passes [on vs. off corrugations]) were obtained for each noise and vibration metric.

3.1.4 Roadside Noise Data Collection

This study generally followed the procedures provided in *AASHTO TP 98-13* [*54*] for the quantitative measurement of sound pressure levels near roadways where individual vehicle pass-by events can be captured without interference from surrounding traffic. A sound level meter was positioned 25 feet from the center of the near travel lane and 5 feet above the pavement surface. The sound meter was used to measure the maximum sound pressure level dBA during each controlled pass-by of the test vehicles. During each pass-by, the test vehicle began contact with the rumble strips approximately 500 feet before the meter location, as marked by a cone, and continued contact until 500 feet after the meter, resulting in roughly 10 seconds of continuous contact with the corrugations. To ensure measurement isolation, no other vehicles were in sight during the entire contact period. Sound pressure data were recorded on the meter using a fast response setting, with an exponential averaging time constant of 0.125 seconds and a sampling interval of 0.1 seconds. Only the maximum sound pressure level measured during each pass-by was recorded. Figure 9 illustrates the roadside noise measurement setup for controlled pass-bys of the test vehicle.

Figure 9. Roadside Noise Measurement Setup

3.1.5 In-vehicle Noise and Vibration Data Collection

In-vehicle sound and vibration were measured during each pass-by event using a sound level meter and a triaxial accelerometer positioned within the vehicle cabin. To measure the in-vehicle noise that would be experienced by the driver, the sound level meter was positioned near the driver's headrest, with the microphone placed approximately at ear level. The sound level meter was securely mounted on a fixed tripod to prevent any movement or rattling during measurements. This setup follows recommendations from *NCHRP Report 1107*, which outlines procedures for evaluating the noise and vibration performance of rumble strip designs [*29*]. A sound calibrator was used to verify the meter's accuracy using two tones (250 Hz and 1,000 Hz) at levels of 94 dB and 114 dB. Figure 10 illustrates the in-vehicle noise measurement setup.

Figure 10. In-Vehicle Noise Measurement Setup

A triaxial accelerometer (TLD356M155, PCB Piezotronics) was mounted on the vehicle's steering column to measure vibrations. The sensor was factory-calibrated to maintain accuracy within ±1 percent over the expected frequency range (1 to 10kHz). The triaxial accelerometer had a dynamic sensitivity of 2.5 mV/g at 100 Hz. Acceleration data were collected using a 4-channel data acquisition unit (DAQ-9171, NI) and later post-processed to root mean square (RMS) values. The accelerometer was oriented so that the X-axis captured lateral motion, the Y-axis recorded longitudinal (fore/aft) motion, and the Z-axis measured vertical motion (Figure 11).

Figure 11. Triaxial Accelerometer Position on Steering Column (left) and Orientation (right)

3.1.6 Statistical Analysis

To analyze the sound and vibration generated during each pass-by event, separate multiple linear regression models were used to evaluate the influence of various factors on roadside noise, in-vehicle noise, and in-vehicle vibration. In the model, the maximum sound or vibration level measured during each pass-by event are considered as the dependent variable, while factors such as vehicle type, speed, corrugation type, and site were included as independent variables to assess their effects on the outcomes. The general form of the multiple linear regression model is given by Equation 1:

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \cdots + \beta_k X_{ik} + \varepsilon_i \qquad (1)$$

where Y_i is the sound or vibration level for pass-by event i, X_{i1} to X_{ik} are independent variables, β_0 is an intercept, β_1 to β_k are estimated regression ε_i coefficients for each independent variable, and σ^2 is a normally distributed error term with variance σ^2. Variable interactions between vehicle type and corrugation type were included in the models to directly assess the differential effects of the corrugation designs between the two different vehicle types.

3.2 Results

3.2.1 Roadside Noise

Figure 12 presents the maximum roadside sound pressure levels in dBA measured across all test conditions. As shown in Figure 12, sinusoidal rumble strips consistently produced lower roadside noise compared to traditional rumble strips under all test conditions. For sinusoidal corrugations roadside noise ranged from 77.7 to 90.9 dBA during the pass-bys, while traditional corrugations produced roadside noise ranging from 82.6 to 104.7 dBA. This supports the idea that sinusoidal rumble strips are a better option in areas where roadside noise is a concern. To better understand the factors influencing roadside noise during pass-by events, a regression model was developed, with the results displayed in Table 5.

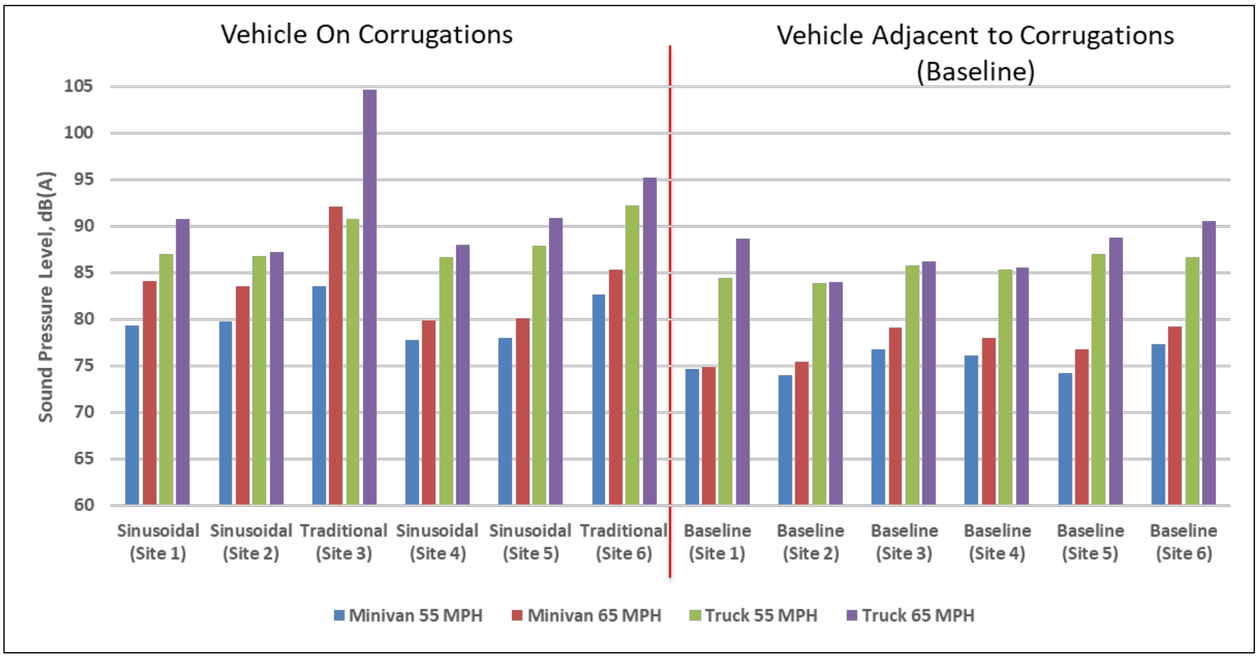

Figure 12. Maximum Roadside Noise Measured During Controlled Pass-bys

Table 5. Linear Regression Model for Maximum Roadside Noise

Parameter	Coefficient	Std. Err	p-value
Intercept	74.182	0.981	<0.001
Site			
Site 2	Baseline		
Site 1	1.113	1.002	0.275
Site 3	3.209	1.175	0.010
Site 4	0.313	1.002	0.757
Site 5	1.113	1.002	0.275
Site 6	1.984	1.175	0.101
Speed			
55-mph	Baseline		
65-mph	1.742	0.818	0.041
Vehicle			
Minivan	Baseline		
Snowplow Truck	10.025	0.818	<0.001
Vehicle Type x Corrugation Type x Speed			
Minivan, Sinusoidal, 55 mph	3.883	1.261	0.004
Minivan, Sinusoidal, 65 mph	5.342	1.261	<0.001
Minivan, Traditional, 55 mph	6.271	1.687	0.001
Minivan, Traditional, 65 mph	10.179	1.687	<0.001
Truck, Sinusoidal, 55 mph	2.233	1.261	0.086
Truck, Sinusoidal, 65 mph	2.617	1.261	0.046
Truck, Traditional, 55 mph	4.646	1.687	0.010
Truck, Traditional, 65 mph	11.404	1.687	<0.001
R^2	0.932		
Adjusted-R^2	0.900		

Note: Dependent variable = Roadside noise (dBA) measured 25 feet from center of nearest lane

The roadside noise effects associated with each parameter may be directly interpreted from the coefficient estimates presented in Table 5. Preliminary analyses found no statistical association between either corrugation depth or corrugation width and roadside noise, prompting these variables to be excluded. Although mostly statistically insignificant, a dummy variable for each site was included in the model to account for unobserved heterogeneity that existed between the sites, such as differences in pavement surface texture and general acoustical differences.

The parameter estimates for corrugation type by vehicle type and speed suggest that traditional shoulder corrugations produced significantly greater roadside noise compared to sinusoidal shoulder corrugations, particularly at 65 mph and especially for the truck. For the minivan at 55 mph, contact with the traditional corrugations increased noise by 6.3 dBA above the baseline, while the sinusoidal corrugations increased noise by only 3.9 dBA above the baseline. A similar difference was observed for the truck at 55 mph, as contact with the traditional corrugations increased noise by 4.7 dBA above the baseline compared to an increase of only 2.2 dBA above the baseline for the sinusoidal corrugations. For the minivan at 65 mph, contact with the traditional corrugations increased noise by 10.2 dBA above the baseline compared to an increase of 5.3 dBA for the sinusoidal design above the baseline. The greatest differences between the two corrugation designs were observed during the pass-bys of the truck at 65 mph. For the truck at 65 mph, the traditional corrugations increased noise by 11.4 dBA over the baseline, while the sinusoidal corrugations only increased noise by 2.6 dBA, representing a difference of 8.8 dBA between the two corrugation designs.

3.2.2 In-vehicle Noise

In-vehicle noise was continuously recorded by a sound meter positioned next to the driver headrest during each pass-by. An example time-series of the in-vehicle noise measured during on-corrugation and off-corrugation pass-bys at a single location is presented in Figure 13. The maximum in-vehicle sound pressure level was obtained from the time series data obtained during each pass-by. These values are presented in Figure 14 for each corrugation type, test vehicle, and speed. To assess the in-vehicle noise generated by the corrugations, the on-corrugation passes must be compared to the baseline passes. This may be performed by direct interpretation of the corrugation-related regression parameter estimates displayed in Table 6.

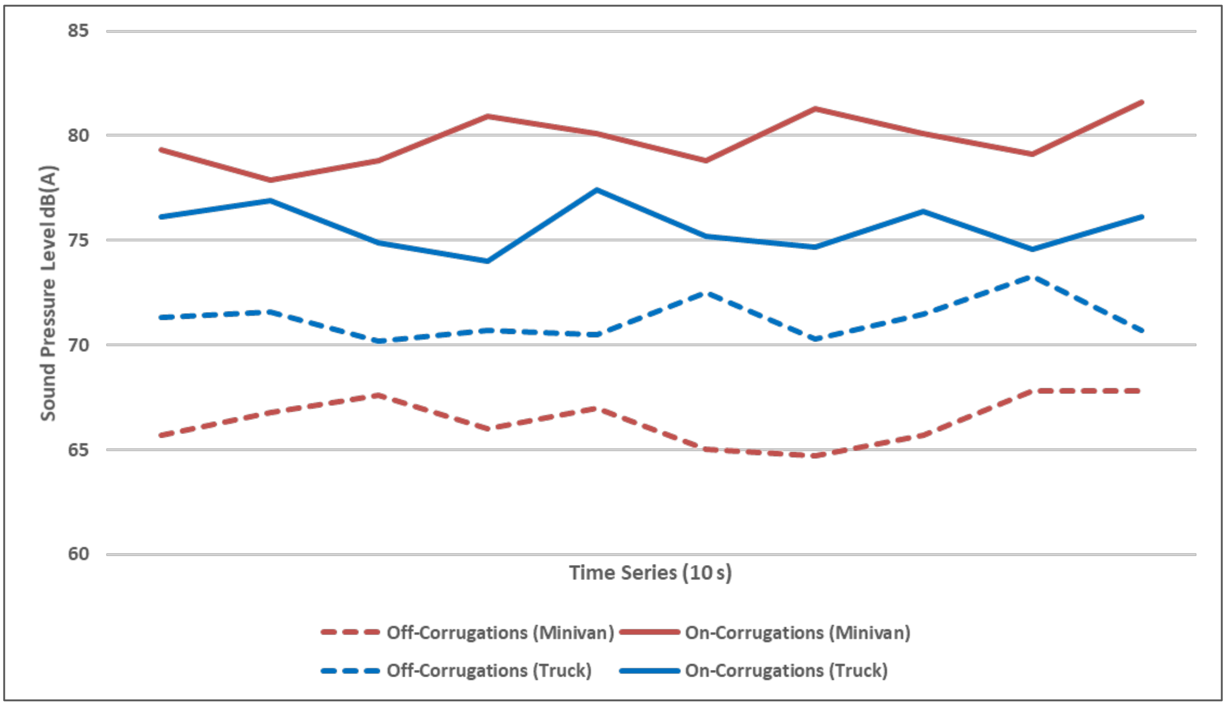

Figure 13. Example Time-series for In-vehicle Noise Measured during Controlled Pass-bys

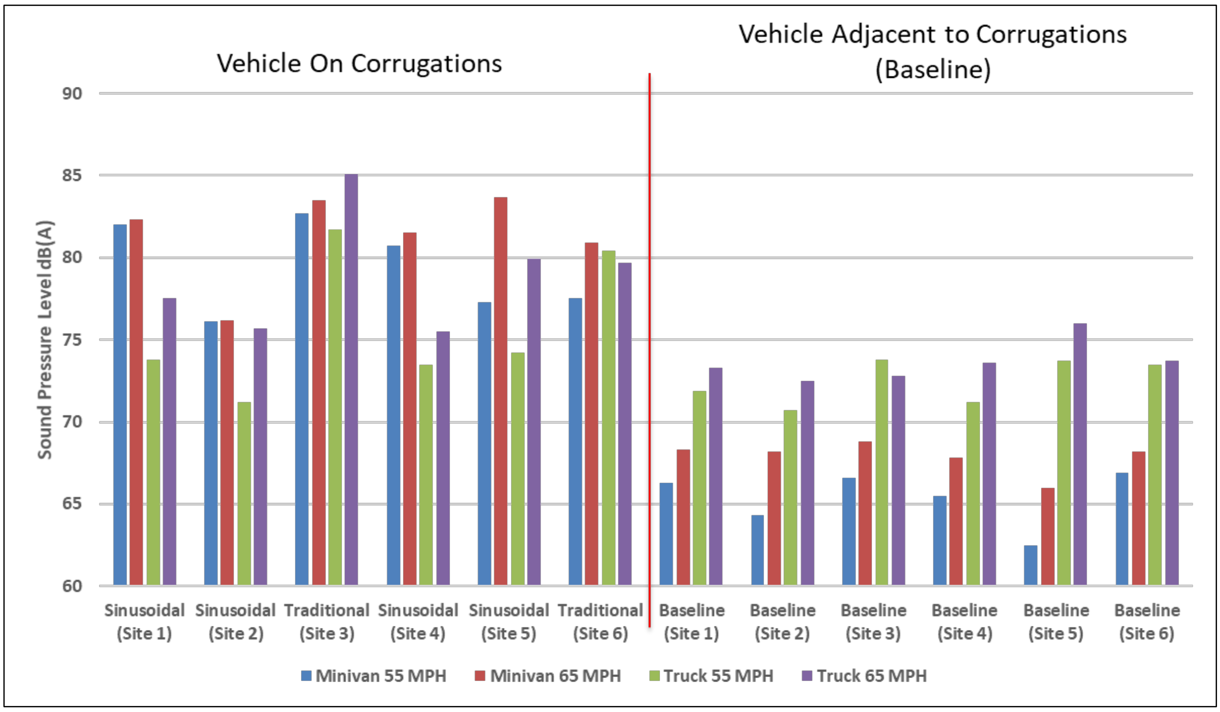

Figure 14. Maximum In-vehicle Noise at Driver Headrest during Controlled Pass-bys

Similar to the roadside noise data, preliminary analyses found no statistical association between either corrugation depth or corrugation width and in-vehicle noise, prompting these variables to be excluded. Furthermore, in contrast to the roadside noise measurements, there was no significant in-vehicle noise effect associated with speed during contact with the corrugations for the minivan, and only a minor effect for the truck. The site factors were again included in the model to account for unobserved heterogeneity that existed between the sites, such as differences in pavement surface texture and general acoustical differences.

The parameter estimates for the minivan show consistent increases for in-vehicle noise over the baseline (13.7 – 14.0 dBA) during contact with the corrugations, regardless of corrugation type or speed. The truck produced much lower in-vehicle noise, particularly during contact with the sinusoidal corrugations, which increased in-vehicle noise by only 1.4 dBA and 3.5 dBA over the baseline at 55 mph and 65 mph, respectively. In comparison, traditional corrugations increased in-vehicle noise between 7.7 and 8.2 dBA over the baseline when contacted by the truck. According to *NCHRP Report 641: Guidance for the Design and Application of Shoulder and Centerline Rumble Strips*, a 6 dBA increase from baseline is recommended to effectively alert drivers [*40*], while a 3 dBA increase is generally considered the minimum required for a noticeable change by the average person. Based on these thresholds, both sinusoidal and traditional rumble strips generated adequate in-vehicle noise to alert the minivan driver. However, the sinusoidal rumble strips did not produce sufficient in-vehicle noise to effectively alert the driver of the snowplow truck at 55 mph.

Table 6. Linear Regression Model for Maximum In-vehicle Noise

Parameter	Coefficient	Std. Err	p-value
Intercept	63.503	0.787	<0.001
Site			
Site 2	Baseline		
Site 1	2.563	0.841	0.004
Site 3	3.603	0.986	0.001
Site 4	1.800	0.841	0.039
Site 5	2.300	0.841	0.010
Site 6	1.828	0.986	0.072
Speed			
55-mph	Baseline		
65-mph	2.196	0.486	<0.001
Vehicle			
Minivan	Baseline		
Snowplow Truck	6.442	0.687	<0.001
Vehicle Type x Corrugation Type x Speed			
Minivan, Sinusoidal, 55 mph	13.688	1.078	<0.001
Minivan, Sinusoidal, 65 mph	13.729	1.078	<0.001
Minivan, Traditional, 55 mph	13.713	1.442	<0.001
Minivan, Traditional, 65 mph	13.954	1.442	<0.001
Truck, Sinusoidal, 55 mph	1.396	1.078	0.205
Truck, Sinusoidal, 65 mph	3.513	1.078	0.003
Truck, Traditional, 55 mph	8.221	1.442	<0.001
Truck, Traditional, 65 mph	7.712	1.442	<0.001
R^2	0.937		
Adjusted-R^2	0.917		

Note: Dependent variable = In-vehicle noise measured at driver headrest (ear-height)

3.2.3 Steering Column Vibrations

Vibration levels were measured in three directions, lateral (X), longitudinal (Y), and vertical (Z), at the steering column of each test vehicle. The accelerometer recorded motion in units of acceleration (g, m/s^2, or ft/s^2), which required post-processing to convert into vibration levels expressed in decibels (dB). The initial step was to smooth the data into usable increments by converting the raw accelerations measured for each axis into moving averages compiled at 1-second increments using Equation 2, as follows:

$$RMS = \sqrt{\frac{1}{n}\sum_i x_i^2} \tag{2}$$

where RMS is the root mean square in m/s^2, n is the number of sample measurements, and x_i is the i^{th} acceleration measurement. From there, the RMS acceleration data were converted into vibratory acceleration values in dB using Equation 3, as follows:

$$\text{Vibration (dB)} = 20\ \text{Log}\left(\frac{a}{a_0}\right), \left[a_0 : \frac{1\mu m}{s^2}\right] \tag{3}$$

where a is the RMS acceleration in m/s^2 and a_0 is a reference value for acceleration equal to 1 $\mu m/s^2$.

An example of the triaxial output resulting from each step of the acceleration-to-vibration data conversion task is provided in Figure 15.

Figure 15. Example Triaxial Vibration Time-series Data from Each Step of the Conversion Process

The maximum vibration, in dB, obtained at the steering column during the pass-bys for each test condition are presented in Figures 16 through 18 for the lateral (X), longitudinal (Y), and vertical (Z) directions, respectively. To assess the amount of vibration generated by the corrugations, the on-corrugation passes must be compared to the baseline passes. This is performed by direct interpretation of the corrugation-related regression parameter estimates displayed in Tables 7, 8, and 9.

Similar to the noise data, preliminary analyses found no statistical association between either corrugation depth or corrugation width and in-vehicle vibration, prompting these variables to be excluded. Furthermore, similar to the in-vehicle noise analysis, there was no significant vibratory effect associated with speed during contact with the corrugations for the minivan, and only a minor effect for the truck. The site factors were again included in the model to account for unobserved heterogeneity between the sites, such as differences in pavement surface texture.

The minivan generally experienced greater vibrations (both in absolute terms and relative to baseline) when contacting the corrugations compared to the snowplow truck. The greatest increases in vibration from baseline were observed in the lateral (X) and longitudinal (Y) directions, while the vertical (Z) direction showed less pronounced differences. This is largely due to the baseline (off-corrugation) vertical vibration being considerably higher than in the lateral or longitudinal directions for both vehicles and at both speeds. For the minivan, the variation between the axial vibration levels during contact with the corrugations is also likely due to the vehicle suspension being more effective at damping vertical vibrations than lateral and longitudinal vibrations. The lateral and longitudinal vibrations during contact with the rumble strips were far less pronounced for the snowplow truck, likely due to the greater vehicle weight and more robust suspension system compared to the minivan.

For the most part, the two types of corrugations produced similar increases in the vibration from baseline across the three axes. Speed generally did not have a significant effect on vibrations for either corrugation type or vehicle type. However, the sinusoidal corrugations produced vibrations that were 2 to 3 dB greater than the traditional corrugations in the lateral and longitudinal directions for the minivan traveling at 65 mph.

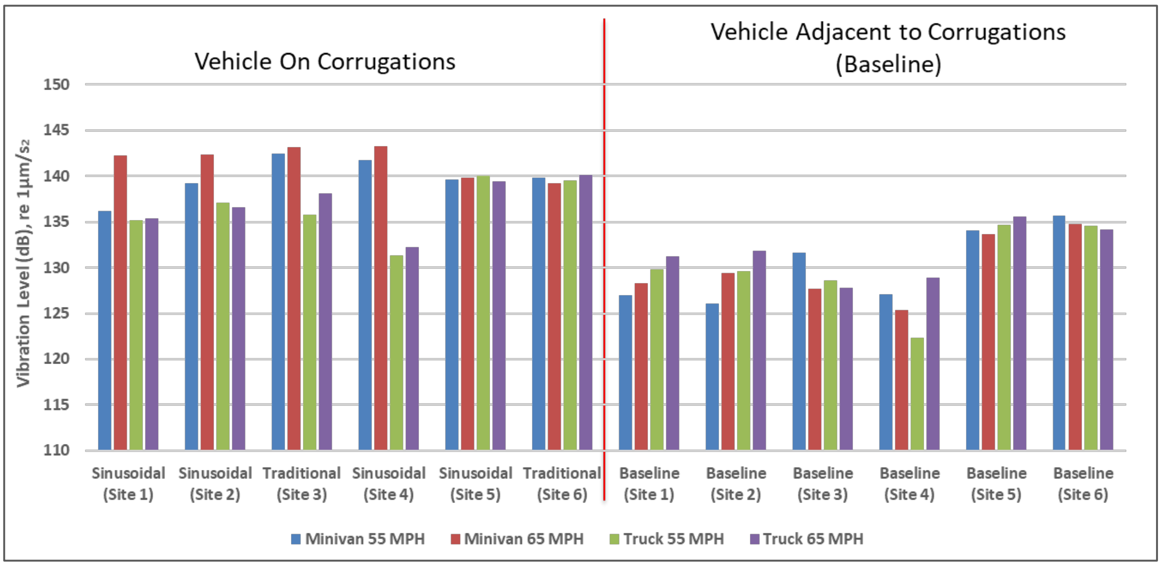

Figure 16. Maximum Vibration at Steering Column in Lateral (X) Direction

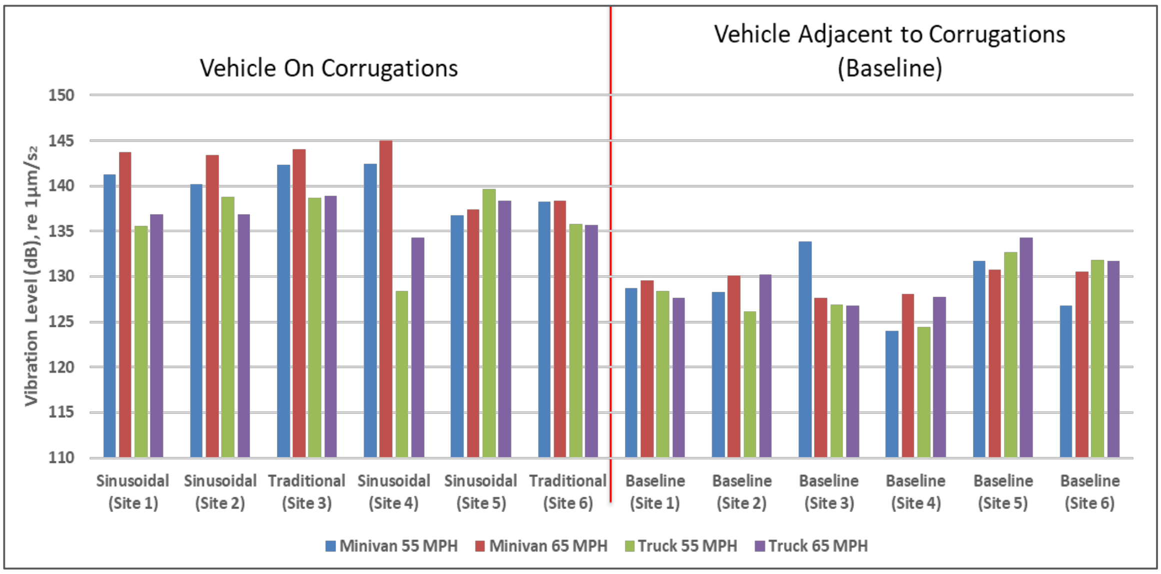

Figure 17. Maximum Vibration at Steering column in Longitudinal (Y) Direction

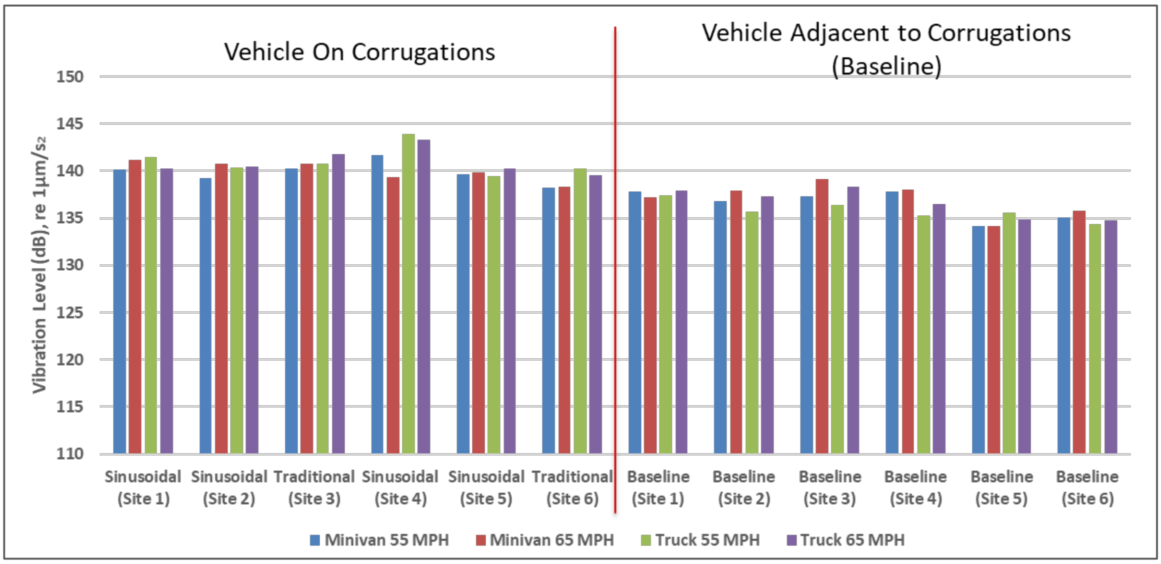

Figure 18. Maximum Vibration at Steering Column in Vertical (Z) Direction

Table 7. Linear Regression Model for Maximum Lateral (X-Axis) Vibration

Parameter	Coefficient	Std. Err	p-value
Intercept	129.092	1.303	<0.001
Site			
Site 2	Baseline		
Site 1	-0.850	1.331	0.528
Site 3	0.713	1.561	0.651
Site 4	-2.487	1.331	0.071
Site 5	3.088	1.331	0.027
Site 6	3.538	1.561	0.030
Speed			
55-mph	Baseline		
65-mph	0.633	1.087	0.564
Vehicle			
Minivan	Baseline		
Snowplow Truck	0.683	1.087	0.534
Vehicle Type x Corrugation Type x Speed			
Minivan, Sinusoidal, 55 mph	10.171	1.675	<0.001
Minivan, Sinusoidal, 65 mph	12.288	1.675	<0.001
Minivan, Traditional, 55 mph	9.933	2.241	<0.001
Minivan, Traditional, 65 mph	9.350	2.241	<0.001
Truck, Sinusoidal, 55 mph	6.188	1.675	0.001
Truck, Sinusoidal, 65 mph	5.554	1.675	0.002
Truck, Traditional, 55 mph	5.750	2.241	0.015
Truck, Traditional, 65 mph	6.567	2.241	0.006
R^2	0.836		
Adjusted-R^2	0.760		

Note: Dependent variable = X-axis vibration at steering column (dB)

Table 8. Linear Regression Model for Maximum Longitudinal (Y-Axis) Vibration

Parameter	**Coefficient**	**Std. Err**	**p-value**
Intercept	128.951	1.453	<0.001
Site			
Site 2	Baseline		
Site 1	-0.275	1.484	0.854
Site 3	0.784	1.740	0.655
Site 4	-2.450	1.484	0.109
Site 5	0.938	1.484	0.532
Site 6	-0.503	1.740	0.774
Speed			
55-mph	Baseline		
65-mph	0.933	1.212	0.447
Vehicle			
Minivan	Baseline		
Snowplow Truck	-0.117	1.212	0.924
Vehicle Type x Corrugation Type x Speed			
Minivan, Sinusoidal, 55 mph	11.621	1.867	<0.001
Minivan, Sinusoidal, 65 mph	12.938	1.867	<0.001
Minivan, Traditional, 55 mph	11.158	2.498	<0.001
Minivan, Traditional, 65 mph	11.125	2.498	<0.001
Truck, Sinusoidal, 55 mph	7.213	1.867	0.001
Truck, Sinusoidal, 65 mph	7.254	1.867	<0.001
Truck, Traditional, 55 mph	8.275	2.498	0.002
Truck, Traditional, 65 mph	7.392	2.498	0.006
R^2	0.825		
Adjusted-R^2	0.743		

Note: Dependent variable = Y-axis vibration at steering column (dB)

Table 9. Linear Regression Model for Maximum Vertical (Z-Axis) Vibration

Parameter	Coefficient	Std. Err	p-value
Intercept	136.421	0.477	<0.001
Site			
Site 2	Baseline		
Site 1	0.600	0.488	0.228
Site 3	1.063	0.572	0.072
Site 4	0.900	0.488	0.074
Site 5	-1.350	0.488	0.009
Site 6	-1.237	0.572	0.038
Speed			
55-mph	Baseline		
65-mph	0.683	0.398	0.096
Vehicle			
Minivan	Baseline		
Snowplow Truck	-0.550	0.398	0.177
Vehicle Type x Corrugation Type x Speed			
Minivan, Sinusoidal, 55 mph	3.692	0.614	<0.001
Minivan, Sinusoidal, 65 mph	3.133	0.614	<0.001
Minivan, Traditional, 55 mph	2.867	0.821	0.001
Minivan, Traditional, 65 mph	2.533	0.821	0.004
Truck, Sinusoidal, 55 mph	5.392	0.614	<0.001
Truck, Sinusoidal, 65 mph	4.483	0.614	<0.001
Truck, Traditional, 55 mph	4.717	0.821	<0.001
Truck, Traditional, 65 mph	4.183	0.821	<0.001
R^2	0.891		
Adjusted-R^2	0.840		

Note: Dependent variable = Z-axis vibration at steering column (dB)

To provide a clearer understanding of the relative effects of vehicle type, corrugation type, and speed, Figure 19 presents a graphical representation of the estimated parameters from the regression models for roadside noise, in-vehicle noise, and triaxial vibrations, along with the 95 percent confidence intervals. The value of each parameter estimate may be interpreted as the increase in noise (dBA) or vibration (dB) over the baseline that is attributed to the particular combination of vehicle type, corrugation type, and speed.

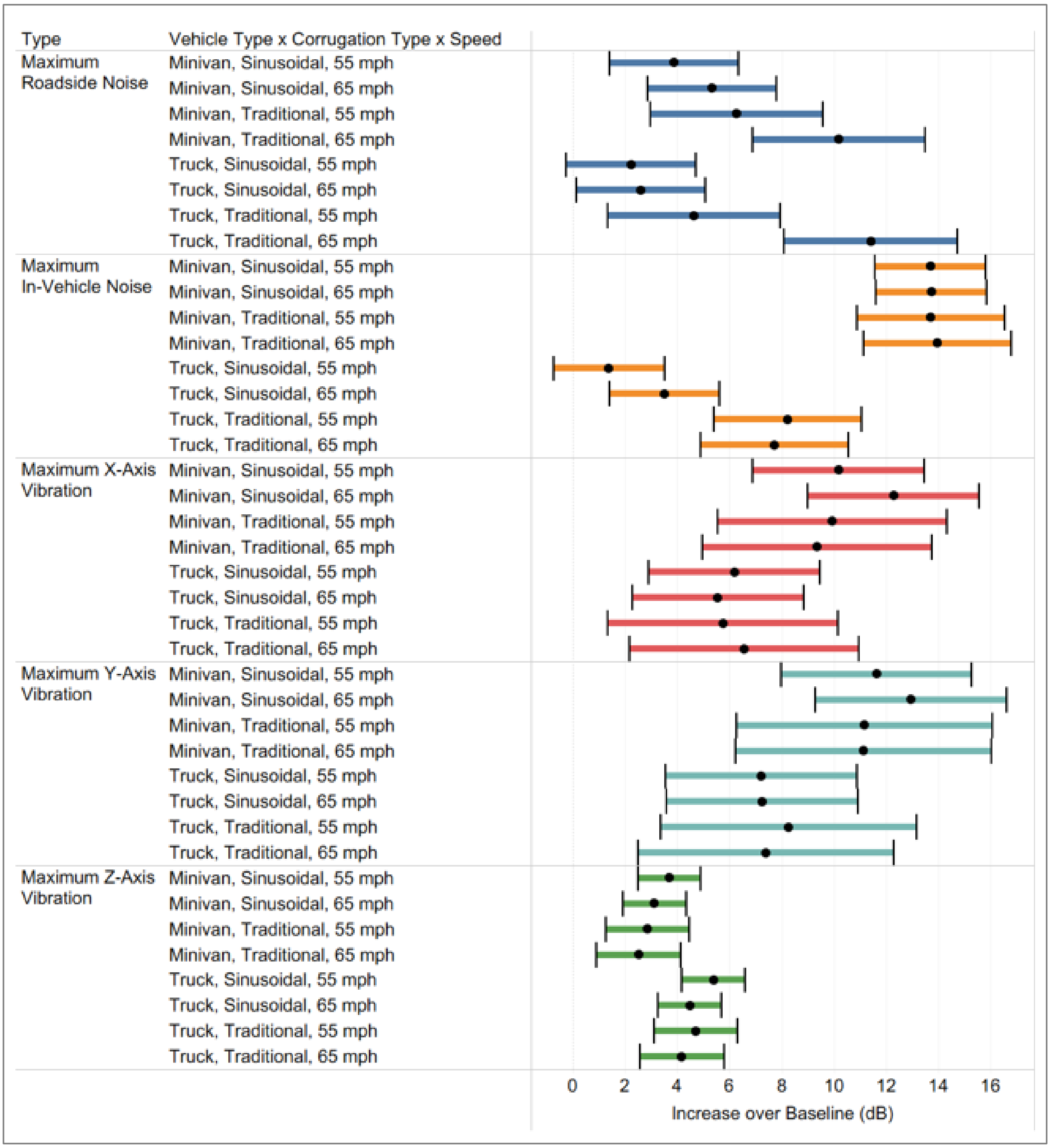

Figure 19. Linear Regression Parameter Estimates for Noise and Vibration

3.3 Conclusions

This study evaluated the noise and vibration performance of sinusoidal corrugations as a potential alternative to traditional rectangular corrugations for non-freeway shoulder applications. The primary objective was to determine if the sinusoidal design provides adequate in-vehicle noise and vibration to effectively alert drivers, while simultaneously minimizing roadside noise. To test this hypothesis, noise and vibration data were collected at six rural highway sites across Michigan. Four of the locations possessed sinusoidal milled shoulder corrugations, while the remaining two locations possessed traditional milled shoulder corrugations.

Controlled pass-bys were made on and off the corrugations at each site using a minivan and a snowplow truck at two travel speeds (55 and 65 mph). Roadside noise was measured 25 ft from the center of the near travel lane during each pass of the test vehicle. Additionally, in-vehicle noise was measured at the driver headrest, while triaxial vibration was measured at the steering column. The data were analyzed using linear regression to assess the influence of corrugation type, vehicle type, and speed.

The noise results confirm that traditional rumble strips produce higher roadside noise than the sinusoidal design, particularly at 65 mph and especially for the truck. At 55 mph, the traditional corrugations generated 2.4 dBA greater roadside noise than the sinusoidal design for both vehicle types. However, at 65 mph, the traditional corrugations generated 4.8 dBA and 8.8 dBA more noise than the sinusoidal corrugations for the minivan and truck, respectively.

Both corrugation designs produced sufficient in-vehicle noise (i.e., greater than 3 dBA) to alert drivers in the minivan, which is consistent with the findings from prior research. However, the in-vehicle noise produced by the sinusoidal design (1.4 dBA) was insufficient to alert drivers in the snowplow truck at 55 mph. These differences are likely due to differences in tire width, cabin noise insulation, and suspension characteristics between the two types of vehicles.

Turning to the vibration results, both sinusoidal and traditional corrugations produced considerable (5.5-13.0 dB) vibration at the steering column in the lateral (X) and longitudinal (Y) directions, while vertical (Z) vibration was much less pronounced (2.5-5.4 dB). The snowplow truck generally experienced less vibration during contact with the corrugations compared to the minivan, likely due to dampening caused by the greater weight and more robust suspension system of the truck. The amount of vibration generated by the corrugations was generally unaffected by speed.

Overall, the findings suggest that sinusoidal shoulder corrugations can effectively reduce roadside noise compared to traditional corrugations without compromising the level of in-vehicle noise or vibration that is necessary to alert drivers, particularly for passenger vehicles. While the in-vehicle noise produced during contact with the sinusoidal corrugations was insufficient to alert drivers in the snowplow truck at 55 mph, adequate levels of steering column vibration did occur. These results support the continued use of sinusoidal shoulder corrugations in noise-sensitive environments, including residential areas, schools, hospitals, and offices.

4. FIELD EVALUATION OF BICYCLIST COMFORT AND STABILITY

Bicyclists encounter a variety of situations that require them to move across a section of shoulder rumble strips, such as to complete a left-turn or to avoid hazards such as loose debris or deteriorated pavement. This underscores the need for deeper investigation into how cyclists navigate rumble strip corrugations and how these features influence their comfort and safety. Despite the relevance of this issue, research on bicycle rumble strip interactions remains limited.

To address this knowledge gap, cyclists' experiences with rumble strips were examined through an on-road field experiment in which a group of riders traversed over traditional and sinusoidal shoulder corrugations. The participating cyclists assessed various comfort and stability aspects of the rumble strips immediately after each traversal of the rumble strips. Additionally, vibration generated during each traversal was quantified using a triaxial accelerometer mounted on the bicycle handlebars, allowing for direct measurement of the vibration experienced by riders while traversing over the rumble strips.

4.1 Location

The field study was conducted along the southbound shoulder of M-66 south of Nashville, Michigan. M-66 is a rural two-lane state highway segment that featured adjacent sections of sinusoidal and traditional rectangular milled shoulder corrugations, as depicted in Figure 20. The corrugation depths were measured at 3/8 inch in each section, which was within the allowable limits of the Michigan Department of Transportation (MDOT) specification for shoulder corrugations on rural non-freeway highways. The study was performed during a single clear/dry weekday in May 2025 between the hours of 10 AM and 3 PM. The study was performed entirely along the southbound shoulder. The adjacent southbound travel lane was closed to traffic by MDOT to ensure rider safety and prevent interference from motor vehicle traffic.

4.2 Participants and Test Conditions

Six experienced touring road bicyclists (four male and two female) were recruited for the evaluation, all of whom were over the age of 50. The research team coordinated with the bicyclists in advance of the field study to determine the test conditions for the evaluation. It was determined that the test rides would be performed using four different bicycle frame materials (aluminum, carbon fiber, steel, and titanium), each of which would be ridden at two speeds (10 and 18 mph), and two tire pressures (low and high, based on the range printed on each tire). Table 10 summarizes the bicycle test conditions used in the field study. The cyclists supplied their own bicycles and riding gear, and many brought multiple frames for collective use by the group during the study. In total, three aluminum frames, five carbon fiber frames, one steel frame, and one titanium frame were utilized during the study. Each rider completed at least one traversal with each frame material, speed, and tire pressure, which allowed for comparisons to be made between the comfort and stability performance of the two corrugation designs across a variety of bicycle and bicyclist conditions.

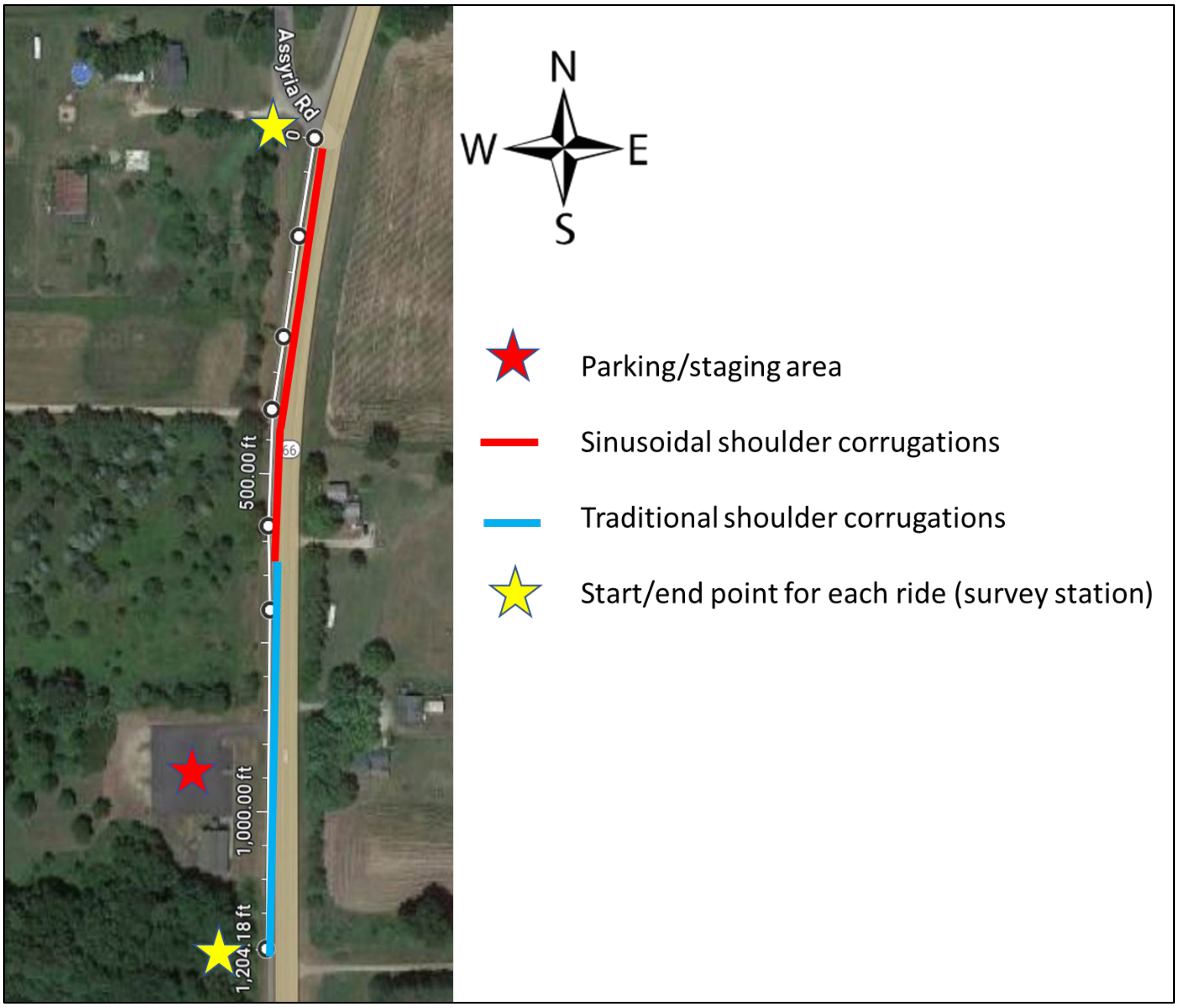

Figure 20. Data Collection Site on M-66 South of Nashville, Michigan

Table 10. Bicycle Test Conditions

Frame Material	Low Tire Pressure (psi)	High Tire Pressure (psi)	Tire Type	Rumble Strip Contact Speed (mph)
Aluminum-1	50-60	80	Gravel	10 and 18
Aluminum-2	60	115-120	Road	10 and 18
Aluminum-3	50	80	Gravel	10 and 18
Carbon Fiber-1	90	120	Road	10 and 18
Carbon Fiber-2	60-80	100	Road	10 and 18
Carbon Fiber-3	60	80	Road	10 and 18
Carbon Fiber-4	60	90	Road	10 and 18
Carbon fiber-5	60	90	Road	10 and 18
Steel-1	80-90	110-120	Road	10 and 18
Titanium-1	80-90	115-120	Road	10 and 18

Note: Each row represents a different bicycle utilized in the field study. Rows are nominally ordered.

4.3 Riding Procedure and Post-Ride Questionnaire

The riders typically rode in a single file group to ensure consistent speeds, which were specified as 10 mph in the northbound direction and 18 mph in the southbound direction. Each directional ride included left and right traversals across each corrugation type, in addition to a minimum of two seconds of continuous contact over each corrugation type. Contact with the rumble strips was made at the same location during all rides, with the contact points marked on the pavement using pink paint. Figure 21 demonstrates the riding procedure.

Figure 21. Bicyclists Contacting Rumble Strips during Test Rides

After each directional ride, riders were asked a series of questions regarding comfort and stability associated with the traditional and sinusoidal rumble strips contacted during the particular ride. Once all rides were completed, participants were given an additional questionnaire with general questions about their overall experience with shoulder rumble strips and their cycling experience in general. These questionnaire forms are provided in Appendix A. A total of 87 rides were completed by the six riders, and questionnaires were collected after each ride for subsequent processing and analysis.

4.4 Vibration Data Collection and Processing

Vibration data were collected using a triaxial accelerometer device (TLD356M155, PCB Piezotronics) mounted on the center of the bicycle handlebar such that the X-axis measured lateral (left/right) motion, the Y-axis measured longitudinal (fore/aft) motion, and the Z-axis measured vertical motion (Figure 22). The sensor was factory-calibrated to ensure accuracy within ±1 percent across the expected frequency range (1–10 kHz) and possessed a dynamic sensitivity of 2.5 mV/g at 100 Hz. The acceleration data were recorded by a 4-channel data acquisition unit (DAQ-9171, NI) and post-processed into root mean square (RMS) values.

As the vibration data collection required considerable equipment setup prior to each ride, it was decided that all vibration measurements would be made by a single rider using one bicycle of each frame material (carbon fiber, aluminum, steel, and titanium) riding in a consistent manner at both 10 mph and 18 mph and using a constant tire pressure. Depending on the bicycle frame, the data acquisition unit and laptop were either placed in a front-mounted basket or carried in a backpack when a basket could not be used. A total of 16 rides were performed in the manner described in the prior section, each of which included contact with both corrugation types along with the non-corrugated pavement surfaces in each section.

Figure 22. Triaxial Accelerometer Position on Handlebar (left) and Orientation (right)

The accelerometer recorded triaxial motion in units of acceleration (g, m/s², or ft/s²), which required post-processing to convert into vibration expressed in decibels (dB). The initial step was to smooth the data into usable increments by converting the raw accelerations measured for each axis into moving averages compiled at 1-second increments using Equation 4:

$$RMS = \sqrt{\frac{1}{n}\sum_i x_i^2} \quad (4)$$

where RMS is the root mean square in m/s^2, n is the number of sample measurements, and x_i is the ith acceleration measurement. From there, the RMS acceleration data were converted into vibratory acceleration values in dB using Equation 5, as follows:

$$\text{Vibration (dB)} = 20 \text{ Log } \left(\frac{a}{a_0}\right), [a_0 : \frac{1\mu m}{s^2}] \quad (5)$$

where a is the RMS acceleration in m/s^2 and a_0 is a reference value for acceleration equal to 1 μm/s^2. The total magnitude of the vibration vector was also calculated to allow for more effective and meaningful comparisons across bicycle types and corrugation patterns. The magnitude of the vibration vector was calculated using the triaxial vibration data obtained during each traversal using Equation 6. This approach has been used for calculating the total vibration vector in previous research on rumble strip vibration [*28*].

$$F_t = 10 * Log\ (\left(10^{\left(\frac{Fx}{10}\right)}\right) + \left(10^{\left(\frac{Fy}{10}\right)}\right) + \left(10^{\left(\frac{Fz}{10}\right)}\right)) \quad (6)$$

where F_t is the total magnitude of the vibration vector and F_x, F_y, and F_z are the vibration level in X, Y, and Z directions, respectively. Using Equation 6, the total magnitude of the vibration vector was calculated for each test condition. Figure 23 presents an example illustrating all four steps of vibration data processing for a single traverse over both corrugation types.

To analyze the vibration generated at the handlebar during each ride, a multiple linear regression model was developed to evaluate the influence of corrugation type, frame type, and speed. In the model, the maximum vibration level measured on and off each corrugation type captured during each ride was considered as the dependent variable, while factors such as corrugation section and contact, bicycle frame material and speed were included as independent variables to assess their effects on the outcomes. The general form of the multiple linear regression model is given by Equation 7:

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \cdots + \beta_k X_{ik} + \varepsilon_i \quad (7)$$

where Y_i is the ith vibration measurement, X_{i1} to X_{ik} are independent variables, β_0 is an intercept, β_1 to β_k are estimated regression coefficients for each independent variable, and ε_i is a normally distributed error term with variance σ^2.

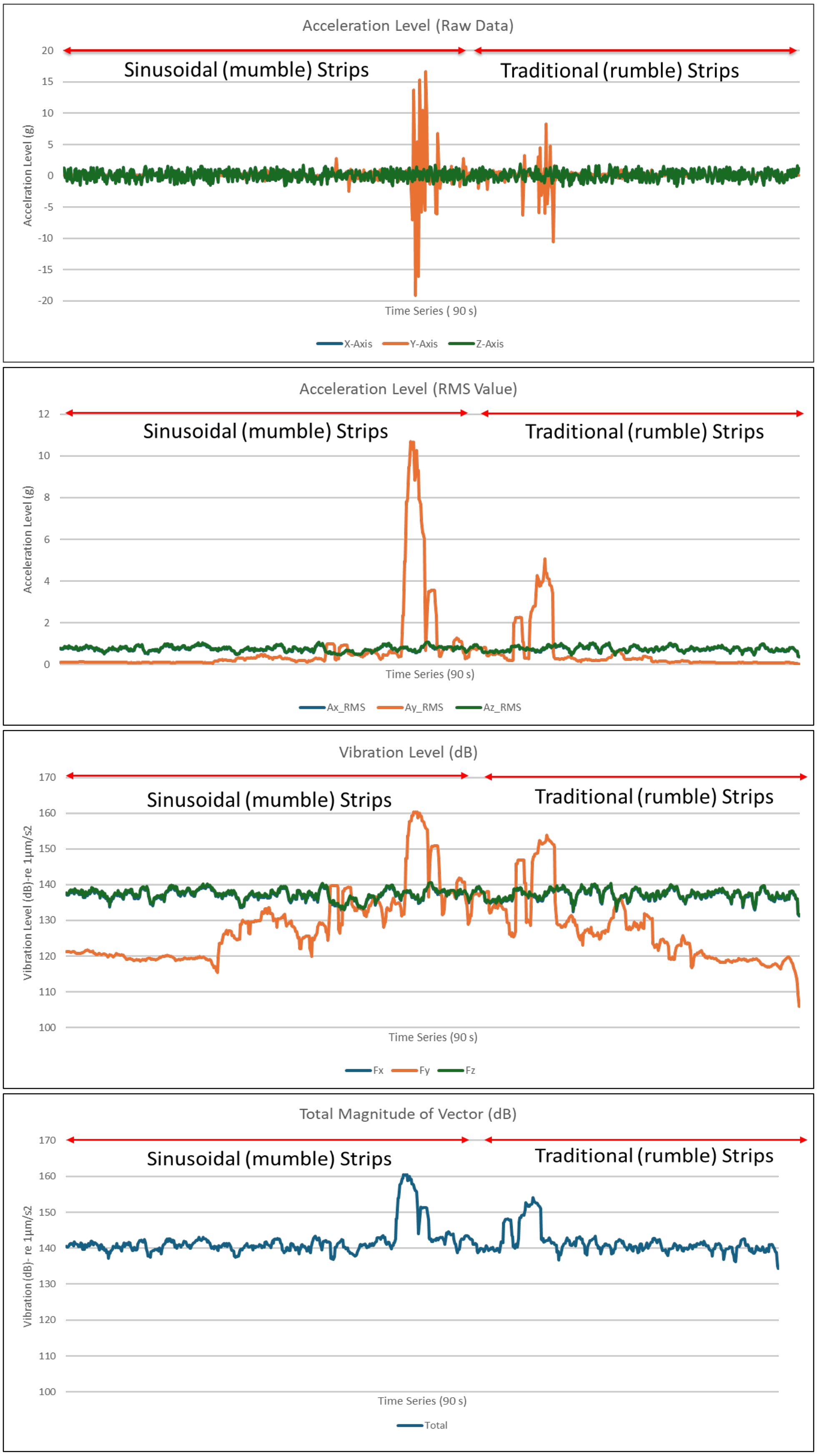

Figure 23. Time-series Data Resulting from Each Step of the Triaxial Acceleration-to-Vibration Data Conversion Process

4.5 Participant Post-Ride Responses

After each ride, the participants were asked to complete a questionnaire consisting of a series of questions regarding their levels of comfort and control during contact with each of the two rumble strip designs. The collective responses from these post-ride questionnaires are presented in Figures 24 through 28. Figures 24 and 25 summarize the participant responses to a set of statements related to the comfort and control experienced during contact with each of the two corrugation designs. For each statement, participants selected one of five response options ranging from “Disagree” to “Agree” using a Likert scale.

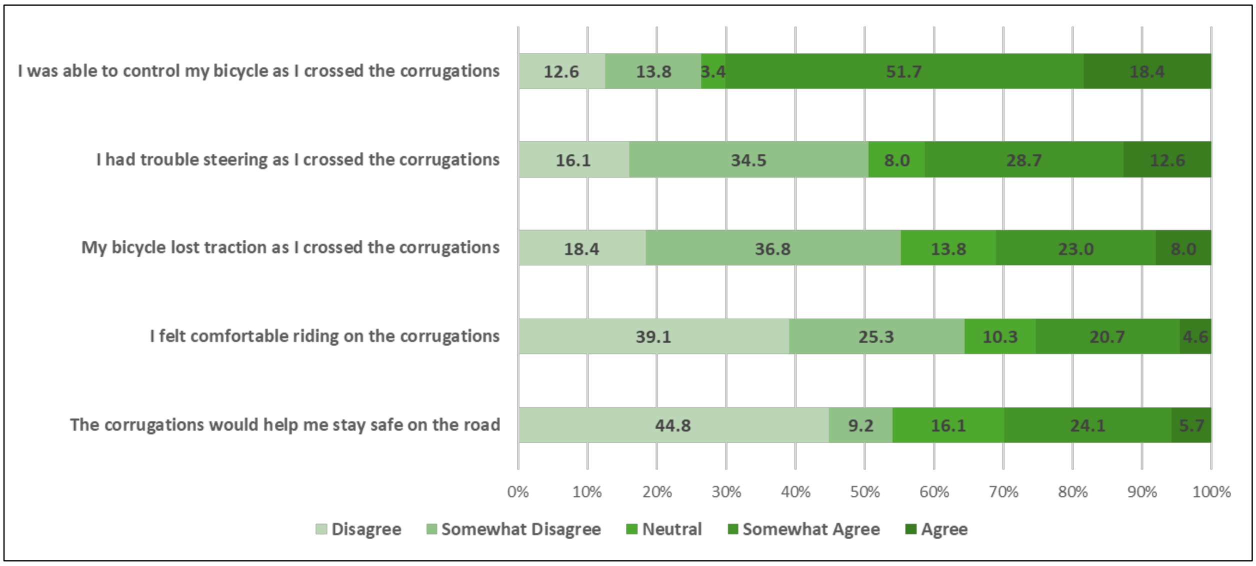

Figure 24. Participant Feedback Regarding Contact with Traditional Rumble Strips

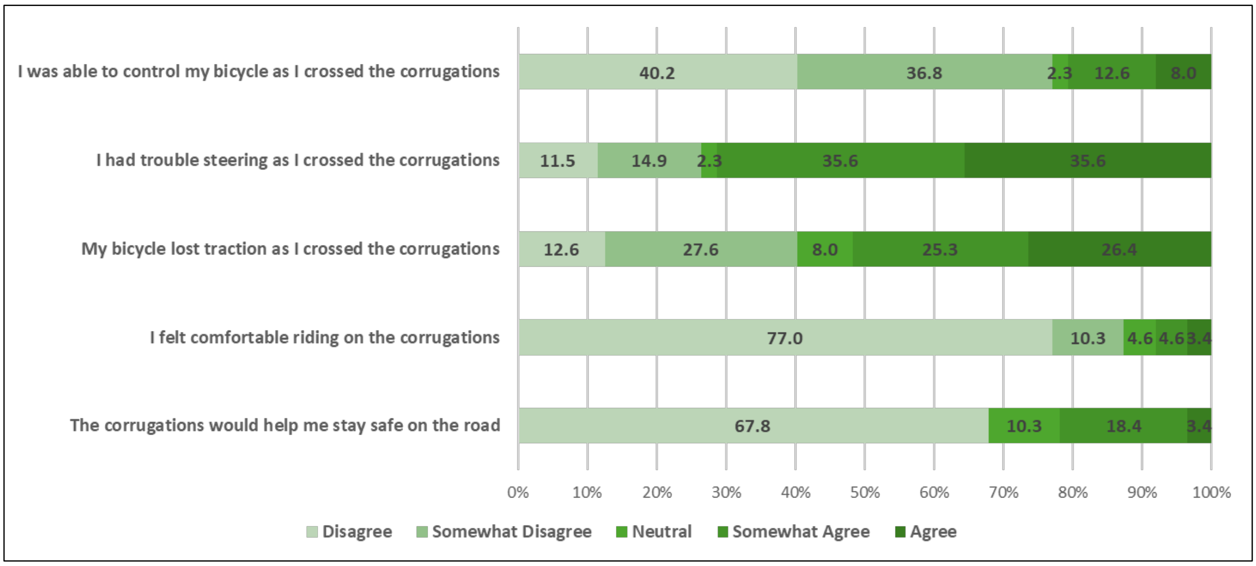

Figure 25. Participant Feedback Regarding Contact with Sinusoidal Rumble Strips

As illustrated in Figures 24 and 25, the two rumble strip designs were perceived differently by the riders. Notably, 77 percent of participants disagreed with the statement that they felt comfortable riding on the sinusoidal design, compared with 39.1 percent for the traditional design. In addition, 40.2 percent of riders disagreed that they could maintain control of their bicycles while crossing the sinusoidal design, whereas only 12.6 percent expressed the same concern for the traditional design. To better understand rider preferences between the two rumble strip designs, participants were presented with a similar set of questions related to comfort and control, but were asked to indicate which design was preferred. As shown in Figure 26, riders consistently preferred the traditional design. With respect to bicycle control, 71.3 percent of riders preferred the traditional design, while only 4.6 percent preferred the sinusoidal design. In terms of comfort, 70.1 percent preferred the traditional design, compared with 4.6 percent who preferred the sinusoidal design. Overall, 58.6 percent of participants preferred the traditional design, 36.8 percent preferred neither design, and only 4.6 percent preferred the sinusoidal design.

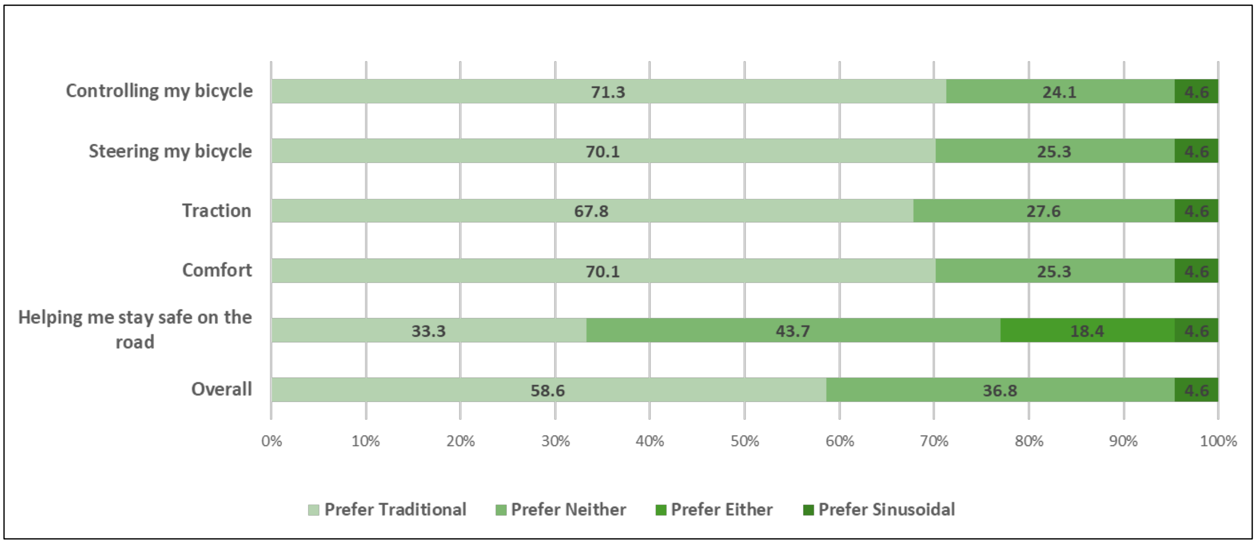

Figure 26. Rumble Strip Design Preferences for Bicycle Comfort and Handling

In addition to overall preferences by corrugation type, rider preferences were further examined by bicycle frame material, as well as by combinations of frame material and rider gender. The results of these analyses are presented in Figures 27 and 28. As shown in Figure 27, the traditional rumble strip design was highly preferred over the sinusoidal design across all bicycle frame types. Notably, none of the riders using steel or titanium frames indicated a preference for the sinusoidal design. Figure 28 summarizes the rumble strip design preferences by bicycle frame material and rider gender. While male riders consistently preferred the traditional design over the sinusoidal design, both female riders reported a preference for neither of the two designs. Investigation of the effects of speed and tire pressure found little variation in rumble strip design preferences.

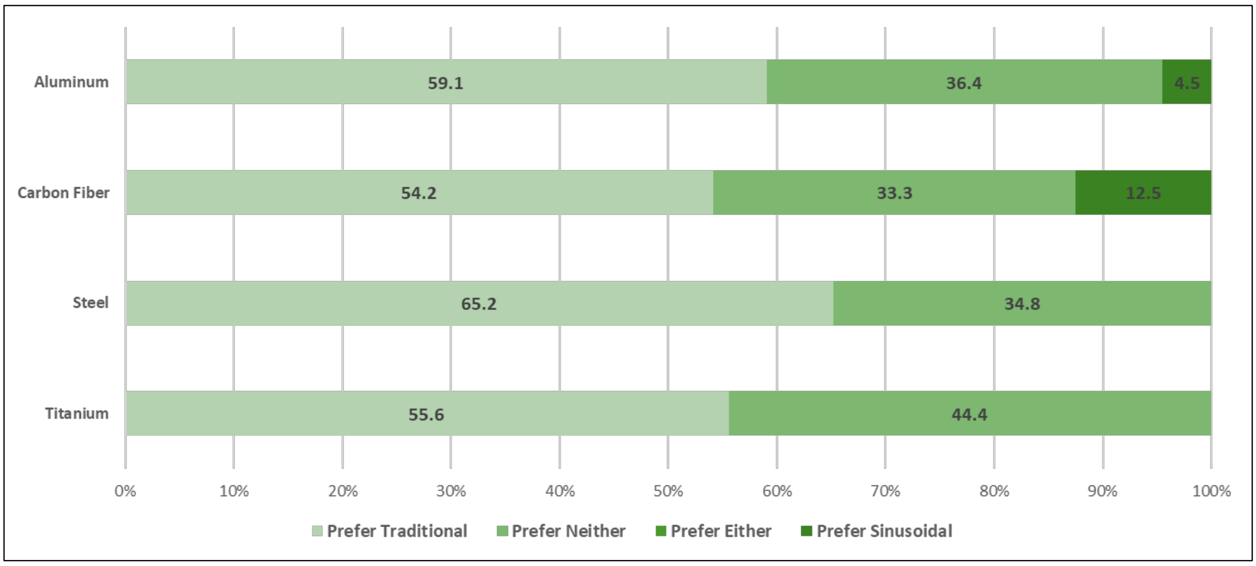

Figure 27. Overall Rumble Strip Design Preference by Frame Material

Figure 28. Overall Rumble Strip Design Preference by Frame Material and Rider Gender

4.6 Handlebar Vibration Results

Handlebar vibrations were measured both on and off the corrugations to provide an objective assessment between the two corrugation designs for each type of bicycle frame material. The vibration measurements provided additional context for interpreting the experiences of participants reported in the post-ride questionnaires. The maximum triaxial vibrations measured at the bicycle handlebars both on and off each set of shoulder corrugations are presented in Figures 29 through 31.

The triaxial vibration results indicate that the highest vibration levels occurred in the longitudinal (Y) direction (Figure 29), with consistently lower vibrations occurring in the lateral (X) and vertical (Z) directions (Figures 30 and 31, respectively). When comparing corrugation types, the two designs produced similar vibrations in the lateral (X) and vertical (Z) directions. However, the sinusoidal (mumble) design generated higher vibration levels than the traditional (rumble) design, particularly in the longitudinal (Y) direction, which exhibited the highest levels of vibration across all bicycle frame types. Additionally, traversal speed influenced vibration magnitude, with higher speeds producing increased vibration levels.

As described previously, combining the three-dimensional vibration components into a single vibration vector allows for a more effective and meaningful comparison across bicycle frame types, traversal speeds, and corrugation designs. The magnitude of the total vibration vector represents the overall vibration exposure experienced by riders during each traversal. The calculated total vibration vectors are presented in Figure 32.

Comparison of the total vibration vectors indicate that the sinusoidal design generated higher total vibration levels than the traditional design across all frame types. Across all corrugation types and speeds, titanium frames consistently produced the highest vibrations, while aluminum frames exhibited the lowest vibrations. The greatest total vibrations were measured during contact with the sinusoidal corrugations at a speed of 18 mph, which produced a total vibration of 160.6 dB, 160.5 dB, 159.4 dB, and 158.5 dB for the titanium, steel, carbon fiber, and aluminum frames, respectively. In comparison, the traditional rumble strips produced consistently lower total vibrations of 158.3 dB, 157.8 dB, 154.2 dB, and 152.4 dB, for the titanium, carbon fiber, steel, and aluminum frames, respectively, during the 18 mph traversals. Similar trends were observed for the 10 mph traversals, although at lower vibrations levels.

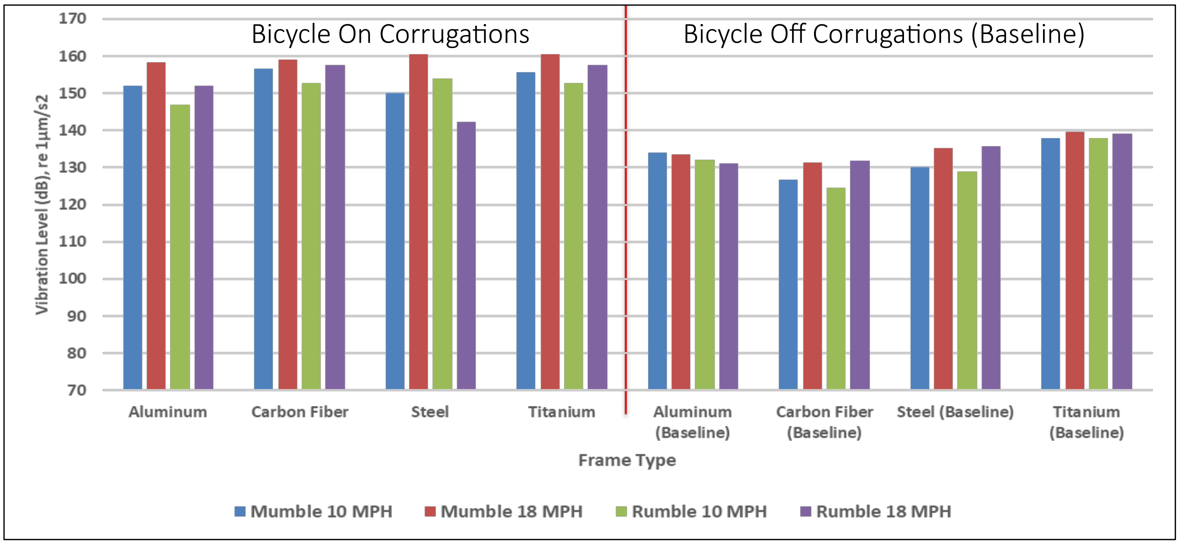

Figure 29. Maximum Handlebar Vibration in the Longitudinal (Y) Direction

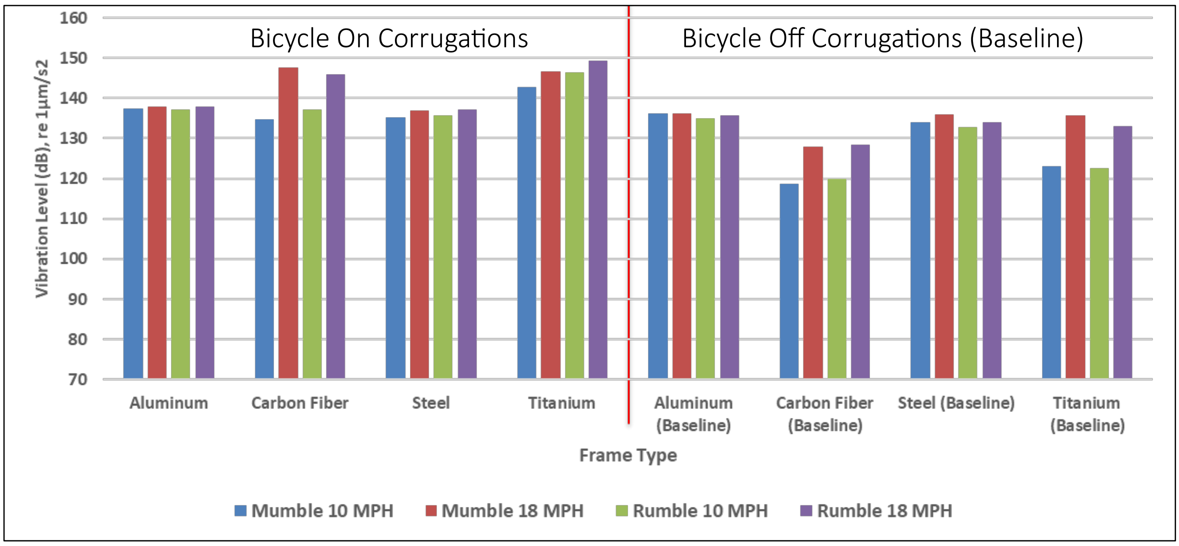

Figure 30. Maximum Handlebar Vibration in the Lateral (X) Direction

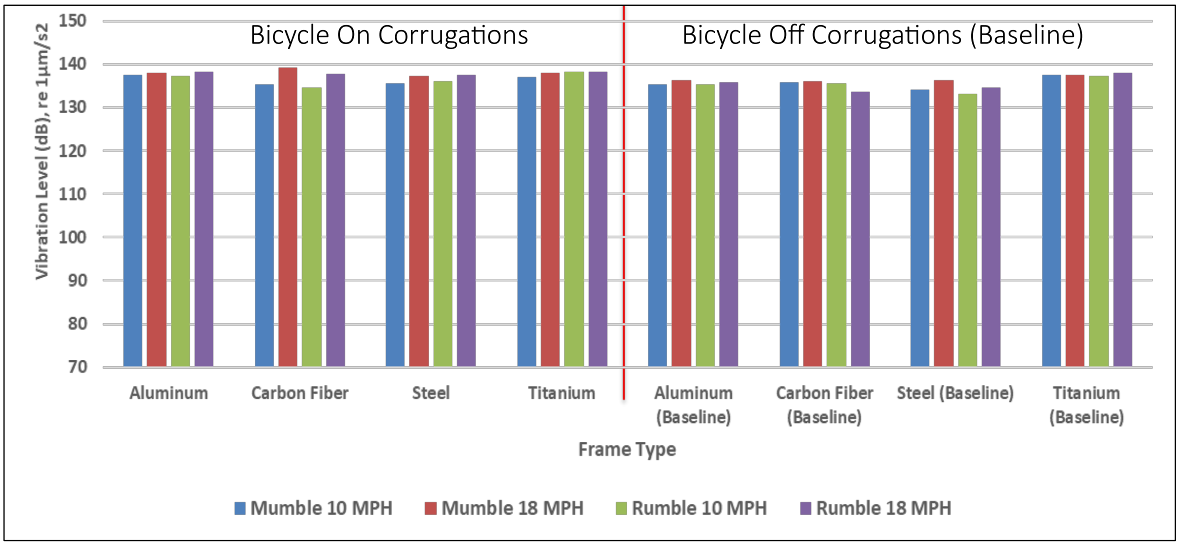

Figure 31. Maximum Handlebar Vibration in the Vertical (Z) Direction

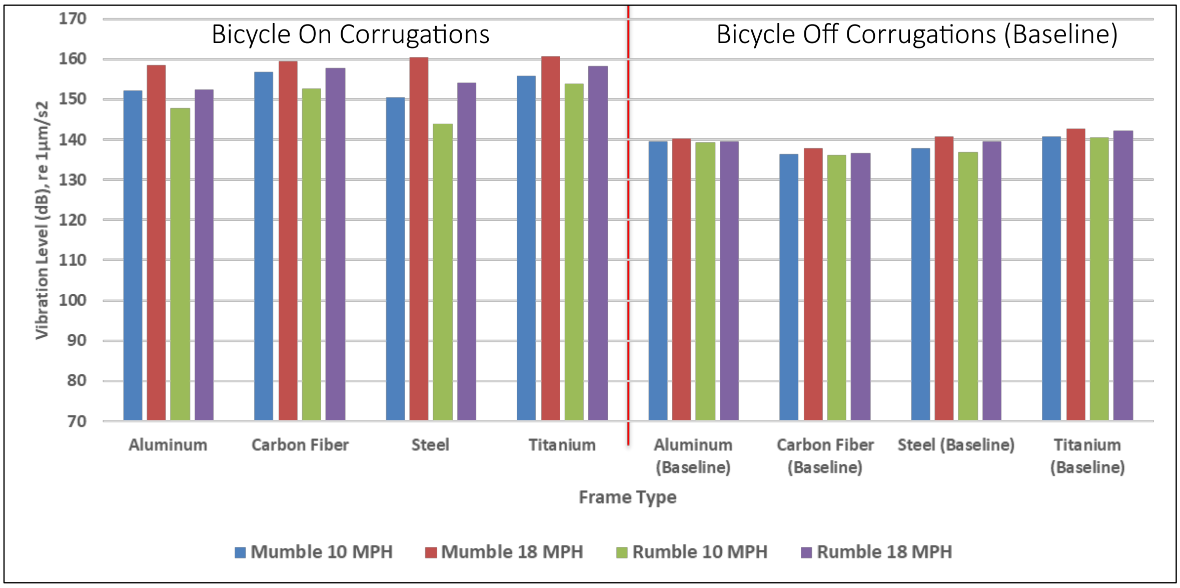

Figure 32. Maximum Total Handlebar Vibration

To assess the amount of vibration generated by the corrugations, the on-corrugation vibration must be compared to the off-corrugation vibration, which represents the baseline. Figure 33 presents the increase in vibration while contacting the corrugations relative to the non-corrugated pavement surface, which was measured prior to contacting the corrugations during each ride. Consistent with the absolute vibration magnitudes shown in Figure 32, the sinusoidal design was associated with greater increases from baseline compared to the traditional rumble strip design across all frame types and speeds. Additionally, higher speeds resulted in larger increases in vibration relative to baseline for both corrugation designs. The largest increase from baseline was 21.6 dB, which occurred with the carbon fiber frame traversing the sinusoidal (mumble) design at 18 mph. In contrast, the smallest increase from baseline was 7.1 dB, which occurred with the steel frame traversing the traditional (rumble) strip design at 10 mph.

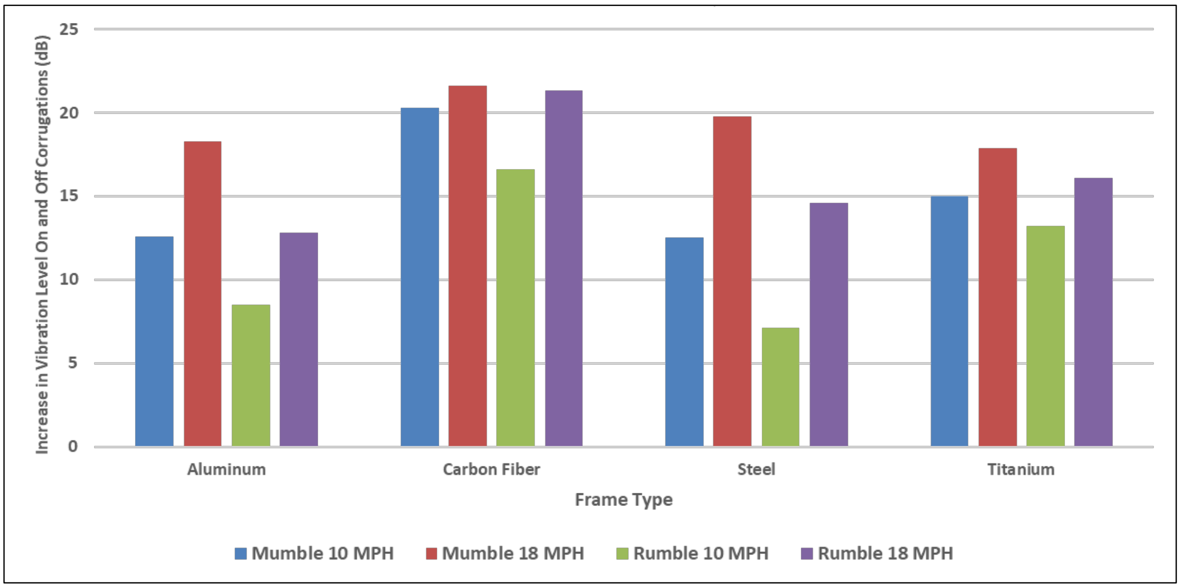

Figure 33. Increase in Total Handlebar Vibration during Contact with the Corrugations

The linear regression results allowed for further assessment of the relative difference in vibration generated between the two types of corrugations by direct interpretation of the corrugation-related regression parameter estimates displayed in Table 11. From Table 11 it can be observed that bicycle contact with the traditional corrugations increased total vibration by 13.8 dB. However, contact with the sinusoidal corrugations increased vibration by 17.9 dB, which when adjusting for the slight difference in off-corrugation vibrations between the two sections, represents 3.5 dB greater vibration from the sinusoidal corrugations compared to the traditional corrugations.

Table 11. Linear Regression Model for Total Vibration at the Bicycle Handlebar

Parameter	Coefficient	Std. Err	p-value
Intercept	135.513	1.223	<0.001
Speed			
10-mph	Baseline		
18-mph	3.775	0.865	<0.001
Vehicle			
Steel	Baseline		
Aluminum	0.675	1.223	0.586
Carbon Fiber	1.175	1.223	0.346
Titanium	3.850	1.223	0.004
Section x Corrugation Contact			
Off Traditional Corrugations	Baseline		
Off Sinusoidal Corrugations	0.688	1.223	0.579
On Traditional Corrugations	13.775	1.223	<0.001
On Sinusoidal Corrugations	17.938	1.223	<0.001
R^2	0.938		
Adjusted-R^2	0.920		

Note: Dependent variable = Total vibration at handlebar (dB)

Overall, the handlebar vibration measurements align closely with the participant feedback from the post-ride questionnaires. The higher absolute vibration levels and greater increases in vibration from the baseline observed for the sinusoidal design corresponded with riders' perceptions of increased discomfort and reduced controllability when contacting or crossing these corrugations. These findings provide objective confirmation of the subjective responses, reinforcing the conclusion that sinusoidal (mumble) strips induce greater rider discomfort compared to traditional rumble strips.

4.7 Conclusions

This portion of the research examined how the shoulder corrugation design influences bicyclists' comfort, stability, and vibration exposure using a controlled field study. The results indicated consistent rider preference for the traditional corrugation design over the sinusoidal design. Riders reported lower comfort and reduced controllability when traversing sinusoidal rumble strips, a finding that was supported by the vibration measurements. The sinusoidal design produced greater vibration than the traditional design across each of the bicycle frame materials (carbon fiber, aluminum, steel, and titanium) and speeds. On average, the sinusoidal corrugations produced 3.5 dB greater vibration at the bicycle handlebar than the traditional corrugations. These objective vibration measurements aligned closely with riders' subjective responses, reinforcing the conclusion that sinusoidal rumble strips impose greater physical disturbance on bicyclists than traditional designs under the conditions evaluated.

5. NATIONWIDE BICYCLIST SURVEY

To supplement the bicyclist field study, an online survey was distributed to cyclists nationwide to obtain broader insights into cyclists' perceptions and experiences with rumble strips across the United States. The survey sought to develop a better understanding of bicyclists' encounters with highway rumble strips, as well as their practices and preferences related to rumble strip design and placement.

5.1 Survey Design and Distribution

The bicyclist survey was developed using Qualtrics, an online platform for survey design, distribution, and analysis. The survey included a series of questions addressing bicyclists' experiences with rumble strips, along with best practices, preferences for rumble strip design, and placement on highways. Demographic information, including but not limited to age, gender, education level, income, and years of bicycling experience, was also collected for each respondent. The questionnaire was initially reviewed and vetted by the research team as well as by bicycle riders who participated in the field study. Following these reviews, the survey was distributed via email in June 2025 to bicyclists across the United States to collect information on their experiences with highway rumble strips. The online bicyclist survey questionnaire form is provided in Appendix B.

5.2 Respondent Demographics

A total of 968 participants responded to the survey. After quality control screening, 679 completed responses were retained for analysis. Responses were excluded if they were incomplete, contained unusual or contradictory answers, or same responses across all questions. Responses were received from participants in 42 states and Canada. The states with the highest representation were Michigan (337 responses), Illinois (53 responses), Virginia (33 responses), and California (28 responses), which together accounted for 66.4 percent of the total sample data. Figure 34 illustrates the geographic distribution of survey participants, including the number of completed responses by state.

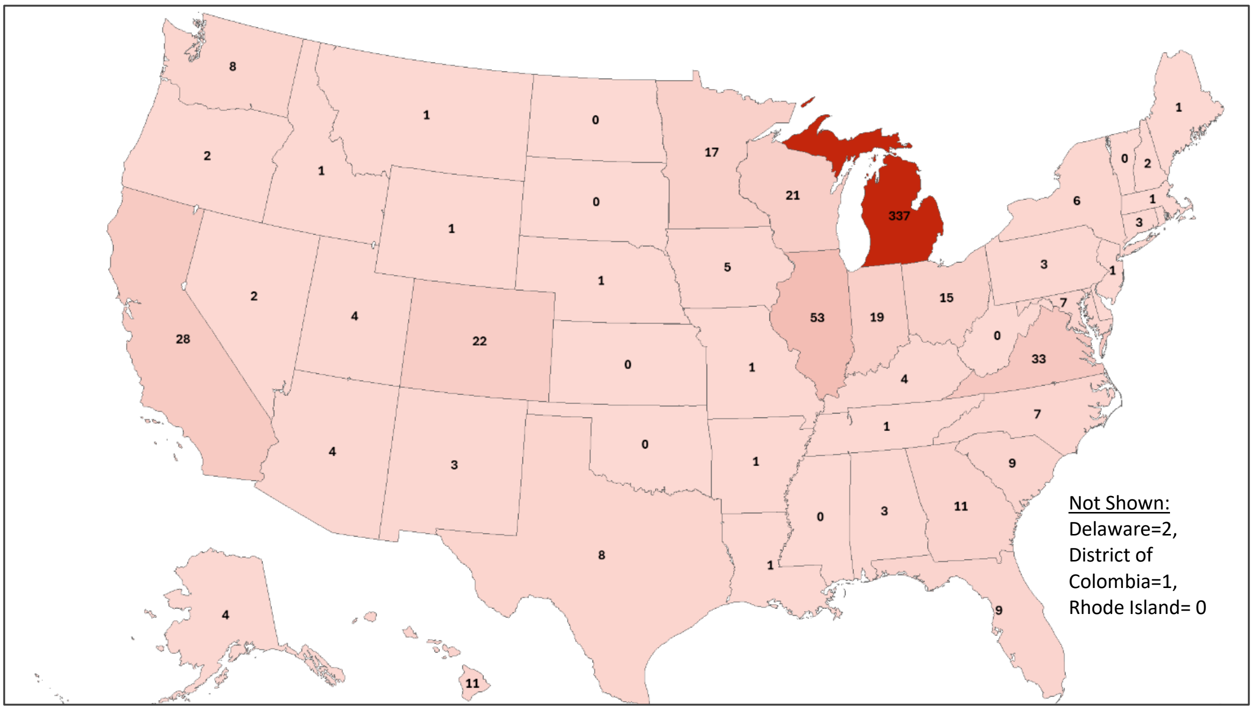

Figure 34. Completed Bicyclist Surveys by State (n=679)

Descriptive statistics for the demographic and exposure variables are presented in Table 12. As shown in Table 12, respondent ages were primarily distributed between the middle-aged (35–64) and older (65 and older) groups, while the younger age group (18–34) accounted for a smaller proportion of the sample. The majority of respondents were male (73.5 percent). Regarding annual household income, respondents earning between $75,000 and $150,000 represented the largest share of the sample, followed by those earning more than $150,000 and then those earning less than $75,000. In terms of educational attainment, more than half of the respondents held a graduate or professional degree, 31.5 percent held a bachelor’s degree, and 15.7 percent reported some college education or a two-year degree. Only 2.1 percent of respondents reported a high school degree as their highest level of education. In terms of cycling experience, 45.6 percent of respondents rode more than 2,000 miles in the year preceding the survey. With respect to exposure to rumble strips, more than 85 percent of respondents reported having contacted rumble strips while cycling at least 10 times over their lifetime. With respect to the influence of rumble strips on bicyclists’ route-planning decisions, responses were nearly evenly split between those who reported being affected and those who did not. Approximately 50.2 percent of respondents indicated that the presence of rumble strips influenced their route planning, while 49.8 percent reported no impact. Similarly, when asked whether they had avoided riding on a roadway because of rumble strips, responses were again evenly distributed, with 51.4 percent of respondents reporting route avoidance and 48.6 percent indicating that they had not avoided a route due to the presence of rumble strips.

Table 12. Demographic Summary Statistics from Online Survey (n = 679)

Variable	Frequency	Percentage
Age (years)		
18–34	26	3.8%
35–64	331	48.8%
65+	322	47.4%
Gender		
Female	173	25.5%
Male	499	73.5%
Non-Binary/ Third Gender	2	0.3%
Prefer Not to Say	5	0.7%
Annual household income		
<$75,000	154	22.7%
≥$75,000 and ≤$150,000	307	45.2%
>$150,000	218	32.1%
Education		
High school degree	14	2.1%
Some college or 2 years degree	107	15.7%
4 years bachelor's degree	214	31.5%
Graduate or professional degree	344	50.7%
Number of miles ridden bicycle in the year prior to survey		
<25	8	1.2%
≥26 and ≤100	28	4.1%
≥101 and <500	99	14.6%
≥501 and ≤1,000	112	16.5%
≥1,001 and ≤2,000	122	18.0%
≥2,001	310	45.6%
Number of times contacted rumble strips in lifetime		
<10	90	13.3%
≥11 and ≤100	341	50.2%
≥101 and ≤500	147	21.6%
≥501	101	14.9%
Do rumble strips affect your route planning when cycling?		
Yes	341	50.2%
No	338	49.8%
Have you ever avoided riding a road because of rumble strips?		
Yes	349	51.4%
No	330	48.6%

5.3 Results

5.3.1 Factors Affecting Bicyclist Safety and Comfort when Shoulder Riding

Graphical summaries of the 679 responses are presented in Figures 35 through 38. Figure 35 illustrates the responses related to the relative importance of design and maintenance characteristics that contribute to a safe and comfortable shoulder for bicycling on rural highways. Respondents were asked to rank several design features from most important to least important. As shown in Figure 35, the availability of an adequate usable shoulder was identified as the most important factor by 72 percent of respondents. A swept shoulder, defined as being free of gravel and debris, was ranked as the most important characteristic by 15.5 percent of respondents, making it the second most frequently selected factor. Other design features, including shallow rumble strip depth, narrow rumble strip width, sufficient gap spacing, and adequate gap length, were selected as the most important factor by only a very small proportion of respondents.

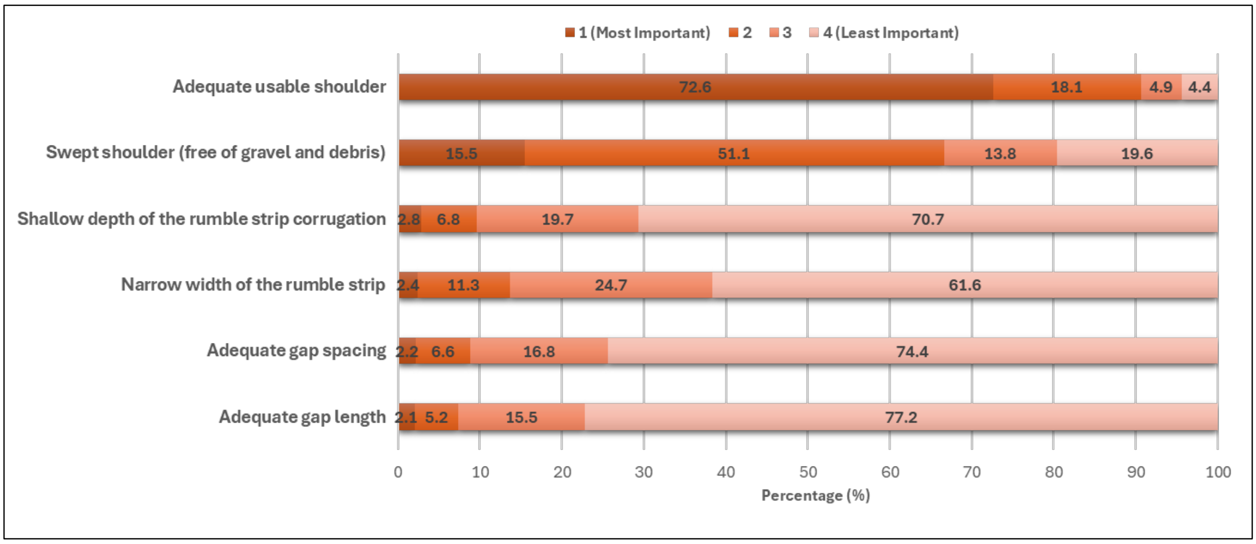

Figure 35. Relative importance of shoulder characteristics for bicyclist safety and comfort (n=679)

Respondents were also asked to assess the perceived risk associated with various roadway characteristics encountered while riding bicycle on roadway shoulders, and to rank these factors from highest to lowest risk. As illustrated in Figure 36, sand and gravel on the pavement were perceived as the highest risk by 48.2 percent of respondents, followed by shoulder corrugation (21.2 percent of respondents) and poor sightlines over hills or at intersections (20.0 percent of respondents). Other roadway characteristics, including fading edge lines, pavement corrugations in the center of the roadway, and steep grades, were each perceived as highest risk by only a small proportion of respondents.

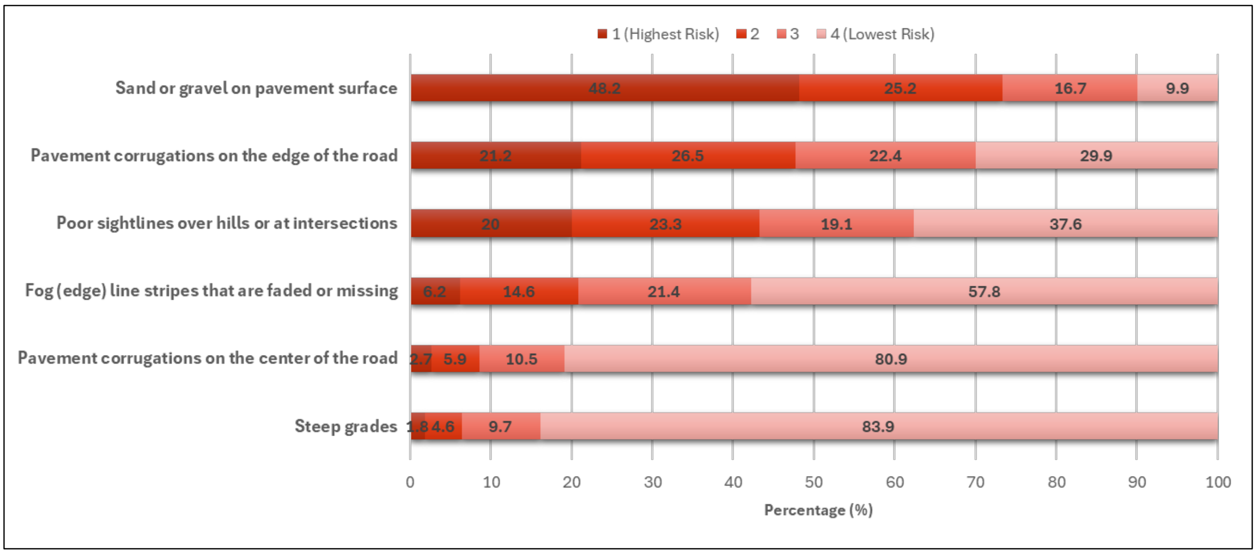

Figure 36. Perceived Risk of Roadway Characteristics Affecting Bicyclist Safety when Shoulder Riding (n=679)

Similar to the previous question, respondents were asked to evaluate the perceived risk associated with various driver behaviors encountered while riding on roadway shoulders, and to rank these behaviors from highest to lowest risk. As illustrated in Figure 37, distracted driving was identified as the highest perceived risk by 44.6 percent of respondents followed by failure to provide adequate lateral clearance with 28.4 percent of respondents. Other driver-related behaviors, including intoxicated driving, failure to adequately check for bicyclists when exiting intersections or driveways, speeding, and drowsy driving, were each perceived as the highest by smaller proportions of respondents.

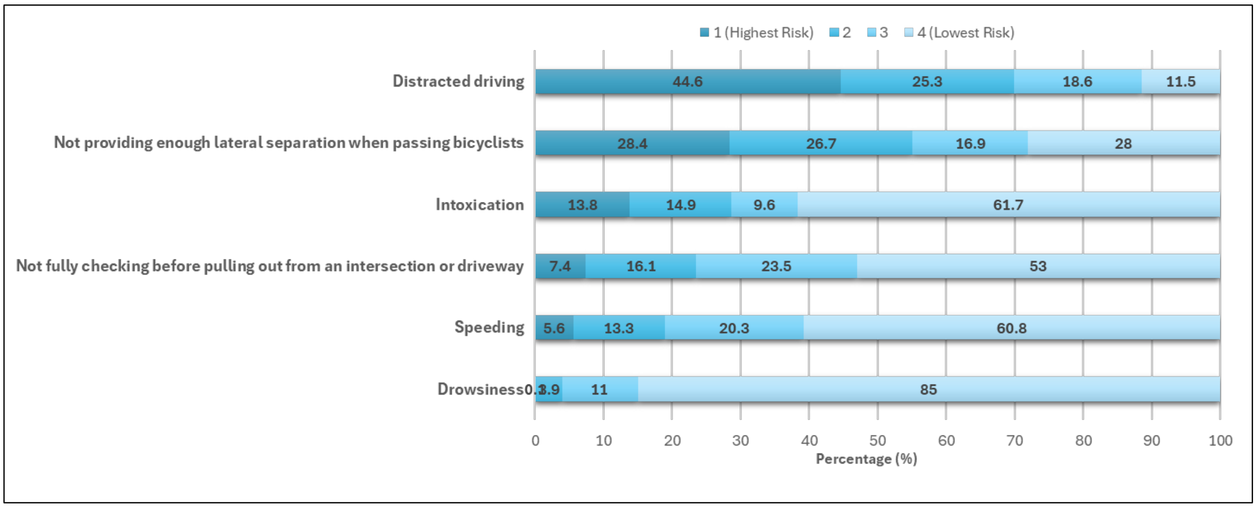

Figure 37. Perceived Risk of Driver Behavioral Characteristics Affecting Bicyclist Safety when Shoulder Riding (n=679)

5.3.2 Design Preferences for Shoulder Rumble Strips

Respondents were also asked a series of questions focusing specifically on rumble strip design characteristics, including lateral placement within the shoulder, shoulder width, gap length between rumble strip segments, and spacing between gaps. Four primary questions were included: (a) “If rumble strips on the edge of the roadway must be used, where should they be placed?”; (b) “When riding on roads with shoulders, what is the minimum width of clear paved shoulder beyond the rumble strip for you to feel safe and comfortable while riding?”; (c) “What is the minimum length of gap between sections of rumble strips to allow safe crossing?”; and (d) “What is the maximum spacing between the gaps in the rumble strips to allow safe crossing?” The responses to these questions are summarized in Figure 38.

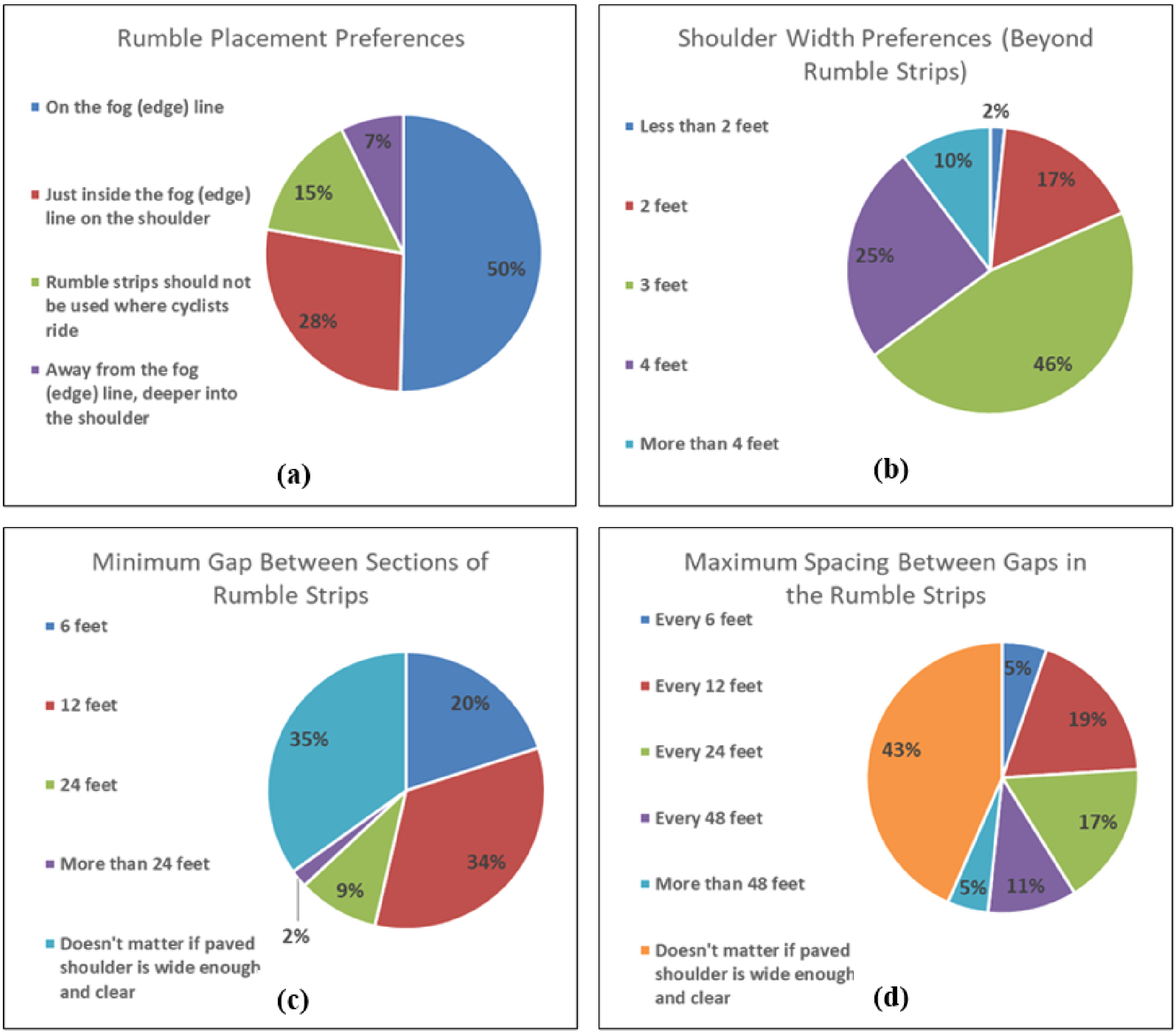

Figure 38. Design Preferences for Shoulder Rumble Strips (n= 679)

As shown in Figure 38(a), 50 percent of respondents preferred rumble strips to be placed at the roadway edge line, while 28 percent preferred placement on the shoulder adjacent to the edge line. Notably, 15 percent of respondents indicated that rumble strips should not be used on roadways where bicyclists ride. Regarding shoulder width, 81 percent of respondents preferred a minimum of 3 ft of clear paved shoulder beyond the rumble strip (Figure 38(b)).

With respect to gap length between successive sections of rumble strips, 35 percent of respondents indicated that the minimum gap length was not important provided that the paved shoulder was sufficiently wide and free of debris (Figure 38(c)). Similarly, when asked about the maximum spacing between gaps, 43 percent of respondents reported that gap spacing was not a concern if adequate, clear shoulder width was available (Figure 38(d)). These responses further reinforce earlier findings that the availability of a sufficiently wide, debris-free shoulder is the most influential factor affecting bicyclists' comfort and perceived safety when shoulder riding.

Collectively, the nationwide survey findings indicate that bicyclists prioritize roadway conditions that preserve a safe and usable shoulder environment over specific geometric features of rumble strips. Adequate usable shoulder width and the presence of a swept, debris-free surface were identified as the most important characteristics for safe and comfortable shoulder riding, whereas features such as rumble strip depth, width, and gap configuration were assigned lower relative importance. In addition, perceived risk while riding on roadway shoulders was primarily associated with surface conditions and visibility constraints, with sand and gravel, shoulder pavement corrugations, and limited sight distance cited most frequently. As for risks associated with drivers, distracted driving and insufficient lateral clearance during passing maneuvers were considered high risk factors. These results suggest that maintaining clear, continuous shoulder space and minimizing surface irregularities may play a central role in bicyclist comfort and perceived safety on roadways where rumble strips are present.

5.4 Statistical Analysis

Statistical models were employed to further examine online survey respondents' experiences with rumble strips. Questions assessing whether respondents were affected by rumble strips were structured as binary ("Yes"/"No") responses. Given the binary nature of these outcomes, binary logistic regression models were used to evaluate the influence of prior experiences with rumble strips and demographic characteristics on respondents' choice. In the modeling framework, the dependent variable represents the probability that a respondent reported being affected by rumble strips under a given scenario. Independent variables included respondents' demographic characteristics and factors related to prior rumble strip encounters. The general form of the binary logistic regression model is given by Equation 8:

$$Y_i = \text{logit}\ (P_i) = \ln\left(\frac{P_i}{1-P_i}\right) = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \cdots \ldots\ldots\ldots\ldots + \beta_k X_{ik} \tag{8}$$

where the response variable, Y_i, is the logistic transformation of the probability P_i that a respondent is affected by rumble strips. The variables X_{i1} to X_{ik} are independent variables included in the model, β_0 is the intercept, and β_1 through β_k are estimated regression coefficients for each independent variable. The results are displayed in Tables 13 and 14.

Table 13. Binary Logistic Regression Results for *"Do rumble strips affect your route planning when cycling?"* (n=679)

Parameter	Coefficient	Std. Err	p-value	Odds Ratio
Intercept	-2.774	0.339	<0.001	0.062
Rumble Strip Experience and Preferences				
Have you ever been forced to ride in the travel lane due to rumble strips? (1 Yes, 0 No)	1.210	0.280	<0.001	3.354
Have you ever lost control because of rumble strips? (1 Yes, 0 No)	0.688	0.176	<0.001	1.990
Do you believe improper placement of rumble strips can increase conflicts with vehicles? (1 Yes, No 0)	0.943	0.241	<0.001	2.567
Perceived Risk of Rumbles on the Edge of the Road				
Low Risk	Baseline			
Medium Risk	0.482	0.201	0.017	1.619
High Risk	0.783	0.225	<0.001	2.187
Income				
<$75,000	Baseline			
≥$75,000 and ≤$150,000	0.364	0.220	0.098	1.440
>$150,000	0.625	0.234	0.008	1.869
Akaike information criterion (AIC)	179.790			
Bayesian Information Criterion (BIC)	215.955			
Log likelihood (LL)	-81.895			

Table 13 summarizes the model results for the question, "Do rumble strips affect your route planning when cycling?" The findings indicate that riders' prior experiences with rumble strips significantly influence route-planning decisions. Specifically, respondents who reported being forced to ride in travel lanes due to the presence of rumble strips were 235 percent more likely to report that rumble strips affected their route planning. Similarly, riders who had experienced a loss of bicycle control when encountering rumble strips were 99 percent more likely to indicate an impact on route planning compared with those who had not experienced such events. Respondents who believed that improper rumble strip placement increases conflicts with motor vehicles were 155 percent more likely to report that their route planning was affected.

Furthermore, greater perceived risk associated with rumble strips was strongly associated with route-planning.

Another question asked in the survey was, “Have you ever avoided riding a road because of rumble strips?” The results for this question are presented in Table 14. Overall, the analysis suggests that cyclists’ past encounters with rumble strips play an important role in whether they choose to avoid certain roadways. Respondents who indicated that rumble strips had forced them to ride in the travel lane were substantially more likely (243 percent) to report avoiding roads with rumble strips. Those who had experienced a loss of bicycle control when crossing rumble strips were also more likely (88 percent) to avoid such routes than riders who had not reported loss-of-control events. Additionally, respondents who believed that poorly placed rumble strips increase interactions with motor vehicles showed a markedly higher likelihood (123 percent) of avoiding affected roadways. Furthermore, heightened risk perceptions associated with rumble strips corresponded to greater route avoidance among cyclists.

Table 14. Binary Logistic Regression Results for “*Have you ever avoided riding a road because of rumble strips?*” (n=679)

Parameter	Coefficient	Std. Err	p-value	Odds Ratio
Intercept	-3.208	0.713	<0.001	0.040
Rumble Strip Experience and Preferences				
Have you ever been forced to ride on travel lane due to rumble strips (1 Yes, 0 No)	1.234	0.274	<0.001	3.434
Have you ever lost control because of rumble strips (1 Yes, 0 No)	0.631	0.174	<0.001	1.880
Do you believe improper placement of rumble strips can increase conflicts with vehicles (1 Yes, No 0)	0.805	0.234	<0.001	2.236
Perceived Risk of Rumbles on the Edge of the Road				
Low Risk	Baseline			
Medium Risk	0.544	0.202	0.007	1.724
High Risk	0.674	0.223	0.003	1.962
Education				
High School Graduate	Baseline			
College attendance and higher	1.225	0.650	0.060	3.403
Region				
Rest of the United States	Baseline			
Midwest	-0.312	0.185	0.092	0.732
Akaike information criterion (AIC)	146.505			
Bayesian Information Criterion (BIC)	182.670			
Log likelihood (LL)	-65.253			

5.5 Conclusions

The nationwide survey indicated that bicyclists give greatest priority to a smooth, debris-free shoulder surface of adequate usable width to ensure safety and comfort while cycling on the shoulder. Rumble strip design characteristics, such as corrugation depth, width, and gap configuration were assigned lower relative importance by bicyclists. In addition, perceived risk while riding on roadway shoulders was primarily associated with surface conditions and visibility constraints, with sand and gravel, shoulder pavement corrugation, and limited sight distance cited most frequently. As for risks associated with drivers, distracted driving and insufficient lateral clearance during passing maneuvers were considered high risk factors when cycling on the shoulder. These results suggest that maintaining clear, continuous shoulder space and minimizing surface irregularities may play a central role in bicyclist comfort and perceived safety on roadways where rumble strips are present. Prior negative experiences with rumble strips, such as being forced into the travel lane or experiencing loss of bicycle control, were strongly associated with both route-planning and route avoidance decisions.

Combined with the findings from the bicyclist field study, this study provides evidence that rumble strip design and placement decisions can meaningfully influence bicyclists' comfort, perceived safety, and riding behavior. The combined findings suggest that preserving a usable debris-free shoulder width of at least 3-ft and minimizing vibration exposure are central considerations for accommodating bicyclists on roadways with rumble strips. While sinusoidal rumble strips have been developed primarily to address roadside noise concerns, the results indicate that their impact on bicyclists warrant careful consideration, particularly on roadway facilities with regular bicycle use.

6. MOTORCYCLIST SURVEY

An online survey was developed using Qualtrics and distributed to motorcycle riders to gather information about their experiences with rumble strips. The questionnaire was first reviewed and vetted by the research team and then administered in July and August 2025. The survey was distributed via QR code from printed flyers that were placed in Rest Areas and Welcome Centers across Michigan and handed to motorcyclists at toll booths for the Blue Water Bridge (connecting Port Huron, Michigan and Sarnia, Ontario) and the Mackinac Bridge. The online survey questionnaire form is provided in Appendix C.

The primary objective of this survey was to collect information regarding motorcyclists' general experiences with highway rumble strips. A total of 61 responses were collected. After data cleaning and quality control checks, 53 valid responses were retained for further analysis. Most respondents resided in Michigan (31 responses), while 11 responses were obtained from motorcyclists from other U.S. states, along with 11 responses from Canadian motorcyclists. Descriptive statistics for the demographic and exposure related questions are presented in Table 15.

Table 15. Demographic Summary Statistics from Online Survey (n = 53)

Variable	Response	Frequency	Percentage
Age (years)	18–34	4	7.5%
	35–64	25	47.2%
	65+	11	20.7%
Gender	Female	5	9.4%
	Male	35	66.0%
	Not Answered	13	24.6%
Annual household income	<$75,000	15	28.3%
	≥$75,000 and ≤$150,000	12	22.7%
	>$150,000	11	20.7%
	Not Answered	15	28.3%
Educational level	High school degree	7	13.2%
	Some college or 2 years degree	13	24.6%
	4 years bachelor's degree	8	15.1%
	Graduate or professional degree	12	22.6%
	Not Answered	13	24.6%
Years riding a motorcycle	1-10 years	8	15.1%
	11-20 years	7	13.2%
	21-30 years	8	15.1%
	More than 30 years	17	32.0%
	Not Answered	13	24.6%
Annual motorcycling mileage	0-3,000 miles	5	9.4%
	3,001-5000 miles	10	18.8%
	More than 5,000 miles	25	47.2%
	Not Answered	13	24.6%

In addition to the demographic questions, respondents were asked a series of questions regarding their experience with rumble strips. At the beginning of the survey, an image of shoulder rumble strips was shown (Figure 39), at which point participants were asked whether they were familiar with rumble strips. All respondents indicated that they were familiar with rumble strips, and 81.1 percent reported that they had previously ridden their motorcycles over rumble strips.

Figure 39. Image Shown to Responders as an Example of Rumble Strips

Respondents were also presented with statements regarding their previous experiences when encountering rumble strips related to control, steering, traction, comfort, noise, vibration, and perception of safety. For each statement, participants selected one of five response options on a Likert scale ranging from “Disagree” to “Agree”. As shown in Figure 40, 77.1 percent of respondents agreed or somewhat agreed that they were able to maintain control when encountering rumble strip, while 14.3 percent disagreed or somewhat disagreed.

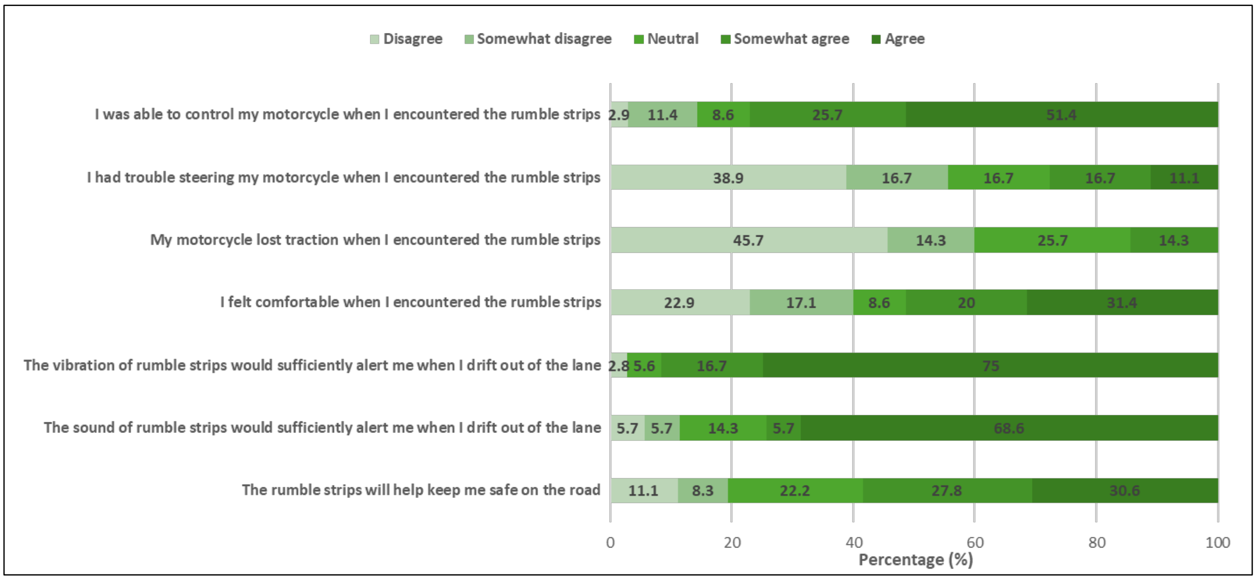

Figure 40. Motorcyclist Response Regarding Contact with Rumble Strips (N = 53)

Regarding steering difficulty, 55.6 percent of respondents disagreed or somewhat disagreed with the statement that they experienced trouble steering when riding over rumble strips. Similarly, 60 percent of respondents disagreed or somewhat disagreed with the statement that they lost traction when encountering rumble strips. Moreover, 51.4 percent of respondents agreed or somewhat agreed that they feel comfortable when riding over rumble strips. When respondents were asked whether the vibration from rumble strips would sufficiently alert them when drifting out of their lane, 91.7 percent agreed or somewhat agreed. Similarly, 74.3 percent of respondents agreed or somewhat agreed that the sound produced by rumble strips would adequately alert them when they drift out of their lane. For the statement “Rumble strips help keep me safe on the road”, 58.4 percent of respondents agreed or somewhat agreed.

Motorcyclists were also asked to rank their perceived risk associated with several roadway characteristics. Figure 41 shows that among the listed options, sand or gravel on the pavement surface was perceived as the highest risk by the overwhelming majority (74.4 percent) of respondents. Poor sightlines at intersections were identified as the highest risk by 10.3 percent of respondents and second highest risk by an additional 46.2 percent of respondents. In contrast, rumble strips located at the edge line and centerline were each considered the highest perceived risk by only 2.6 percent of respondents.

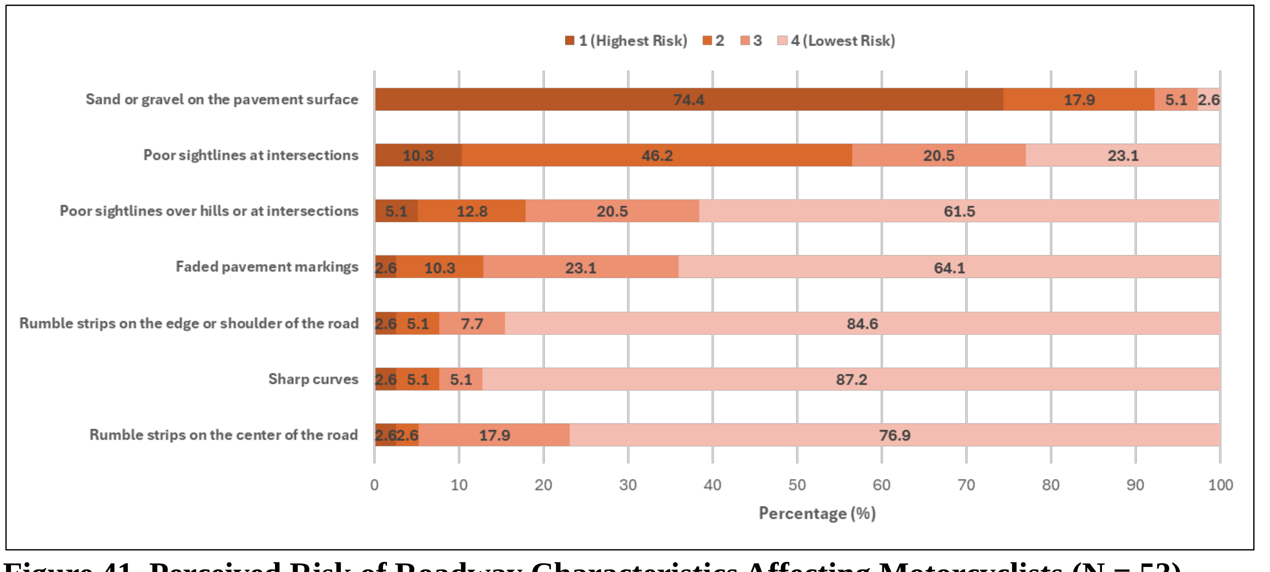

Figure 41. Perceived Risk of Roadway Characteristics Affecting Motorcyclists (N = 53)

Additionally, respondents were asked about the perceived risks posed by other drivers to motorcyclists. Figure 42 shows that distracted driving was identified as the highest perceived risk by 55.3 percent of respondents. Driving under the influence and failure to check blind spots when changing lanes were considered the highest risks by 23.7 and 10.7 percent of respondents, respectively.

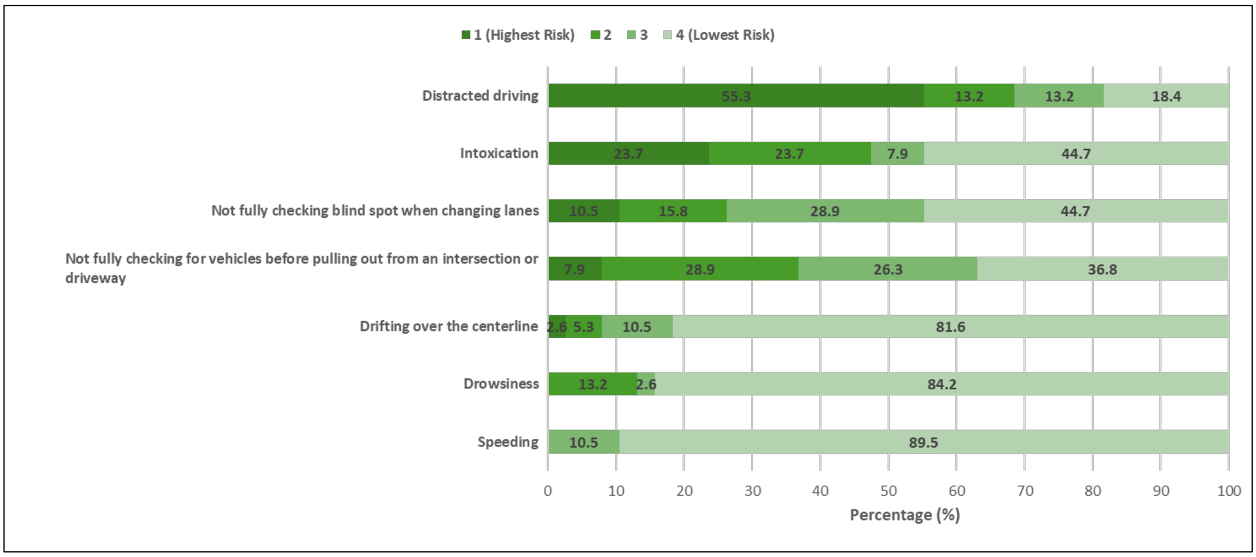

Figure 42. Perceived Risk of Driver Behaviors Affecting Motorcyclists (N = 53)

Finally, motorcyclists were asked whether they had any additional experiences or thoughts regarding rumble strips when riding along the edge line, shoulder, or center of the roadway. This question was presented in an open-ended text format, allowing respondents to share their personal experiences. Among the responses, pavement surface crack sealant was frequently mentioned as a potential safety hazard due to the material, which typically consists of emulsified asphalt, becoming slippery particularly during hot or wet weather. With respect to rumble strips, respondents suggested that additional signage should be provided to warn riders of the presence of rumble strips on the roadway. This was noted as particularly important in construction zones, where roadway conditions may change and riders may encounter rumble strips unexpectedly.

7. SAFETY PERFORMANCE ANALYSIS AND CMF DEVELOPMENT

7.1 Data Description

MDOT began installing sinusoidal shoulder rumble strips in 2018 on rural two-lane highways in the Superior Region. By 2025, more than 1,100 miles of sinusoidal shoulder corrugations had been installed on two-lane highways across Michigan. MDOT provided the research team with the list of rural highway segments on which sinusoidal rumble strips had been installed between 2018 and 2025, including the begin/end mile points, year of installation, corrugation width and offset, prior shoulder corrugation presence/absence, and centerline corrugation presence/absence. Additional information about each segment, including annual traffic volume (AADT), segment length, number of lanes, lane width, shoulder width, and posted speed limit, were also included.

To ensure accuracy, the research team conducted a data verification process using Google Street View imagery to confirm installation locations. Following verification and data cleaning, 930 miles of roadway segments were identified as treatment sites for the crash analysis. During the cleaning process, segments with installation dates after 2023 were excluded due to crash data availability. In addition, the small number of locations that previously had traditional shoulder rumble strips prior to the sinusoidal installations were removed, as the study was designed to compare sinusoidal shoulder corrugations with segments having no shoulder corrugations.

A sample of control sites were also selected for comparison. These sites were selected to closely match the treatment segments in terms of traffic volume and roadway characteristics, including number of lanes, shoulder width, and posted speed limit. In total 601 miles of two-lane segments were selected as control sites. The primary distinction between treatment and control sites was the absence of sinusoidal shoulder corrugations at the control locations. Shoulder corrugations were not installed at the control sites due to a variety of factors, most commonly noise concerns or shoulder use by non-motor vehicles. This approach enabled a rigorous assessment of the safety effects of sinusoidal shoulder rumble strips by comparing treated segments with comparable untreated reference sites. Figure 43 illustrates the treatment and control sites that were included in the crash analysis.

Figure 43. Rural State Highway Treatment and Control Segments for Safety Performance Analysis

The treatment segments included in the study had sinusoidal shoulder rumble strips installed between 2018 and 2023. Therefore, the available before and after observation periods varied depending on the installation year. For before–after safety evaluations, a period of approximately three to five years of data on each side of the installation is generally recommended [*55*]. Accordingly, crash and traffic volume data from 2014 through 2024 were assembled and applied to each segment based on its specific installation year. Tables 16 and 17 present summaries of crashes at the treatment sites by severity level and by crash type, respectively. In addition to lane-departure crashes involving single vehicles (the primary target crash group for sinusoidal shoulder corrugations) the analysis also considered total crashes, single motor-vehicle (SMV) crashes, SMV excluding animal-involved crashes, and lane-departure crashes. Because animal-related crashes represent a substantial share of SMV crashes, conducting the analysis both including and excluding these crashes was important to accurately assess the safety effects [*56, 57*]. Data for two additional relevant crash types, commercial vehicle lane departures and bicycle-involved, were also collected and included in Table 17. However, these crash types were not included in the analysis due to the small sample sizes.

Table 16. Crash Severity Level Data Summary for Treatment Sites (2014-2024)

Year	Total (KABCO)	Severe Injury (KA)	Minor Injury (B)	Possible Injury (C)	Property Damage Only (O)
2014	1860	49	59	118	1634
2015	1750	48	47	115	1540
2016	1779	42	66	104	1567
2017	2156	55	75	119	1907
2018	2050	50	84	108	1808
2019	2025	41	51	101	1832
2020	1710	55	61	88	1506
2021	1823	57	58	73	1635
2022	2029	47	62	115	1805
2023	1808	35	67	113	1593
2024	1814	41	71	103	1599

Table 17. Crash Type Data Summary for Treatment Sites (2014-2024)

Year	Total	SMV	SMV Excluding Animal	Lane Departure	SMV Lane Departure	Commercial Vehicle Lane Departure	Bicycle Involved
2014	1860	1488	359	357	324	12	3
2015	1750	1392	372	371	343	11	1
2016	1779	1425	321	326	280	13	3
2017	2156	1800	381	366	335	21	1
2018	2050	1713	417	417	382	14	1
2019	2025	1671	365	369	325	21	3
2020	1710	1420	304	297	268	14	0
2021	1823	1506	303	312	274	16	0
2022	2029	1684	348	349	307	19	1
2023	1808	1471	235	255	223	8	0
2024	1814	1488	247	260	232	18	2

As shown in Table 16, the majority of crashes at the treatment sites were property-damage-only crashes, accounting for more than 85 percent of all reported crashes. Consequently, separate analyses by crash severity were not performed, as the small number of observations within individual severity categories would not support statistically significant results. Instead, the analysis focused on evaluating the effect of sinusoidal shoulder rumble strips on the specific crash types of interest.

7.2 Methodology

The Empirical Bayes (EB) methodology was used to evaluate the safety effectiveness of shoulder line sinusoidal rumble strips for five different crash types: (1) total crashes, (2) single motor vehicle crashes, (3) single motor vehicle crashes excluding animal crashes, (4) lane departure crashes, and (5) lane departure crashes that include only single motor vehicle. Considering that animal-related crashes account for a large portion of total crashes in Michigan, it is imperative that safety analysis be conducted with and without animal-related crashes [*56,57*]. As part of this analysis, safety performance functions (SPFs) were developed to predict crashes for different crash types. SPFs are mathematical equations that predict crash frequency based on traffic and roadway characteristics. For analyzing count data, two types of regression models are commonly used: the Poisson model and the Negative Binomial (NB) model. The Poisson model is limited in that it does not account for the inherent overdispersion issue that crash data often exhibit (i.e., variance is not equal to the mean). A negative binomial model addresses this limitation by introducing an overdispersion parameter into the variance formulation [*58*]. The variance can be expressed as shown in the following equation:

$$Var(Y_i) = \mu_i + k\mu_i^2 \tag{9}$$

where, μ_i= mean crash frequency on segment i; and k = the overdispersion parameter.

In general, the NB models take the following form:

$$N_{predicted,i} = \mu_i = \exp(\beta_0 + \beta_1 X_{1i} + \cdots + \beta_p X_{pi}) \tag{10}$$

where β_0 = intercept; β_p = regression coefficient for the variable p; and X_{pi}= predictor variable number p for segment i [*59*]. In some cases, datasets can contain observed and unobserved correlations that can affect estimation process and lead to biased and inaccurate parameter estimate. Consequently, error term correlation becomes a concern because the attributes of each segment tend to be correlated. For example, in the dataset used to estimate the SPFs, crash observations are repeated annually for each control segment over a 10-year period. To account for the potential correlation among crash counts observed for the same site across multiple years, a random-effects modeling framework was employed. The random effects model allows the constant term to vary across segments as shown in Equation 11.

$$\beta_{0i} = \beta_0 + \omega_i \tag{11}$$

where ω_i is a randomly distributed random effect for segment i and all other variables are defined as previously.

Observational before-after EB methods have been frequently used in road safety research to evaluate countermeasure safety effectiveness [*12,35,60,61*]. A major advantage of the EB method over other methods is that it can address the regression-to-the-mean (RTM) bias in the crash data [*62*]. Four main steps were followed to assess the effectiveness of the sinusoidal rumble strips in this study using the observational before-after EB method: (1) predicting crash frequency in the before period, (2) predicting crash frequency in the after period, (3) estimating treatment effectiveness, and (4) statistical precision of treatment effectiveness. The *Highway Safety Manual* (HSM) provides the step-by-step procedure for implementing the EB method to investigate roadway countermeasure effectiveness [*55*]. The following equations are used to perform the process:

$$N_{expected,B} = w_i N_{predicted,B} + (1 - w_i) N_{observed,B} \tag{12}$$

$$w_i = \frac{1}{(1 + k_i \times N_{predicted,B})} \tag{13}$$

where $N_{expected;B}$ = expected number of crashes in the before period; $N_{Predicted;B}$ = predicted number of crashes obtained using SPF in the before period; $N_{Observed;B}$ = observed number of crashes in the before period; w_i = weighting factor; and k_i = overdispersion parameter calculated from the SPFs developed.

$$N_{expected,A} = N_{expected,B} \times r_i \tag{14}$$

$$r_i = \frac{\sum N_{predicted,A}}{\sum N_{predicted,B}} \tag{15}$$

where $N_{expected;A}$ = expected number of crashes in the after period without the treatment; r_i = adjustment factor; and $N_{Predicted;A}$ = predicted number of crashes for after period calculated using developed SPFs.

$$CMF = \frac{\sum N_{observed,A} \,/\, \sum N_{expected,A}}{1 + \frac{Var(\sum N_{expected,A})}{(\sum N_{expected,A})^2}} \tag{16}$$

$$Var\left(\sum N_{expected,A}\right) = \sum \left[r_i^2 \times N_{expected,B} \times \left(1 - w_{i,B}\right)\right] \tag{17}$$

where $Var\left(\sum N_{expected,A}\right)$ = variance of expected crash frequency in the after period. Using these equations, crash modification factors (CMFs) for the target crash groups were estimated. A CMF greater than 1.0 indicates an expected increase in crashes, whereas a CMF less than 1.0 indicates an expected reduction in crashes following implementation of the safety treatment, in this case, sinusoidal shoulder rumble strips. Detailed results are given in the following sections.

7.3 SPF Model Results

The safety performance functions were estimated using the control sites, which included 176 roadway segments, representing a total of 601 miles of two-lane highways. As noted previously, control sites were selected to closely match the treatment segments in terms of traffic volumes and roadway characteristics, but without shoulder rumble strips. Ten years of crash data (2015–2024) were used to estimate the SPFs. Annual segment crash frequency served as the dependent variable, while geometric and traffic characteristics were included as independent variables. The natural logarithm of AADT was included in each model along with the natural logarithm of segment length, which was specified as an offset variable with its coefficient constrained to unity. This specification implies that crash frequency increases proportionally with segment length. The additional variables considered in each model included, but were not limited to, lane width (ft), shoulder width (ft), speed limit (mph), regional indicator variables for Michigan, and terrain type. Multiple random-effects negative binomial models were estimated, and various combinations of explanatory variables were evaluated during the model development process. Variables that were not statistically significant (p-value > 0.1) were excluded from the final models.

Tables 18 through 22 present the estimated SPFs based on crash type. In each model, the parameter estimates for natural logarithm of AADT were less than 1.0, indicating an inelastic relationship between crash frequency and traffic volume; in other words, crashes increase at a rate that is proportionally lower than the increase in AADT. As noted previously, the coefficient for the natural log of segment length was constrained to 1.0 in each model, meaning that for each 1 percent increase in segment length, crashes are also expected to increase by 1 percent.

For the total crash model displayed in Table 18, the only additional variable affecting total crash occurrence is the variable for Superior Region. As the Superior Region parameter is negatively associated with total crashes, this indicates that segments located in the Superior Region, which comprises Michigan's entire upper peninsula, experienced fewer total crashes compared to segments located in other regions of Michigan.

Table 19 presents the results for single motor vehicle crashes. The results indicate that roadways with shoulder widths greater than 8 ft experience fewer SMV crashes. The 8-ft threshold was selected based on the average shoulder width of the treatment sites (and the corresponding control sites chosen to match them). Similar to the total crash model, the results also show that the Superior Region is associated with a lower frequency of SMV crashes.

As previously noted, given the high frequency of animal-related crashes in Michigan, an additional model was estimated for SMV crashes excluding animal-related crashes (Table 20). In this model, the Grand Region, which encompasses the west-central portion of Michigan's lower peninsula, was associated with a higher frequency of crashes. Consistent with prior research, wider shoulder widths were associated with fewer non-animal involved SMV crashes.

Finally, two additional models were estimated for lane departure crashes. The model for total lane departure crashes (including single-vehicle and multi-vehicle) is displayed in Table 21, while the model for lane departure crashes involving single vehicles only is displayed in Table 22. Consistent with the previous models, shoulder widths wider than 8-ft were associated with fewer lane departure crashes. The Grand and Southwest regions were each associated with higher lane departure crash frequencies.

Table 18. Estimated Random Effect Negative Binomial Model for Total Crashes

Parameter	Coefficient	Std. Err	p-value
Intercept	-3.496	0.542	<0.001
Ln (AADT)	0.591	0.062	<0.001
Superior Region (1 if yes, 0 otherwise)	-0.660	0.137	<0.001
Ln (Length)	-	-	-
Overdispersion Parameter (k)	0.253	-	-
Random Effect Covariance			
Variance (Intercept)	0.279	0.037	<0.001
Number of Observations	10 * 176		
Pseudo-R^2 (Marginal)	0.475		
Pseudo-R^2 (Conditional)	0.689		

Table 19. Estimated Random Effect Negative Binomial Model for Single Motor Vehicle Crashes

Parameter	Coefficient	Std. Err	p-value
Intercept	-1.842	0.577	0.001
Ln (AADT)	0.359	0.067	<0.001
Shoulder Width (1if more than 8 ft, 0 otherwise)	-0.187	0.109	0.087
Superior Region (1 if yes, 0 otherwise)	-0.959	0.147	<0.001
Ln (Length)	-	-	-
Overdispersion Parameter (k)	0.294	-	-
Random Effect Covariance			
Variance (Intercept)	0.281	0.038	<0.001
Number of Observations	10 * 176		
Pseudo-R^2 (Marginal)	0.370		
Pseudo-R^2 (Conditional)	0.592		

Table 20. Estimated Random Effect Negative Binomial Model for Single Motor Vehicle Crashes Excluding Animal

Parameter	Coefficient	Std. Err	p-value
Intercept	-6.112	0.436	0.001
Ln (AADT)	0.673	0.054	<0.001
Shoulder Width (1if more than 8 ft, 0 otherwise)	-0.287	0.104	0.006
Grand Region (1 if yes, 0 otherwise)	0.461	0.136	<0.001
Ln (Length)	-	-	-
Overdispersion Parameter (k)	0.388	-	-
Random Effect Covariance			
Variance (Intercept)	0.191	0.035	<0.001
Number of Observations	10 * 176		
Pseudo-R^2 (Marginal)	0.196		
Pseudo-R^2 (Conditional)	0.286		

Table 21. Estimated Random Effect Negative Binomial Model for Lane Departure Crashes

Parameter	Coefficient	Std. Err	p-value
Intercept	-6.303	0.480	<0.001
Ln (AADT)	0.696	0.060	<0.001
Shoulder Width (1if more than 8 ft, 0 otherwise)	-0.217	0.112	0.054
Grand Region (1 if yes, 0 otherwise)	0.491	0.152	0.001
Southwest Region (1 if yes, 0 otherwise)	0.276	0.165	0.095
Ln (Length)	-	-	-
Overdispersion Parameter (k)	0.326	-	-
Random Effect Covariance			
Variance (Intercept)	0.250	0.040	<0.001
Number of Observations	10 * 176		
Pseudo-R^2 (Marginal)	0.226		
Pseudo-R^2 (Conditional)	0.352		

Table 22. Estimated Random Effect Negative Binomial Model for Single Motor Vehicle Lane Departure Crashes

Parameter	Coefficient	Std. Err	p-value
Intercept	-5.970	0.471	<0.001
Ln (AADT)	0.637	0.059	<0.001
Shoulder Width (1if more than 8 ft, 0 otherwise)	-0.234	0.109	0.033
Grand Region (1 if yes, 0 otherwise)	0.530	0.147	< 0.001
Southwest Region (1 if yes, 0 otherwise)	0.257	0.155	0.097
Ln (Length)	-	-	-
Overdispersion Parameter (k)	0.291	-	-
Random Effect Covariance			
Variance (Intercept)	0.224	0.039	<0.001
Number of Observations	10 * 176		
Pseudo-R^2 (Marginal)	0.196		
Pseudo-R^2 (Conditional)	0.306		

7.4 CMF Estimation Results

Using the estimated SPFs and following the guidelines in the *Highway Safety Manual* [*55*], CMFs were calculated for each of the various crash types with the results displayed in Table 23. For total crashes, a CMF of 0.917 was estimated, corresponding to an 8.3 percent reduction in total crashes at the treatment sites following the installation of sinusoidal corrugations. For total SMV crashes, the CMF was 1.026 and was not statistically significantly (p-value > 0.1) different from 1.0. However, for SMV crashes excluding those that were animal-related, the CMF was estimated at 0.688, indicating a 31.2 percent reduction in these crashes at treatment sites. This finding suggests that animal-related crashes have a substantial influence on overall SMV crash results and highlights the importance of conducting analyses both with and without animal-related crashes to fully capture the effects of a safety countermeasure—in this case, sinusoidal rumble strips.

Lane departure crashes are the primary target crash type for sinusoidal shoulder corrugations. For total lane departure crashes, a CMF of 0.712 was estimated, corresponding to a safety effectiveness of 28.8 percent. For lane departure crashes involving only single vehicles, the CMF was 0.704, indicating a 29.6 percent reduction following installation of sinusoidal shoulder corrugations. These results demonstrate that sinusoidal corrugations are effective in reducing lane departure crashes. Overall, these findings are consistent with the existing literature on the safety effectiveness of sinusoidal rumble strips, including *Evaluating the Safety Effectiveness of Edge Line Sinusoidal Rumble Strips on Lane Departure Crashes Prevention* [*42*], which reported approximately a 30 percent reduction in total lane departure crashes on rural two-lane highways. The results are also comparable to prior research on traditional rumble strips, which has found reductions in lane departure crashes ranging from 13 percent to 32.1 percent [*39, 63*].

Table 23. Crash Modification Factors for Sinusoidal Shoulder Corrugations

Crash Type	CMF	Safety Effectiveness (Percent Crash Reduction)	Standard Error of Safety Effectiveness	P-value
Total	0.917	8.3	1.542	< 0.001
Single Motor Vehicle	1.026	-2.6	1.869	0.149
Single Motor Vehicle, Excluding Animal	0.688	31.2	2.701	< 0.001
Lane Departure	0.712	28.8	2.792	< 0.001
Lane Departure, Single Motor Vehicle	0.704	29.6	2.818	< 0.001

8. CONCLUSIONS AND IMPLEMENTATION RECOMMENDATIONS

Although traditional rumble strips are generally understood to provide safety benefits, their presence on highways also leads to several potentially adverse effects, including potential bicycle instability and increased roadside noise levels. Sinusoidal rumble strips were designed to alleviate noise concerns by reducing roadside noise for residents, while maintaining adequate levels of in-vehicle noise and vibration. However, questions remain as to impacts of sinusoidal rumble strips on noise, vibrations, and safety impacts to all road users.

Research was conducted to evaluate the effectiveness of sinusoidal shoulder corrugations as a traffic safety strategy, considering noise and vibration, stability and comfort for bicyclists, and traffic crashes. Five primary tasks were conducted to address the research objectives, which are summarized as follows:

- A field study was conducted to evaluate the differences in roadside noise and in-vehicle noise and vibration produced by sinusoidal rumble strips compared to traditional rumble strip designs for various vehicle types and speeds.
- A second field study was conducted to evaluate the impacts of sinusoidal rumble strips on bicyclist comfort and stability compared to traditional rumble strip designs.
- A nationwide survey of bicyclists was conducted to obtain broader insights into cyclists' perceptions and experiences with rumble strips across the United States.
- A survey of motorcyclists traveling in Michigan was conducted to determine motorcyclists' perceptions and experiences with rumble strips.
- A safety performance analysis was performed to develop crash modification factors for sinusoidal shoulder rumble strips.

Synthesis of the findings from these tasks allowed for development of recommendations for future rumble strip design and implementation, which will help inform subsequent changes to policy and standards.

8.1 Summary of Findings

8.1.1 Noise and Vibration

The noise results confirm that traditional rumble strips produce higher roadside noise than the sinusoidal design, particularly at 65 mph and especially for the truck. At 55 mph, the traditional corrugations generated 2.4 dBA greater roadside noise than the sinusoidal design for both vehicle types. However, at 65 mph, the traditional corrugations generated 4.8 dBA and 8.8 dBA more noise than the sinusoidal corrugations for the minivan and truck, respectively.

Both corrugation designs produced sufficient in-vehicle noise (i.e., greater than 3 dBA) to alert drivers in the minivan, which is consistent with the findings from prior research. However, the in-vehicle noise produced by the sinusoidal design (1.4 dBA) was insufficient to alert drivers in the snowplow truck at 55 mph. These differences are likely due to differences in tire width, cabin noise insulation, and suspension characteristics between the two types of vehicles.

Turning to the vibration results, both sinusoidal and traditional corrugations produced considerable (5.5-13.0 dB) vibration at the steering column in the lateral (X) and longitudinal (Y) directions, while vertical (Z) vibration was much less pronounced (2.5-5.4 dB). The snowplow truck generally experienced less vibration during contact with the corrugations compared to the minivan, likely due to dampening caused by the greater weight and more robust suspension system of the truck. The amount of vibration generated by the corrugations was generally unaffected by speed.

There was no statistical association between the depth (3/8 inch or 1/2 inch) or width (8 inches or 12 inches) of the corrugations and noise or vibration. Pavement type (hot mix asphalt or chipseal) was also not found to meaningfully affect corrugation noise or vibration.

8.1.2 Bicyclist Considerations

Results from the bicyclist field study indicated consistent rider preference for the traditional rumble strip design over the sinusoidal design across nearly all evaluated conditions. Riders reported lower comfort and reduced controllability when traversing sinusoidal rumble strips, a finding that was supported by the vibration measurements. The sinusoidal design produced greater vibration than the traditional design across each of the bicycle frame materials (carbon fiber, aluminum, steel, and titanium), speeds, and tire pressures. These objective vibration measurements aligned closely with riders' subjective responses, reinforcing the conclusion that sinusoidal rumble strips impose greater physical disturbance on bicyclists than traditional designs under the conditions evaluated.

The nationwide bicyclist survey indicated that bicyclists give greatest priority to a smooth, debris-free shoulder surface of adequate usable width to ensure safety and comfort while cycling on the shoulder. Rumble strip design characteristics, such as corrugation depth, width, and gap configuration were assigned lower relative importance by bicyclists. In addition, perceived risk while riding on roadway shoulders was primarily associated with surface conditions and visibility constraints, with sand and gravel, shoulder pavement corrugations, and limited sight distance cited most frequently. As for risks associated with drivers, distracted driving and insufficient lateral clearance during passing maneuvers were considered high risk factors when cycling on the shoulder. These results suggest that maintaining clear, continuous shoulder space and minimizing surface irregularities may play a central role in bicyclist comfort and perceived safety on roadways where rumble strips are present. Prior negative experiences with rumble strips, such as being forced into the travel lane or experiencing loss of bicycle control, were strongly associated with both route-planning and route avoidance decisions.

8.1.3 Motorcyclist Considerations

The motorcyclist survey found that most riders are able to maintain control of their motorcycle without steering difficulties or traction loss when crossing rumble strips. The vast majority of motorcyclists also indicated that rumble strips provide an adequate noise or vibration alert when drifting out of the lane. The respondents further indicated that debris on the pavement surface, such as sand or gravel, and driver-related factors, such as distracted driving, are far greater safety concerns for motorcyclists than rumble strips, which were perceived as the lowest risk.

Overall, the results suggest that motorcyclists generally do not experience significant safety or control issues when riding over rumble strips. When properly designed and installed, rumble strips appear to provide useful warning benefits while posing minimal risk to riders. The inclusion of warning signage for rumble strips, particularly in construction zones where motorcyclists are shifted onto the shoulder, may further enhance awareness and comfort for motorcyclists.

8.1.4 Safety Performance

This study also sought to determine whether sinusoidal shoulder corrugations provide measurable crash reduction benefits compared to roadways without any shoulder corrugations, particularly for lane departure crashes. An observational before–after Empirical Bayes methodology was applied following procedures outlined in the Highway Safety Manual. Safety Performance Functions were developed using ten years (2015–2024) of crash data from 176 matched control segments representing 601 miles of two-lane highways without shoulder rumble strips. Random-effects negative binomial regression models were estimated to account for overdispersion and repeated annual observations within segments. Separate SPFs were developed for five crash types: (1) total crashes, (2) single motor vehicle (SMV) crashes, (3) SMV crashes excluding animal-related crashes, (4) lane departure crashes, and (5) lane departure crashes involving only SMVs. The EB method was then used to estimate expected crashes in the after period and compute Crash Modification Factors for 930 miles of treatment segments where sinusoidal shoulder corrugations were installed between 2018 and 2023.

The SPF model results indicated that greater shoulder width is associated with a lower occurrence of SMV crashes (with or without animal involvement) and lane departure crashes. Regional effects were mixed: the Superior Region was associated with lower total and SMV crashes, while the Grand Region was associated with higher SMV (non-animal) and lane departure crashes, and the Southwest Region was associated with higher lane departure crashes.

The CMF results demonstrated measurable safety benefits associated with sinusoidal shoulder rumble strips. For total crashes, a CMF of 0.917 was estimated, corresponding to an 8.3 percent reduction in crashes at treated sites. For SMV crashes, a CMF of 1.026 was estimated; however, this 2.6 percent increase was not statistically significant. When animal-related crashes were excluded, the CMF for (SMV-Animal) crashes was 0.688, indicating a statistically significant 31.2 percent reduction. Lane departure crashes—the primary target crash type for shoulder rumble strips—experienced substantial reductions after installation of the sinusoidal shoulder rumble strips. A CMF of 0.712 was estimated for total lane departure crashes, corresponding to a 28.8 percent reduction. For lane departure crashes involving only single vehicles, the CMF was 0.704, indicating a 29.6 percent reduction. Overall, the magnitude of the crash reductions observed in this study are consistent with the extensive prior research on the safety performance of traditional rumble strips, in addition to the limited prior research on sinusoidal rumble strips.

8.2 Conclusions

Overall, it was concluded that sinusoidal shoulder corrugations can effectively reduce roadside noise compared to traditional corrugations without compromising the level of in-vehicle noise or vibration that is necessary to alert drivers, particularly for passenger vehicles. While the in-vehicle noise produced during contact with the sinusoidal corrugations was insufficient to alert drivers in the snowplow truck at 55 mph, adequate levels of steering column vibration did occur. In terms of safety performance, the results of the EB analysis suggest that sinusoidal shoulder rumble strips provide meaningful crash reductions, including an 8.3 percent reduction in total crashes and a 29.6 percent reduction in single vehicle lane departure crashes, while addressing community noise concerns associated with traditional designs.

In contrast, results from the bicycle field study indicated a consistent rider preference for the traditional rumble strip design over the sinusoidal design. Riders reported lower comfort and reduced controllability when traversing sinusoidal rumble strips. This finding was supported by the vibration measurements, as the sinusoidal corrugations produced greater vibration than the traditional design across each of the tested bicycle frame materials, speeds, and tire pressures. These results suggest that additional design strategies, such as regular gaps in the corrugations, be considered along highways utilized by bicyclists. Both the bicyclist field study and the nationwide bicyclist survey found that bicyclists value a smooth and debris-free shoulder of at least 3-ft in width as the most important aspect towards ensuring comfort, stability, and overall safety. Motorcyclists were in general agreement with bicyclists in that debris on the pavement surface represents a greater safety concern than rumble strips, as motorcyclists generally do not experience significant safety or control issues when encountering rumble strips.

8.3 Implementation Recommendations for Sinusoidal Shoulder Rumble Strips

From a policy and implementation perspective, these results support the continued deployment of sinusoidal shoulder rumble strips as an effective and context-sensitive countermeasure for reducing lane departure crashes on rural two-lane roadways. To that end, the continued use of sinusoidal shoulder corrugations in noise-sensitive environments is recommended. Examples of appropriate environments would include residential areas, schools, hospitals, offices, and other noise-sensitive areas.

In terms of corrugation dimensions, although no meaningful differences in noise or vibrations were observed between the different corrugation depths or widths, 3/8 inch corrugation depths are preferred in areas frequented by bicyclists. Furthermore, a corrugation width of 8 inches placed at the edge line would help ensure an adequate usable paved shoulder for bicyclists, which the nationwide survey of bicyclists suggested should be a minimum width of 3-feet, smooth, and free of debris. Additionally, due to the considerable comfort and stability issues faced by bicyclists when traversing over sinusoidal corrugations, adequate gaps in the rumble strips should be provided. The inclusion of warning signage for rumble strips, particularly in construction zones where motorcyclists are shifted onto the shoulder, may further enhance awareness and comfort for motorcyclists. While this research provided substantial evidence of the noise, vibration, and safety effects of sinusoidal shoulder rumble strips, future research should explore alternative corrugation designs that can meet the noise and vibration objectives, while providing a more comfortable and controlled experience for bicyclists.

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Appendix A – Post-Ride Questionnaire Form for Bicycle Field Study Participants

Please answer the following questions after completion of each ride:

Q1. Considering your most recent ride, rate the following statements for the **Traditional** shoulder corrugations (Section A):

	Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Agree
I was able to control my bicycle as I crossed the corrugations	O	O	O	O	O
I had trouble steering as I crossed the corrugations	O	O	O	O	O
My bicycle lost traction as I crossed the corrugations	O	O	O	O	O
I felt comfortable riding on the corrugations	O	O	O	O	O
The corrugations would help me stay safe on the road	O	O	O	O	O

Q2. Considering your most recent ride, rate the following statements for the **Sinusoidal** shoulder corrugations (Section B):

	Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Agree
I was able to control my bicycle as I crossed the corrugations	O	O	O	O	O
I had trouble steering as I crossed the corrugations	O	O	O	O	O
My bicycle lost traction as I crossed the corrugations	O	O	O	O	O
I felt comfortable riding on the corrugations	O	O	O	O	O
The corrugations would help me stay safe on the road	O	O	O	O	O

Q3. Which type of shoulder corrugation do you prefer in terms of:

	Prefer Traditional	Prefer Sinusoidal	Prefer Either	Prefer Neither
Controlling my bicycle	O	O	O	O
Steering my bicycle	O	O	O	O
Traction	O	O	O	O
Comfort	O	O	O	O
Helping me stay safe on the road	O	O	O	O
Overall	O	O	O	O

Please answer the following questions once after completion of <u>all</u> rides

Q1. Your Name:

Q2. How many years have you been riding a bicycle?

- O 1-5 years
- O 11-20 years
- O 31-40 years
- O 6-10 years
- O 21-30 years
- O More than 40 years

Q3. How many years have you been cycling on rural highways?

- O 1-5 years
- O 11-20 years
- O 31-40 years
- O 6-10 years
- O 21-30 years
- O More than 40 years

Q4. Approximately how many miles per year do you cycle on rural highways?

- O 0
- O 10-25 miles
- O 101-200 miles
- O 1-10 miles
- O 25-100 miles
- O More than 200 miles

Q5. How confident are you with cycling on the shoulder of a rural highway?

- O Not confident
- O Somewhat confident
- O Neutral
- O Moderately confident
- O Extremely confident

Q6. Please rank each of the following **Roadway** characteristics in terms of risk to your safety when riding a bicycle on the shoulder of a rural roadway. Please order as follows: 1 = HIGHEST risk to 5 = LOWEST risk

- Poor sightlines over hills or at intersections
- Steep grades
- Sand or gravel on pavement surface
- Pavement corrugations on the edge of the road
- Pavement corrugations on the center of the road

Q7. Please rank each of the following **Driver Behavioral** characteristics in terms of risk to your safety when riding a bicycle on the shoulder of a rural roadway. Please order as follows: 1 = HIGHEST risk to 5 = LOWEST risk

- Distracted driving
- Drivers not providing enough lateral separation when overtaking
- Speeding
- Intoxication
- Drowsiness

Q8. Do you have any specific concerns with either shoulder corrugations design? Use the other side for additional space

Q9. Would you change any design aspect of either shoulder corrugations design? Use the other side for additional space

Q10. From the perspective of a road bicyclist, please share any additional thoughts, comments, or experiences you had with the shoulder corrugations you tested today. Use the other side if for additional space

Appendix B – Online Questionnaire Form for Bicyclist Experience with Rumble Strips

Rumble strips are a series of milled corrugations or raised elements on the pavement, typically placed on the edge, shoulder, or center of the road, which are designed to alert drivers by vibrating or making noise when contacted. The following is an example of milled shoulder rumble strips:

Q1 Do rumble strips affect your route planning when cycling?
- ○ Yes
- ○ No

Q2 Have you ever avoided riding a road because of rumble strips?
- ○ Yes
- ○ No

Q3 Have rumble strips ever caused you to stop riding or turn around during a ride?
- ○ Yes
- ○ No, any issues with rumble strips have not been significant enough for me to stop or turn around
- ○ No, but only because there was no other route option

Q4 Have you ever encountered rumble strips that you considered well-designed for cyclist safety and comfort?
- ○ Yes (please explain what you liked about the design)
- ○ No
- ○ Not sure

Q5 Please rank-order the relative importance of characteristics for a safe and comfortable rumble strip design (1 being most important)
- Narrow width of the rumble strip
- Shallow depth of the rumble strip corrugation
- Adequate gap length
- Adequate gap spacing
- Adequate usable shoulder
- Swept shoulder (free of gravel and debris)
- Other (please specify)

Q6 Do you think improper rumble strip placement increases the risk of vehicle-cyclist conflict?
- ○ Yes
- ○ No

- Not sure

Q7 Have you ever been forced to ride in the vehicle travel lane due to rumble strips making the shoulder unsafe or unusable?

- Yes
- No

Q8 While riding in the travel lane due to rumble strips, have you or your riding group experienced a near-miss or collision with a vehicle?

- Yes
- No

Q9 If yes, what happened? (select all that apply)

- A vehicle cut me or my group off while completing a pass
- A vehicle came up quickly from behind
- A vehicle did not give adequate lateral separation when passing
- A vehicle in the opposing direction crossed over the centerline and towards me or my group
- Other (please explain):

Q10 Did a collision or fall occur as a result?

- Yes
- No

Q11 What was the nature of the collision? (select all that apply)

- Collision between the vehicle and cyclist(s)
- Collision between two or more cyclists
- One or more cyclist struck the pavement
- One or more cyclist struck the roadside (ground or object)
- Collision between two or more vehicles
- Vehicle collided with roadside or fixed object
- Other; please specify:

Q12 Were you or another cyclist injured as a result?

- Yes, I was injured (feel free to explain, if comfortable with doing so)
- Yes, another cyclist in my group was injured (feel free to explain, if comfortable with doing so)
- No injury occurred

Q13 Have rumble strips ever caused you to lose control of your bicycle or make a dangerous maneuver?

- Yes
- No

Q14 What was the primary cause? (select all that apply)

- Contacted the rumble strip
- Swerved to avoid contact with rumble strip
- Hit debris in the shoulder
- Swerved to avoid contact with debris in the shoulder
- Contacted the edge of the shoulder or roadside (due to the inadequate shoulder width caused by the rumble strip)
- Other; please specify:

Q15 What maneuver resulted? (select all that apply)

- Swerved into the traffic lane
- Lost balance
- Went off the pavement and onto the roadside
- Braked uncomfortably hard
- Other; please specify:

Q16 Was there a collision or near-miss? (select all that apply)

- Collision with another cyclist
- Near-miss with another cyclist
- Collision with a vehicle
- Near-miss with a vehicle
- Struck the pavement
- Struck the roadside (ground or object)
- Other; please specify:
- No collision or near-miss occurred

Q17 Were you or another cyclist injured as a result?

- Yes, I was injured (feel free to explain, if comfortable with doing so)
- Yes, another cyclist in my group was injured (feel free to explain, if comfortable with doing so)
- No injury occurred

Q18 Other than the cases already noted in prior questions, have you experienced any injuries or witnessed injuries to other cyclists that were caused by rumble strips?

- Yes, I was injured (please explain what happened)
- Yes, another cyclist was injured (please explain what happened)
- No additional injuries caused by rumble strips

Q19 When riding on roads with shoulders, what is the minimum width of clear paved shoulder beyond the rumble strip for you to feel safe and comfortable while riding?

- Less than 2 feet
- 2 feet
- 3 feet
- 4 feet
- More than 4 feet

Q20 If rumble strips on the edge of the roadway must be used, where should they be placed?

- On the fog (edge) line
- Just inside the fog (edge) line on the shoulder
- Away from the fog (edge) line, deeper into the shoulder
- None of the above — rumble strips should not be used where cyclists ride

Q21 What is the minimum length of gap between sections of rumble strips to allow safe crossing?

- 6 feet
- 12 feet
- 24 feet
- More than 24 feet
- Doesn't matter if paved shoulder is wide enough and clear

Q22 What is the maximum spacing between the gaps in the rumble strips to allow safe crossing?

- Every 6 feet
- Every 12 feet
- Every 24 feet
- Every 48 feet
- More than 48 feet
- Doesn't matter if paved shoulder is wide enough and clear

Q23 When riding across gaps in rumble strips, how difficult is it to safely align with the gap?

- Not difficult
- Occasionally difficult
- Frequently difficult
- I avoid crossing them while riding

Q24 Do you support requiring state DOTs to follow national design guidelines for rumble strips?

- Yes
- No
- Not sure

Q25 Can you describe a time when rumble strips affected your ride, for better or worse?

Q26 If you could speak to your state DOT about rumble strip design, what would you tell them?

Q27 From the perspective of a bicyclist, please share any additional thoughts, comments, or experiences you had with rumble strips

Q28 In your lifetime, how many times would you estimate that you have contacted rumble strips while riding a bicycle?

- 0
- 1-10
- 11-50
- 51-100
- 101-250
- 251-500
- More than 500

Q29 How many years have you been bicycling on rural roads?

- 1-5 years
- 6-10 years
- 11-20 years
- 21-30 years
- 31-40 years
- More than 40 years

Q30 Approximately how many miles per year do you ride your bicycle on rural roads?

- 1-25 miles
- 26-100 miles
- 101-200 miles
- 201-500 miles
- 501-1000 miles
- 1000-2000 miles
- More than 2000 miles

Q31 Please select the bicycle body frame you typically use for road riding (select all that apply)

- Steel
- Carbon Fiber
- Aluminum
- Titanium
- Other; please specify.

Q32 Rank-order each of the following **Roadway** characteristics in terms of risk to your safety when riding a bicycle on the shoulder of a rural roadway. 1 = HIGHEST risk; 6 = LOWEST risk

- Poor sightlines over hills or at intersections
- Steep grades
- Sand or gravel on pavement surface
- Pavement corrugations on the edge of the road
- Pavement corrugations on the center of the road
- Fog (edge) line stripes that are faded or missing

Q33 Rank-order each of the following **Driver Behaviors** in terms of risk to your safety when riding a bicycle on the shoulder of a rural roadway: 1 = HIGHEST risk; 6 = LOWEST risk

- Distracted driving
- Not providing enough lateral separation when passing bicyclists
- Speeding
- Intoxication
- Drowsiness
- Not fully checking before pulling out from an intersection or driveway

Q34 Which state do you currently live in?

Q35 Please select your gender.

- Male
- Female
- Non-binary / third gender
- Prefer not to say

Q36 Please select your age.

- 18-34 years old
- 35-64 years old
- 65 years or older

Q37 Please select your education level.

- Less than high school
- High school graduate
- Some college
- 2 year degree
- 4 year degree
- Graduate or Professional degree
- Doctorate

Q38 Please select your income level.

- Less than $10,000
- $10,000 - $24,999
- $25,000 - $49,999
- $50,000 - $74,999
- $75,000 - $99,999
- $100,000 - $149,999
- More than $150,000

Appendix C – Online Questionnaire Form for Motorcyclist Experience with Rumble Strips

Q1. Rumble strips are a series of milled corrugations or raised elements on the pavement, typically placed on the edge, shoulder, or center of the road, which are designed to alert drivers by vibrating or making noise when contacted. The following is an example of milled shoulder rumble strips:

Q2. Are you familiar with rumble strips similar to the type shown in the image above?
- O Yes
- O No

Q3. Have you ever ridden a motorcycle on or over rumble strips at the edge or center of the road?
- O Yes
- O No

Q4. Considering your previous encounter(s) with rumble strips while on a motorcycle, please rate the following statements on a scale of 1 (Disagree) to 5 (Agree):
- I was able to control my motorcycle when I encountered the rumble strips
- I had trouble steering my motorcycle when I encountered the rumble strips
- My motorcycle lost traction when I encountered the rumble strips
- I felt comfortable when I encountered the rumble strips
- The vibration of rumble strips would sufficiently alert me when I drift out of the lane
- The sound of rumble strips would sufficiently alert me when I drift out of the lane
- The rumble strips will help keep me safe on the road

Q5. Please rank each of the following Roadway characteristics in terms of risk to your safety when riding your motorcycle. Please order as follows: 1 = HIGHEST risk to 7 = LOWEST risk
- Faded pavement markings
- Poor sightlines at intersections
- Rumble strips on the center of the road
- Sharp curves
- Poor sightlines over hills
- Sand or gravel on the pavement surface
- Rumble strips on the edge or shoulder of the road

Q6. Please rank each of the following characteristics of Other Drivers in terms of risk to your safety when riding your motorcycle. Order as follows: 1 = HIGHEST risk to 7 = LOWEST risk
- Not fully checking for vehicles before pulling out from an intersection or driveway
- Distracted driving
- Drifting over the centerline
- Not fully checking blind spot when changing lanes
- Intoxication
- Drowsiness
- Speeding

Q7. Which U.S. state do you currently live in?

Q8. Please select your gender.
- Male
- Female
- Non-binary / third gender Prefer not to say

Q9. Please select your age.
- 18-34 years old
- 35-64 years old
- 65 years or older

Q10. Please select your education level.
- Less than high school
- High school graduate
- Some college
- 2 year degree
- 4 year degree
- Graduate or Professional degree
- Doctorate

Q11. Please select your income level.
- Less than $10,000
- $10,000 - $24,999
- $25,000 - $49,999
- $50,000 - $74,999
- $75,000 - $99,999
- $100,000 - $149,999
- More than $150,000

Q12. How many years have you been riding a motorcycle?
- 1-5 years
- 6-10 years
- 11-20 years
- 21-30 years
- 31-40 years
- More than 40 years

Q13. Please select the style of motorcycle that you most often ride on highways
- Cruiser
- Touring
- Sportbike
- Standard
- Dual-Sport
- Adventure Bike
- Café Racer
- Sport Touring
- Chopper
- Trike
- Scrambler
- Other, please specify

Q14. Approximately how many miles per year do you ride your motorcycle?
- Less than 1,000 miles
- 1,001- 3,000 miles
- 3,001-5,000 miles
- More than 5,000 miles

Q15. From the perspective of a motorcyclist, please share any additional thoughts, comments, or experiences you had with rumble strips on the edge, shoulder, or center of the road.