Evaluation on Effectiveness of Audible and Vibratory Treatment (AVT) Installations on Arterials and Collectors Based on FDOT Context-based Design Criteria

BED25-977-03

Final Report

Prepared for

Florida Department of Transportation

September 2023

CUTR
CENTER FOR URBAN TRANSPORTATION RESEARCH

UNIVERSITY of SOUTH FLORIDA

Evaluation on Effectiveness of Audible and Vibratory Treatment (AVT) Installations on Arterials and Collectors Based on FDOT Context-based Design Criteria

BED25-977-03

Final Report

Prepared for:

Florida Department of Transportation
David S. Amato (PM)
State Roadway Design Engineer
Brenda Young, P.E., CPM (Co-PM)
State Safety Engineer
605 Suwannee St.
Tallahassee, FL 32399

Prepared by:

USF Center for Urban Transportation Research
Dr. Pei-Sung Lin, P.E., PTOE, FITE (PI)
Dr. Cong Chen, P.E., RSP1, M.ASCE (Co-PI)
Dr. Yaye Keita
Shubhankar Chintamani Shindgikar, Ph.D. student
Ela Białkowska-Jelińska, GISP, Ph.D. student

September 2023

Disclaimer

The opinions, findings, and conclusions expressed in this publication are those of the authors and are not necessarily those of the Florida Department of Transportation.

Metric Conversion

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC

Technical Report Documentation

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Evaluation on Effectiveness of Audible and Vibratory Treatment (AVT) Installations on Arterials and Collectors Based on FDOT Context-based Design Criteria		**5. Report Date** 09/30/2023 **6. Performing Organization Code**
7. Author(s) Pei-Sung Lin, Cong Chen, Yaye Keita, Shubhankar Chintamani Shindgikar, Ela Białkowska-Jelińska		**8. Performing Organization Report No.**
9. Performing Organization Name and Address Center for Urban Transportation Research (CUTR) University of South Florida 4202 E Fowler Avenue, CUT100 Tampa, FL 33620-5375		**10. Work Unit No.** **11. Contract or Grant No.**
12. Sponsoring Agency Name and Address Florida Department of Transportation 605 Suwannee Street, MS 30 Tallahassee, FL 32399-0450		**13. Type of Report and Period Covered** Final Report 04/01/2022 - 09/30/2023 14. **Sponsoring Agency Code**
15. Supplementary Notes		

16. Abstract

This research project evaluated the effectiveness of three Florida Department of Transportation (FDOT) sinusoidal rumble strip designs with respect to their abilities to reduce exterior noise, properly alert drivers, and enhance safety. A literature review, agency interviews, noise studies, and safety evaluation of sinusoidal rumble strips were performed to assess both noise reduction and safety effectiveness of sinusoidal rumble strips. For the safety analysis, an Empirical Bayes (EB) approach was used to develop Crash Modification Factors (CMFs) and a multinomial logit model was applied to assess the influence of sinusoidal rumble strip presence on lane departure crash severity. Among the three designs, Type 2 was determined to be the best when driver experience, noise study results, and pitch of sounds are considered. To accommodate bicyclists, agencies should ensure that they leave at least 4 ft (1.2 m) of space between the rumble strips and the edge of the pavement. For the safety evaluation results, considering all crashes, sinusoidal rumble strips were found to reduce total lane departure crashes by 57% (CMF=0.43) overall, 30% (CMF=0.70) for rural two-lane roadways, and 61% (CMF=0.39) for rural multi-lane roadways. Furthermore, they can significantly reduce lane departure crash severity. Overall, sinusoidal rumble strips are an effective safety countermeasure to lower exterior noise, address noise issues, properly alert drivers, and significantly reduce lane departure crashes and their severities.

17. Key Words		**18. Distribution Statement**	
Sinusoidal rumble strip, roadway departure crashes, arterials, safety, countermeasure, Audible and Vibratory Treatment, AVT, noise control, bicycle accommodation, crash modification factor, CMF		No restriction	
19. Security Classif. (of this report)	**20. Security Classif. (of this page)**	**21. No. of Pages**	**22. Price**
Unclassified	Unclassified	115	

Acknowledgment

The research team at the Center for Urban Transportation Research (CUTR) at the University of South Florida (USF) sincerely thanks FDOT Project Manager (PM) Mr. David S. Amato (Roadway Design Engineer), Co-PM Ms. Brenda Young, P.E., CPM (State Safety Engineer), and former FDOT Roadway Design Criteria Administrator Mr. Gevin McDaniel, P.E. for their full support, guidance, and assistance on this important research. Our appreciation also goes to FDOT Research Center Manager Mr. Darryll Dockstader, Research Development Coordinator Ms. Jennifer Clark, Performance and Workforce Coordinator Mr. Jason Tuck, and Business Systems Coordinator Ms. Ta'rika Green, for their support and assistance. Finally, the CUTR research team would like to thank all the interviewees from California, Indiana, Kentucky, Minnesota, and Washington, who provided valuable insights into their state sinusoidal rumble strip design, implementation, and evaluation.

Executive Summary

The safety of roadway users is among the top priorities of the Florida Department of Transportation (FDOT). Roadway departure is the top contributing factor to traffic fatalities and the second highest contributing factor to serious injuries in Florida. According to the Florida Strategic Highway Safety Plan (SHSP) published in March 2021, lane departures accounted for 34 percent of all crashes and 42 percent of traffic fatalities on Florida roadways for 2015–2019. Audible Vibratory Treatments (AVTs), commonly referred to as rumble strips, have proved to reduce roadway departure crashes. Noise and vibration from rumble strips alert drivers when their vehicles leave the travel lane.

Due to complaints from residents regarding the noise from the vehicular impacts of AVTs and from bicyclists regarding the presence of some shoulder rumble strips and the gap length between rumble strips on edgelines, the FDOT has developed context-based design standards for AVTs on arterials and collectors that address noise impacts on residents and businesses adjacent to roadways and accommodate bicyclists. Three sinusoidal rumble strip designs (Type 1, Type 2, and Type 3) were considered to replace traditional cylindrical ground-in and profiled thermoplastic rumble strips at locations with complaints from residents and the modification of array dimensions to better accommodate cyclists.

Sinusoidal rumble strips, which are wave-shaped and designed to alert distracted or sleepy drivers through sound and vibration, are an alternative to cylindrical ground-in and profiled thermoplastic rumble strips. Various patterns of sinusoidal rumble strips exist with varying applicability, amplitude of the sine curve, grinding methods, and other factors. This project focused on the evaluation of three FDOT sinusoidal ground-in rumble strip designs to address exterior noise issues and the evaluation on effectiveness of sinusoidal rumble strips to reduce roadway departure crashes and their severities.

To draw conclusions, the project team carried out four primary tasks: 1) an in-depth literature review synthetizing practices of sinusoidal rumble strips designs, implementations, and evaluations in other states and in Florida, 2) interviews with selected transportation agencies across the nation on sinusoidal AVT design, implementation, and evaluation, 3) noise evaluations from noise tests conducted by the FDOT Materials Office, and a focus group study conducted by the Center for Urban Transportation Research (CUTR) at the University of South Florida (USF), and 4) a safety evaluation via before-after studies and development of Crash Modification Factors (CMFs) for sinusoidal rumble strips using an Empirical Bayes (EB) approach. For the safety evaluation, a multinomial logit model was also applied to assess the influence of sinusoidal rumble strip presence on lane departure crash severity outcomes.

The results from the literature review indicate that sinusoidal rumble strips are more effective in addressing noise issues compared to other types of rumble strips, as they reduce exterior noise while still effectively alerting drivers when they depart from the travel lane. Thus, sinusoidal rumble strips can alleviate the noise burdens on residents living near rumble strips. The same findings were confirmed during the agency interviews by experts from California, Indiana, Kentucky, Minnesota, and Washington, which are the pioneer states of sinusoidal rumble strips. These five states implemented sinusoidal rumble strips due to their potential to

reduce exterior noise. All of the experts reached a consensus that utilizing sinusoidal rumble strips is an efficient way to address the problem of exterior noise and reduce the complaints of residents. Information obtained from the literature review and agency interviews also revealed that rumble strips must be designed and installed to suit all roadway users, including bicyclists. To mitigate the negative impact of rumble strips on bicyclists, rumble strips should be designed to make it easier for bicyclists to ride on roadway shoulders. Bicyclists should have at least 4 ft (1.2 m) of space between the rumble strips and the edge of the pavement, with more (5 ft and over) if safety barriers are present.

The results of the noise evaluation from the FDOT Materials Office noise studies and CUTR focus group noise study suggest that Type 2 and Type 3 sinusoidal rumble strips are superior to Type 1 FDOT design. During the CUTR focus group noise study, drivers preferred Type 2 slightly more than Type 3 based on their travel experience, consistency, and the pitch of sounds. Various other factors like speed, vehicle type, or vehicle model can affect the noise levels inside and outside of vehicles when driving on the sinusoidal rumble strips. The performance of the rumble strips may also depend on driving angle or whether the drivers are driving in a straight line or weaving on the strips. In addition, edgeline sinusoidal rumble strips were found to produce more noise (both inside and outside) than shoulder rumble strips.

The findings from an Empirical Bayes (EB) safety evaluation and CMFs development reveal that the sinusoidal rumble strips are effective in reducing lane departure crashes as indicated with all three estimated CMFs at less than 1.0. Overall, sinusoidal rumble strips can reduce total lane departure crashes by 57% (CMF=0.43). Sinusoidal rumble strips are expected to reduce total lane departure crashes on rural two-lane roadways by 30% (CMF=0.70) and by 61% (CMF=0.39) on rural multi-lane roadways.

The CMFs for crash severity, including both fatalities and incapacitating injuries, were also estimated. Based on the results, sinusoidal rumble strips can reduce fatal and serious lane departure crashes by 62% (CMF=0.38). Sinusoidal rumble strips are expected to reduce fatal and serious lane departure crashes on rural two-lane roadways by 82% (CMF=0.18). On rural multi-lane roadways, sinusoidal rumble strips can decrease fatal and serious lane departure crashes by 57% (CMF=0.43). The results from the multinomial logit model confirmed that the presence of sinusoidal rumble strips has a significant influence at a 90% confidence level on lane departure crash severity. Other factors that significantly impact lane departure crash severity include foggy/smoggy/smoky weather, alcohol or drug involvement in crash, dark lighting condition, two-lane road configuration, roadway function, aggressive driving behavior, and high Annual Average Daily Traffic (AADT).

Based on all project findings, sinusoidal rumble strips are an effective solution to lower exterior noise and reduce noise issues with nearby residents. Among the three FDOT sinusoidal rumble strip designs, Type 2 is better than Types 1 and Type 3. Sinusoidal rumble strips can significantly reduce lane departure crashes with sufficient interior noise and vibrations to alert drivers. A greater level of safety effectiveness in reducing serious crashes is expected, especially for two-lane rural roadways. Considering all crashes, sinusoidal rumble strips are more effective at reducing rural multi-lane roadway lane departures. To accommodate bicyclists, at least 4 ft (1.2 m) of space between the rumble strips and the edge of the pavement are recommended.

Table of Contents

List of Figures

List of Tables

Abbreviations and Acronyms

AADT	Annual Average Daily Traffic
ADT	Average Daily Traffic
AVTs	Auditory Vibratory Treatments
CALTRANS	California Department of Transportation
CLRS	Centerline Rumble Strips
CMF	Crash Modification Factor
CUTR	Center for Urban Transportation Research
GIS	Geographic Information System
EB	Empirical Bayes
FDM	Florida Design Manual
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
FR	Front to Rear
INDOT	Indiana Department of Transportation
JTRP	Joint Transportation Research Program
MI	Minor Injury
MLE	Maximum Likelihood Estimation
MnDOT	Minnesota Department of Transportation
MNL	Multinomial Logit
MP	Milepost
NCHRP	National Cooperative Highway Research Program
NI	No Injury
ODOT	Oregon Department of Transportation
RwD	Roadway Departure
SHSP	Strategic Highway Safety Plan
SI	Severe Injury
SPF	Safety Performance Function
SRS	Shoulder Rumble Strips
SVROR	Single-Vehicle Run-Off-Road
USF	University of South Florida
VMT	Vehicle Miles Traveled
WSDOT	Washington State Department of Transportation

1 Introduction

Lane departure crashes are among the most common crashes in Florida and in the USA, and preventing those crashes is the priority of many DOTs across the nation. Auditory Vibratory Treatments (AVTs), or rumble strips, are frequently used to prevent or reduce lane departure incidents. Various types of rumble strips exist, some of which produce exterior noise that can be a burden to nearby residents and can often cause trouble for bicyclists. In consideration of noise issues, a few DOTs, including the Florida Department of Transportation (FDOT), have been considering a new type of AVT called sinusoidal rumble strips. This project evaluates the noise and safety effectiveness of sinusoidal rumble strips in Florida and in other states where they have been implemented. It explores the potential for sinusoidal rumble strips to reduce exterior noise while appropriately alerting drivers when leaving the travel lane. The FDOT designed three types of sinusoidal rumble strips, which are also evaluated with respect to noise and crash reduction capability. A literature review, agency interviews, focus group noise study, FDOT field noise study evaluations, and safety evaluations were performed as part of the project. This chapter focuses on the introduction, as well as the background, research objectives, and organization of the report.

1.1 Background

The Federal Highway Administration (FHWA) defines a roadway departure (RwD) crash (or lane departure crash) as a crash that occurs after a vehicle crosses an edgeline or a center line or otherwise leaves the travelway. From 2016 to 2018, an average of 19,158 fatalities resulted from roadway departures, accounting for 51% of all traffic fatalities in the US. RwD is also a top contributing factor for traffic crashes in Florida; according to the 2021 Florida Strategic Highway Safety Plan (SHSP), more people are killed in lane departure crashes than any other type of crash in Florida. About one-third of lane departure crashes result in a collision with another moving vehicle, possibly head-on, and two-thirds involve hitting a tree or another fixed object. A little more than half of fatal lane departure crashes occur in rural areas where there are more two-lane roadways, narrow shoulders, and long stretches of relatively empty roadway. The most recent Florida crash data (2015–2019) revealed that lane departure was the top contributing factor to traffic crash fatalities and the second highest contributing factor to serious injuries, as shown in Figure 1-1. In 2015–2019, lane departures accounted for 34% of all crashes and 42% of traffic fatalities on Florida roadways, as shown in Figure 1-2.

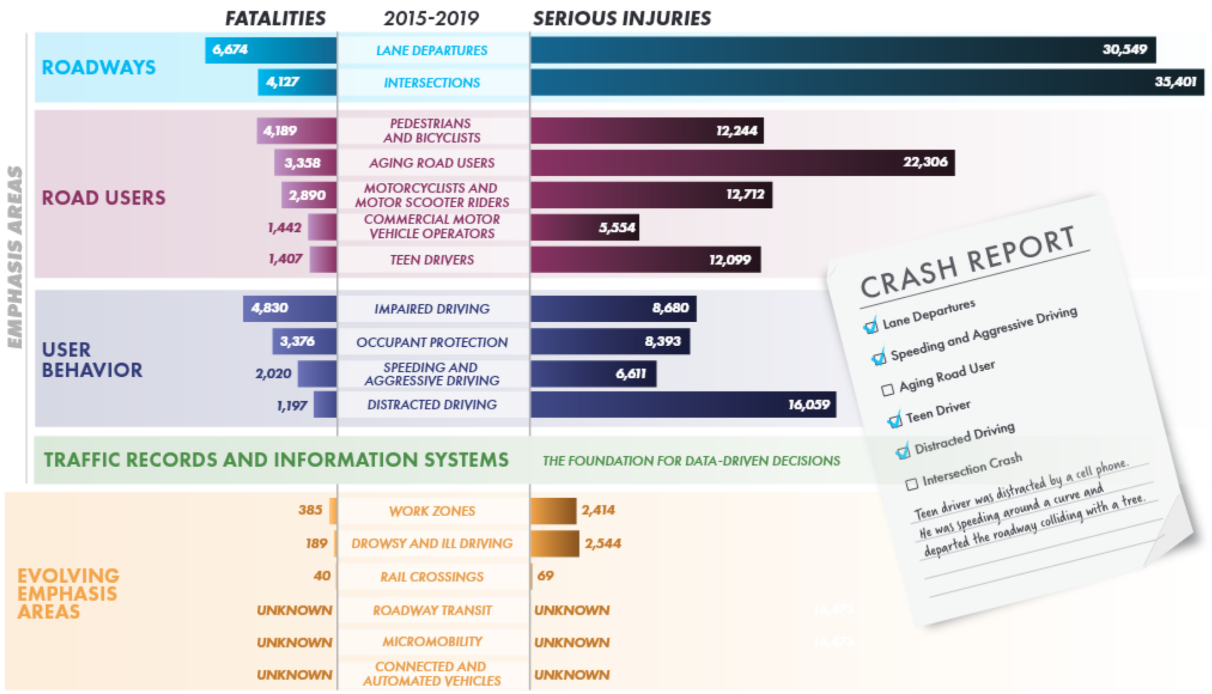


Figure 1-1. Top contributing factors and emphasis areas, Florida traffic crashes, 2015–2019

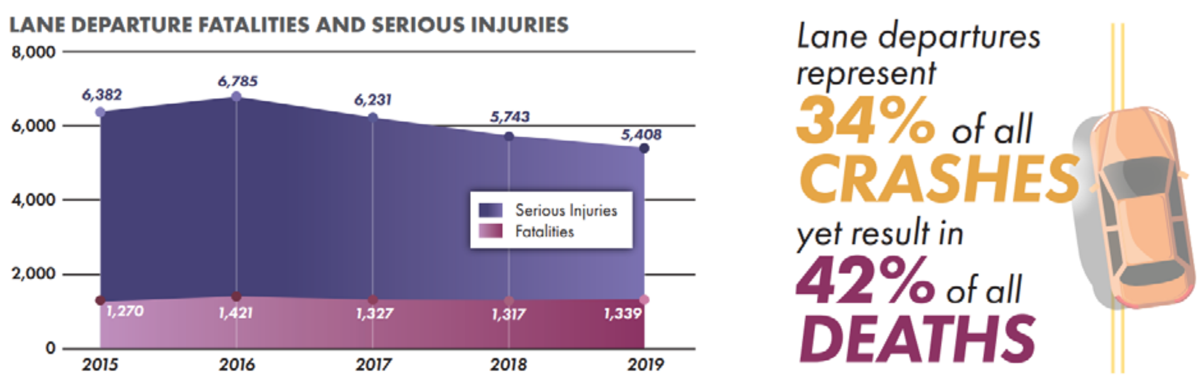


Figure 1-2. Lane departure crash statistics, Florida, 2015–2019

Because of complaints by residents regarding the noise from the vehicular impacts of AVTs and by bicyclists regarding the presence of some shoulder rumble strips and the gap length between rumble strips on edgelines, FDOT has developed context-based design standards for AVTs on arterials and collectors that address noise impacts on residents and businesses adjacent to roadways and accommodate bicyclists when selecting an appropriate AVT. Primary changes in the new standards include the following:

- Reduced depth of cylindrical ground-in rumble strips from ½ in. to 3/16 in. based on noise testing of various patterns and depths.
- Reduced width of centerline rumble strips from 16 in. to 8 in.
- Modified array dimensions to better accommodate cyclists.

- Research and implementation on the use of a sinusoidal ground-in rumble strip pattern that lessens the potential for noise pollution.
- Creation of ground-in configurations (Types A, B, C) for consistent placement of edgeline rumble strips.

Three types of rumble strips are used by FDOT, all of which can be installed on a shoulder, an edgeline of the travel lane, or at or near the center line of an undivided roadway:

- Profiled thermoplastic
- Cylindrical ground-in rumble strips
- Sinusoidal ground-in rumble strips

A profiled thermoplastic rumble strip is an AVT used on concrete pavement to aid in avoiding lane departures and centerline crossover crashes (Figure 1-3). When compared to standard lane markings, this technique creates a rumbling effect and improves visibility, especially at night and in wet conditions, by increasing vision because the profiled marking provides a high retro-reflectivity and improved water shedding capabilities. As snowplowing can destroy these markings, it is primarily used in locations with warm weather (FHWA, 2018). There are two types of profiled markings—raised and inverted, as illustrated in Figure 1-4.

Figure 1-3. Examples of profiled thermoplastic rumble strips

Source: Intan Traffic Engineering, 2018

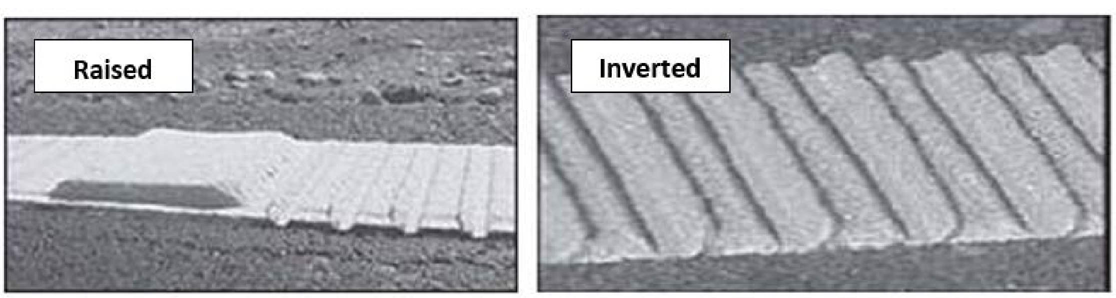


Figure 1-4. Types of profiled thermoplastic rumble strips

Source: FHWA

Cylindrical ground-in rumble strips are designed in such a way that they cause vehicle tires to engage with the grooves, exerting pressure on both the tire and the air within the groove. This interaction leads to the generation of noise and vibrations. (see Figure 1-5) (Kalathas, Parrish & Zhang, 2019).

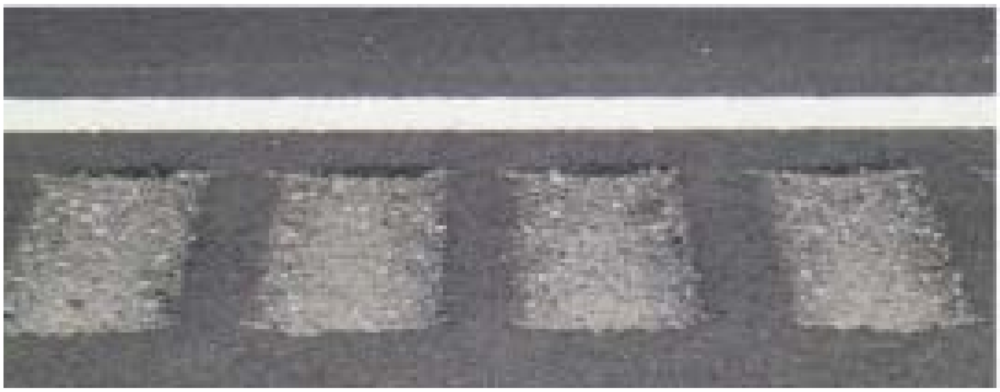


Figure 1-5. Example of cylindrical rumble strips

Source: Paris Kalathas et al., 2019

A sinusoidal rumble strip (see Figure 1-6) is a wave-shaped rumble strip designed to alert distracted or sleepy drivers by producing noise and vibration. These strips produce less external noise and are an alternative to cylindrical ground-in rumble strips. FDOT Standard Plan, Index 546-010, provides three configurations (Types A, B, and C) for ground-in rumble strips along edgelines. The selection of Type A, B, or C is as follows:

- Type A is used on the outside paved shoulder when the width is between 1 and 5 feet. This type should not be used for sinusoidal ground-in rumble strips, or when there are residents within a minimum of 650 feet of the proposed edgeline.
- Type B is used on the outside paved shoulder when the width is ≥ 5 feet, and on inside paved shoulder when the width is ≥ 1 foot.
- Type C is used on flush shoulder roadways with buffered striping.

Types B and C are recommended at noise-sensitive locations under the following conditions:

- Type B is on outside paved shoulder when width is ≥ 5 ft and on inside paved shoulder when width is ≥ 1 foot.
- Type C is on flush shoulder roadways with buffered striping.

Figure 1-6. Example of sinusoidal rumble strip

Source: Terhaar et al., 2016

Based on a review of studies in other states, sinusoidal ground-in rumble strips have proved to be more durable and cost-effective and provide lower external noise than other patterns. Patterns also vary by applicability, amplitude of the sine curve, grinding methods, and other factors. This project focuses on sinusoidal ground-in rumble strips, with the goal to compare and summarize the effectiveness of different sinusoidal rumble strip patterns in noise pollution control and crash reduction based on relevant studies conducted in other states and in Florida and provide recommendations on AVT design and installations for FDOT's future consideration.

1.2 Research Objectives

The overall goal of this proposed research project is to evaluate the effectiveness of AVT installations, defined in RDB 18-03 and the current FDM, on Florida arterials and collectors based on FDOT context-based design criteria in roadway departure crash prevention and injury severity mitigation, taking into consideration reducing noise pollution and accommodating bicyclists. With this goal, this project aimed to:

- Conduct a comprehensive literature review and interview selected transportation agencies on sinusoidal rumble strip pattern design, implementation, and evaluation of crash prevention and injury severity mitigation by considering noise pollution and accommodation of bicyclists.

- Select arterial and collector segments for study sites, collect relevant data, and conduct analysis to evaluate effectiveness of AVTs based on FDOT context-based design criteria.
- Collect additional data as needed to analyze the effectiveness of sinusoidal rumble strip patterns based on studies of other states.
- Document all research analysis and findings and provide recommendations on AVT design and installations for FDOT future consideration.

1.3 Organization of Report

The rest of this report is organized as follows: Section 2 presents the findings from the literature review and interview of selected transportation agencies on sinusoidal AVT design, implementation, noise, and safety evaluation, as well as the accommodation of bicyclists. Section 3 covers the research methodology of this project regarding study site selection, analytical approaches, and data collection. Section 4 discusses the results and findings on sinusoidal AVT effectiveness assessment regarding noise control and safety effectiveness in crash reduction, and the corresponding crash modification factors (CMF) that were developed with respect to roadway types. Section 5 concludes this research with the summary of research findings and recommendations.

2 Literature Review and Agency Interviews

This chapter summarizes the literature review and agency interviews. It covers findings from an online review of available documents on rumble strip noise, safety benefits, and bicyclist accommodation, with a focus on sinusoidal rumble strips in other states and in Florida. The agency interview process and results are also synthetized as part of this chapter. The goal of the interviews was to confirm the information gathered from the online review and to acquire any additional information or resources that may have been available.

2.1 Literature Review

This section elaborates on the findings from the literature review. Based on the prior research, rumble strip safety benefits and recommendations regarding accommodating bicyclists is presented. Included in the discussion are the types of sinusoidal rumble strip designs that have been implemented in different states, along with the comparisons, evaluations, and outcomes when compared to other types of strips.

2.1.1 Safety Benefits of Rumble Strips

Many states use rumble strips as a low-cost, proven safety countermeasure to decrease or prevent lane departure collisions by providing a vibratory and/or audible warning to distracted drivers. Shoulder and centerline rumble strips/stripes have been shown to reduce the number of single-vehicle run-off-road (SVROR) crashes, opposite direction sideswipe incidents, and head-on collisions (Ahmed et al., 2015). Rumble strips, including profiled thermoplastic, cylindrical, and sinusoidal, have been shown to reduce lane departure crashes by 10 percent to 93 percent on various types of highways, according to the 2010 Highway Safety Manual. The research team at the Center for Urban Transportation research (CUTR) at the University of South Florida (USF) could not identify any studies from the literature review that focused on the comparison of safety benefits among different sinusoidal rumble strip designs. Safety advantages of rumble strips, regardless of specific designs, have been analyzed by a few State transportation departments, and will be summarized next.

In 2004, the Washington State Department of Transportation (WSDOT) built approximately 100 miles of centerline rumble strips (CLRS) as an experimental countermeasure to decrease cross-centerline collisions. From 2004–2010, WSDOT added over 1,400 miles of CLRS to the state highway system (WSDOT, 2011). These installations were monitored, and CLRS were tested to see if they were effective in reducing cross centerline crashes. The results of the study showed reduced lane departure collisions on Washington State roadways after CLRS implementation.

The Minnesota Department of Transportation (MnDOT) demonstrated the positive influence of CLRS on roadway safety performance and stressed the importance of concentrating on target crashes during research efforts to get a more accurate assessment of the positive influence of CLRS. Some results include the following (MnDOT, 2006):

- 4% reduction in fatal and severe crashes per year in the “after” period (0.3 fewer per year)
- 12% increase in total crashes per year (7 more total crashes per year)

- 3% increase in crash rate in the "after" period
- 11% reduction in severity rate in the "after" period
- 12% increase in crash density in the "after" period
- 9% increase in Average Daily Traffic (ADT)

2.1.2 Accommodation of Bicyclists

Rumble strips must be designed and installed to suit all roadway users, according to the Federal Highway Administration (FHWA). Rumble strips have been recognized as having a particularly negative impact on cyclists. Often, cyclists are forced to ride in travel lanes in circumstances where rumble strips are built on the shoulder without proper room for cyclists (Ahmed et al., 2015). This condition exposes bicyclists to vehicle traffic threats that may result in crashes leading to severe injuries or fatalities.

Rumble strips should be selected to make it easier for bicyclists to ride on the shoulders. Bicyclists should have at least 4 ft (1.2 m) of space between the rumble strips and the edge of the pavement, with more (5 ft) space if safety barriers are present (Advocacy, 2010; Ahmed et al., 2015). In a survey of bicyclists riding on roadways with shoulder rumble strips, one-third of respondents said that 4 ft of clear shoulder width is enough to ride comfortably. Additionally, to allow cyclists to exit and enter, a gap of 12 ft (3.7 m) of standard pavement is proposed for every 60 ft (18.3 m) of rumble strip (Bucko, 2001; Ahmed et al., 2015). Figure 2-1 shows recommendations from a survey of bicyclists about appropriate rumble strip gaps. Many bicyclists stated that gaps that are placed more thoughtfully will help them ride more comfortably. Table 2-1 summarizes the proposed dimensions for sinusoidal rumble strips for maximizing bicyclist safety and minimizing noise.

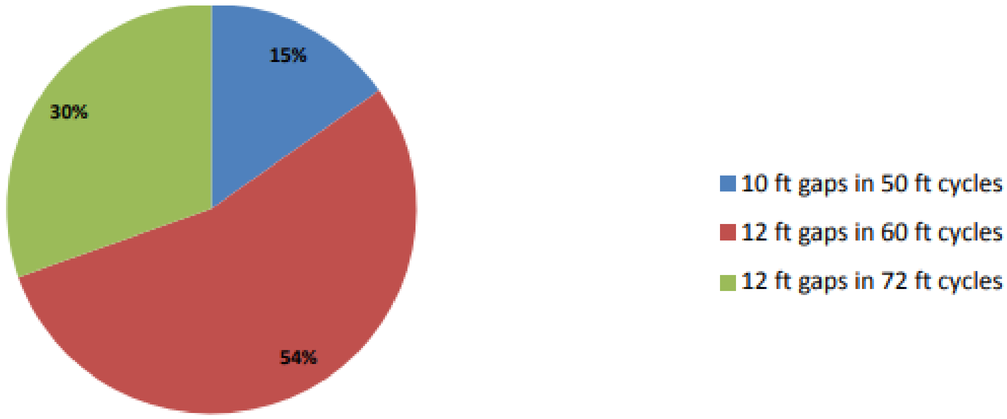


Figure 2-1. Recommended bicyclist gaps

Source: Ahmed et al., 2015

Table 2-1. Suggested Sinusoidal Rumble Strip Parameters to Maximize Bicyclist Safety and Minimize Noise

Wavelength (in.)	Peak-to-Peak Depth (in.)	Length (in.)	Offset		Gap (ft)
			Outward from Edge Lane (in.)	*Inward from Edge of Pavement (ft)*	
Road speed/37*	0.16, 0.28**	≤ 8	12	4	12-ft regular pavement for every 60 ft

*Note that it has been suggested that 14 inches may be ideal regardless of speed; results are needed to validate the suggestion.
**Both providing low-noise outcomes

Source: Cybulski et al., 2011

Shoulder rumble strips are not recommended on routes designated as bicycle paths or in high bicycle-use zones. When constructing rumble strips in residential areas, many states consider bicyclists by either not installing rumble strips within city limits or, if necessary, evaluating collision data and adopting modified shallower depth rumble strips. According to a national survey conducted by Wyoming DOT, the most favorable option for accommodating bicyclists, selected by 47 percent of respondents, was to increase the clear shoulder width, followed by placing Shoulder Rumble Strips (SRS) close to traffic lane, and sweeping the shoulder more frequently, as shown in Figure 2-2 (Ahmed et al., 2015).

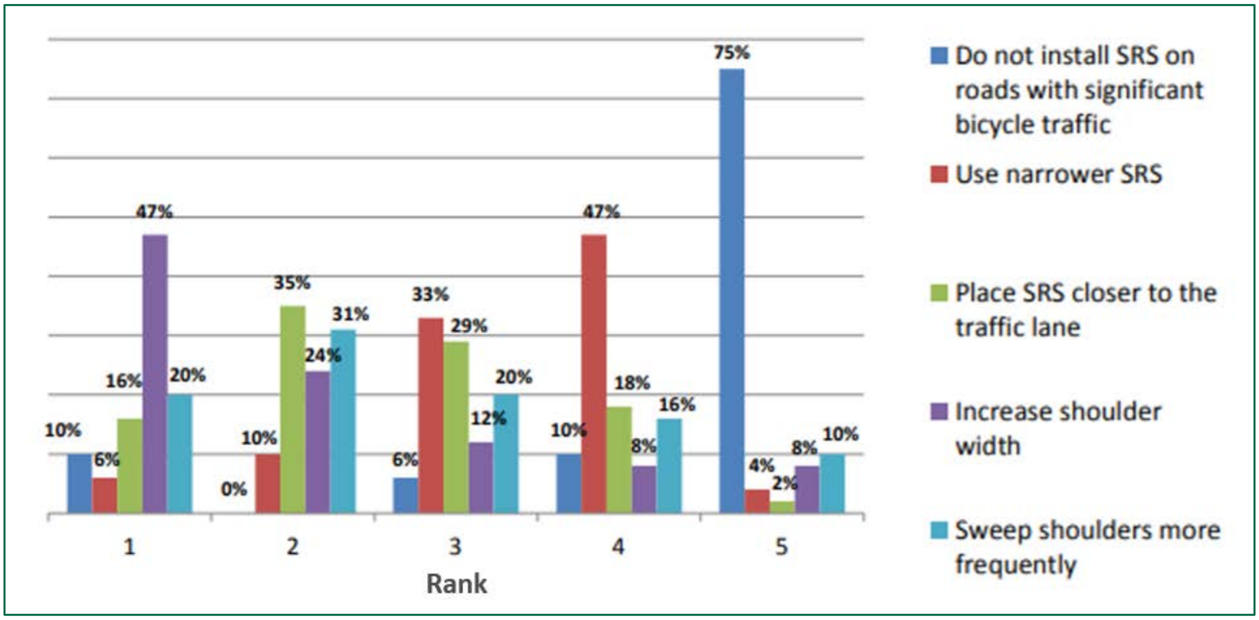


Figure 2-2. Recommendations for accommodating bicyclists

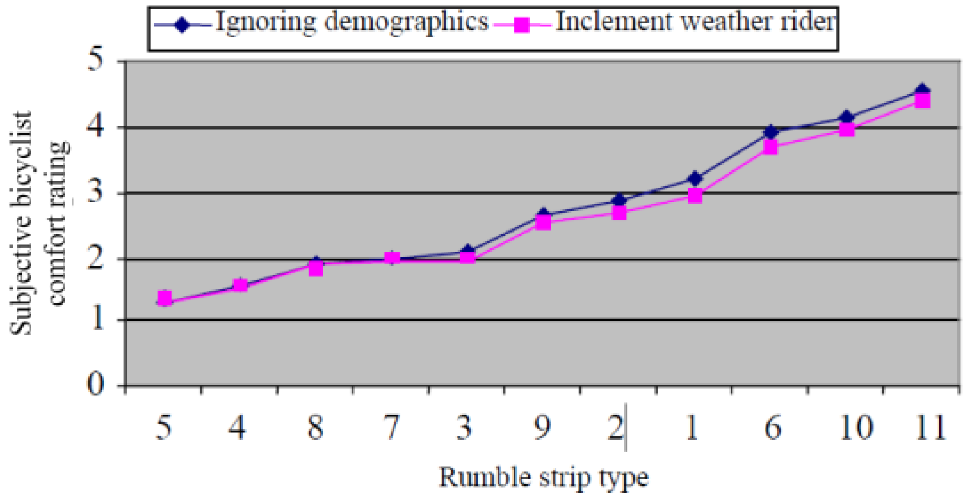
Source: Ahmed et al., 2015

Another study in California tested the effectiveness of the following types of rumble strips as well as accommodating to bicyclists (Himes, Scott et al.,2017):

1. Rolled rumble strips with 24-in length, 2-in. width, 1-in. depth, and 7.9-in. center to-center spacing.
2. Milled rumble strips with 16-in. length, 4.8-in. width, 0.2-in. depth, and 12-in. center-to-center spacing
3. Milled rumble strips with 16-in. length, 5.9-in. width, 0.4-in. depth, and 12-in. center-to-center spacing
4. Milled rumble strips with 16-in. length, 6.9-in. width, 0.5-in. depth, and 12-in. center-to-center spacing
5. Milled rumble strips with 16-in. length, 7.6-in. width, 0.6-in. depth, and 12-in. center-to-center spacing
6. Chip seal application
7. Raised pavement marker single run on 12-in. centers
8. Raised pavement marker skewed double run on 12-in. centers; a second run was placed 6 in. to the right of the first and skewed 6 in. for two skewed runs of pavement markers
9. Rumble strip bars placed 2 ft on center and 2 ft wide
10. Raised and inverted thermoplastic stripe
11. Raised thermoplastic stripe

A total of 55 bicyclists with varying degrees of expertise, ranging in age from 26–60+, participated in field testing. Participants used provided bicycles or their own bicycle and rode over 11 different types of rumble strips at various speeds and angles, both in groups and individually (Himes et al., 2017). At the end, they were asked to rate the amount of comfort and control on a scale of 1–5, with 1 indicating the least pleasant and 5 indicating the most comfortable.

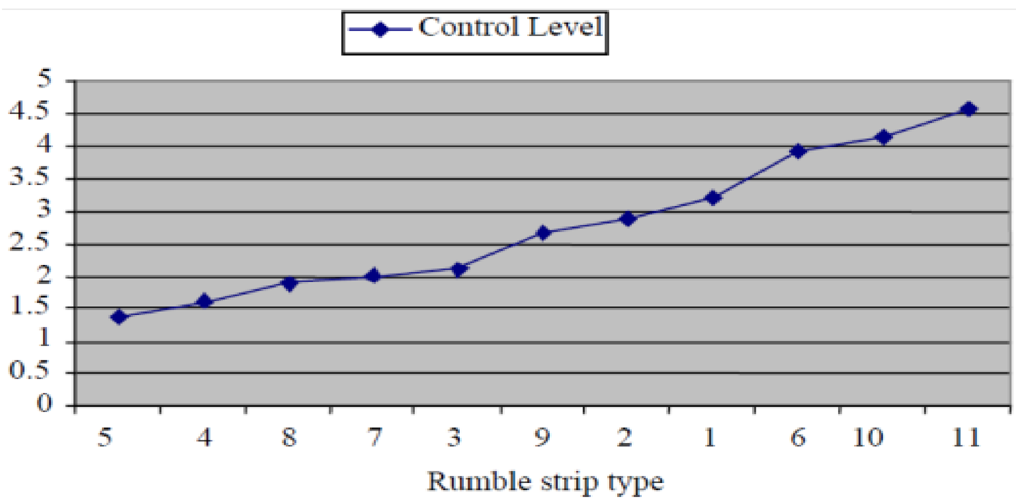
As shown in Figure 2-3 and Figure 2-4, the results showed that Strips 6, 10, and 11 gave a higher level of comfort and control than strip 1 (baseline) when specific demographic groups are not considered and for inclement weather riders. Bicyclists found Strips 1, 2, and 9 to be about the same in terms of comfort and control, and rumble strips Type 3 offered almost 70 percent of the degree of comfort recorded for strip 1. When considering vehicles, rumble strips Type 2, 6, 10, and 11 produced higher levels of noise and vibration than Strip 1 (baseline) (Himes et al., 2017). Ultimately, the Type 3 rumble strips were selected to make a balance between the effectiveness and costs of installation and maintenance. Type 3 was also chosen because it produced superior levels of noise and vibration for vehicles while providing sufficient comfort for bicyclists.



©California Department of Transportation.
Note: 5 indicates most comfortable and 1 indicates least comfortable.

Figure 2-3. Bicyclist comfort rating

Source: Himes et al., 2017



©California Department of Transportation.
Note: 5 indicates most comfortable and 1 indicates least comfortable.

Figure 2-4. Bicyclist control rating

Source: Himes et al., 201

2.1.3 Sinusoidal Rumble Strip Pattern Designs

Design specifications and implementation requirements of sinusoidal rumble strip patterns involve several aspects, including types of waveforms, amplitude of sine curve, dimensions of striping pattern, and applicability of striping based on right-of-way type. The various types of waveforms are illustrated in Figure 2-5. Additional details on the specifications in Florida and in other states are summarized in the next sub-sections.

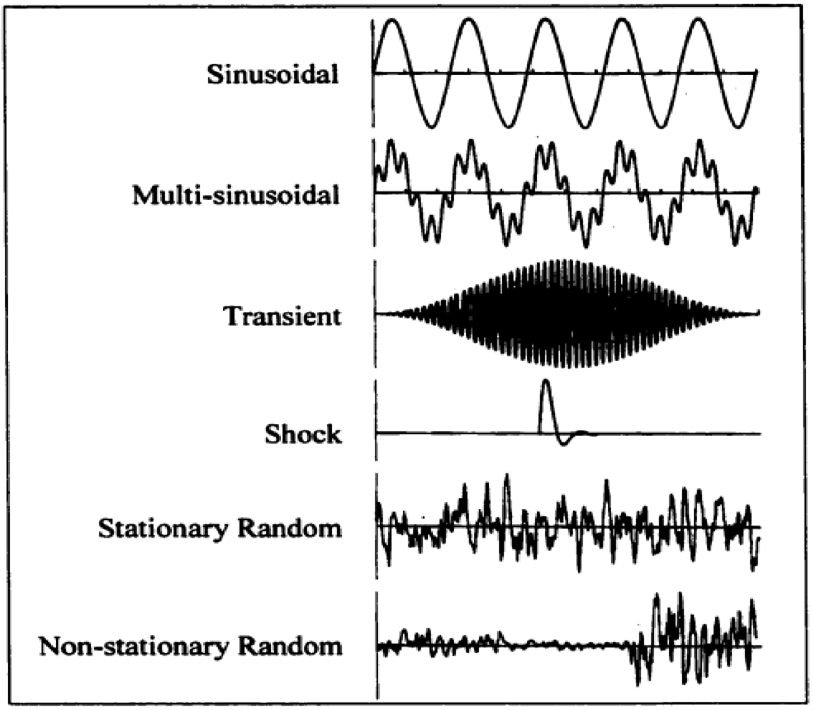


Figure 2-5. Waveforms

Source: Griffin, 1990; Torbic, 2001

2.1.3.1 Florida Design Specifications

In 2019, FDOT announced modifications to the audible and vibratory highway characteristics used on arterial and collector roadways. The typical sinusoidal rumble strip design in Florida has a 14-in. wavelength, an 8-in. width, and a maximum depth of 5/16 in. and is flat with the pavement surface at its highest. This design is different from many other states. In most states, the top of the wave is dipped 1/16 in. below the pavement level, allowing the full stripe painted on the rumble to be protected below the concrete surface to protect the pavement from future snow clearance or other activities, which is not required in Florida (Staats et al., 2020).

To address noise pollution, FDOT designed three types of sinusoidal rumble strips. Details related to those designs are shown in Figure 2-6.

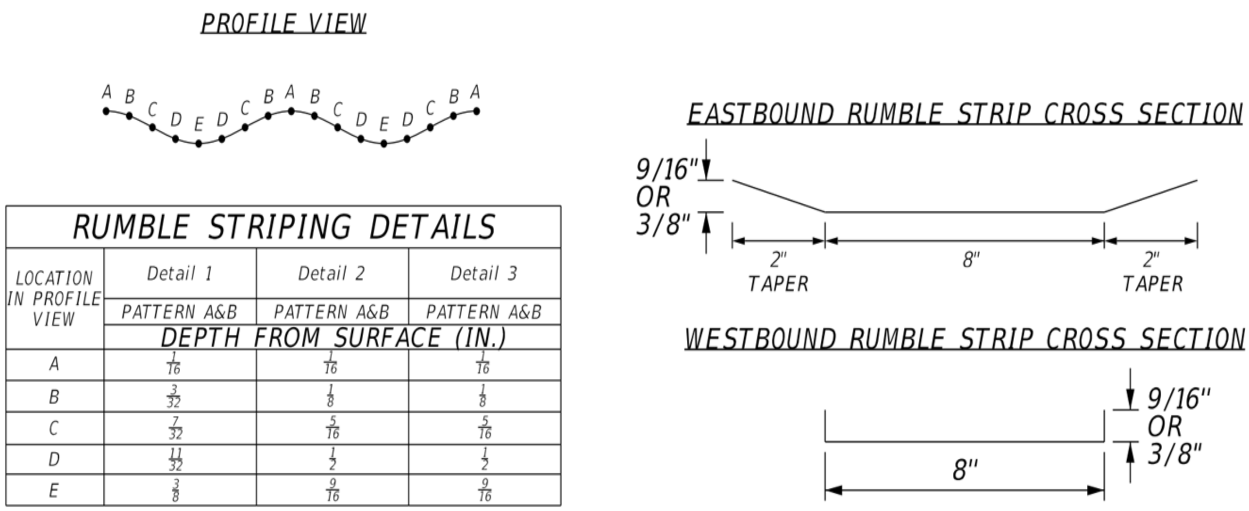


Figure 2-6. Details of three types of FDOT sinusoidal rumble strips

Source: FDOT, n.d.

2.1.3.2 Design Specification in Other States

A summary of sinusoidal rumble strip design specifications in other states is shown in Table 2-2. A summary of findings from studies evaluating the proper dimensions of rumbles strips is discussed below.

Table 2-2. Summary of Sinusoidal Rumble Strip Designs by State

State	Wavelength (in.)	Max. Depth (in.)	Min. Depth (in.)	Width (in.)
MN	14	½	1/16	8–12
IN	12	½	1/8	>= 8
WA	16	½	Not specified	12
CA	14	5/16	Not specified	8
OR	16	3/8	1/16	14

Source: Staats et al., 2020

Wavelength and Depth

Shorter wavelengths significantly increase exterior noise, whereas longer wavelengths do not provide enough noise and vibration to alert drivers (Watt, 2001). Researchers concluded that using a waveform with a frequency of 37 Hz (frequency = speed/wavelength) produces the best warning effect (Cybulski et al., 2011). As a result, the optimal wavelength is influenced by vehicle speed and should be computed using the following formula: Wavelength = Road speed/37. Another study suggested that 14 in. (0.36m) wavelength is excellent for vehicle speeds of 40–60 mph and may be the best regardless of speed (Donavan, 2009). Peak-to-peak depths of 0.28 and 0.16 in. (4 mm and 7 mm) have been studied, with low exterior noise results in both cases (Kragh, 2007; Watts, 2001).

Length

Longer rumble strips, about 12 in. (30.5 cm) and longer, make more noise than shorter rumble strips, around 8 in. (20.3 cm) or shorter (Russell, 2006). However, whether an 8-in. (20.3-cm) length effectively shakes a vehicle for the sinusoidal design may depend on tire width in relation to rumble strip length.

2.1.4 Sinusoidal Rumble Strip Implementations in Other States Focused on Noise Pollution Control

Some states have a longer history of applying sinusoidal rumble strips on their roadways than Florida. This section covers the implementation of sinusoidal rumble strips from transportation agencies in other states, most of which implemented the sinusoidal rumble strip design to reduce noise pollution. This information can serve FDOT in its decision-making related to appropriate sinusoidal rumble strips.

2.1.4.1 California

A researcher in California, sponsored by the California Department of Transportation (CALTRANS), published a study in 2018 that compared steering column vibration, outside noise, and interior noise produced by driving over sinusoidal mumble strips, elevated pavement markings, and conventional milled rumble strips (Donavan, 2018; Staats et al., 2020). The research was initiated due to complaints from citizens about the noise levels from rumble strips. The research team designed the sinusoidal rumble strips using computer-based models to ensure that when driving over the strips using standard vehicles, the inside noise and vibration are optimized, and the exterior noise is kept to a minimum. The final and proposed model is a sinusoidal rumble strip design of 14-in. spacing and a 5/16-in. depth (see Figure 2-7), called a mumble strip.

Figure 2-7. Mumble strips installed on US-101 (California)

Source: Donavan, 2018

The final sinusoidal mumble strip model was implemented and tested in the field. Five vehicles, including a Chevy Malibu, a Honda Civic, a Ford Expedition, a Ford Fusion, and an international 4-yd dump truck (Figure 2-8), were used as test vehicles and were driven at 60 mph to assess interior noise, external noise, and steering column vibration. When compared to a conventional rumble strip design, the sinusoidal mumble strips lowered the frequency of external noises by 6 dBA, on average, for passenger vehicles and 3 dBA for the dump truck (Donavan, 2018; Staats, et al., 2020) (Figure 2-9).

Figure 2-8. Test vehicles

Source: Donavan, 2018

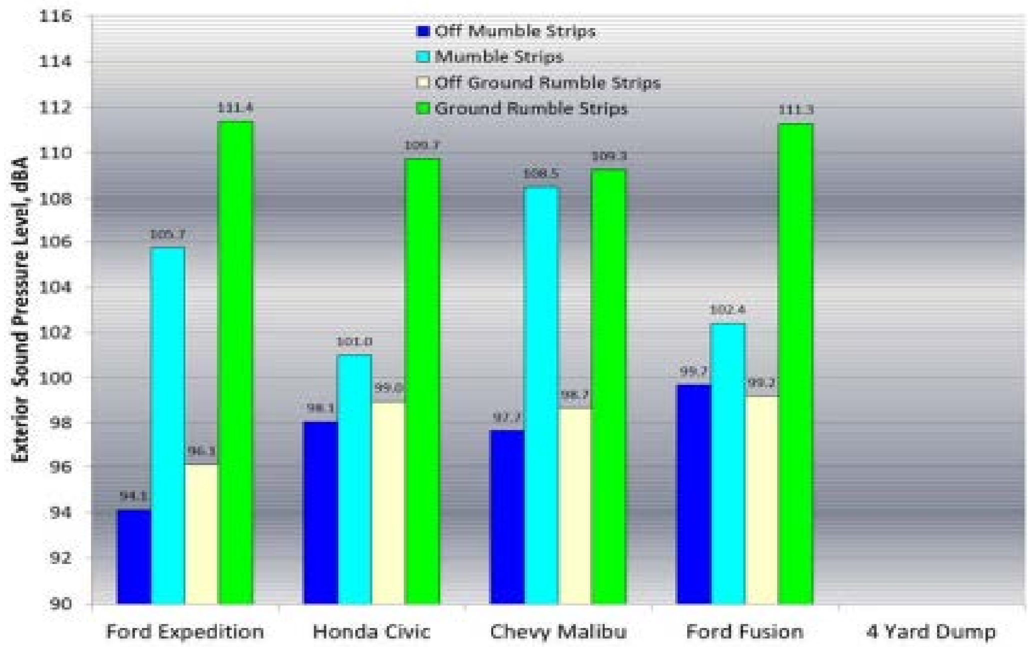


Figure 2-9. Exterior sound pressure levels for four test vehicles on mumble and ground rumble strips

Source: Donavan, 2018

Interior noise levels in passenger vehicles traveling on the mumble (sinusoidal rumble) and ground (conventional) rumble strips were 14.4 dB and 13.9 dBA greater than the noise in vehicles traveling off the strips, respectively (Donavan, 2018; Staats, et al., 2020) (Figure 2-10). For the dump truck, the interior noise differences between on and off strips were only 2.6 dBA for sinusoidal mumble and 7.6 dBA with the conventional rumble strips. The conventional rumble strips and the round raised pavement markers produced similar noise levels. The research team concluded that the sinusoidal mumble strip design had sufficient interior noise and vibration to alert drivers when they leave the travel way and can also reduce the exterior noise (Donavan, 2018).

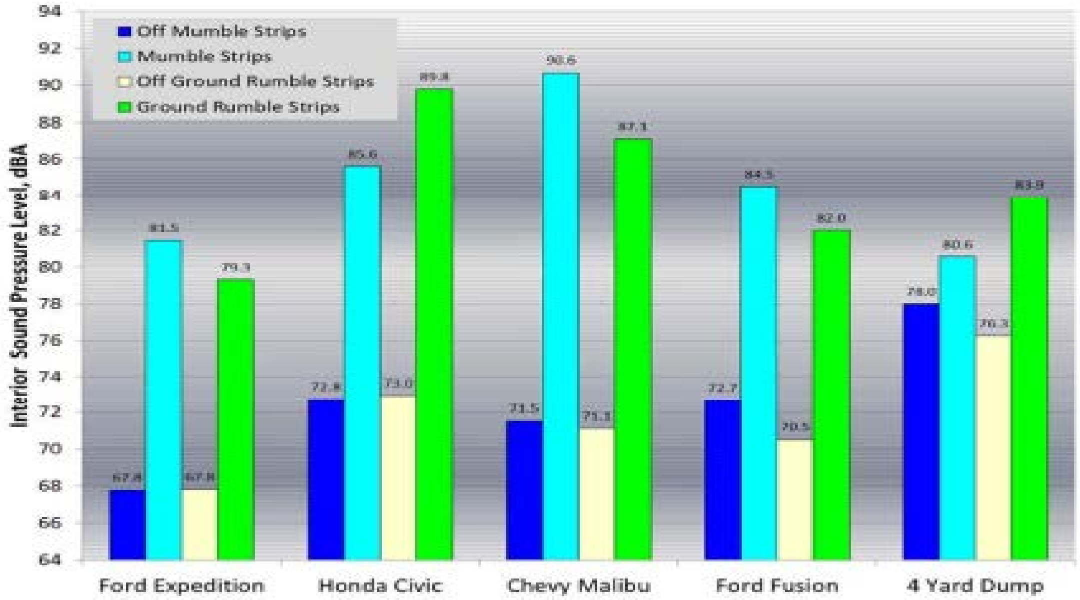


Figure 2-10. Interior sound pressure levels for five test vehicles on mumble and ground rumble strips

Source: Donavan, 2018

2.1.4.2 Washington

The Washington State Department of Transportation (WSDOT) evaluated new rumble strip designs to minimize roadside noise and increase safety (Laughlin et al., 2018). This study was also initiated because of several complaints from residents about noise from rumble strips along major roadways in Washington. Four alternative designs were analyzed by WSDOT, including a sinusoidal rumble strip design and three other milled cylinder rumble strips (Staats et al., 2020). The dimensions of the rumble strips for each design are given in Table 2-3.

Table 2-3. WSDOT Design Dimensions and Comparison of Interior Noise Levels with Exterior Noise Levels

Design Type	Design Dimensions (in.)				Avg. Interior Sound Level Increase Above Background			Avg. Exterior Measured Values	
	Depth	*Width*	*Length*	*Spacing*	*Lmax (dBA)*	*Descriptor*	*Rank Order*	*Lmax (dBA)*	*Rank Order*
Sinusoidal	0.5	12	16	-	8	Target level	2	82	1
Design 1	0.25	6.9	8	18	7	Target level	1	89	3
Design 2	0.25	6.9	12	12	13	Loud	4	88	2
Design 3	0.25	6.9	12	18	8	Target level	2	93	4

Source: Laughlin et al., 2018

All four design types were tested using a mid-sized SUV moving at a speed of 60 mph. Exterior sound levels were recorded at 25 ft and 50 ft from the center of the travel lanes. Interior sound levels were measured from the passenger seat at ear level (Staats et al., 2020). The results suggested that the sinusoidal rumble strip design had the lowest sound levels outside the vehicle followed by Design 1 and Design 2. Based on the requirements set in National Cooperative Highway Research Program (NCHRP) 641, all four designs produced sufficient interior noise. In general, the sinusoidal design and Design 1 were the leading designs they produced the lowest overall sound levels, as illustrated in Figure 2-11 and Figure 2-12 (Laughlin et al., 2018).

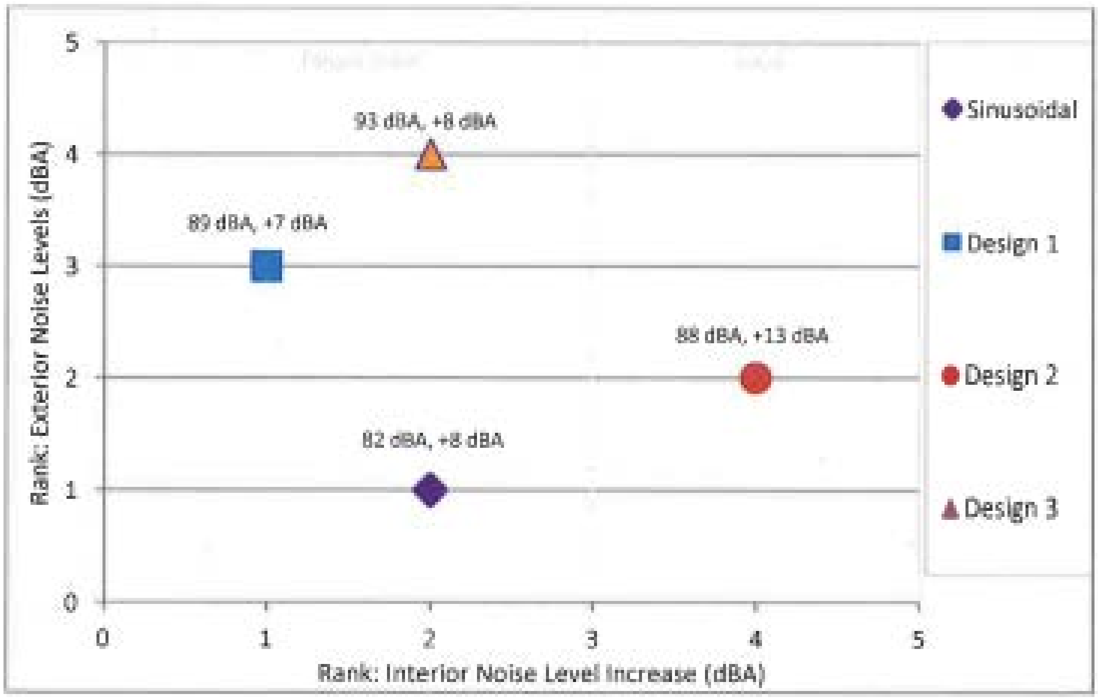


Figure 2-11. Comparison of rank order for interior and exterior noise levels

Source: Laughlin et al., 2018

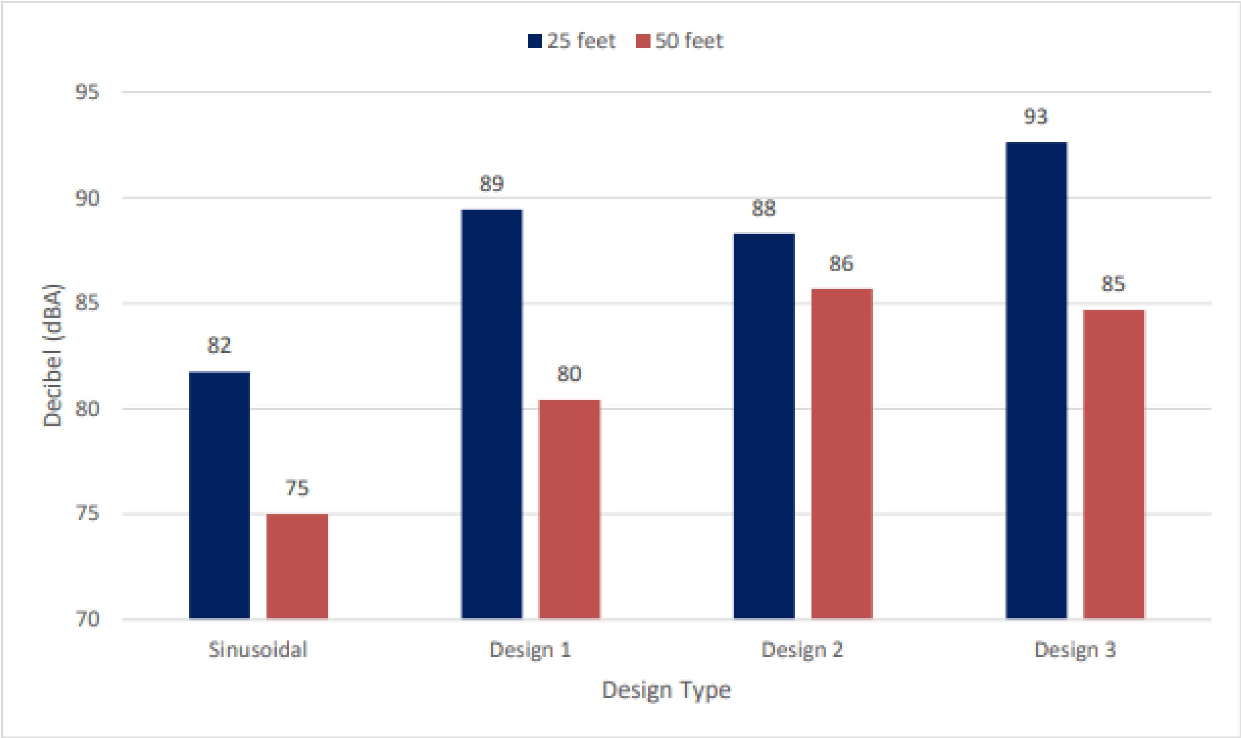


Figure 2-12. Average maximum sound levels for single vehicle at 25 ft and 50 ft (Lmax)

Source: Laughlin et al., 2018

2.1.4.3 Minnesota

The Minnesota Department of Transportation (MnDOT) funded a research study in 2016 to address noise issues and increased concerns expressed by Minnesota residents about the excessive noise produced from conventional rumble strips. The agency worked with other researchers to evaluate conventional rumble strips to replace them with sinusoidal rumble strips (Staats et al., 2020), which were selected because they were proven to maintain a reduced noise level outside the vehicle and necessary noise needed inside the vehicle to alert the driver.

The research team installed and evaluated four sinusoidal rumble strip designs on TH-18, a two-lane rural roadway in east central Minnesota. Details on each design are given in Table 2-4. To measure the outside and inside noise, the team kept a noise meter at 50 ft and 75 ft away from the roadway and placed a noise meter inside each test vehicle. Three vehicles were used to assess the noise level—a passenger car (Ford Fusion), a small truck (Ford F-150), and a dump truck (Sterling Class 35). The noise meters were used to obtain the sound levels in decibels (dBA). The four rumble strip designs performed differently in the study for all three vehicle categories. The authors recommended Design 3 when compared to the other designs (Terhaar et al., 2016) (see Figure 2-13 to Figure 2-15, and Table 2-5).

Table 2-4. Minnesota Rumble Strip Test Designs

Design 1	Design 2
Sinusoidal with straight edge	Sinusoidal with straight edge
14-in. center-to-center wavelength	14-in. center-to-center wavelength
14 in. wide	Two 8-in.-wide rumble strips separated by 4 in.
1/15–3/8 in. depth	1/16-1/2 in. depth
Design 3	**Design 4**
Sinusoidal with straight edge	Sinusoidal with straight edge
14-in. center-to-center wavelength	14-in. center to center wavelength
14-in. wide	Two 8-in.-wide rumble strips separated by 4 in.
1/16–1/2 in. depth	1/16–3/8 in. depth

Source: Terhaar et al., 2016

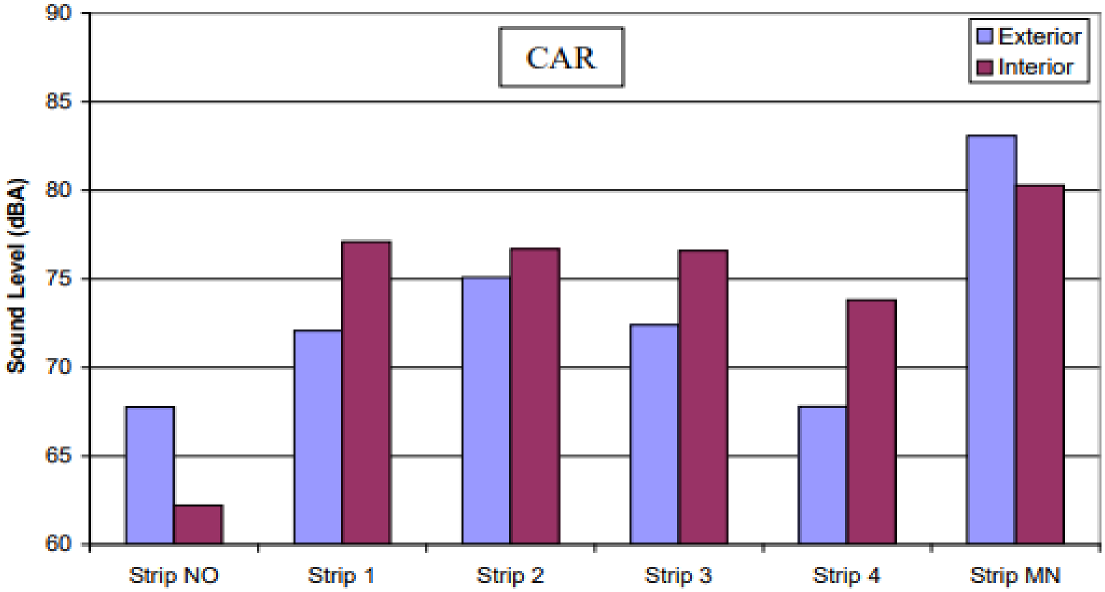


Figure 2-13. Exterior and interior sound levels with car

Source: Terhaar et al., 2016

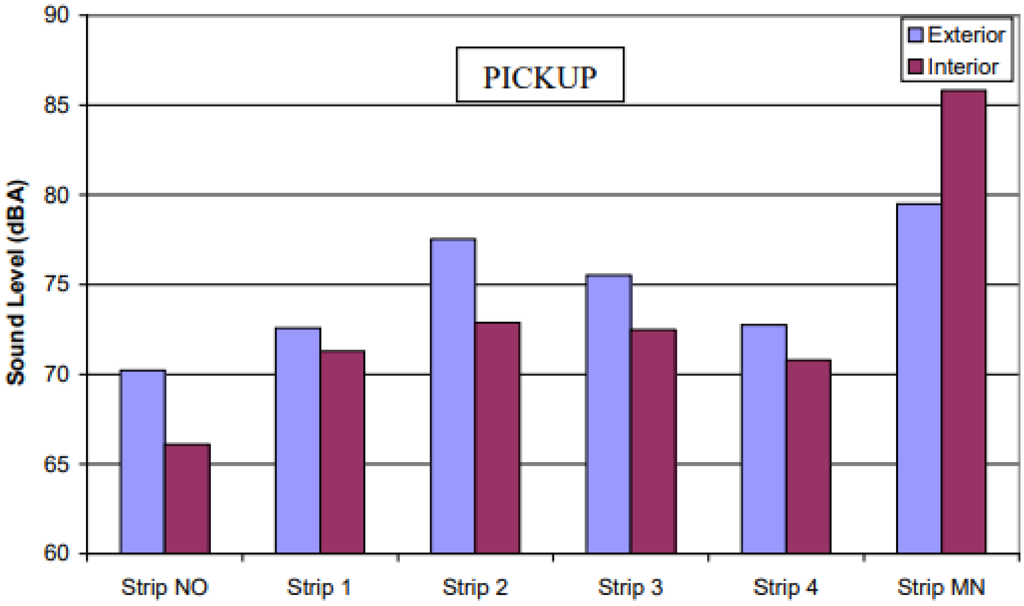


Figure 2-14. Exterior and interior sound levels with pickup truck

Source: Terhaar et al., 2016

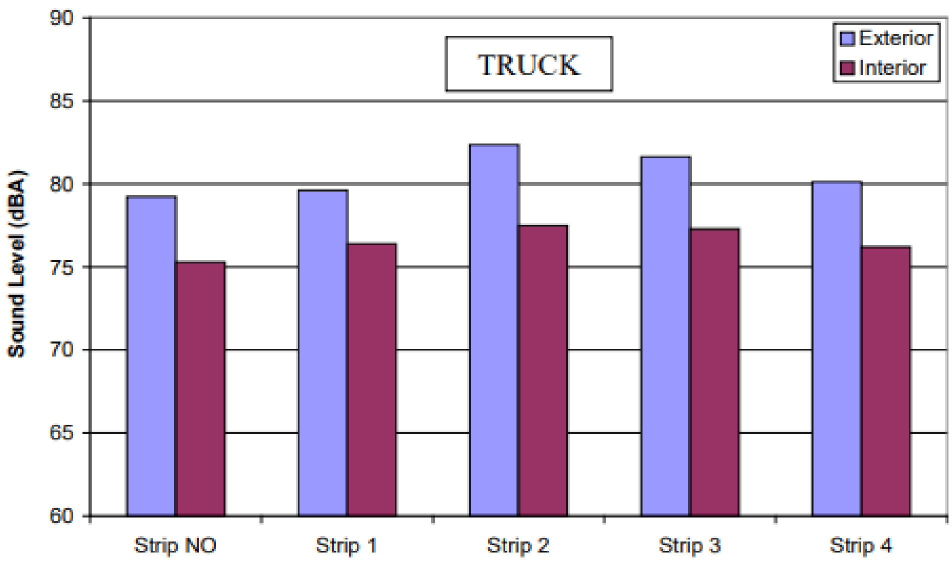


Figure 2-15. Exterior and interior sound levels with dump truck

Source: Terhaar et al., 2016

Table 2-5. Minnesota DOT, Over No-strip for Rumble Strip Designs

	Increase (dBA) over No-Strip		
Rumble Strip	**Exterior at 50 ft.**	**Exterior at 75 ft.**	**Interior**
Car			
Strip 1	4.5	3.3	14.9
Strip 2	6.4	8.6	15.2
Strip 3	5.9	5.2	14.7
Strip 4	2.3	2.4	12.5
Minnesota Design[1]	18.5	na	16.7
Pickup			
Strip 1	3.0	2.2	5.7
Strip 2	5.8	6.8	5.9
Strip 3	5.8	6.1	6.8
Strip 4	2.9	2.1	4.5
Minnesota Design[1]	13.7	na	8.4
Truck			
Strip 1	-0.4	-1.1	0.8
Strip 2	3.0	2.8	2.7
Strip 3	2.5	2.3	1.4
Strip 4	1.8	0.1	1.2

Source: Terhaar et al., 2016

2.1.4.4 Indiana

The Indiana Department of Transportation (INDOT) and Purdue University evaluated different sinusoidal rumble strip designs on Indiana's highway network, including sinusoidal rumble strips with 12-, 18-, and 24-in. wavelengths, and compared the interior and exterior noise produced from these rumble strips to Indiana’s conventional rumble strip design. Traditional rumble strips started at the pavement surface and were milled to a depth of 1/2 in., whereas the other three designs were recessed into the pavement to a depth ranging from 1/2 in. at the bottom of the rumble to 1/8 in. at the top (Mathew et al., 2018). Figure 2-16 shows the comparison of the four rumble strip designs, and Figure 2-17 shows examples of traditional and sinusoidal rumble strips.

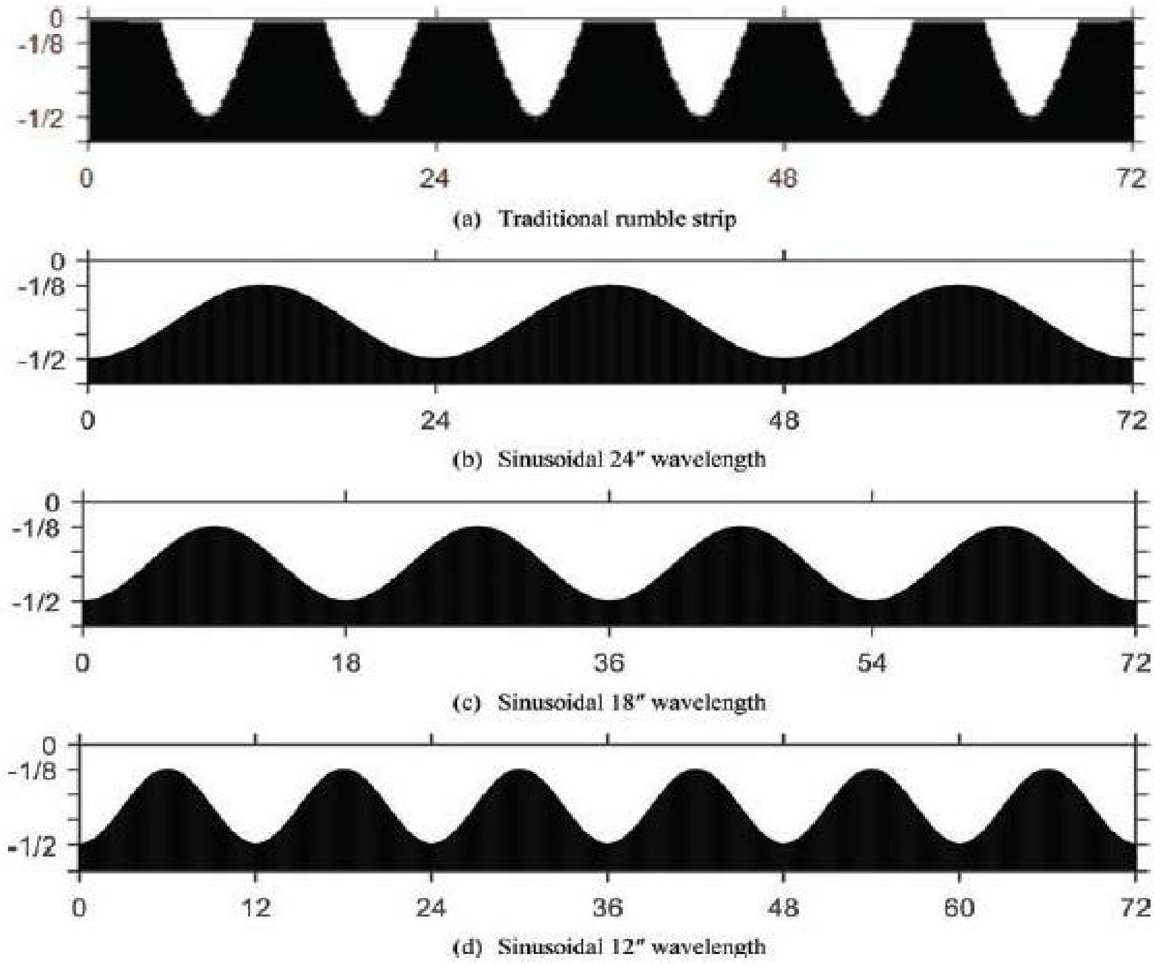


Figure 2-16. Profile of alternative rumble strip configurations (not to scale)

Source: Mathew et al., 2018

Figure 2-17. Traditional and sinusoidal rumble strip

Source: Mathew et al., 2018

Six vehicles (Figure 2-18), ranging from a car to a semi-truck, drove over the four rumble strip designs at a fixed speed of 50 mph, and interior sound levels were measured in the cabin and exterior sound levels were measured 50 ft from the edgeline. The three sinusoidal rumble strip designs produced 5-11 dBA less exterior noise and 9 dBA higher noise inside the vehicle when compared with the conventional rumble strip (Mathew et al., 2018; Staats et al., 2020).

Figure 2-18. Test vehicles: (a) tandem axle, (b) single axle, (c) semi-trailer, (d) Chevrolet Suburban, (e) Chevrolet Impala, and (f) Ford E-150 minivan

Source: Mathew et al., 2018

The study concluded that the sinusoidal rumble strip produced greater than the minimum threshold required by INDOT specifications (Figure 2-19) (Mathew et al., 2018). Based on the results, the research team recommended the 12-in. wavelength sinusoidal rumble strip design, as it consistently delivered the appropriate sound levels for all vehicle types, as described in NCHRP 641 (Staats et al., 2020). That recommendation was adopted by INDOT, which became effective after March 1, 2019.

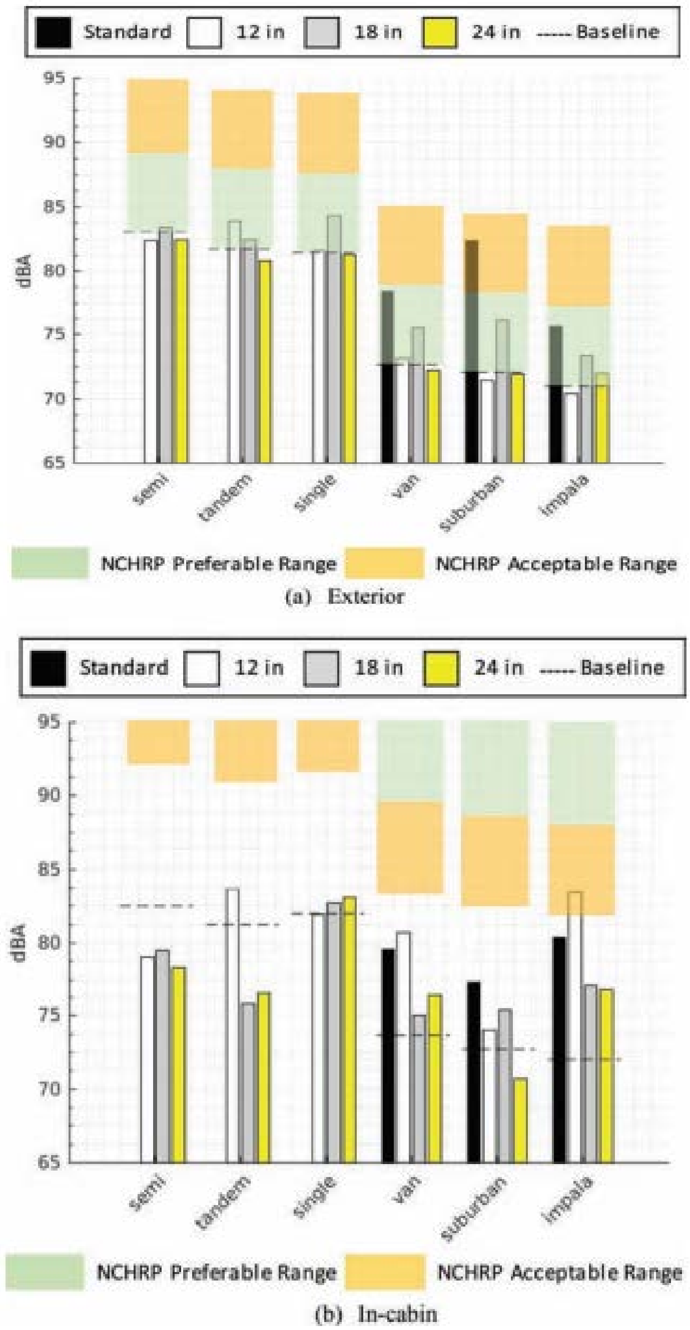


Figure 2-19. Sound level comparison for all vehicles on center line rumble at 50 mph

Source: Mathew et al., 2018

2.1.4.5 Oregon

The Oregon Department of Transportation (ODOT) assessed the feasibility of replacing rounded milled rumble strips with sinusoidal rumble strips on Oregon roadways. Three vehicle classes (passenger car, van, and dual-tire heavy vehicle) were driven at 55 mph to test the interior noise, exterior noise, and interior vibrations produced by two rumble strip designs (Hurwitz et al., 2019; Kalathas et al., 2019). The sinusoidal rumble strips considered were 14-in. wide with a 16-in. wavelength, a peak depth of 1/16 in., and a maximum depth of 3/8 in.; the milled rumble strips were 9.5-in. wide, 8-in. long, 7/16-in. deep, and 12-in. spaced.

The results of the test confirmed that rounded rumble strips produced an exterior noise of 5 dBA higher than the baseline condition (no strips) for both the passenger car and the van, whereas the sinusoidal rumble strips generated 3 dBA higher than the no-strips condition for the car and no noticeable difference compared to no strips for the van (Table 2-6). The rounded rumble strips generated interior noise levels of 10 dBA and 12 dBA higher than the baseline for both the passenger car and the van, respectively, (Kalathas et al., 2019), and the sinusoidal rumble strips produced interior noise levels that were 4.6–5.8 dBA greater than the baseline (no-strips) (Table 2-6). NCHRP recommends a 6–12 dBA increase in noise threshold for alerting drivers that they are leaving the roadway (NCHRP, 2009), but the Oregon sinusoidal rumble strip design failed that requirement. However, according to FHWA, as little as 3 dBA increase and ideally 5 dBA increase in internal noise threshold would be enough to alert drivers (Hurwitz et al., 2019; Staats et al., 2020).

The dual tire heavy vehicle failed to make noticeable interior or external noise on the conventional rumble strips because those strips have narrower widths (9.5 in.), which cause the dual tire heavy vehicle to bridge over them. On the wider (14 in.) sinusoidal rumble strips the dual tire heavy vehicle yielded perceivable noise differences of 5.7 dBA more of outside noise and 6.8 dBA more of interior noise than the no strips baseline conditions (Hurwitz et al., 2019; Staats et al., 2020).

Table 2-6. Average dBA Magnitudes for Different Rumble Strip Designs by Vehicle Type

VEHICLE TYPE	RS TYPE	CONDITION	EXTERIOR Avg dBA	INTERIOR Avg dBA
Passenger Car	Sinusoidal	Baseline	84.6	99.0
		Strike	87.1	104.8
	Rounded	Baseline	83.9	100.4
		Strike	90.3	111.8
Van	Sinusoidal	Baseline	85.9	96.9
		Strike	86.0	101.2
	Rounded	Baseline	89.4	96.9
		Strike	94.2	107.0
Heavy Vehicle	Sinusoidal	Baseline	88.5	101.1
		Strike	94.5	108.1
	Rounded	Baseline	91.6	103.1
		Strike	95.0	104.0

Source: Hurwitz et al., 2019

To investigate the process of installing sinusoidal rumble strips compared to conventional milled rumble strips, a separate part of the study involved a survey sent to contractors. Based on the results, the process of installing sinusoidal rumble strips takes longer than conventional rumble strips because sinusoidal design requires continuous cutting (Kalathas et al.,2019). Contractors also mentioned that it was easier to install sinusoidal rumble strips on asphalt pavement compared to concrete pavement, but sinusoidal rumble strips can still be used on concrete pavement. According to some contractors, the tapered edges of sinusoidal rumble strips can prevent water ponding and increase the mobility of bicyclists (Staats et al., 2020). Finally, the contractors recommended sinusoidal rumble strips that have widths of more than 8 in. to ensure their effectiveness with a variety of tire widths.

2.2 Interviews with Selected Transportation Agencies

Based on the literature review results in Section 5, the research team conducted interviews with selected transportation agencies on their experience in sinusoidal AVT design and implementation to ascertain information that could benefit the sinusoidal AVT implementation in Florida. The interview questionnaire was designed to collect more details on the following aspects:

- Sinusoidal AVT Designs and Implementations (design specifications, design variations and state guidelines, installation and maintenance experience and cost)
- Noise Evaluation Experience and Results
- Safety Evaluation Experience and Results
- Consideration of Bicycle Accommodation in Sinusoidal AVT Implementation

Additional documents with the above information, such as evaluation results reports or white papers, design guidelines, standard design plans or profile drawings, etc., if available, were also collected from the agencies being interviewed. Those documents were reviewed, and important information was integrated in this section. The detailed interview questionnaire is attached in Appendix A. Agencies from five different states, including California, Indiana, Kentucky, Minnesota, and Washington, were interviewed and their responses were summarized below.

2.2.1 California

The expert of Noise Vibration and Hydroacoustics at California Department of Transportation (Caltrans) participated in the interview and provided responses to the questionnaire, which are summarized below.

2.2.1.1 Sinusoidal AVT Designs and Implementations

California has been conducting research on noise since the 1950's and has developed their own noise model. California is among the pioneers of sinusoidal AVT because noise has been a major cause of community dissatisfaction. The sinusoidal rumble strip design adopted in California was 14-inch spacing and a 5/16 in-depth. The state designed their sinusoidal rumble strips to provide an increased inside noise level, while reducing the outside noise level. The sinusoidal rumble strip was implemented because of the complaints they got from the public due to a higher outside noise level caused by cars. There are no weather-related guidelines for sinusoidal rumble strips, such as guidelines related to poor visibility, snow removal, excess rain, and hydroplaning. There is currently no maintenance process for the sinusoidal rumble strips because it is brand new.

2.2.1.2 Sinusoidal AVT Noise Evaluation

The implemented sinusoidal rumble strips in California were able to reduce the exterior noise while still providing enough interior noise to alert the driver. The state has considered just a unique sinusoidal rumble strips design.

2.2.1.3 Sinusoidal AVT Safety Evaluation

California has not conducted any before-after safety evaluations on sinusoidal rumble strips regarding roadway departure crashes, injury, and fatality reduction. There were not any other safety evaluations of sinusoidal rumble strips in the state.

2.2.1.4 Sinusoidal AVT Bicyclists Accommodation

The interviewee did not know details about bicyclist considerations for shoulder sinusoidal rumble strip installation.

2.2.2 Indiana

Two transportation professionals from the Indiana Department of Transportation (INDOT), including Senior Traffic Engineer of Signals and Markings, and District Traffic Engineer of INDOT Fort Wayne District, participated in the interview. Their responses to the questionnaire are summarized below.

2.2.2.1 Sinusoidal AVT Designs and Implementations

The sinusoidal AVT design in Indiana was based on a Joint Transportation Research Program (JTRP) research project report “Assessment of Alternative Sinusoidal Rumble Stripe Construction” that was published in 2018 (Mathew et al., 2018). The specifications or dimensions chosen for the design were INDOT Standard Drawings 606-SHCG-07, 08, and 10. Beginning in March of 2023, the dimensions will be changed slightly to accommodate INDOT’s using 6-inch markings instead of 4-inch markings. The new dimensions have been issued as recurring plan detail 606-T-234.d. Indiana does not have weather-related guidelines for sinusoidal rumble strips, such as guidelines related to poor visibility, snow removal, excess rain, and hydroplaning.

The INDOT’s rumble stripe implementation was based on the recommendations from NCHRP 641 guidelines. A minimum shoulder width was implemented for both shoulder and edgeline sinusoidal rumble strips. While an 11-ft lane with 3-ft paved shoulder can also be used with shoulder rumble strips, the standard minimum paved shoulder width is 4 ft. The paved shoulder must be at least a 2-ft width. In Indiana, the typical price for sinusoidal rumble strips is $0.49 per linear foot, which is roughly $0.05 per linear foot more expensive than the typical price for conventional rumble strips. Now, INDOT only uses resurfacing contracts to install sinusoidal rumble strips. After chip seals or other comparable pavement preservation activities, INDOT does not maintain the rumble strips. There are no guidelines to instruct the maintenance process.

2.2.2.2 Sinusoidal AVT Noise Evaluation

Sinusoidal AVT noise evaluation was also conducted in the abovementioned JTRP research project "Assessment of Alternative Sinusoidal Rumble Stripe Construction," in which their selected design was compared with other sinusoidal designs. The results showed that the sinusoidal rumble strips design implemented in Indiana was able to reduce the exterior noise while still providing enough interior noise to alert the driver. The sinusoidal rumble strips have resolved the noise problems INDOT received concerning the rumble strips from surrounding property owners. When the paved shoulder is large enough, it is common practice to use shoulder rumble strips rather than edgeline rumble strips, which has addressed drivers' and motorists' complaints about the effective lane width being too narrow.

2.2.2.3 Sinusoidal AVT Safety Evaluation

There is a follow-up study underway, SPR-4739 on Sinusoidal Rumble Strips Measures of Effectiveness, to evaluate the effectiveness of sinusoidal rumble strips. This study will estimate and compare the safety performance of conventional and sinusoidal rumble strips to inform INDOT's decision of rumble strip design. Edgeline rumble strips narrower than standard 12-inch will be checked for safety and warning effectiveness to accommodate pedestrians and bicyclists within existing road shoulders together with strips. Crash Modification Factors will be estimated for several types of crashes at three levels of crash severity to help select alternative safety countermeasures including rumble strips lateral location: centerline only, shoulder only, and centerline plus shoulder (Tarko & Romero, 2022).

Other than the ongoing study above, they have not conducted any before-after safety evaluations on sinusoidal rumble strips regarding roadway departure crash, injury, and fatality reduction, or any other safety evaluations of sinusoidal rumble strips.

2.2.2.4 Sinusoidal AVT Bicyclists Accommodation

Indiana takes bicycle accommodations into account for sinusoidal AVT implementation, but they do not have separate standards for bicycle locations and non-bicycle locations. In Indiana, paved shoulder width is a significant factor in deciding whether to use edgeline rumble strips or shoulder rumble strips.

The ongoing study SPR-4739: Sinusoidal Rumble Strips Measures of Effectiveness (Tarko & Romero, 2022), will also check edgeline rumble strips narrower than standard 12-inch for safety and warning effectiveness to accommodate pedestrians and bicyclists within existing road shoulders together with strips.

2.2.3 Kentucky

An expert and research engineer at the Kentucky Transportation Center of the University of Kentucky, participated in the interview and provided his responses to the questionnaire, which are summarized below.

2.2.3.1 Sinusoidal AVT Designs and Implementations

In Kentucky, the first sinusoidal rumble strip design was a 14" broad centerline rumble with a minimum depth of 1/8" and a maximum depth of 7/16" and a 14" wavelength. This design was based on the results of the literature review on other state's experiences with sinusoidal rumble strips. The detailed specifications for the implemented sinusoidal rumble stripe were provided by the participants. Kentucky has installed several test locations of sinusoidal rumble strips based on findings from other studies, including NCHRP 641 (Torbic et al., 2009) and the FHWA Rumble Strip Guideline (Federal Highway Administration, 2015), and the interviewees provided contract documents and designs for all locations.

The installation requirements of rumble strip installation in Kentucky depend on the type of roadway, minimum pavement width, and shoulder width. The detailed specifications for edgeline and shoulder rumble strips in Kentucky were also provided by the participants, and they illustrate the various design specifications for a specified pavement width and shoulder width. In Kentucky, local contractors reported that a roadway would require 4' of shoulder to make room for the sinusoidal rumble strip milling machinery.

Kentucky does not have weather-related guidelines for sinusoidal rumble strips, such as guidelines related to poor visibility, snow removal, excess rain, and hydroplaning. Usually, Kentucky's rumble strips are only maintained during resurfacing projects or if there is a reported damage.

The cost of sinusoidal rumble strips in Kentucky was $0.26/LF on average in 2021, which was more expensive than the cost of other rumble strips. This price is for just the milling of the rumble and not the striping. For comparison purposes: Standard edgeline rumbles cost $0.22/LF; standard shoulder rumbling strips cost $0.17/LF; and standard 12" centerline rumble strips cost $0.17/LF.

In addition, as responded by the participants, sinusoidal rumbles are easier to install on roads with gentle curves and longer tangents. Due to the need to achieve continuous milling, the equipment is not as capable on most of Kentucky's lower volume local roads which have more extreme vertical and horizontal alignments. Kentucky is interested in the protection of the striping that is offered by rumble strips since the striping is recessed below the pavement surface. The snow plowing that occurs annually in Kentucky can damage striping, so a sinusoidal rumble strip protects any investment the state makes in a more expensive and reflective striping material.

2.2.3.2 Sinusoidal AVT Noise Evaluation

For the implemented sinusoidal rumble stripe design, although there were no official studies conducted to test noise and vibration levels, several members of the Kentucky Transportation Cabinet and researchers from Kentucky had driven on Kentucky's sinusoidal rumble strips and felt sufficient vibration and noticed less outside noise and enough interior noise to alert the driver.

2.2.3.3 Sinusoidal AVT Safety Evaluation

The first sinusoidal rumble strip was installed at a site in Kentucky before COVID-19, and a few more sinusoidal rumble strips were installed during the COVID-19 shutdowns. No safety evaluations have been done yet for two reasons: (1) the crash trends changed dramatically during COVID-19 and (2) the "after" period since the implementation is only about 2 years, which is too short for data collection. The Kentucky Traffic Safety Data Service (KTSDS), a service provided by the Kentucky Transportation Cabinet, offers safety data for specific locations for free upon request. Accordingly, a summary of crash data at a specific sinusoidal rumble strip location in Kentucky can be provided if requested.

2.2.3.4 Sinusoidal AVT Bicyclists Accommodation

Regardless of bicycle traffic, Kentucky's design guidelines (see Figure 2-20) require shoulder rumble strips to have a 10' bicycle gap every 50' if the shoulders are 3' or wider.

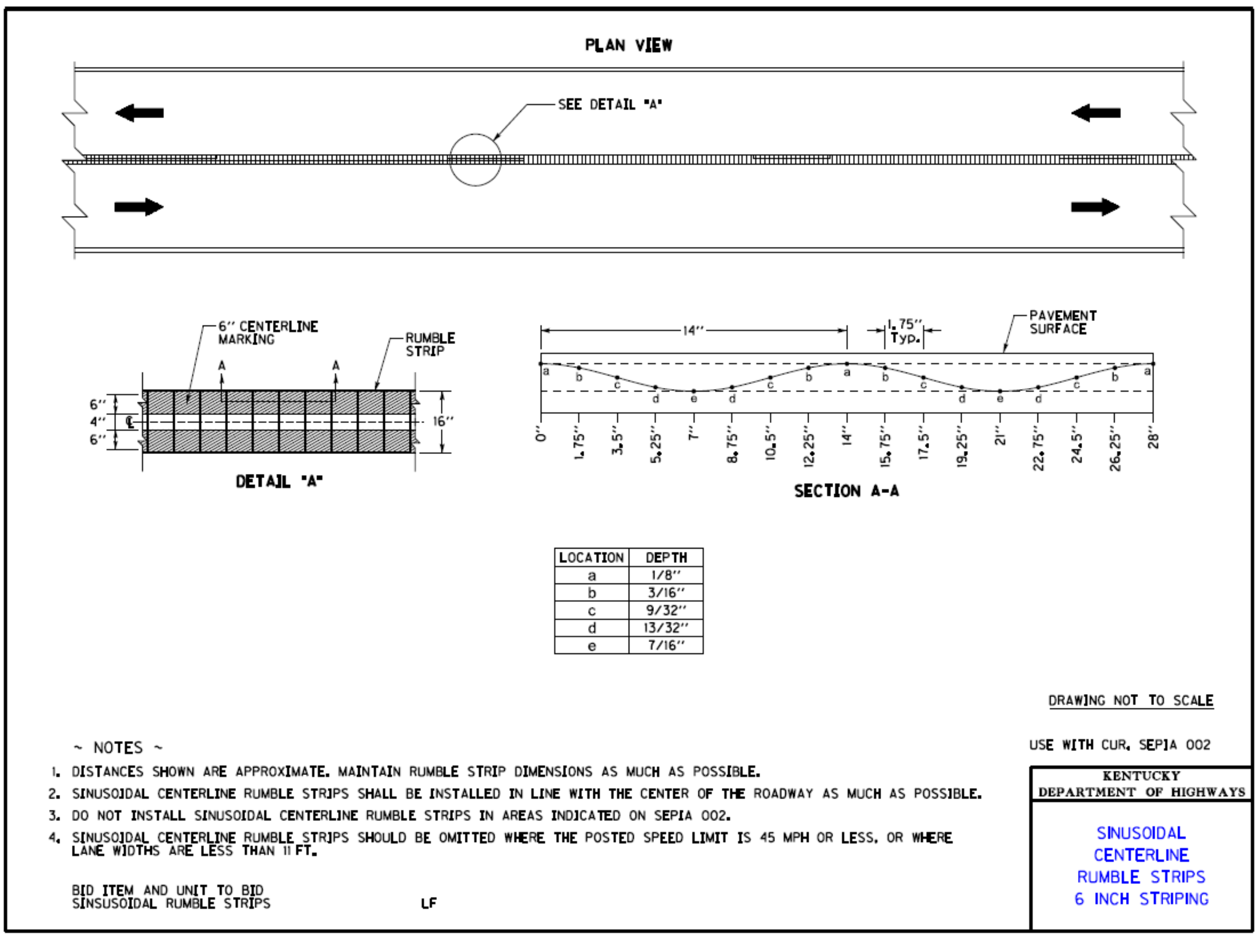


Figure 2-20 Kentucky sinusoidal centerline rumble strips

2.2.4 Minnesota

Two transportation professionals from Minnesota Department of Transportation (MnDOT), including State Pavement Marking & Crashworthy Engineer, and Assistant State Traffic Engineer at the Office of Traffic Engineering, participated in the interview, and their responses to the questionnaire are summarized below.

2.2.4.1 Sinusoidal AVT Designs and Implementations

MnDOT used the sinusoidal rumble strips mainly for noise sensitive areas. The specifications for MnDOT sinusoidal rumble strip and rumble stripe patterns are documented in MnDOT Rumble Strip and Rumble Stripe Typical Details, MnDOT Specifications for Construction (see 2582 Pavement Markings for grinding), and MnDOT Boilerplate Special Provisions (see 2232 Milled Rumble Strips).

Minnesota did not perform any noise and safety studies to compare their selected design with other sinusoidal designs, but there is a safety study underway for MnDOT's sinusoidal rumble strip design that is scheduled to be completed in 2023.

In the MnDOT Traffic Engineering Manual Chapter 11 – Traffic Safety, there is no required minimum shoulder width for implementing shoulder or edgeline sinusoidal rumble strips in Minnesota. MnDOT does not have weather-related guidelines for sinusoidal rumble strips, such as guidelines related to poor visibility, snow removal, excess rain, and hydroplaning. MnDOT does not have an estimated cost of the sinusoidal rumble strips installations, and the sinusoidal rumble costs are similar to rectangular corrugated rumble costs. MnDOT has a state guideline, Sinusoidal Rumbles and Chip Seal Preventative Maintenance, to instruct the maintenance process.

The success factors and lessons learned from implementing sinusoidal rumble strips in Minnesota is that sinusoidal rumbles continue to give drivers who are deviating from the road/lane auditory and tactile input while essentially eliminating complaints based on disturbances in noise sensitive areas. According to crash statistics for the years 2016 to 2020, run-off-road crashes accounted for 32% of all fatal/serious injury collisions, and head-on collisions accounted for 11% of all fatal/serious injury collisions.

2.2.4.2 Sinusoidal AVT Noise Evaluation

MnDOT state has conducted noise evaluation studies by comparing:

- The Minnesota design, with square-edged rumbles 3/8 inch to 1/2 inch deep, 16 inches wide and 12 inches from the center of one rumble to the center of the next.
- The California design, with sinusoidal rumbles 1/32 inch to 5/8 inch deep, 8 inches wide and 14 inches from center to center.
- The Pennsylvania design, with sinusoidal rumbles 1/8 inch to 1/2 inch deep, 8 inches wide and 24 inches from center to center.

The entire effort and results were documented in Rumble Strip Noise Evaluation, MnDOT 2015-07 and Wave-Shaped Rumble Strips Reduce Nuisance Noise (technical summary of previously mentioned study). In these studies, it was found that:

- California's rumble strip design had the best exterior-to-interior sound ratio - it produced as much noise inside the vehicle as the Minnesota design, but less sound outside of the vehicle. Pennsylvania's design produced lower exterior and interior sound levels and may not produce adequate feedback to alert inattentive drivers.
- California's design also had a better tonal quality than MnDOT's current design. Minnesota's design produces a single, strong tonal peak at 125 hertz, which stands out against ambient noise because few sounds in the natural environment produce similar tones. California's design produces two smaller peaks at 100 hertz and 200 hertz, so the sound is less abrupt.
- The noise of a rumble strip is considered detectable if it produces a sound level at a listener's location greater than the ambient noise at any frequency. In passenger vehicles driving at 60 mph, the California design has been modeled as just detectable at 3,000 feet, while the Minnesota design would be detectable at well beyond 3,000 feet in some rural settings.
- California's design only produces its full sound when a tire is fully on the rumble strip. Minnesota's design provided feedback to the driver immediately after the tire made contact with the rumble strip.

2.2.4.3 Sinusoidal AVT Safety Evaluation

Minnesota did not conduct any before and after safety evaluations on sinusoidal rumble strips regarding roadway departure crash, injury, and fatality reduction. In Minnesota, a study was completed on rectangular rumble strip safety evaluation (Rectangular Rumble Strip Safety Evaluation). The safety effectiveness of sinusoidal rumble strips was initially evaluated, but the sample size of road segments with sinusoidal rumble strips was too small to provide reliable estimates of safety effectiveness.

2.2.4.4 Sinusoidal AVT Bicyclists Accommodation

MnDOT presumptively anticipates the presence of bikes everywhere outside those areas limited by Commissioner's Orders (mostly interstates), but they do not have separate standards for bicycle locations and non-bicycle locations. As for the specific design used for bicycle accommodations in rumble strip implementation, Minnesota uses 12' gap/48' as rumble strips gaps for bicyclists and tries to provide a minimum shoulder of 4-ft wide smooth bikeable surface, but that is not possible where the rumble strip is recommended to be installed on the outside of the shoulder.

2.2.5 Washington

The technical manager for Acoustics, Air Quality and Energy at Washington Department of Transportation (WSDOT), attended the interview and provided responses to the questionnaire, which are summarized below.

2.2.5.1 Sinusoidal AVT Designs and Implementations

To decrease the number of complaints from people who live close to rumble strips, WSDOT looked for a quieter rumble strip design, similar to those used in California and Minnesota. WSDOT has their own WSDOT Design Manual for sinusoidal AVT implementation. In locations where a low noise design is needed, sinusoidal rumble strips may be implemented (WSDOT Design Manual), and WSDOT adopted the 16-inch option as the final design.

Currently in Washington State, installing sinusoidal rumble strips costs more than installing normal milled rumble strips. The reason is that few contractors have the specialized tools needed to install sinusoidal rumble strips; however, as this situation changes, it is estimated that the cost will decrease over time. WSDOT has not installed a lot of sinusoidal rumble strips.

So far, WSDOT does not have a process for maintaining sinusoidal or other rumble strips, and they are thinking of putting up a study to determine how many chip seal overlays should be permitted before a rumble strip becomes worthless and needs to be replaced. They do not have weather-related guidelines for sinusoidal rumble strips, such as guidelines related to poor visibility, snow removal, excess rain, and hydroplaning.

2.2.5.2 Sinusoidal AVT Noise Evaluation

In 2018, WSDOT conducted a noise study on modifications to its standard milling rumble strip design spacing, which was found to be a little bit quieter than a sinusoidal rumble strip design (Laughlin & Donahue, 2018). As part of this research, WSDOT used the NCHRP 641 guidance for in-cabin vehicle sound level increases to alert the drivers.

In addition, supported by NCHRP 15-68: Effective Low-Noise Rumble Strips, the research team led by Dr. Paul Donovan of Illingworth and Rodkin, Inc. facilitated the installation of a 16-inch sinusoidal rumble strip design on a rural highway in WA State. The work has not yet been published.

Although with limited experience and data on sinusoidal rumble strip implementation, WSDOT found that their sinusoidal rumble strip design does reduce wayside noise while still alerting the drivers, which makes it a viable tool to use when residents are within 600 feet of a rumble strip installation.

2.2.5.3 Sinusoidal AVT Safety Evaluation

WSDOT is planning to perform a before and after study of the implemented sinusoidal rumble strips but will need a lot more installations and time to do it successfully. It is indicated as of now that the implemented sinusoidal rumble strip is operating successfully as anticipated. In addition, WSDOT has not yet performed any other safety evaluations of sinusoidal rumble strips in the state.

2.2.5.4 Sinusoidal AVT Bicyclists Accommodation

In Washington State, bicyclists are not considered for shoulder sinusoidal rumble strip installation specifically, but are considered for rumble strip installation in general, and WSDOT engages the Headquarters Bicycle and Pedestrian Coordinators in the decision-making process on bicycle accommodation depending on bicycle traffic levels. The bicycle accommodations of rumble strip implementation in Washington State are explicitly documented in WSDOT Design Manual, and the required minimum shoulder width for implementing shoulder or edgeline sinusoidal rumble strips is specified in Section 1600.05(1).

3 Study Site Selection and Evaluation Methodology

This chapter describes the study site selection and evaluation methodologies. The location of the CUTR focus group noise study sites and FDOT Materials Office noise study sites for the noise evaluations are detailed below. The description of the sites for the safety assessment is also included. In addition to the site locations, the noise and safety evaluation methodologies are specified in this chapter. The methodology sections cover the data collection processes and analysis techniques.

3.1 Study Site Selection

Information about noise and safety evaluation study sites is available in this section. Details about the Focus group noise study sites as well as the sites used by FDOT to conduct their field studies are summarized. The sites selected by the project team for the safety evaluation and the reasons for selecting those sites are noted in the sub-sections below.

3.1.1 Study Sites for Noise Evaluation

Details about the two sites selected for noise evaluation, which consisted of a Center for Urban Transportation Research (CUTR) focus group noise study and FDOT Materials Office field noise studies are described in the subsequent sections.

3.1.1.1 Focus Group Noise Study

The research team conducted a noise study at two different sites—US-301 and SR-100. The sites were selected based on FDOT guidance and due to the fact that each site had three different sinusoidal rumble strip designs, which was the focus of the project. The exact locations of these two sites using milepost information were obtained from Geographic Information System (GIS) and Google Maps. The plan sheet for each site provided by the FDOT has important details about the mileposts, the type of rumble strips available, and the directions of travel. For example, US-301 southbound has six 1200-ft test sections with three different sinusoidal rumble strips on the shoulder and three different sinusoidal rumble strips at the edgeline, as detailed in Figure 3-1. Similarly, SR-100 eastbound and westbound have twelve 1200-ft test sections with three different sinusoidal rumble strips on the shoulder and three different sinusoidal rumble strips at the edgeline for each direction (see Figure 3-2).

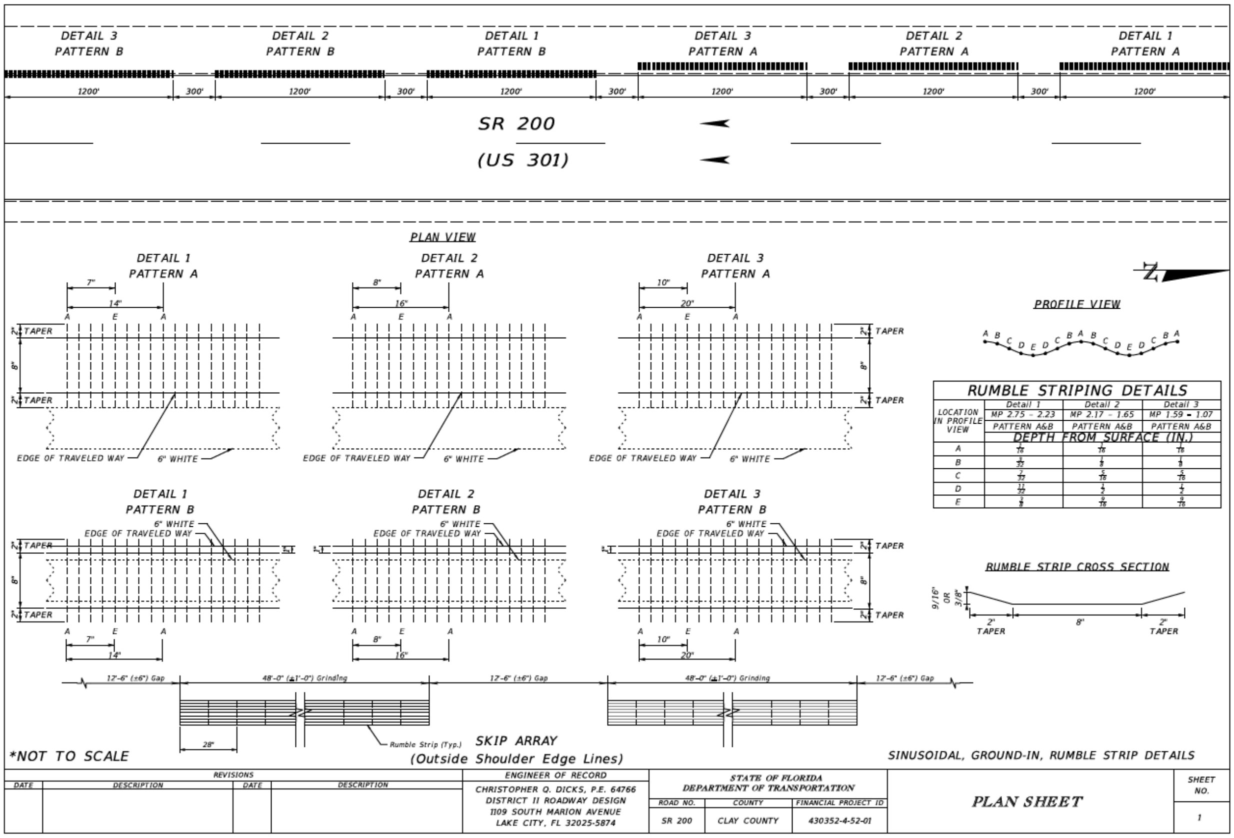


Figure 3-1. US-301 plan sheet

Source: FDOT

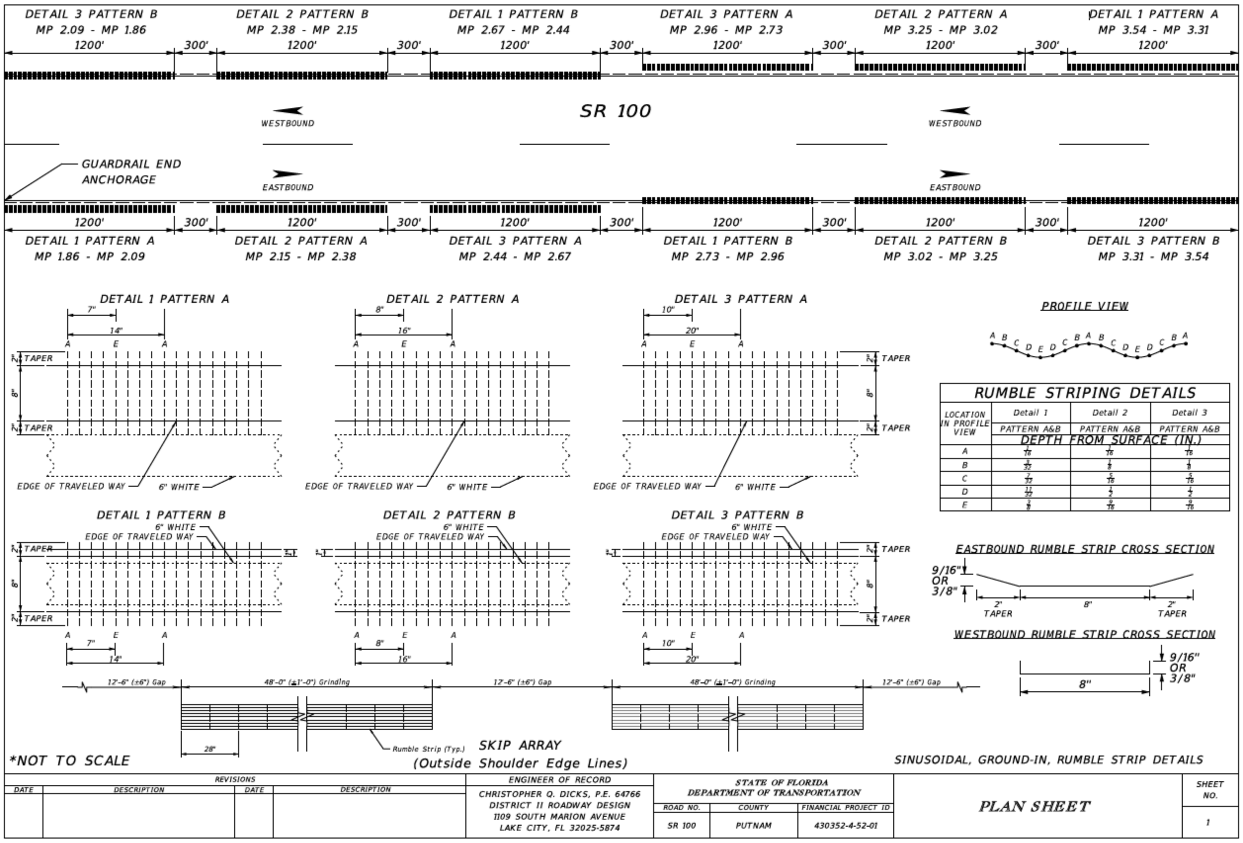


Figure 3-2. SR-100 plan sheet

Source: FDOT

3.1.1.2 FDOT Materials Office Noise Studies

For the overall noise assessment, in addition to the CUTR focus group noise study, the research team used the findings from the noise studies performed by the FDOT Materials Office. The FDOT studies assessed the noise level of three sinusoidal rumble strip designs at the same two locations as the focus study sites—US-301 and SR-100.

First, noise levels of the edgeline rumbles installed on the north and southbound travel lanes of US-301 in Clay County were tested in one of the FDOT studies. The noise from three different patterns (1, 2, 3) of sinusoidal strips were measured using six 1200-ft.-long aligned test sections per direction on the edge of US-301. Two types of rumble strips were included in the six test sections—Type A and Type B. Type A rumbles were installed outside the roadway edgeline markings, and Type B rumbles were installed with the edgeline markings overlaid (Figure 3-3). The dimensions of the six different rumble strips for northbound and southbound (A1, A2, A3, B1, B2, B3) are summarized in Table 3-1.

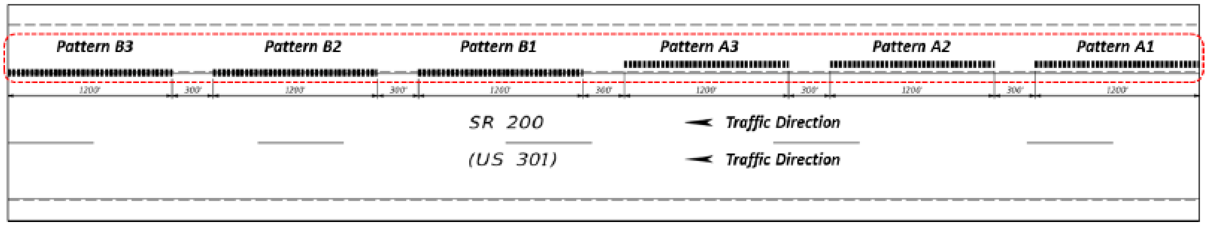


Figure 3-3. US-301 test sections

Source: FDOT, 2022a

Table 3-1. Design and Measured Dimensions of US-301 Rumble Strips

Direction	Pattern	Design Value (in.)				Measured Value (in.)		
		Elevation A	Elevation E	Depth (A-E)	length	Elevation A	Elevation E	Depth (A-E)
NB	A1	-0.06	-0.38	0.31	14	-0.31	-0.52	0.21
	A2	-0.06	-0.56	0.50	16	-0.23	-0.67	0.45
	A3	-0.06	-0.56	0.50	20	-0.23	-0.63	0.40
	B1	-0.06	-0.38	0.31	14	0.12	-0.30	0.43
	B2	-0.06	-0.56	0.50	16	0.13	-0.39	0.52
	B3	-0.06	-0.56	0.50	20	0.03	-0.57	0.60
SB	A1	-0.06	-0.38	0.31	14	-0.33	-0.56	0.23
	A2	-0.06	-0.56	0.50	16	-0.26	-0.65	0.39
	A3	-0.06	-0.56	0.50	20	-0.27	-0.76	0.49
	B1	-0.06	-0.38	0.31	14	0.10	-0.47	0.56
	B2	-0.06	-0.56	0.50	16	-0.03	-0.51	0.49
	B3	-0.06	-0.56	0.50	20	-0.01	-0.41	0.40

Source: FDOT, 2022a

Similarly, the FDOT Materials Office conducted a second noise study that tested the noise levels on the edgeline rumbles installed on the eastbound and westbound travel lanes of SR-100 in Putnam County. The noise levels were measured using six 1200-ft. long test sections per direction on the edge of SR-100. Two types of rumble strips (A and B) and three different patterns (1, 2, and 3) of sinusoidal strips were considered (Figure 3-4). Dimensions of the six different rumble strips (A1, A2, A3, B1, B2, and B3) are given Table 3-2.

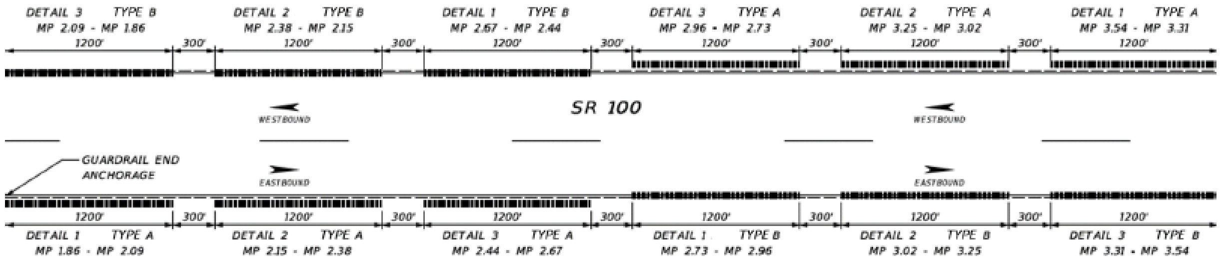


Figure 3-4. SR-100 test sections

Source: FDOT, 2022b

Table 3-2. Design and Measured Dimensions of SR-100 Rumble Strips

Rumble Strip Pattern	Design Value (in.)				Measured Value (in.)		
	Elevation A	Elevation E	Depth (A-E)	length	Elevation A	Elevation E	Depth (A-E)
A1	-0.06	-0.38	0.31	14	0.25	0.46	0.21
A2	-0.06	-0.56	0.50	16	0.24	0.54	0.30
A3	-0.06	-0.56	0.50	20	0.23	0.51	0.27
B1	-0.06	-0.38	0.31	14	0.21	0.41	0.19
B2	-0.06	-0.56	0.50	16	0.28	0.49	0.21
B3	-0.06	-0.56	0.50	20	0.24	0.48	0.24

Source: FDOT, 2022b

3.1.2 Study Sites for Safety Evaluation: Crash Analysis

For the safety evaluation, the research team selected roadway segments where sinusoidal AVTs were implemented following FDOT context based AVT design criteria defined in RDB18-03 and the current Florida Design Manual (FDM). Based on the most recent information provided by the FDOT project manager, FDOT implemented sinusoidal AVT on the roadway segments, as identified with 5-digit Roadway Section Number and beginning and ending milepost (MP) information.

After locating the implementation sites, information regarding road functional classification, lane number, and Annual Average Daily Traffic (AADT) was collected for each site. Based on this information, we manually selected the reference site for each implementation site. An effort was made to select reference sites of the same length, possibly on the same FDOT roadway, and with similar characteristics, and following the same "before" and "after" data collection periods as the implementation site as counterpart. The implementation sites and reference sites are shown in Figure 3-5.

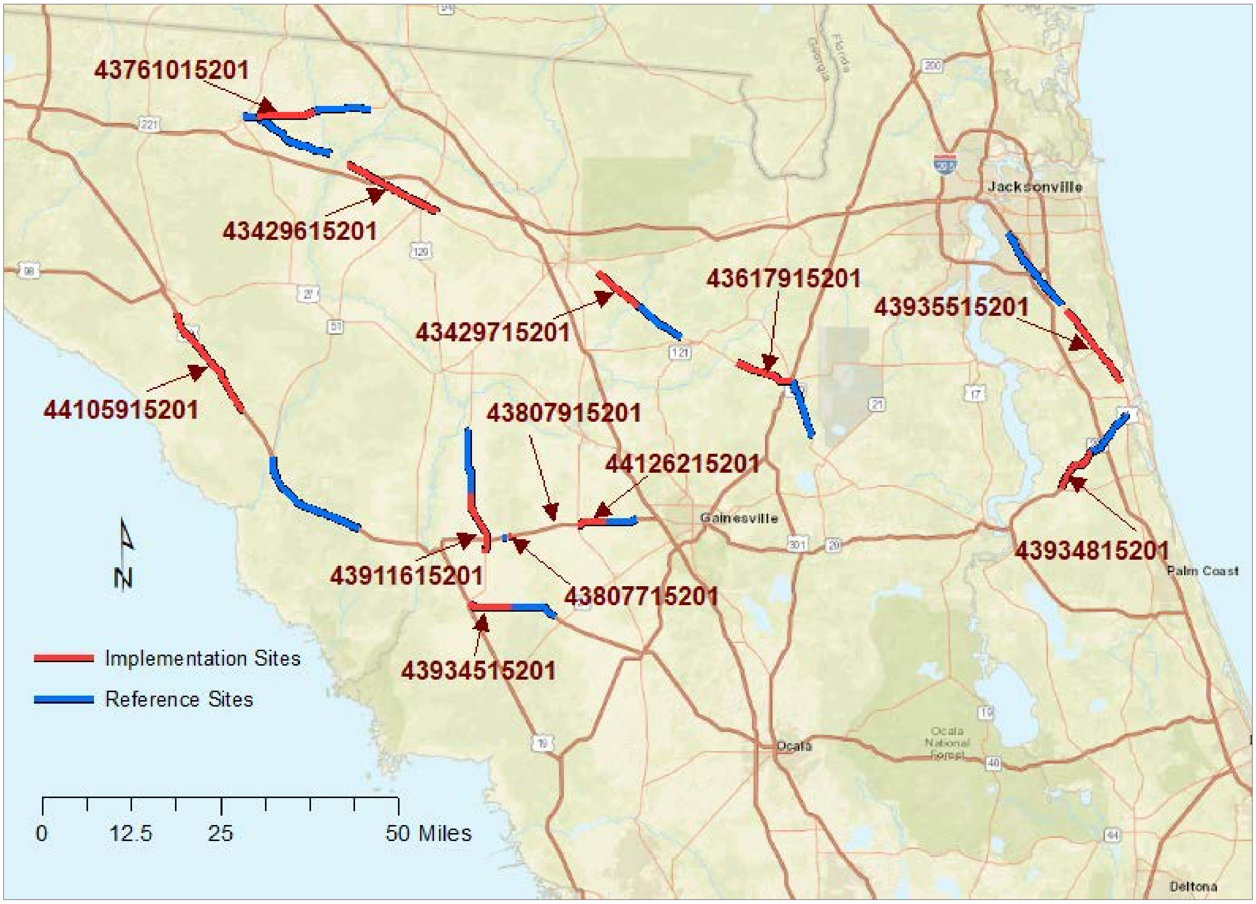


Figure 3-5. Implementation and reference sites for sinusoidal rumble strips

3.2 Evaluation Methodology and Data Collection

Evaluation methods and data collection processes are summarized in this section. Noise evaluation and safety evaluation are elaborated in different sub-sections. The noise evaluation methods and data collection processes specified the method and data collection process used for the focus group and the methods and data collection processes used by FDOT during their field studies. For the safety evaluation, the data collection and evaluation methods are also described.

3.2.1 Noise Evaluation

The noise evaluation covers the focus group approach and the methods used by FDOT for their field noise studies. Details about the methods used are in the following section.

3.2.1.1 Focus Group Noise Study

For the focus group noise study, four cars (see Figure 3-6 through Figure 3-9) were used to test inside noise levels for the ability to alert drivers of potential roadway departures when driving over the rumble strips (shoulder rumble strip and edgeline rumble strip) on US-301 and SR-100. Drivers and passengers took turns driving the vehicles at the designated speed limit and 5 mph above the speed limit. Some participants did two test runs when necessary to confirm their ratings. After each test, passengers and drivers completed the focus group questionnaire (see Appendix A) with their ratings and explanations for those ratings. When the testing at each site was complete, the team held a group discussion with participants about their ratings for that site and why they thought their selected type of rumble strip was better.

Figure 3-6. Vehicle 1 (SUV, Toyota 4 Runner)

Figure 3-7. Vehicle 2 (Sedan, Toyota Corolla)

Figure 3-8. Vehicle 3 (Pickup Truck, Chevrolet Colorado)

Figure 3-9. Vehicle 4 (SUV, Toyota 4 Runner)

For both shoulder and edgeline implementations, there are three types of sinusoidal rumble strips implemented. Images of the tested rumble strips are shown in Figure 3-10 through Figure 3-17. The order of rumble strips on each road was as follows:

- Type 1 (Detail 1 in plan sheet)
- Type 2 (Detail 2 in plan sheet)
- Type 3 (Detail 3 in plan sheet)

For US-301, images were captured for Shoulder Rumble Strip Type 1 (Figure 3-10) and Edgeline Rumble Strip Type 3 (Figure 3-11). For SR-100, images were captured for all three types of rumble strips located at shoulder and edgeline locations as shown in Figure 3-12 to Figure 3-17.

Figure 3-10. US-301 shoulder rumble strip Type 1

Figure 3-11. US-301 edgeline rumble strip Type 3

Figure 3-12. SR-100 shoulder rumble strip Type 1

Figure 3-13. SR-100 shoulder rumble strip Type 2

Figure 3-14. SR-100 shoulder rumble strip Type 3

Figure 3-15. SR-100 edgeline rumble strip Type 1

Figure 3-16. SR-100 edgeline rumble strip Type 2

Figure 3-17. SR-100 edgeline rumble strip Type 3

3.2.1.2 FDOT Materials Office Studies

The FDOT Materials office also conducted noise studies at the same sites as the focus group: US-301 and SR-100. This section summarizes their data collection process.

US-301

Noise levels of the edgeline rumbles installed on the northbound and southbound travel lanes of US-301 in Clay County (see Figure 3-18) were tested by FDOT. The noise from three different types (1, 2, 3) of sinusoidal strips were measured using six 1200-ft.-long aligned test sections per direction on the edge of US-301. Type A and Type B rumble strips were included in the six test sections. More details and images about the Type A and Type B rumble strips are available in Figure 3-19 and Figure 3-20.

Figure 3-18. Satellite image of test location on US-301 (Google Map, 2021)

Source: FDOT, 2022a

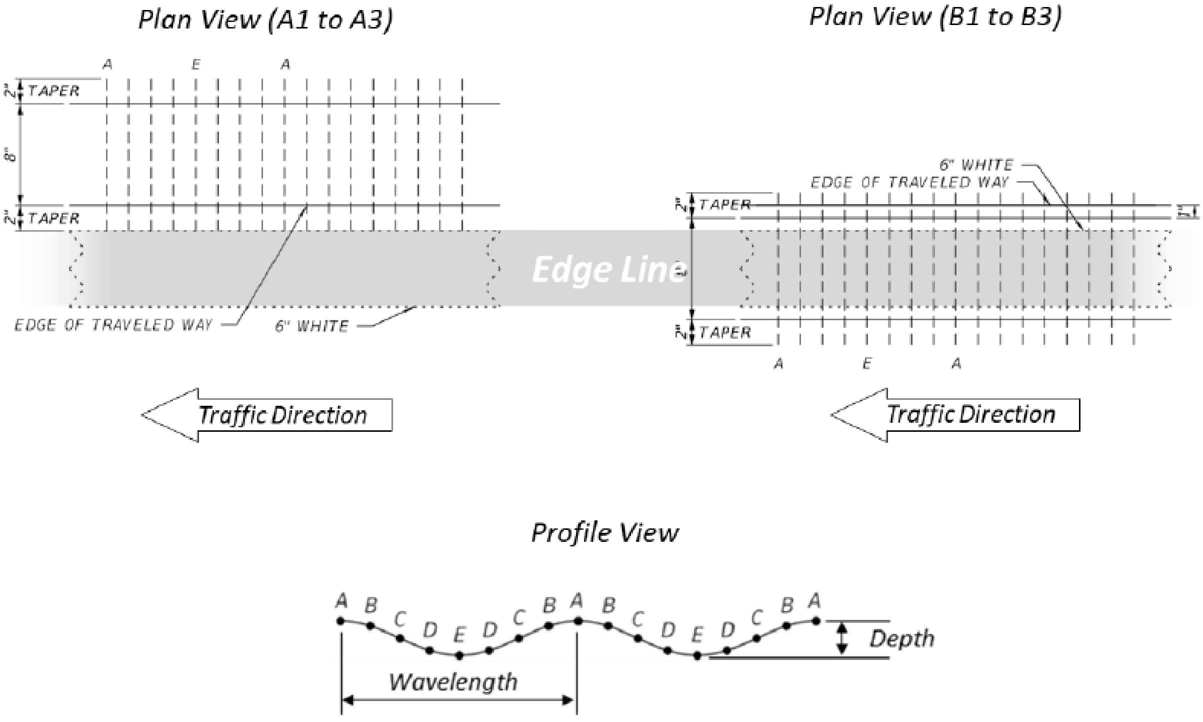


Figure 3-19. Details of both Type A and Type B rumble strips

Source: FDOT, 2022a

Figure 3-20. Comparison of US-301 rumble strips between Type A and Type B

Source: FDOT, 2022a

FDOT used OBSI to measure the outside noise at the tire/pavement interface using two microphones mounted vertically 4 in. from the outside tire sidewall of the rear passenger side tire (Figure 3-21). For each test section, the noise levels were measured three times for five seconds at 60 mph.

Figure 3-21. OBSI testing setup

Source: FDOT, 2022a

FDOT measured the cabin (inside) noise of the test truck by using a CESVA SC 310 sound level meter (see Figure 3-22) and by placing the sound level meter 5 in. above the center of the rear seat. Likewise, the noise levels were assessed three times for five seconds at 60 mph for each test section.

Figure 3-22. Cabin noise testing setup

Source: FDOT, 2022a

SR-100

As with US-301, FDOT tested the noise levels on the shoulder and edgeline rumbles installed on the eastbound and westbound travel lanes of SR-100 in Putnam County (see Figure 3-23). The noise levels were measured using six 1200-ft.-long test sections per direction on the edge of SR-100. As mentioned previously, two types of rumble strips (A and B) (Figure 3-24) of sinusoidal strips were considered.

Figure 3-23. Satellite image of test location on SR-100 (Google Map, 2021)

Source: FDOT, 2022b

Figure 3-24. Comparison of SR-100 rumble strips between Type A and Type B

Source: FDOT, 2022b

FDOT employed OBSI to measure the outside noise levels of the strips on SR-100. The noise levels were measured three times for five seconds at 60 mph for each test section.

Cabin (inside) noise levels were also measured by placing the sound level meter 5 in. above the center of the rear seat. Each test section was tested three times for five seconds at 60 mph.

3.2.2 Safety Evaluation

Information on the data collection and safety evaluation methods is emphasized in this section. Details related to the number, roadway name, length, number of lanes, traffic volume, and functional class of the sites are incorporated, as well as specifics of the crash data. Statistical methods used to analyze the data are mentioned in this section.

3.2.2.1 Data Collection

The data collection process began with locating the treatment sites for implementing sinusoidal rumble strips as mentioned in the last section. The FDOT provided the site information, including Roadway ID and the beginning and end MP numbers. Twelve sites in FDOT District 2 were selected for the analysis, each with a unique FPID identifier. Additional data collected for the analysis were downloaded from FDOT Open Data Hub and included:

- Roadway functional class
- Number of lanes
- Historical AADT data (2016-2021)

The functional class, number of lanes, and historical traffic volume data were assigned to each implementation site through the data joined in the GIS environment. If the implementation site consisted of two functional classes, the implementation site was further divided into smaller segments, and the start/end MP was adjusted appropriately. Three sites consisted of two functional classes. If the number of lanes changed along the implementation sites, the most common lane was assigned. The historical AADT data was assigned to each of the 12 segments for the years 2016 - 2021. The details on implementation sites are presented in Table 3-3.

Table 3-3. Details on Sinusoidal Rumble Strip Implementation Sites.

No.	Road Name	FPID	Roadway			Functional Class	Lane number
			ID	MP Begin	MP End		
1	SR-10	43429615201	37010000	0.900	10.515	6	1
				10.515	15.051	16	1
2	SR-100	43429715201	29060000	7.350	0.000	6	1
3	SR-100	43617915201	28020000	20.000	13.173	6	1
				13.173	11.598	16	1
4	SR-6	43761015201	35020000	0.132	8.138	6	1
5	SR-26	43807715201	31010000	10.792	11.341	4	1
6	SR-26	43807915201	31010000	17.572	17.730	4	1
7	SR-49	43911615201	31030000	0.000	9.276	6	1
8	SR-500	43934515201	34010000	8.323	14.679	4	2
9	SR-207	43934815201	78051000	3.139	10.406	4	2
10	SR-5	43935515201	78020000	2.315	8.138	14	2
				8.138	15.036	4	2
11	SR-55	44105915201	38010000	7.812	24.695	4	2
12	SR-5	44126215201	26070000	2.962	7.202	4	2

1) Before-After Crash Data Collection for Sinusoidal Rumble Strip Implementation Site

Lane departure crashes were downloaded from the Signal Four Analytics application. Data for the time period, Roadway ID, mile point range, and emphasis area were used to select lane departure crashes that occurred along implementation sites before and after the sinusoidal rumble strips were implemented. Figure 3-25 presents factors considered during data collection in Signal Four Analytics. Given that the sinusoidal rumble strips were implemented at different times as shown in Table 3-4, the following rule were used to define the before and after time periods for data collection:

- For each site, the “before” period is defined as three full years backward from the last month before the implementation work began. For example, the implementation work of sinusoidal rumble strip for Site #1 was January 25, 2019, therefore, the three-year “before” period for crash data collection is January 1, 2016, through December 31, 2018.
- For each site, the “after” period is defined as three full years starting from the first month after the implementation work was completed if there are three years available after the work. For example, for Site #2, the implementation work was completed on October 15, 2019, so the “after” data collection period was November 1, 2019, through October 31, 2022.

- If the implementation work was completed less than three years upon the research team started data collection, one or two years of crash data after the implementation work was completed, depending on data availability. For example, a two-year “after” period was applied for Site #8, and a one-year after period was applied for Site #11.
- If the implementation work was completed less than a year upon the research team started data collection, the research team collected the most quarters of a year based on data availability. For example, for Site #10, the implementation work was completed on February 7, 2022, and the research team started the data collection in January 2023, so a nine-month “after” period was defined for crash data collection.

Following these rules, a total of 334 lane departure crashes occurred before the sinusoidal rumble strip implementation, and 139 crashes occurred after the implementation. Figure 3-26 presents the before and after lane departure crash locations.

Figure 3-25. Crash data collection process

Table 3-4. Before and After Time Periods for Lane Departure Crash Data Collection at Implementation Sites

Site #	FPID	Implementation Site			Implementation Time	Before Period	After Period
		Roadway ID	MP Begin	MP End			
1	43429615201	37010000	0.900	15.051	Work Began: 1-25-19; Completed: 5-12-20	1-1-2016 through 12-31-2018	6-1-2020 through 5-31-2022
2	43429715201	29060000	7.350	0.000	Work Began: 5-30-19; Completed: 10-15-19	5-1-2016 through 4-30-2019	11-1-2019 through 10-31-2022
3	43617915201	28020000	20.000	11.598	Work Began: 7-22-19; Completed: 7-8-20	7-1-2016 through 6-30-2019	8-1-2020 through 7-31-2022
4	43761015201	35020000	0.132	8.138	Work Began: 11-14-19; Completed: 5-22-20	11-1-2016 through 10-31-2019	6-1-2020 through 5-31-2022
5	43807715201	31010000	10.792	11.341	Work Began: 3-16-20; Completed: 10-23-20	3-1-2017 through 2-29-2020	11-1-2020 through 10-31-2022
6	43807915201	31010000	17.572	17.730	Work Began 8-13-20; Completed: 1-11-21	8-1-2017 through -31-2020	2-1-2020 through 1-31-2023
7	43911615201	31030000	0.000	9.276	Work Began: 1-6-20; Completed: 9-15-20	1-1-2017 through 12-31-2019	10-1-2020 through 9-30-2022
8	43934515201	34010000	8.323	14.679	Work Began: 1-27-20; Completed: 8-24-20	1-1-2017 through 12-31-2019	9-1-2020 through 8-31-2022
9	43934815201	78051000	3.139	10.406	Work Began: 11-12-19; Completed: 7-29-20	11-1-2016 through 10-31-2019	8-1-2020 through 7-31-2022
10	43935515201	78020000	2.315	15.036	Work Began: 2-28-20; Completed: 2-7-22	2-1-2017 through 1-31-2020	3-1-2022 through 12-31-2022
11	44105915201	38010000	7.812	24.695	Work Began: 9-8-20; Completed: 9-15-21	9-1-2017 through 8-31-2020	10-1-2021 through 9-30-2022
12	44126215201	26070000	2.962	7.202	Work Began: 10-19-20; Completed: 6-14-21	10-1-2017 through 9-30-2020	7-1-2021 through 6-30-2022

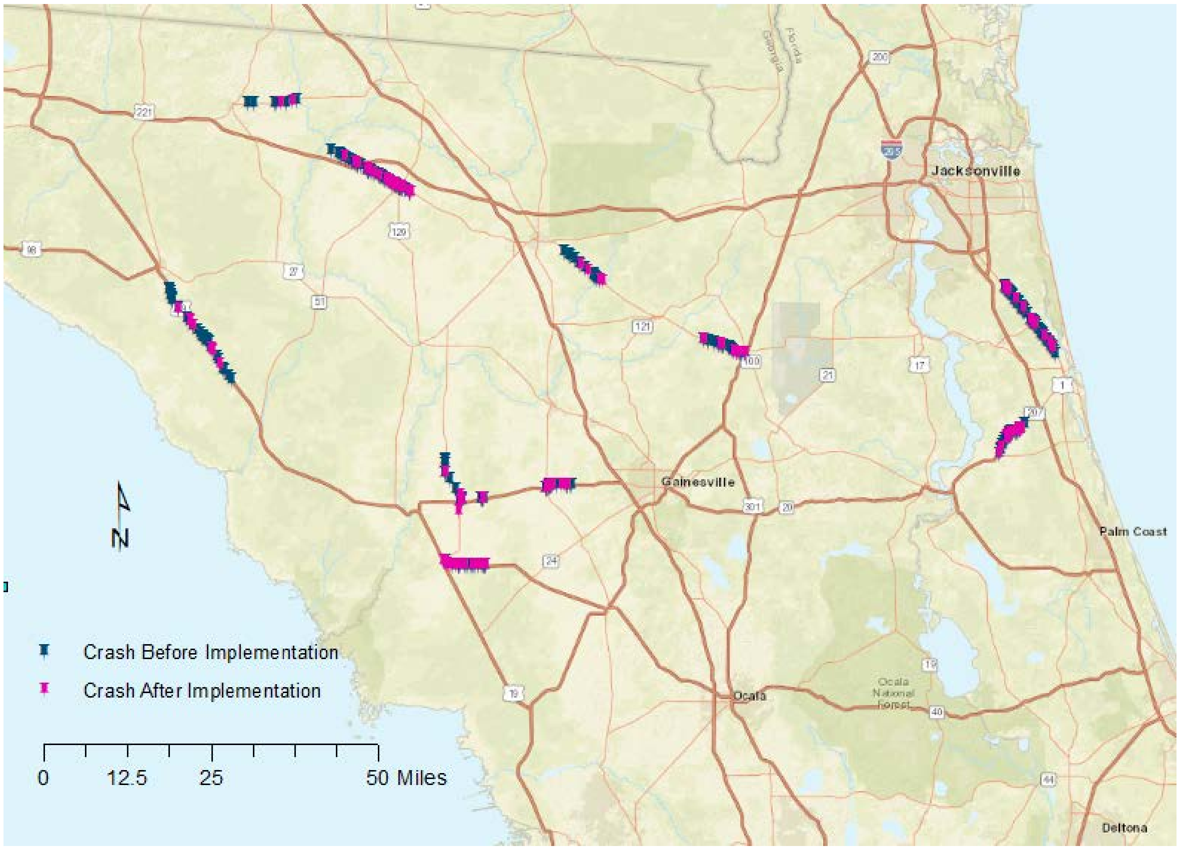


Figure 3-26. Before and after lane departure crashes - implementation sites

2) Reference Site Crash Data Collection

Similar data collection procedure was also conducted to gather the crash data for the 12 reference sites. As mentioned before, an effort was made to select reference sites of the same length, possibly on the same FDOT roadway, and with similar characteristics, and following the same "before" and "after" data collection periods as the implementation site as counterpart. A total of 529 lane departure crashes occurred on 12 reference sites before the sinusoidal rumble strip implementation, and 272 crashes occurred after the implementation. Table 3-5 presents the crash locations.

Table 3-5. Before and After Time Periods for Lane Departure Crash Data Collection at Reference Sites

FPID of Implementation Site	Reference Site			Before Period	After Period
	Roadway ID	MP Begin	MP End		
43429615201	35010000	20.218	34.369	1-1-2016 through 12-31-2018	6-1-2020 through 5-31-2022
43429715201	39010000	6.662	14.012	5-1-2016 through 4-30-2019	11-1-2019 through 10-31-2022
43617915201	28020000	3.196	11.598	7-1-2016 through 6-30-2019	8-1-2020 through 7-31-2022

FPID of Implementation Site	Reference Site			Before Period	After Period
	Roadway ID	MP Begin	MP End		
43761015201	32050000	0.096	8.102	11-1-2016 through 10-31-2019	6-1-2020 through 5-31-2022
43807715201	31010000	9.903	10.485	3-1-2017 through 2-29-2020	11-1-2020 through 10-31-2022
43807915201	31010000	16.666	16.824	8-1-2017 through 7-31-2020	2-1-2020 through 1-31-2023
43911615201	31030000	9.276	18.552	1-1-2017 through 12-31-2019	10-1-2020 through 9-30-2022
43934515201	34010000	14.679	21.04	1-1-2017 through 12-31-2019	9-1-2020 through 8-31-2022
43934815201	78051000	10.406	17.673	11-1-2016 through 10-31-2019	8-1-2020 through 7-31-2022
43935515201	72070000	0	12.721	2-1-2017 through 1-31-2020	3-1-2022 through 12-31-2022
44105915201	30010000	0	16.883	9-1-2017 through 8-31-2020	10-1-2021 through 9-30-2022
44126215201	26070000	7.202	11.742	10-1-2017 through 9-30-2020	7-1-2021 through 6-30-2022

3.2.2.2 Analytical Methods

A few analytical methods were used in this project to evaluate the safety effectiveness of sinusoidal AVTs based on the crash rate. The crash rate is defined as

$$Crash\ Rate = \frac{Average\ Crash\ Frequency\ in\ a\ Period}{Exposure\ in\ Same\ Period} = \frac{\frac{C}{N}\times 1{,}000{,}000}{365\times V\times L} \quad (3.1)$$

where, C = total number of crashes occurring along a road segment; V = AADT, which is the total volume of vehicle traffic for a year divided by 365 days; N = total number of years considered in the calculation; and L = the length of the roadway segment. The unit for the crash rate is (crashes/million vehicle miles traveled, VMT). Analytical methods including statistical analysis and significant test, Empirical Bayes (EB) before-after analysis, and development of crash modification factors (CMF) were used. Regression models were also used to identify the contributing factors in lane departure crashes.

1) Significance Test

Significance tests were conducted to determine whether the crash rate at the treatment sites is significantly different from the control sites, and also test if the crash rate before the treatment implementation is significantly different from that after the treatment. All significance tests were conducted at a minimum confidence level of 90%.

2) Empirical Bayes (EB) Before-After Analysis and Florida-Specific Crash Modification Factor (CMF) on Sinusoidal AVTs

The empirical Bayes (EB) method is a comparison group method accounting for the regression-to-the-mean effect in crash frequency. The goal of the EB method provides relatively accurate estimation of the number of crashes that would have happened at any individual treated site (indicate as $N_{expected,T,A}$) where the after-period treatment has not been put in place. The impact of the safety treatment is calculated by comparing the total of estimates for the total number of crashes should the treatment not be implemented for all treated locations with the actual number of crashes reported after treatment.

In accounting for regression-to-the-mean, the number of crashes expected in the before period without the treatment ($N_{expected,T,B}$) is a weighted average of information from two sources:

- The number of crashes observed in the before period at the treated sites ($N_{observed,T,B}$).
- The number of crashes predicted at the treated sites based on reference sites with similar traffic and physical characteristics ($N_{predicted,T,B}$).

To estimate the weights and the number of crashes expected on sites with similar traffic and physical characteristics, the comparison group of sites similar to the treated sites as mentioned above will be identified, and relevant data for these untreated comparison sites will be collected. The data from the untreated comparison group are used to first estimate a safety performance function (SPF) that relates crash experience of the sites to their traffic and physical characteristics. An SPF is a mathematical model that predicts the mean crash frequency for similar locations with the same characteristics. These characteristics typically include traffic volume and may include other variables such as traffic control and geometric characteristics. This SPF is then used to derive the second source of information for the empirical Bayes estimation — the number of crashes predicted at treated sites based on sites with similar operational and geometric characteristics ($N_{predicted,T,B}$).

A CMF is a multiplicative factor that is used to determine the predicted number of crashes after the use of a specific countermeasure at a particular location. The predicted crash frequency without treatment is multiplied by the CMF. The CMF for a given crash type at a treated site is estimated by first summing the observed crashes for both the treatment and comparison site groups for the two time periods (assumed equal). A CMF greater than 1.0 indicates an expected increase in crashes, and a CMF less than 1.0 indicates an expected reduction in crashes after implementation of a given countermeasure.

In this research, the SPFs defined in Chapter 10 for rural two-lane roads and Chapter 11 for rural multi-lane roads in the Highway Safety Manual, 1st Edition (HSM1) were used. Detailed methodological descriptions of the EB before-after analysis and development of CMF are presented below in Section 4.2 with step-by-step calculations.

3) Crash Severity and Contributing Factor Analysis

It is also necessary to investigate the effects of crash, traffic, roadway, and driveway characteristics on crash severity outcomes. A commonly used unordered discrete modeling approach, multinomial logit (MNL) model, was adopted to identify the significant variables and assess their respective impact. In this study, the research team plans to aggregate the KABCO injury scale to severe injury (K and A), minor injury (B and C) and no injury (O) crashes for the reason as noted previously. This analysis will be performed using Equation (3.2) (Washington et al., 2020).

$$P_n(k) = \frac{EXP[\beta_k X_{kn}]}{\sum_{\forall K} EXP[\beta_k X_{kn}]} \tag{3.2}$$

where, $P_n(k)$ is the probability in crash n that will result in most severe-injury severity outcome k and K is the set of the three possible injury-severity outcomes. Based on maximum likelihood estimation (MLE) methods, all the significant variables are identified at the significant level of p=0.05.

4 Sinusoidal AVT Effectiveness Assessment Results

This chapter outlines the results of both noise and safety evaluations. For the noise, the findings from the focus group noise study and FDOT field noise studies are included. The results from the safety analysis are also highlighted in this chapter. All the results together show the effectiveness of sinusoidal rumble strips related to exterior noise reduction and safety.

4.1 Sinusoidal AVT Noise Evaluation Results

The noise evaluation encompasses the focus group and FDOT field noise studies. The results from those studies are synthetized in this section. The objective of the noise studies was to understand the types of sinusoidal rumble strips that work better at reducing exterior noise while maintaining enough interior noise to alert drivers when leaving the travel way.

4.1.1 Focus Group Noise Study

This sub-section elaborates on the focus group noise study results. It incorporates the results of the focus group data analysis, as well as the group discussion. Results are separated by sites and the major findings are also included.

4.1.1.1 Data Analysis and Group Discussion

For the focus group noise study, data acquired from all participants was included in an Excel spreadsheet. The information included ratings for the three types of rumble strips for shoulder and edgeline for US-301 and SR-100, whether the participant was a passenger or driver, the type and model of vehicle used, and the driving speed at which the test was performed. Three different aspects were rated—inside noise, vibration, and overall. The data for each site were then analyzed separately using simple summary statistics of average ratings for all participants for each type and charting those averages using column charts. In addition, information from the group discussions was synthetized to identify common and main points. Results and main findings from the analysis are summarized in the next section.

4.1.1.2 Analysis Results and Summary

This section covers the results of CUTR focus group noise study. In addition to testing each of the rumble strip detail types, the analysis also compared the following:

- Drivers and passengers
- Shoulder and edgeline
- Speed limit vs. speed limit +5 mph
- Noise, vibration, overall (Note: Overall ratings were directly provided by the focus group participants and are not based on the computed average of the ratings of noise and vibration.)

A summary of the focus group discussions is also included. Results are presented separately for each site.

US-301 Drivers

The ratings for both Type 2 and Type 3 were higher than for Type 1 regardless of the speed or whether edgeline or shoulder was considered. Type 2 and Type 3 had very similar ratings for shoulder and edgeline. At higher speeds, for both Type 2 and Type 3, the noise from the rumble strips was more noticeable than was the vibration. Vibration, on the other hand, was the same for Type 2 at both speeds, but higher for Type 3 at lower speed. These results were the same for both shoulder and edgeline. For shoulders, overall, the performance of Type 2 and Type 3 were similar, and the difference was insignificant. Considering the edgeline, overall, Type 2 slightly outperformed Type 3. Comparing driver ratings for US-301, edgeline strips got higher ratings than shoulder strips at both 65 mph and 70 mph (see Figure 4-1, Figure 4-2, and Table C 1).

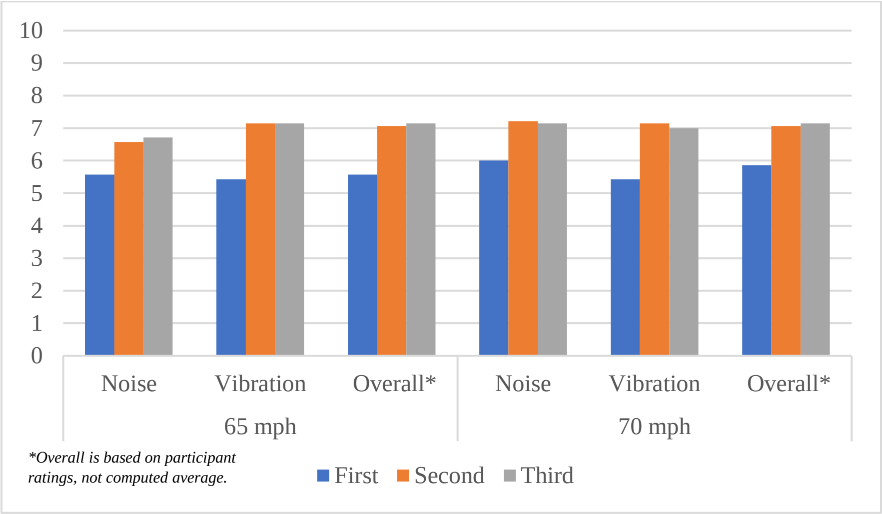


Figure 4-1. Average driver ratings for US-301 shoulder sinusoidal rumble strips

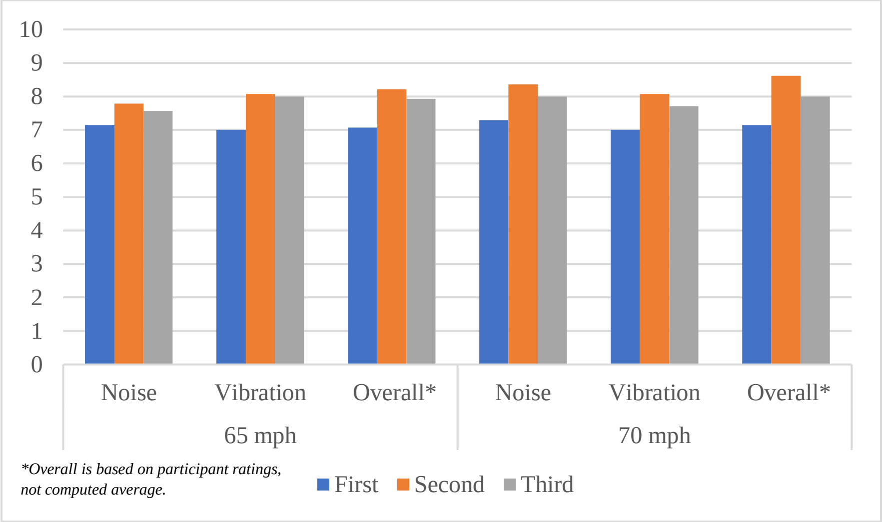


Figure 4-2. Average driver ratings for US-301 edgeline sinusoidal rumble strips

US-301 Passengers

Similar results were observed for passengers. For shoulder strips, Type 2 and Type 3 were rated higher than Type 1 regardless of speed. The noise and vibration from Type 2 and Type 3 shoulder strips were more alarming at higher speed than lower speed, leading to higher ratings for higher speed on all aspects. Contrary to driver ratings, edgeline Type 1 sometimes surpassed edgeline Type 2 and Type 3 based on passenger ratings. The results of passenger ratings for edgeline strips had mixed findings; however, overall, Type 2 edgeline strips outperformed at higher speed and Type 3 edgeline outperformed at lower speed.

The difference between passenger and driver ratings may be because passengers felt the vibration and noise from the bottom of the car seat, whereas drivers felt the vibration from the steering wheel. In addition, as the driver was focusing on the roadway, it may have been difficult to make a good judgment. Similar to drivers, passengers also had higher ratings for edgeline strips than shoulder strips at both 65 mph and 70 mph. These results are shown in Figure 4-3 and Figure 4-4 and in Table C 1 in the appendix.

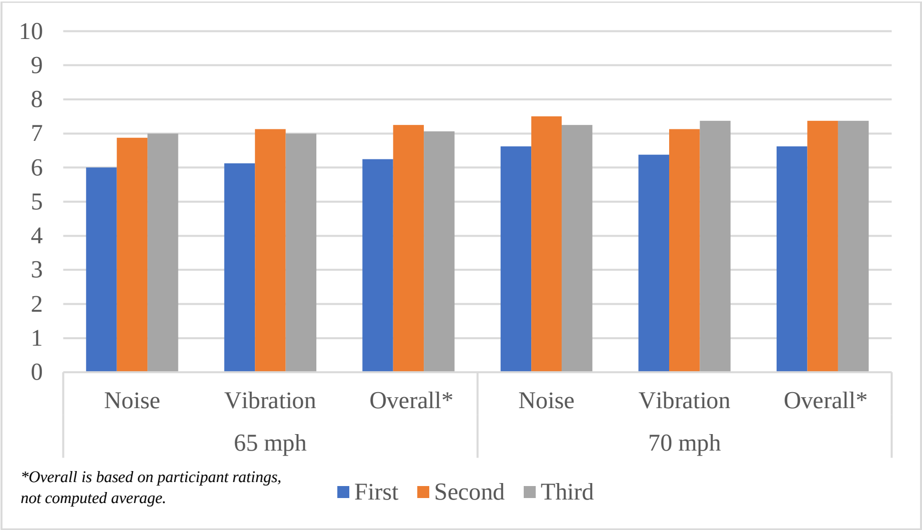


Figure 4-3. Average passenger ratings for US-301 shoulder sinusoidal rumble strips

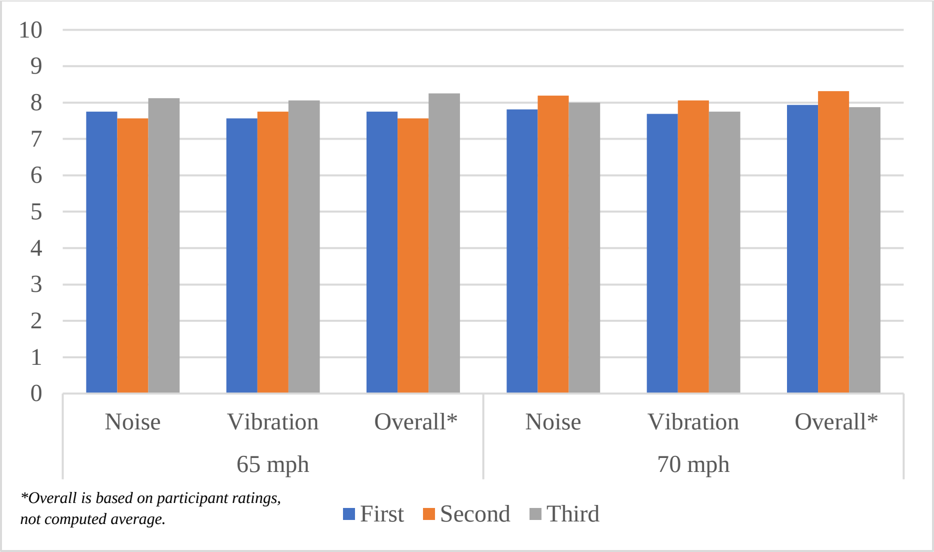


Figure 4-4. Average passenger ratings for US-301 edgeline sinusoidal rumble strips

SR-100 Drivers

In contrast to US-301, the SR-100 section was curvy, which made it difficult for drivers to maintain the required speed; this may have impacted their ratings. Regardless, Type 1 underperformed compared to Type 2 and Type 3 for both shoulder and edgeline strips at 60 mph and 65 mph. For SR-100, Type 3 was rated higher than Type 2 for shoulder and edgeline related to noise, vibration, and overall. At higher speed, for both Type 2 and Type 3, noise from the rumble strips was higher than at lower speed. Like US-301, edgeline strips had higher ratings than shoulder strips for SR-100 at 60 mph and 65 mph. More details about these findings are available in Figure 4-5, Figure 4-6, and Table C 2.

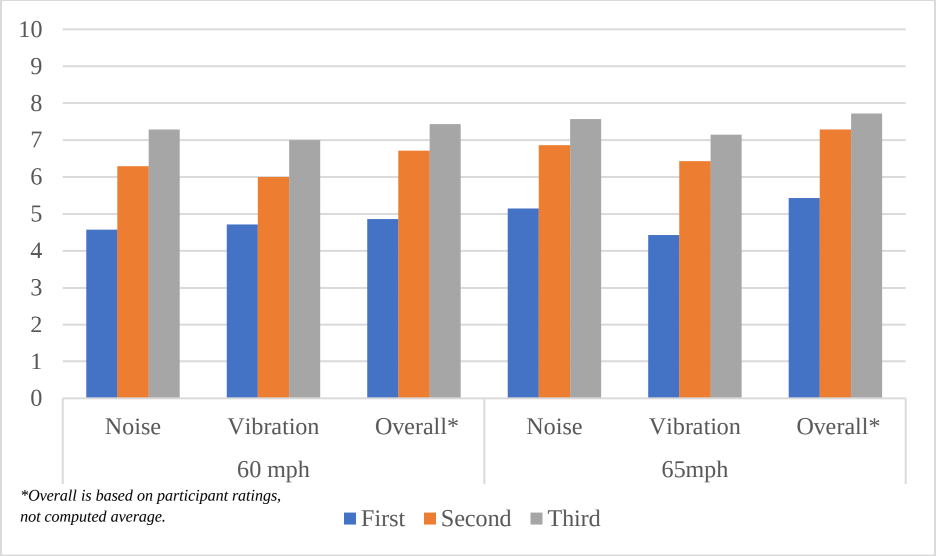


Figure 4-5. Average driver ratings for SR-100 shoulder sinusoidal rumble strips

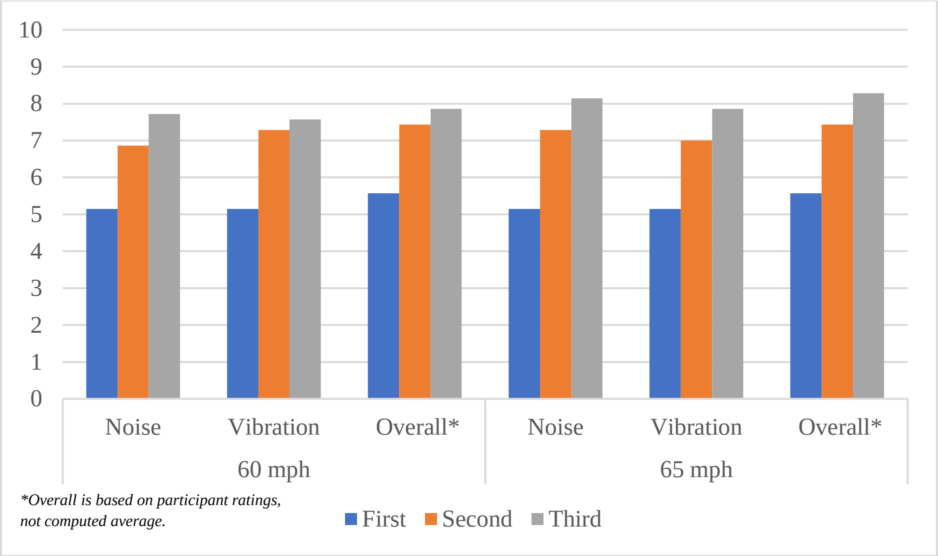


Figure 4-6. Average driver ratings for sR-100 edgeline sinusoidal rumble strips

SR-100 Passengers

Passenger ratings for SR-100 indicated that Type 3 surpassed both Type 2 and Type 1, with Type 1 having the lowest performance among the three. These results applied at 60 and 65 mph for noise, vibration, and overall as well as for shoulder and edgeline. For the shoulder, noise and vibration were more alerting at higher speed than lower speed. Overall, higher speed yielded better results for shoulder strips. As with US-301, the SR-100 edgeline ratings from passengers showed mixed results. Nevertheless, vibration for edgeline strips seems to perform better at higher speed for passengers. Like the others, the edgeline strips had better ratings than shoulder strips at both 60 mph and 65 mph. The results are shown in Figure 4-7, Figure 4-8, and Table C 2.

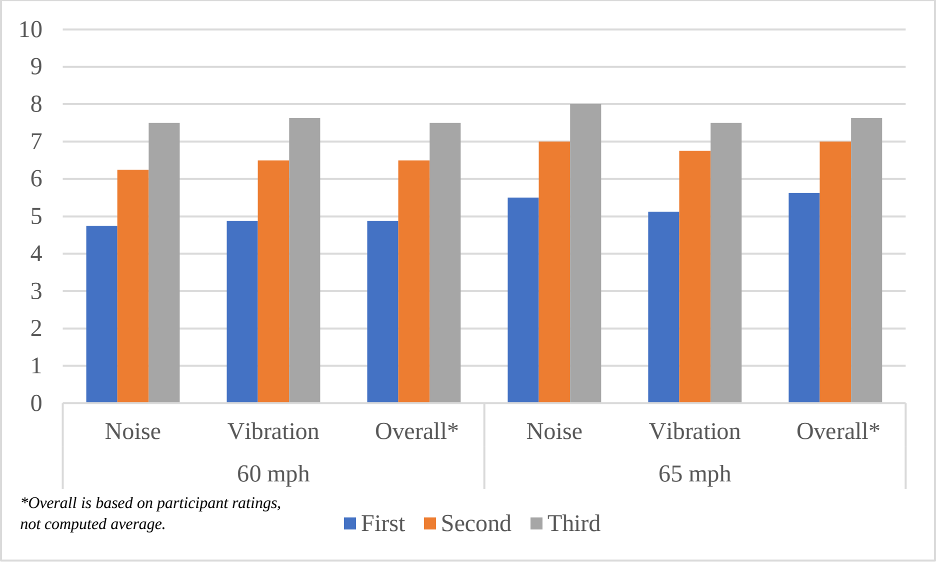


Figure 4-7. Average passenger ratings for SR-100 shoulder sinusoidal rumble strips

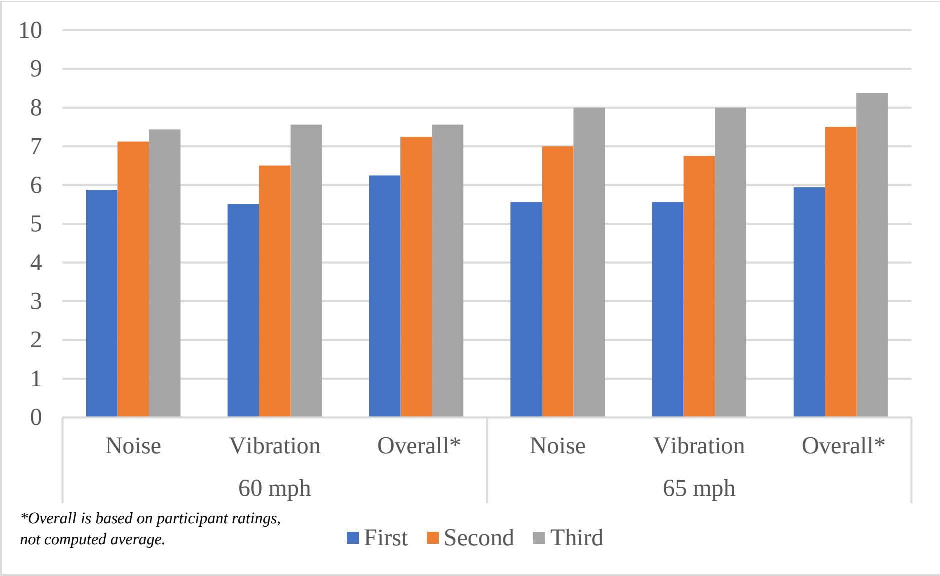


Figure 4-8. Average passenger ratings for SR-100 edgeline sinusoidal rumble strips

4.1.1.3 Major Findings

The major findings from the analysis and focus group discussions include the following:

- Noise and vibration from Type 1 shoulder and edgeline strips were not as noticeable as for Type 2 and Type 3, such that Type 1 underperformed overall compared to Type 2 and Type 3.
- Type 2 and Type 3 performed similarly most of the time, with Type 2 performing better under some conditions and Type 3 surpassing Type 2 under other circumstances.
- The performance of the rumble strips may have depended on how the driver hit them—for example, the driving angle or whether they kept driving on the strips or weaving.
- Edgeline rumble strips were more effective than shoulder rumble strips at both sites.
- Speed could make a difference when evaluating noise and vibration from rumble strips, especially on a curvy roadway.
- Passengers and drivers felt the rumble strips differently, which may be because drivers were alerted directly from the noise and vibration from the steering wheel, whereas passengers heard noise and sensed the vibration from the bottom of their seat. The fact that drivers were more focused on the roadway may have affected their ratings as well.
- Vehicle type and model made a difference—for example, vibration from the rumble strips was felt more when in a sedan compared to an SUV.

4.1.2 FDOT Materials Office Studies

This section summarizes the results of FDOT field studies. The findings are also separated by sites. The effectiveness of sinusoidal rumble strips related to both exterior and interior noise are considered.

4.1.2.1 US-301

For the outside noise results by the FDOT materials office, the average OBSI (noise) levels of the test sections along with the mainline are shown in Figure 4-9. For Type B (edgeline), all the outside noise levels of three study types were all above the noise level of the mainline. Overall, Type 2 had the best performance which consistently produced lower outside noise levels than those from Type 1 or 3.

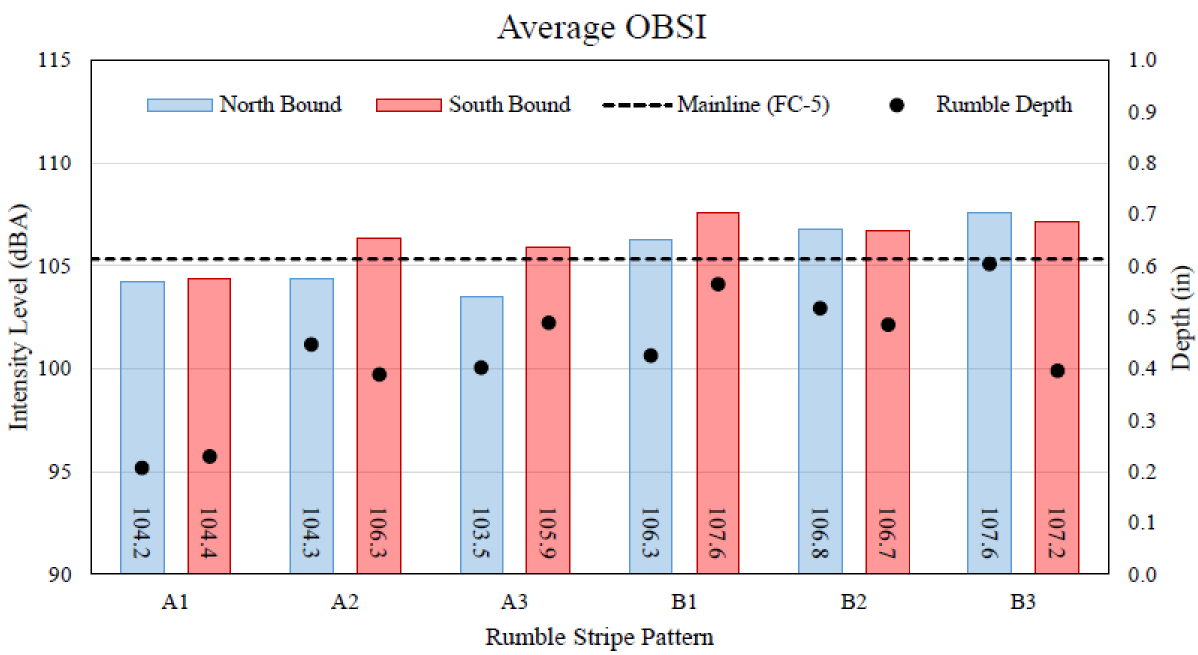


Figure 4-9. Comparison of US-301 OBSI levels

Source: FDOT, 2022a

A more in-depth study by FDOT using single linear regressions shows that rumble type and depth are more related to the outside noise measurements (OBSI) than the rumble length (see Table 4-1, Figure 4-10, and Figure 4-11).

Table 4-1. Single Linear Regression Model ANOVA Table (OBSI)

Regression Model	ANOVA	df	SS	MS	F	Significance F
OBSI vs Type	Regression	1	15.073	15.073	20.320	0.001
	Residual	10	7.417	0.742		
	Total	11	22.490			
OBSI vs Depth	Regression	1	10.639	10.639	8.978	0.013
	Residual	10	11.851	1.185		
	Total	11	22.490			
OBSI vs Length	Regression	1	0.225	0.225	0.101	0.757
	Residual	10	22.265	2.226		
	Total	11	22.490			

Source: FDOT, 2022a

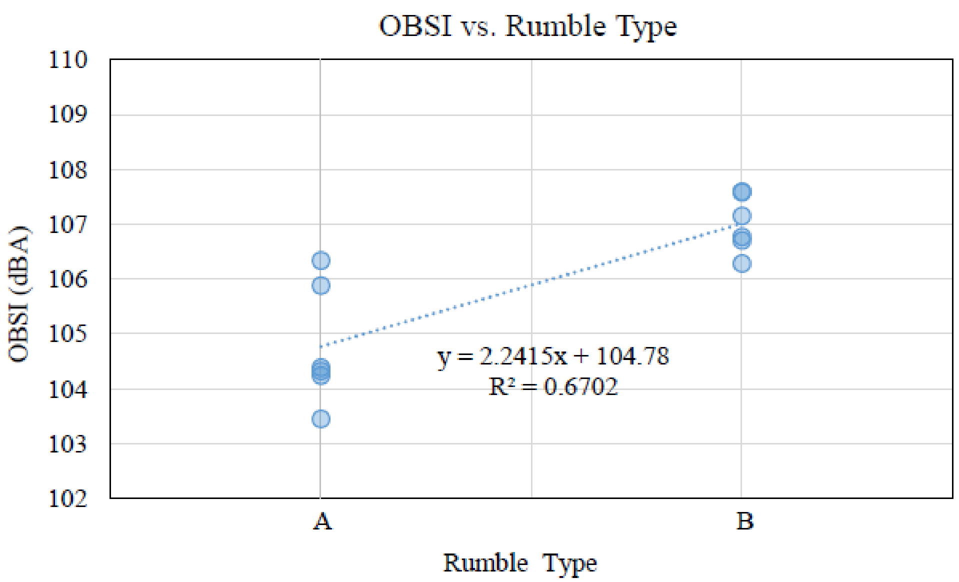


Figure 4-10. Relationship between OBSI and rumble type

Source: FDOT, 2022a

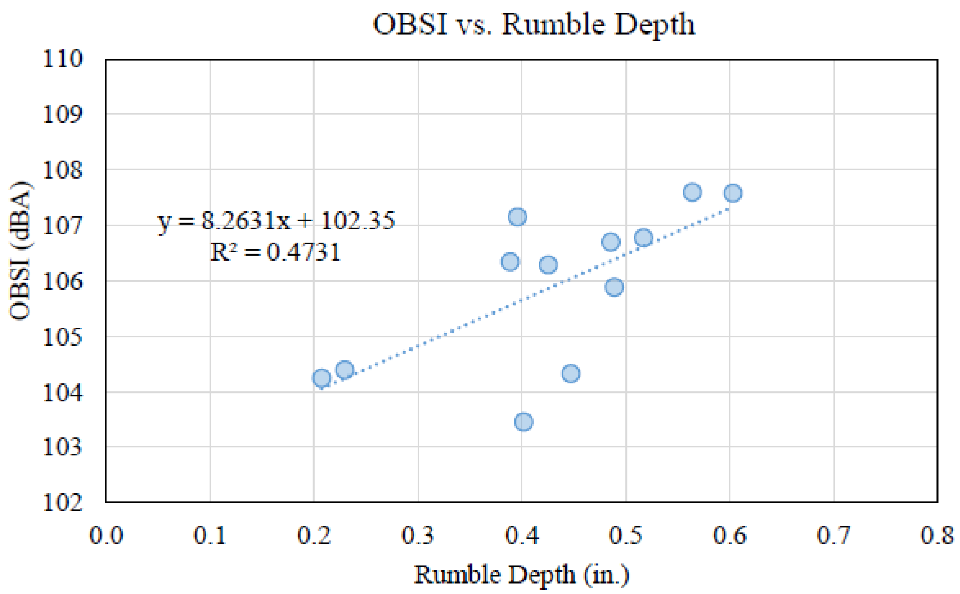


Figure 4-11. Relationship between OBSI and rumble depth

Source: FDOT, 2022a

The average cabin noise levels of the test sections together with the mainline are shown in Figure 4-12. The cabin (inside) noise levels for all three types were all much higher than that of the mainline, which means all three types can effectively provide alerts to drivers on potential lane departures. For Type A (shoulder), there was little difference on the inside noise levels measured among the three types. For Type B (edgeline), the inside noise levels of Types 1 and 3 are higher, but Type 2 can effectively provide alerts to drivers on potential lane departures.

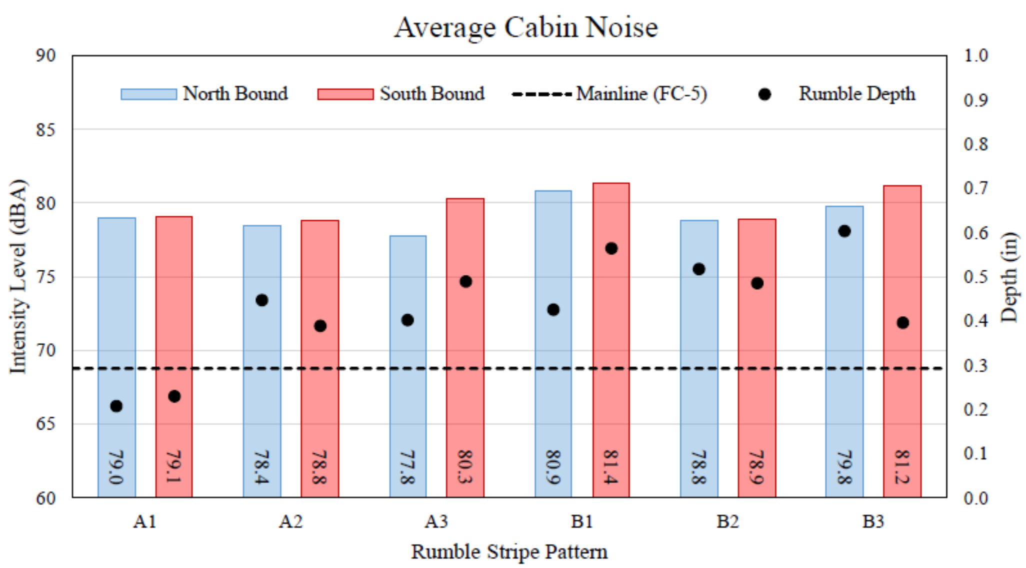


Figure 4-12. Comparison of US-301 cabin noise levels

Source: FDOT, 2022a

An extended analysis also shows that rumble type rather than rumble depth and length is related to the inside vehicle noise measurement. The relation between rumble type and inside vehicle noise is exemplified in Figure 4-13.

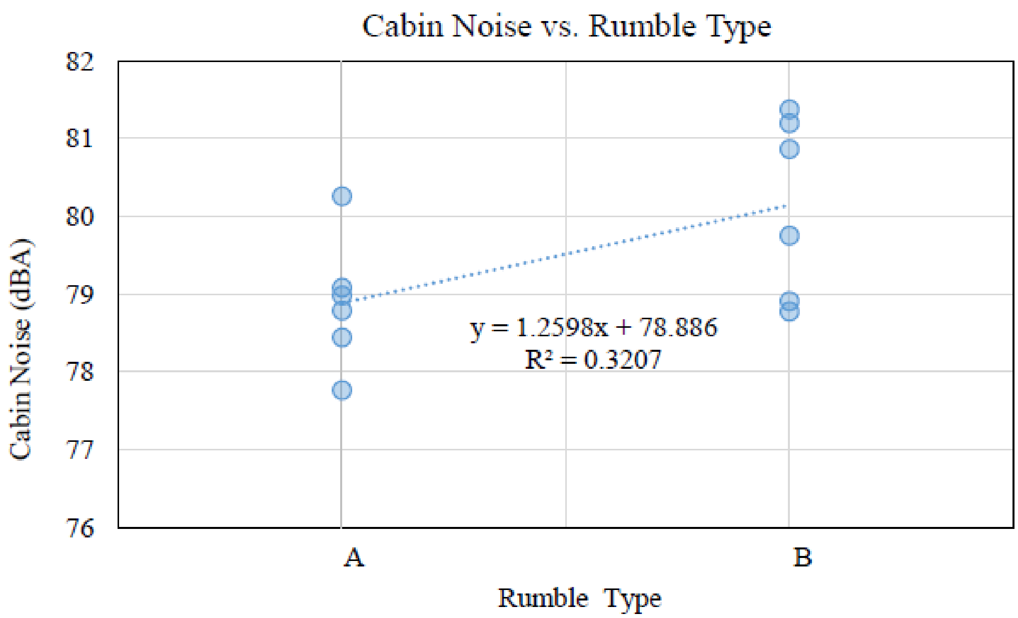


Figure 4-13. Relationship between cabin noise and rumble type

Source: FDOT, 2022a

4.1.2.2 SR-100

For SR 100, the average OBSI (outside noise) levels of the six types of sinusoidal rumble strips along with the nearby asphalt surface and profiled thermoplastic rumble strips are provided in Figure 4-14. On average, the outside noise levels of the three study types were similar and had no major difference. There were some variations of the outside noise levels for Type 1 between Type A and Type B. All three sinusoidal types produced much less noises than that from profiled thermoplastic rumble strips.

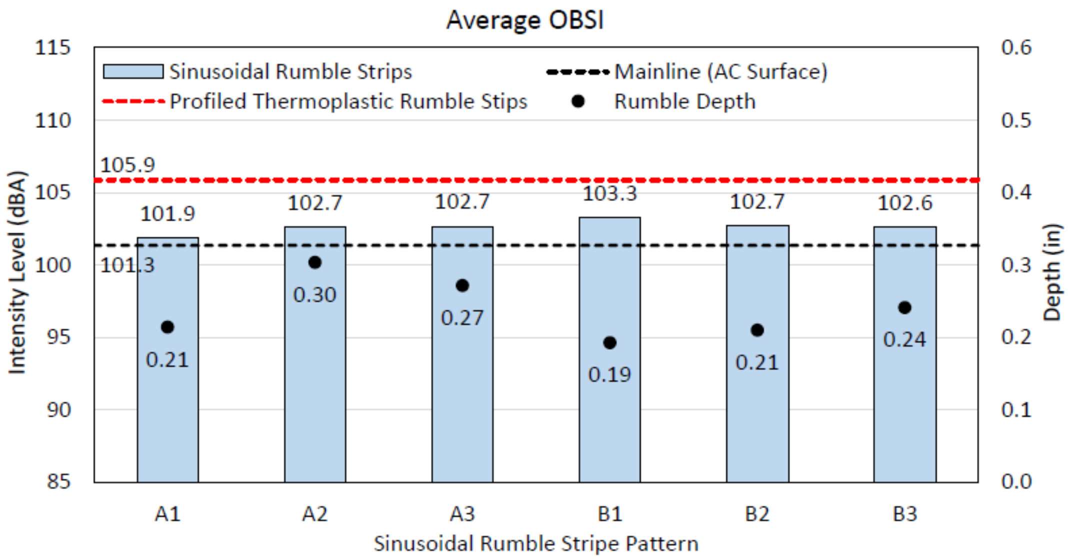


Figure 4-14. Comparison of SR-100 OBSI levels

Source: FDOT, 2022b

The average cabin noise (inside noise) levels of the six types of sinusoidal rumble strips with the nearby asphalt surface and profiled thermoplastic rumble strips are displayed in Figure 4-15. The inside noise levels for all three types were all much higher than those of the mainline and profiled thermoplastic rumble strips, which means all three types can effectively provide alerts to drivers and they are better for reducing outside noises than the profiled thermoplastic rumble strips. For Type A, there was little difference on the inside noise levels measured among the three types. For Type B, the inside noise levels of Types 1 and 3 are higher.

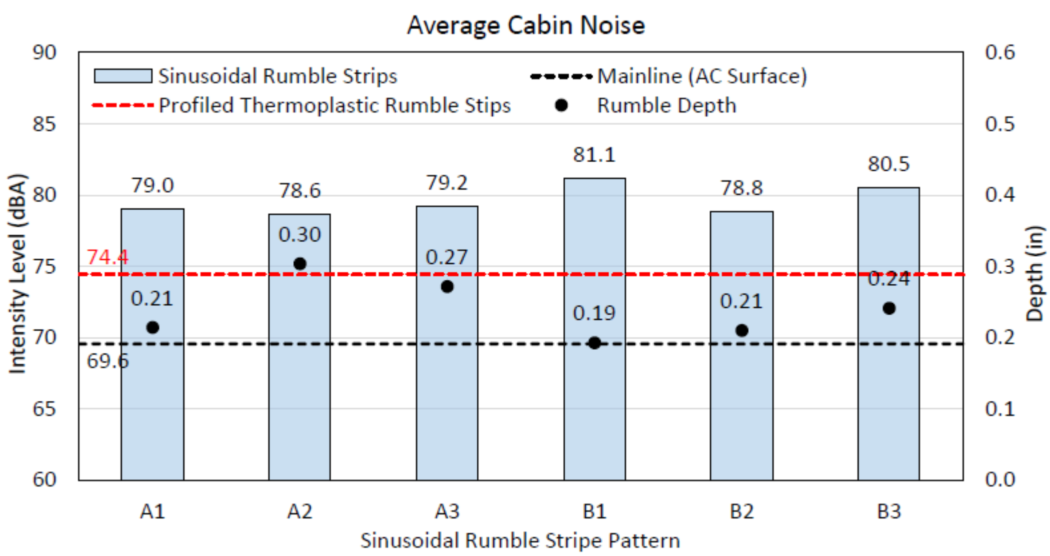


Figure 4-15. Comparison of SR-100 cabin noise levels

Source: FDOT, 2022b

4.1.3 Effects of Pitch of Sounds on Drivers' Alertness

The pitch of a sound is different from the volume. The pitch is based on frequency while the volume is based on amplitude. Amplitude measures the loudness or quietness of a sound, whereas pitch measures the highness or lowness of a sound. A higher frequency sound has a higher pitch, and a lower frequency sound has a lower pitch. Drivers' sensitivity to different pitch ranges can vary. Some drivers may have greater sensitivity to high-pitched sounds, while others may be more sensitive to low-pitched sounds. It is stated that human ears are generally more sensitive to sounds in the mid-frequency range, which corresponds to the frequencies of many human speech sounds. Among the three types of sinusoidal rumble strips evaluated during the noise studies, type 1 was found to produce high-pitched sound while Type 3 was determined to yield low-pitched sound. Among the three types, the sound from Type 2 was intermediate, thus allowing drivers to be alerted effectively. Additionally, based on a driving study performed by FDOT, which included the former project manager and his colleagues, there was a consensus that the pitch level of the sound generated by vehicles on Type 2 sinusoidal rumble strips is the best to inform drivers of a vehicle departure risk among the three FDOT designs of sinusoidal rumble strips. Their assessment result was also consistent with the fact that the pitch level of the sound in the middle (not too high or too low) is effective and pleasant to alert people.

4.1.4 Main Takeaways from CUTR and FDOT Studies

From the perspective of outside noise levels, Type 2 produced more consistent and less noise than those from Type 1 and Type 3, so Type 2 sinusoidal design is the best design to reduce outside noise. From the perspective of inside noise levels measured by the FDOT Materials Office, although Type 1 and Type 3 sinusoidal designs produced slightly higher inside noises from the edgelines of US-301, the inside noises generated from all three types of sinusoidal design were much higher than those of the mainline and profiled thermoplastic rumble strips, which means all three types can effectively provide alerts to drivers and they are also better for reducing outside noises than the profiled thermoplastic rumble strips. Based on the CUTR focus study on inside noise level comparison among the three sinusoidal design types, Types 2 and 3 were recommended since the ratings from participants were similar. From the perspective of effects of pitch of sounds on drivers' alertness, Type 2 is the best selection among the three sinusoidal designs and supported by the former FDOT project manager with the FDOT Roadway Design Office.

Overall, the Type 2 sinusoidal rumble strip design is the best among the three sinusoidal designs in this study based on the above detailed assessment and evaluation results from CUTR, FDOT Materials Office, and FDOT Roadway Design Office. Compared to other strips, sinusoidal rumble strips have lower outside noise and louder inside noise. Therefore, the CUTR project team recommended and confirmed that Type 2 sinusoidal rumble strips are the best for FDOT future implementations if deemed needed to reduce outside noise level and other roadway or lane departure problems.

4.2 Sinusoidal AVT Safety Assessment Results based on Florida Data

This section notes the findings from the safety evaluations, which were based on FDOT sinusoidal rumble strip implementation data. This is an important and innovative part of the project since no studies are available on the safety benefits of sinusoidal AVT to the project team knowledge. The results of the overall crashes and severe crashes are organized separately.

4.2.1 Effectiveness Evaluation of Sinusoidal AVT on Crash Reduction

Understanding the effects of sinusoidal AVT on overall crash reduction is useful and it is an addition to the current related body of literature. This sub-section informs readers about the significance test and CMF results for overall crash analysis. Different variations of the results, including variance and confidence intervals are emphasized. Equations used to reach results are also included.

4.2.1.1 Significance Test

An overall significance test was conducted to determine whether the crash rate (number of crashes per year) before and after the treatment at the implemented sites were significantly different. Due to the nature of the data, t-tests were conducted to check the significance. It was found that the crash rate before and after the treatment was significantly different. The p-value for the t-test was found out to be 0.06 meaning a 90% confidence level. The mean crash rate before was 0.93 while the mean crash rate after was 0.41 showing significant reduction in crash rate after the sinusoidal rumble strips were implemented.

For comparison purpose, the Welch two sample t-test was performed crash rate for the reference sites, given the same before and after periods with the corresponding implemented site, and that there were no sinusoidal rumble strips implemented. It was found out that the rash rates at the control sites in the before and after periods were not significantly different. The mean crash rate before the treatment at the control sites was 0.57 while after was 0.39.

4.2.1.2 Development of Florida-Specific Crash Modification Factor (CMF) on Sinusoidal AVTs

CMF calculations using the Empirical Bayes before-after method

A safety performance function (SPF) is a statistical model used to predict the average number of crashes per year at a location. SPFs are usually based on traffic volume and roadway segment length. In this study, we used a negative binomial model due to the existing overdispersion of the variable. Since the analyzed data consisted of segments containing rural two-lane and rural multi-lane segments, Equations (4.1) and (4.2) are SPFs for rural two-lane roads and rural multi-lane roads respectively, which are defined in the Highway Safety Manual to estimate the predicted crash frequencies (Chapter 10, Chapter 11).

$$N_{spf\ rs} = AADT \times L \times 365 \times 10^{-6} \times e^{-0.312} \quad (4.1)$$

$$N_{spf\ ru} = e^{a+b\times\ln(AADT)+\ln(L)} \quad (4.2)$$

Where,

$N_{spf\ rs}$: predicted total crash frequency for roadway segment for two-lane rural roads
$N_{spf\ ru}$: predicted total crash frequency for roadway segment for multilane highways
a, *b*: Coefficients obtained from the negative binomial model
AADT: average annual daily traffic volume (vehicle per day)
L: length of roadway segment (mile)

Using the SPF model coefficients, the predicted total crash frequencies for the implemented sites were calculated. The CMF for lane widths were calculated from the highway safety manual. Using this CMF, a calibration factor (C_x) of 1.1 and SPF predicted crashes, the $N'_{predicted}$ crashes were calculated which are the weighted crashes using the following equation:

$$N'_{predicted} = N_{spf} \times (CMF_{ra}) \times C_x \tag{4.3}$$

Next, the SPF weighting factor was calculated for each individual site using equation (4.4)

$$w = \frac{1}{1 + N'_{predicted} \times Y \times \alpha} \tag{4.4}$$

Where, *w* is the SPF weight, *Y* is the number of observation years and alpha is the overdispersion parameter. Next the expected crashes for the before period for the treatment site were calculated using the following equation:

$$N_{expected,T,B} = w\left(N_{predicted,T,B}\right) + (1 - w)\left(N_{observed,T,B}\right) \tag{4.5}$$

Next, the ratio between the predicted after and before crashes for the treatment site ($N_{predicted,T,A}/N_{predicted,T,B}$) is calculated which is used to calculate the expected after crashes at the treatment site. The equation used to calculate is:

$$N_{expected,T,A} = N_{expected,T,B}\left(\frac{N_{predicted,T,A}}{N_{predcited,T,B}}\right) \tag{4.6}$$

Where,

$N_{expected,T,A}$ = the adjusted empirical Bayes estimate
$N_{expected,T,B}$ = the unadjusted empirical Bayes estimate
$N_{predicted,T,B}$ = the predicted number of crashes estimated by the SPF in the before period
$N_{predicted,T,A}$ = the predicted number of crashes estimated by the SPF in the after period

The variance of $N_{expected,T,A}$ is estimated from $N_{expected,T,A}$, the before and after SPF estimates and the SPF weight (*w*). The equation is:

$$Var\left(N_{expected,T,A}\right) = N_{expected,T,A}\left(\frac{N_{predicted,T,A}}{N_{predicted,T,B}}\right)(1 - w) \tag{4.7}$$

According to CMF Guide by Federal Highway Administration (FHWA) (Gross et al., 2010), $N_{expected,T,A}$ and $Var(N_{expected,T,A})$ are computed for each site individually and then summed to be used in the calculation of the CMF. Next, the CMF and its variance are calculated through Equations (4.8) and (4.9) respectively:

$$CMF = \frac{\left(\frac{N_{observed,T,A}}{N_{expected,T,A}}\right)}{\left(1 + \left(\frac{Var\left(N_{expected,T,A}\right)}{N_{expected,T,A}^2}\right)\right)} \tag{4.8}$$

$$Var(CMF) = \left(\frac{CMF^2\left(\left(\frac{1}{N_{observed,T,A}}\right) + \left(\frac{Var\left(N_{expected,T,A}\right)}{N_{expected,T,A}^2}\right)\right)}{\left(1 + \left(\frac{Var\left(N_{expected,T,A}\right)}{N_{expected,T,A}^2}\right)\right)^2}\right) \tag{4.9}$$

Using the above equations, the overall CMF based on the overall dataset is computed as 0.43 for the sinusoidal rumble strips, and the variance of the CMF is computed as 0.03. This result means that the implemented sinusoidal rumble strips are expected to reduce total lane departure crashes by (1-CMF) ×100% = (1-0.43) × 100%=57%. Accordingly, the standard error is $\left(\sqrt{Var(CMF)}\right)$ which is computed as 0.18 while the 95% confidence interval for the CMF is $(0.43 \pm 1.96 \times 0.18)$ which came up to be (0.08,0.78). Therefore, this overall CMF is significant at the 95% confidence interval.

To better capture the safety effectiveness of sinusoidal rumble strips on different types of roadways, an individual CMF was computed for rural two-land road and rural multi-lane roads, respectively. In detail,

- For the rural two-lane roadway type, the CMF was computed as 0.70 with a variance of 0.07 and a standard error as 0.27. This result means that the sinusoidal rumble strip is expected to reduce total lane departure crashes on rural two-lane roads by (1-0.70) ×100% =30%. The 95% confidence interval of the CMF for the rural two-lane road was computed to be (0.17, 1.23), and the 90% confidence interval is (0.25, 1.15). Therefore, this CMF is not significant at the 90% confidence level.
- For the rural multi-lane roadway type, the CMF was computed as 0.39 with a variance of 0.04 and a standard error of 0.20. This result means that the sinusoidal rumble strip is expected to reduce total lane departure crashes on rural multi-lane roads by (1-0.39) ×100% =61%. The 95% confidence interval was computed as (0, 0.78). Therefore, this CMF is significant at the 95% confidence interval.

Next, the CMFs for the severe injury severity, including both fatality (K) and incapacitating injury (A), were also computed for combined roadways, rural two-lane roadways, and rural multi-lane roadways. Interpreted similarly,

- The CMF for fatal and serious injury crashes based on the overall dataset was 0.38 with a variance of 0.03 and a standard error of 0.17. This result means that the sinusoidal rumble strip is expected to reduce fatal and serious lane departure crashes by (1-0.38) ×100% =62%. This CMF is significant at the 95% confidence interval.
- For the rural two-lane roadway type, the CMF for fatal and serious injury crashes was computed as 0.18 with a variance of 0.12 and a standard error as 0.35. This result means that the sinusoidal rumble strip is expected to reduce fatal and serious lane departure crashes on rural two-lane roads by (1-0.18) ×100% =82%. This CMF is significant at the 95% confidence interval.
- For the rural multi-lane roadway type, the CMF for fatal and serious injury crashes was computed as 0.43 with a variance of 0.03 and a standard error of 0.19. This result means that the sinusoidal rumble strip is expected to reduce fatal and serious lane departure crashes on rural multi-lane roads by (1-0.43) ×100% =57%. This CMF is significant at the 95% confidence interval.

The CMF is less than 1.0 for all the six models, which indicates an expected reduction in total number of lane departure crashes after implementation of the sinusoidal rumble strip. The summary of these results is shown below in Table 4-2.

Table 4-2. CMFs by Roadway and Crash Severity Type

No.	Model	CMF	Variance	Standard Error	95% Confidence Interval
1	Combined Roadways	0.43	0.03	0.18	(0.08, 0.78)
2	Two-lane Rural Road	0.70	0.07	0.27	(0.17, 1.23)
3	Multilane Highway	0.39	0.04	0.20	(0, 0.78)
4	Combined Roadways (Fatal and Serious Injury)	0.38	0.03	0.17	(0.05, 0.71)
5	Two-lane rural road (Fatal and Serious Injury)	0.18	0.12	0.35	(0, 0.86)
6	Multilane rural road (Fatal and Serious Injury)	0.43	0.03	0.19	(0.05, 0.81)

4.2.2 Crash Severity and Contributing Factor Analysis

It is also necessary to investigate the influence of sinusoidal rumble strip presence on lane departure crash severity outcomes, along with the potential influence of other crashes, traffic, roadway, and driveway characteristics on crash severities. The research team used the multinomial logit (MNL) model, an effectiveness-proven unordered discrete modeling approach in contemporary literature, to identify the significant variables and assess their respective impact. Florida adopted the “KABCO” injury scale defined by the Federal Highway Administration (FHWA) to document crash and road user injury severities, where “K” indicates fatality, “A” represents “incapacitating injury,” “B” denotes non-incapacitating injury, “C” is possible injury, and “O” is no injury (property damage only). Fatal and incapacitating injury crashes are of the highest interest in traffic safety but often account for a very small proportion of all crashes. Therefore, in this study, the research team aggregated the KABCO injury scale to severe injury (K and A), minor injury (B and C) and no injury (O) crashes for modeling process. Marginal effect analysis was conducted to quantify the magnitude of influence of these identified variables. Table 4-3 show the available variables for model estimation and their descriptions. As seen in the table we have a total of 42 variables in the model for estimation in which “Crash Severity” is the dependent variable. Table 4-3 shows the list of available variables. There is a total of 1,641 observations available in the dataset. Table 4-4 shows the summary statistics of the variables used in the model.

Table 4-3. Variables for Driver Injury Severity Model Estimation

Variable No.	Variable Description
1	Crash year
2	Crash date
3	Crash time
4	Total number of vehicles involved in crash
5	Latitude
6	Longitude
7	Road system identifier (State, U.S., Local, Parking lot, Private Roadway, Other, Interstate, County, Forest Road)
8	Type of shoulder (Paved, Unpaved, Curb)
9	Light condition (Dark – Lighted, Dark - Not Lighted, Dark – Unknown Lighting, Dawn, Daylight, Dusk, Unknown)
10	Weather conditions (Clear, Cloudy, Fog, Smog, Smoke, Other, Rain, Severe Crosswinds)
11	Road surface condition (Dry, Mud, Dirt, Gravel, Other, Unknown, Water (standing/moving), Wet)
12	Type of impact (Other, Sideswipe, Same Direction, Sideswipe, Opposite Direction, Front to Rear, Front to Front, Angle, Rear to Side, Rear to Rear)
13	Location (Gore, In Parking Lane or Zone, Median, Off Roadway, On Roadway, Roadside, Shoulder, Unknown)

Variable No.	Variable Description
14	Crash type simplified (Off-Road, Other, Rollover, Rear End, Animal, Sideswipe, Left Turn, Head On, Angle, Pedestrian, Unknown, Bicycle, Right Turn)
15	Crash severity (No Injury [NI], Minor Injury [MI], Serious Injury [SI])
16	Crash severity detail (No Injury, Non-Incapacitating Injury, Incapacitating Injury, Possible Injury, Fatal (within 30 days), Non-Traffic Fatality)
17	Aggressive driving indicator variable (1 - Yes, 0 - No)
18	Drug-related crash indicator variable (1 - Yes, 0 - No)
19	Alcohol-related crash indicator variable (1 - Yes, 0 - No)
20	Commercial Vehicle involvement indicator variable (1 - Yes, 0 - No)
21	Distracted driving indicator variable (1 - Yes, 0 - No)
22	Hit and run indicator variable (1 - Yes, 0 - No)
23	Non-motorist count variable
24	FPID (unique ID)
25	Functional class of roadway
26	Lane count of roadway
27	AADT for 2022
28	AADT for 2021
29	AADT for 2020
30	AADT for 2019
31	AADT for 2018
32	AADT for 2017
33	AADT for 2016
34	Sinusoidal rumble strip present indicator variable (1-Yes, 0-No)
35	Site (1-Implemented Site, 0-Reference Site)
36	Period (1-After, 0-Before)
37	Population
38	County Area
39	AADT in accident year
40	Growth Rate of roadway
41	Natural log of AADT

Table 4-4. Summary Statistics for Model Variables.

Variable Description	Mean	Std. Dev.	Min	Max
Aggressive driving indicator variable (1 if yes, 0 if no)	0.048	0.209	0	1
Crash severity (No Injury [NI], Minor Injury [MI], Serious Injury [SI])	0.333	0.472	0	1
Two-lane road indicator variable (1 if two-lane road, 0 otherwise)	0.881	0.324	0	1
Alcohol or drug related indicator variable (1 if alcohol or drug related, 0 otherwise)	0.061	0.239	0	1
Front to rear (FTR) collision type indicator variable (1 if FTR collision, 0 otherwise)	0.024	0.154	0	1
Side impact indicator variable (1 if yes, 0 otherwise)	0.338	0.473	0	1
Crash type indicator variable (1 if angle crash, 0 otherwise)	0.064	0.245	0	1
Weather indicator variable (1 if weather is foggy, smoggy, or smoke, 0 otherwise)	0.010	0.101	0	1
Lighting condition indicator variable (1 if lighting is dark, 0 otherwise)	0.179	0.384	0	1
State Roadway function indicator variable (1 if state road, 0 otherwise)	0.438	0.496	0	1
Local Roadway function indicator variable (1 if local road, 0 otherwise)	0.148	0.355	0	1
Multi-vehicle crash indicator variable (1 if multi-vehicle crash, 0 otherwise)	0.441	0.497	0	1
High AADT indicator (1 if AADT in accident year is greater than 15000, 0 otherwise)	0.656	0.475	0	1

Table 4-5 shows the MNL modeling and marginal effects estimation results. Using No Injury (NI) as the base condition, a total of 17 parameters were found to be significant in predicting Minor Injury (MI) or Severe Injury (SI) or both at a minimum of 10% significance level. Both the constant terms for minor injury and severe injury also were significant at the 1% significance level. All included variables have a t-statistic above 1.9 which means that we are more than 90% confident that the estimated parameters are statistically different from zero when conducting a two-tailed t-test. The probability of no injury, minor injury and severe injury severity is:

$$P(n) = \frac{e^{V_n}}{e^{V_n} + e^{V_m} + e^{V_s}}, P(m) = \frac{e^{V_m}}{e^{V_n} + e^{V_m} + e^{V_s}}, P(s) = \frac{e^{V_s}}{e^{V_n} + e^{V_m} + e^{V_s}} \quad (3.10)$$

where P(n), P(m) and P(s), are the probabilities for the no injury (NI), minor injury (MI) and severe injury (SI) respectively and V_n, V_m and V_s are corresponding indirect utility functions. Based on the parameter estimates in Table 4-5, the estimated utility functions are:

$$\boldsymbol{V_n = 0} \quad \mathbf{(3.11)}$$

$$V_m = -1.30 + 0.81 * (front\ to\ rear\ collision) + 0.80 * (alcohol\ and\ drug\ use\ indicator) + 0.53 * (angle\ impact) - 0.43 * (multi - car\ collision) - 0.65 * (high\ AADT) + 0.29 * (dark\ lighting) + 0.65 * (two - lane\ indicator) + 0.27 * (state\ road) \quad (3.12)$$

$$V_s = -2.45 + 1.87 * (alcohol\ and\ drug\ use\ indicator) + 0.77 * (aggressive\ driving) - 0.96 * (high\ AADT) - 1.57 * (side - to - side\ impact) + 0.73 * (two - lane\ indicator) - 1.96 * (local\ road\ system) + 1.38 * (foggy\ weather) \quad (3.13)$$

It shows in the above utility functions that there is no constant term for V_n. This is because constants are estimated as variables that do not vary across alternate outcomes and therefore can appear in at most (i–1) functions (constants are estimated as βX with X being a vector of 1's, and this vector does not vary across alternate outcomes). The lack of constant in the no injury severity function establishes it as a 0 baseline. Thus, all else being equal, the minor injury severity is more likely to occur relative to the severe injury severity (with its smaller negative constant). And all else being equal, the severe injury severity is less likely to occur than the minor and no injury severity. All the variables used in the analysis do not vary across alternate outcomes so at most are estimated in (i-1) functions (in this case two). Hence, these variables are implicitly set to zero and the same relativity logic discussed above for the constants applies.

Table 4-5. Accident Severity Proportions Estimations Results with Multinomial Logit Model

Variable Description	Estimated Parameter	*t*-stat	Marginal Effects		
			No Injury	Minor Injury	Severe Injury
Constant **[MI]**	-1.30***	-6.86	-	-	-
Constant **[SI]**	-2.45***	-7.50	-	-	-
Front to rear (FTR) collision type indicator variable (1 if FTR collision, 0 otherwise) **[MI]**	0.81**	2.45	-0.0089	0.0109	-0.0089
Alcohol or drug-related indicator variable (1 if alcohol or drug-related, 0 otherwise) **[MI]**	0.80***	3.28	-0.0171	0.0318	-0.0171
Angle crash indicator variable (1 if angle crash, 0 otherwise) **[MI]**	0.53**	2.32	-0.0103	0.0234	-0.0103
Multi-vehicle crash indicator variable (1 if multi-vehicle crash, 0 otherwise) **[MI]**	-0.43***	-3.09	0.0346	-0.1537	0.0346
High AADT indicator (1 if AADT in accident year is greater than 15000, 0 otherwise) **[MI]**	-0.65***	-4.34	0.0919	-0.3403	0.0919
Lighting condition indicator variable (1 if lighting is dark, 0 otherwise) **[MI]**	0.29*	1.91	-0.0172	0.0344	-0.0172
Two-lane road indicator variable (1 if two-lane road, 0 otherwise) **[MI]**	0.65***	3.14	-0.1426	0.4331	-0.1426
State roadway function indicator variable (1 if state road, 0 otherwise) **[MI]**	0.27**	2.27	-0.0310	0.0887	-0.0310
Alcohol or drug-related indicator variable (1 if alcohol or drug-related, 0 otherwise) **[SI]**	1.87***	6.17	-0.0273	-0.0273	0.0866

Variable Description	Estimated Parameter	*t*-stat	Marginal Effects		
			No Injury	Minor Injury	Severe Injury
Aggressive driving indicator variable (1 if yes, 0 if no) **[SI]**	0.77**	2.18	-0.0061	-0.0061	0.0292
High AADT indicator (1 if AADT in accident year is greater than 15000, 0 otherwise) **[SI]**	-0.96**	-3.80	0.0228	0.0228	-0.6073
Side impact indicator variable (1 if yes, 0 otherwise) **[SI]**	-1.57***	-3.81	0.0067	0.0067	-0.5215
Two-lane road indicator variable (1 if two-lane road, 0 otherwise) **[SI]**	0.73***	2.03	-0.0361	-0.0361	0.6086
Roadway function indicator variable (1 if local road, 0 otherwise) **[SI]**	-1.96***	-2.70	0.0024	0.0024	-0.2873
Weather indicator variable (1 if weather is foggy, smoggy, or smoke, 0 otherwise) **[SI]**	1.38**	2.21	-0.0034	-0.0034	0.0110
Number of observations	1,641				
Number of estimated parameters	17				
Log-likelihood at convergence	-1,151.44				

SI = Severe Injury; MI = Minor Injury; NI = No Injury.
***, **, *: significance at 1%, 5%, 10% level

Looking at the utility function for the minor injury severity and severe injury severity, there are variables which provide insights in the influence on the potential of occurrence for these crash severity levels. Based on the result of the multinomial logit analysis, it should be noted that if a roadway departure crash is unavoidable, the presence of sinusoidal rumble strips was not found to have a significant influence to reduce lane departure crash severity levels. The discussions of significant factors that could increase or decrease the crash severity if a roadway departure crash is unavoidable are presented as follows.

Impact type: The positive parameter on front to rear collision indicator variable in the minor injury utility function indicates that crashes with this collision type are more likely to suffer a minor injury. The marginal effects give us a change in the mean number of crashes per one-unit change in the independent variable. The marginal effects for the front to rear collision indicator variable also suggest that a unit change in this variable will increase the probability by 0.01 of a minor injury crash.

On the other hand, if we look at the severe injury utility function, we see a negative sign on the parameter estimate for the side-to-side impact variable. This suggests that if a side-to-side crash occurs, the likelihood of a severe injury reduces. The marginal effects suggest the probability of severe injury to reduce by 0.52 in a side-to-side impact crash.

Alcohol and drug involvement: The positive parameter on the alcohol and drug use indicator variable in the minor injury utility function indicates that if the commuter is driving under the influence of alcohol or drugs, the likelihood of a minor severity crash increases. The marginal effects suggest that the probability increases by 0.03 by a unit change in this variable.

It is also found a positive parameter of this variable on the severe injury utility function denoting the same. The marginal effects for this variable in the severe injury also suggest an increase in the probability by 0.08 per unit change in this variable.

Angle collision: The positive parameter on the crash type indicator variable in the minor injury utility function indicates that if the commuter gets into an angle crash, the likelihood of a minor severity crash increases. The marginal effects also suggest that a unit change in this variable will increase the probability by 0.02 of a minor injury crash.

Multi-vehicle crash: The negative sign on the multi-vehicle crash indicator variable in the minor injury utility function indicates that if the commuter gets into a multi-vehicle crash, the likelihood of a minor severity crash decreases. The marginal effects also suggest that a unit change in this variable will reduce the probability by 0.15 of a minor injury crash. However, a multi-vehicle crash will increase the probability by 0.03 of severe injury in the crash.

High AADT effect: The negative sign on the high AADT indicator variable in the minor injury utility function indicates that if the commuter gets into a crash on a roadway with AADT higher than 15000 vehicle per day, the likelihood of a minor severity crash decreases. The marginal effects also suggest that a unit change in this variable will reduce the probability by 0.34 of a minor injury crash. This could be due to slower speeds on high volume roads and people being more cautious.

It is also found a negative sign for the parameter of this variable on the severe injury utility function denoting the reduced likelihood of the crash causing severe injury. The marginal effects for this variable in the severe injury also suggest a decrease in the probability by 0.61 per unit change in this variable.

Lighting condition: The positive parameter on the lighting indicator variable in the minor injury utility function indicates that if the commuter gets into a crash when the lighting is dark, the likelihood of a minor injury severity crash increases. The marginal effects also suggest that a unit change in this variable will increase the probability by 0.03 of a minor injury crash.

Two-lane roadway: The positive parameter on the two-lane road indicator variable in the minor injury utility function indicates that crashes on two-lane roadways are more likely to suffer a minor injury. The marginal effects also suggest that a unit change in this variable will increase the probability by 0.43 of a minor injury crash.

We see a positive parameter for this variable in the severe injury utility function too which also indicates an increased likelihood that a crash on a two-lane road will increase the likelihood of a severe injury. The marginal effects suggest an increase in the probability of 0.60 of a severe injury in the crash.

Roadway function effect: The positive parameter on the roadway function indicator variable suggests an increase in the likelihood of minor injury if the crash were to happen on a state road which is usually through a rural area. The marginal effects also suggest an increase in the probability by 0.08 of a minor injury if the crash were to happen on a state road.

However, if looking at the severe injury utility function, we see a negative sign on the parameter estimate for the local road indicator variable. That means, if a crash were to occur on a local road or a parking lot or a private roadway, the likelihood of severe injury reduces by 0.28 in the crash.

Aggressive driving: The positive sign on the parameter for the aggressive driving indicator variable in the severe injury utility function suggests that drivers driving aggressively are more likely to get severely injured. The marginal effects suggest an increase in the probability by 0.02 per unit change in the indicator variable for the driver to sustain severe injuries.

Weather conditions: The positive parameter estimate of this variable in the severe injury utility function signifies that if the weather is foggy or if there is smoke or smog on the road, the likelihood of a severe injury in the crash increases. The marginal effects suggest this increase in the probability to be around 0.01.

4.3 Additional Data Collection and Analysis

The project team made efforts to collect additional safety data during the various interviews that were conducted in Task 2 with the states that implemented sinusoidal rumble strips. Representatives from all the states that participated in the interviews confirmed a lack of safety evaluation studies or safety data related to sinusoidal rumble strips. Thus, the team could not obtain any additional and national data from the interviews that could help demonstrate the safety benefits among different sinusoidal rumble strip designs. The lack of safety evaluation studies or safety data related to sinusoidal rumble strips was also identified in the literature. Although the general safety benefits of rumble strips are highlighted, limited studies exist that compare the reduction of roadway departure fatalities, injuries, and crashes among different rumble strip designs. Related to the general benefits, the 2010 Highway Safety Manual confirmed that rumble strips can reduce lane departure crashes by 10–93 percent on various types of highways. Other work focused on the benefits of the locations of the rumble strips. For example, a study demonstrated that shoulder and centerline rumble strips can reduce the number of single vehicles run-off-road (SVROR) crashes, as well as opposite direction sideswipe and head-on collisions (Ahmed et al., 2015).

5 Summary of Research Findings and Recommendations

Roadway departure is the leading contributing factor to traffic fatalities and the second highest contributing factor to serious injuries in Florida. Noise and vibration from rumble strips have proved to reduce roadway departure crashes by warning drivers when their vehicles leave the travel lane. Different types of rumble strips are available, including cylindrical, thermoplastic, and sinusoidal. Sinusoidal rumble strips were considered and implemented by several states including Minnesota, Indiana, Washington, California, and Oregon to address the issues of exterior noise that bothered nearby residents. The exterior noise issues prompted FDOT to evaluate three different FDOT designs of sinusoidal rumble strips (Type 1, Type 2, and Type 3) for implementations on Florida's arterials and collectors to reduce noise pollution. This research project conducted a detailed literature review, agency surveys, FDOT noise study analysis, and a CUTR focus group noise study to make recommendations to the FDOT on the most effective one among three sinusoidal rumble strip designs to reduce the exterior noise while still providing enough interior noise and vibration to alert a driver.

Many studies showed significant benefits of using rumble strips to reduce roadway departure fatalities, severe injuries, and crashes. However, there were very limited studies in the literature to compare the safety effectiveness among different rumble strip types. No study could be found in the literature review and agency interviews that specifically evaluated the safety effectiveness of sinusoidal rumble strip designs in reducing roadway departure fatalities, injuries, and crashes. This research project performed before-after studies to evaluate the effectiveness of sinusoidal rumble strip deployments in Florida to reduce roadway departure crashes and their severities.

The first objective of this project was to confirm that sinusoidal rumble strips could effectively address the exterior noise issues and determine which one of the three FDOT sinusoidal designs is most effective to reduce exterior noise while still being able to properly alert drivers when departing from the travel lane. The second major project objective was to assess the effectiveness of sinusoidal rumble strips with respect to preventing or reducing lane departure crashes and their severities. A literature review, agency interviews, a CUTR focus group noise study, FDOT field noise study result evaluation, and before-after crash analysis were performed as part of the research. The summary of research findings and recommendations are provided in the following sections.

5.1 Summary of Research Findings

The findings reveal that sinusoidal rumble strips are the most effective type of roadway departure prevention strips that can address the noise issues while helping with safety.

The literature review on best practices on sinusoidal rumble strip design and implementation, and the interviews with selected state transportation agencies with sinusoidal rumble strip deployments revealed the following advantages and disadvantages of sinusoidal rumble strips:

- Sinusoidal Rumble Strip Advantages
  - Effective in reducing lane departure crashes and fatalities on roadways

- Effective in reducing vehicle speeds at some locations
- Maintain a reduced noise level outside the vehicle while maintaining the necessary noise needed inside to alert the driver, thus addressing noise pollution concerns
- Visible, particularly at night and while raining, due to the sinusoidal rumble strips being striped with wet-reflective media
- Protect high-cost, wet-reflective pavement markings and provide greater lifespan for pavement markings done below surface of pavement
- Easy to install on asphalt pavement

- Sinusoidal Rumble Strip Disadvantages
    - Can be uncomfortable for motorcyclists and bicyclists if not properly designed (with at least 4 ft (1.2 m) of space between the rumble strips and the edge of the pavement, with more (5 ft and over) if safety barriers are present)
    - May be slippery when wet in raised pavement
    - Can be expensive because the shape requires continuous milling and a need for additional labor and cleanup
    - Takes longer to install due to continuous cutting requirements
    - Somewhat difficult to install on concrete pavement

Related to the noise control, the results from the CUTR focus group noise study and FDOT field noise studies revealed that FDOT's Type 2 or Type 3 sinusoidal rumble strip designs in Florida are more promising than Type 1. Although both Type 2 and Type 3 are similar, the experience of drivers during the CUTR and FDOT noise studies favored Type 2 more than Type 3. Various factors like speed, vehicle type, or vehicle model can affect the noise levels inside and outside of vehicles when driving on the sinusoidal rumble strips. Several drivers felt that Type 2 performed consistently better regardless of speed and vehicle types. Additionally, based on the various evaluations, edgeline sinusoidal rumble strips produced more noise (both inside and outside) than shoulder rumble strips. Based on the FDOT and CUTR studies, it can be concluded that sinusoidal rumble strips have lower outside noise levels and louder inside noise levels than other rumble strips. Considering the noise levels, the performance of the rumble strips may also depend on driving angle or whether driving in a straight line or weaving on the strips.

This study further evaluated the safety effectiveness of implemented sinusoidal rumble strips at 12 selected sites based on FDOT's context-based design criteria using an Empirical Bayes approach and developed the corresponding CMFs. This pioneering study, to the best of the project team's knowledge, was the first to evaluate the safety effectiveness of sinusoidal rumble strips. It was found that the sinusoidal rumbles strips are effective in reducing lane departure crashes based on the before-after analysis of lane departure crashes at the 12 treatment sites as well as the 12 selected reference sites, as all three CMFs calculated were much less than 1.0 as described below.

- The CMF based on the overall dataset is 0.43 for the sinusoidal rumble strips, indicating that the implemented sinusoidal rumble strips are expected to reduce total lane departure crashes by 57%. This overall CMF is significant at the 95% confidence interval.
- For the rural two-lane roadway type, the estimated CMF is 0.70, indicating that the implemented sinusoidal rumble strips are expected to reduce total lane departure crashes on rural two-lane roadways by 30%. This CMF is not significant at the 90% confidence level due to less sample size.
- For the rural multi-lane roadway type, the estimated CMF is 0.39, indicating that the implemented sinusoidal rumble strips are expected to reduce total lane departure crashes on rural multi-lane roadways by 61%. This CMF is significant at the 95% confidence interval.

The CMFs for fatal and serious injury crashes, including both fatality (K) and incapacitating injury (A), were also computed, and it is revealed that,

- The CMF for fatal and serious injury crashes based on the overall dataset is 0.38, suggesting that the sinusoidal rumble strip is expected to reduce fatal and serious lane departure crashes by 62%. This CMF is significant at the 95% confidence interval.
- For the rural two-lane roadway type, the CMF for fatal and serious injury crashes is 0.18, indicating that the sinusoidal rumble strip is expected to reduce fatal and serious lane departure crashes on rural two-lane roads by 82%. This CMF is significant at the 95% confidence interval.
- For the rural multi-lane roadway type, the CMF for fatal and serious injury crashes is 0.43, indicating that the sinusoidal rumble strip is expected to reduce fatal and serious lane departure crashes on rural multi-lane roads by 57%. This CMF is significant at the 95% confidence interval.

A multinomial logit analysis was used to investigate the influence of sinusoidal rumble strip presence on lane departure crash severity outcomes, along with the potential influence of other crashes, traffic, roadway, and driveway characteristics on crash severities. Based on the result of the multinomial logit analysis, it should be noted that if a roadway departure crash is unavoidable, the presence of sinusoidal rumble strip was not found to have a significant influence to reduce lane departure crash severity levels. If a roadway departure crash is unavoidable, the factors found to have a significant influence on lane departure crash severity include the following: front-to-rear collision, angle collision, side impact, multi-vehicle crash, foggy/smoggy/smoky weather, alcohol or drug involvement in crash, dark lighting condition, two-lane road configuration, roadway function, aggressive driving behavior, and high AADT. Detailed analysis results can be found in Section 4.2.2.

5.2 Recommendations

Based on the literature review, agency interviews, field noise studies, focus group noise study, and before-after crash analysis in this project, the research team would like to provide the following recommendations:

- Among all the three types (details) of sinusoidal rumble strip patterns developed by FDOT, Type 2 is the most promising design in terms of reduction of exterior noise and noise pollution, and sufficient alertness by inside noise, vibration, and sound pitch; therefore, it was recommended, and adopted by FDOT via RDB 22-04.
- The sinusoidal rumble strip was found to be effective in reducing lane departure crashes through the before-after analysis with Empirical Bayes (EB) approach. Therefore, it is recommended to either be implemented at locations with high numbers of lane departure incidents, or for systematic implementation within jurisdiction when funding is available.
- Comparing the CMFs for total lane departure crashes from the overall dataset (0.43), the rural two-lane road subset (0.70), and the rural multi-lane road subset (0.39), it was found that the sinusoidal rumble strip is most effective on rural multi-lane roadways for total lane departure crash reduction, suggested by the lowest CMF value. Therefore, it is highly recommended to implement sinusoidal rumble strips on rural multi-lane roadways.
- Comparing the CMFs for fatal and serious lane departure crashes from the overall dataset (0.38), the rural two-lane road subset (0.18), and the rural multi-lane road subset (0.43), it was found that the sinusoidal rumble strip is most effective in reducing the total number of fatal and serious lane departure crashes on rural two-lane roadways, suggested by the lowest CMF value. Therefore, it is also strongly recommended to implement sinusoidal rumble strips on rural two-lane roadways. These results verify the necessity of systematic implementation of sinusoidal rumble strips on Florida roadways.
- Alcohol or drug involvement was found to have a significant influence on lane departure crash severity. Therefore, in addition to sinusoidal rumble strip implementation, law enforcement on alcohol or drug involvement is also recommended to be implemented to reduce lane departure crash severity.
- It was found that the state roadway function type is associated with an increased potential of minor injury severity in lane departure crashes; on the other hand, a local road is associated with a decreased probability of severe injuries on lane departure

crashes. Therefore, it is recommended to focus more on state roadways for lane departure crash mitigation.

- The CMF for sinusoidal rumble strips for total lane departure crashes on rural two-lane roadways is not significant at 90% confidence interval. A possible reason is that there were only a small number of treatment sites included in this study based on data availability. In addition, most of these treatment sites were constructed in recent years and there were less than three years as the after period. Therefore, it is recommended to conduct a more comprehensive assessment later with more treatment sites and crash data of longer periods after the sinusoidal rumble strip implementation (typically at least three years).
- Since publication of FDOT RDB 18-03 in 2018, more implementations of sinusoidal rumble strips have begun. With the publication of FDOT RDB 22-04 in October 2022, more statewide data for sinusoidal rumble strip implementations will be available. In the next 1 -2 years, more solid 3 years of after roadway departure crash data will be available. It is highly recommended for FDOT to conduct a follow-up research project based on the success of the current project to 1) develop comprehensive and high-quality CMFs for implementation of sinusoidal rumble strips to reduce roadway departure fatalities, injuries, and crashes, and 2) assess statewide sinusoidal rumble strip implementations, and present assessment results and findings, and 3) provide further recommendations.

6 References

Advocacy Advance Team. (2010). Bicycling and rumble strips. League of American Bicyclists and Alliance for Biking and Walking. Retrieved from http://www.bikeleague.org/resources/reports/pdfs/rumble_strips.pdf.

Ahmed, M., Sharif, M. A., & Ksaibati, K. (2015). Developing an effective shoulder and centerline rumble strips/stripes policy to accommodate all roadway users. Wyoming Department of Transportation. Retrieved from https://rosap.ntl.bts.gov/view/dot/29526/dot_29526_DS1.pdf.

Annino, J. M. (2003). Rumble strips in Connecticut: A before/after analysis of safety benefits. Connecticut Department of Transportation.

Briese, M. (2008). Safety effects of centerline rumble strips in Minnesota (No. MN/RC-2008-44). Minnesota. Department of Transportation. Retrieved from https://rosap.ntl.bts.gov/view/dot/37978/dot_37978_DS1.pdf.

Bucko, T. (2001). Evaluation of milled-in rumble strips, rolled-in rumble strips and audible edge strips. California Department of Transportation.

Cybulski, J. D., Rochat, J. L., & Read, D. R. (2013). Roadway departure warning indicators: synthesis of noise and bicycle research (No. DOT-VNTSC-NPS-11-24). National Park Service, U.S. Department of Transportation. Retrieved from https://www.adventurecycling.org/sites/default/assets/File/Travel_Initiatives/Rumble%20Strips/NPSrumblesynthesis2013.pdf.

Donavan, P., & Buehler, D. (2018). Design and acoustic evaluation of optimal sinusoidal rumble strips versus conventional ground-in rumble strips (Tech. No. CTHWANP-RT18-365.01.2). California Department of Transportation, Sacramento, CA. Retrieved from https://dot.ca.gov/-/media/dot-media/programs/environmental-analysis/documents/env/noise-mumble-strip-report-a11y.pdf.

Donavan, P. (2009). Recommendation for initial sinusoidal rumble strip design. Technical Memorandum to Dennis McBride and Bruce Rymer at California Department of Transportation, August 4.

Federal Highway Administration. (2015). FHWA Rumble Strip Guidelines for Shoulder and Centerline Applications. Retrieved from https://flh.fhwa.dot.gov/resources/design/library/FLH-Rumble-Strip-Guidelines.pdf.

Florida Department of Transportation (FDOT). (2022a). US-301 rumble strips noise test. Memorandum. Tallahassee, FL.

Florida Department of Transportation (FDOT). (2022b). SR-100 rumble strips noise test in Putnam County. Memorandum.

Florida Department of Transportation (FDOT). (n.d.). US-301 Plan Sheet.

Himes, S., McGee, H., Levin, S., & Zhou, Y. (2017). State of the practice for shoulder and center line rumble strip implementation on non-freeway facilities (No. FHWA-HRT-17-026). Federal Highway Administration, Office of Safety Research and Development. Retrieved from https://www.fhwa.dot.gov/publications/research/safety/17026/17026.pdf.

Hurwitz, D. S., Horne, D., Jashami, H., Monsere, C. M., & Kothuri, S. (2019). Quantifying the performance of low-noise rumble strips (No. FHWA-OR-RD-19-07). Retrieved from https://www.oregon.gov/ODOT/Programs/ResearchDocuments/SPR800FinalReport.pdf.

Intan Traffic Engineering. (2018). Profiled thermoplastic road line marking. Retrieved from http://www.intantraffic.com.my/profiled-thermoplastic.html.
Kalathas, P., Parrish, C., & Zhang, Y. (2019). Rumble strip design evaluation based on exterior noise using finite element analysis (No. OR-RD-19-10). Oregon Department of Transportation. Retrieved from https://www.oregon.gov/ODOT/Programs/ResearchDocuments/RumbleStripsFinal.pdf.
Kragh, J. & Andersen, B. (2007). Traffic noise at rumble strips. Danish Road Institute Report 156.
Laughlin, J., Donahue, J. (2018). Evaluation of new rumble strip designs to reduce roadside noise and promote safety. Washington State Department of Transportation. Retrieved from https://www.wsdot.wa.gov/research/reports/fullreports/881-1.pdf.
Mathew, J. K., Balmos, A. D., Plattner, D., Wells, T., Krogmeier, J. V., & Bullock, D. M. (2018). Assessment of alternative sinusoidal rumble stripe construction. Indiana Department of Transportation. Retrieved from https://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=3191&context=jtrp.
National Cooperative Highway Research Program (NCHRP). (2009). Guidance for the Design and Application of Shoulder and Centerline Rumble Strips. NCHRP Report 641. Transportation Research Board, Washington, D. C. Retrieved from http://www.cmfclearinghouse.org/studydocs/nchrp_rpt_641-GuidanceRumbleStrips.pdf.
Russell, E. R., & Rys, M. (2006). Reducing crossover accidents on Kansas highways using milled centerline rumble strips. Report No. K-TRAN: KSU-00-4, Kansas State University, Lawrence, KS.
Sacramento County Department of Transportation. (n.d.) Rumble strip. Retrieved from https://sacdot.saccounty.net/Pages/NTMP-RumbleStrip.aspx.
Savolainen, P. T., Sharma, A., Barrette, T., Vafaei, B., & Kirsch, T. J. (2017). Installation guidance for centerline and edgeline rumble strips in narrow pavements (No. IHRB Project TR-696). Iowa. Highway Research Board. Retrieved from https://intrans.iastate.edu/app/uploads/2018/04/installation_guidance_for_narrow_pvmt_rumble_strips_w_cvr-1.pdf.
Staats, W. N., Agent, K. R., & Howell, B. K. (2020). Evaluation of alternative rumble strip designs. Kentucky Transportation Center, Kentucky Transportation Cabinet. Retrieved from https://uknowledge.uky.edu/cgi/viewcontent.cgi?article=2716&context=ktc_researchreports.
Tarko, A., & Romero, M. (2022). SPR-4739: Sinusoidal Rumble Strips Measures of Effectiveness. Retrieved January 27, 2023, from TRB Research in Progress website: https://rip.trb.org/view/2026877.
Terhaar, E., Braslau, D., & Fleming, K. (2016). Sinusoidal rumble strip design optimization study (No. MN/RC 2016-23). Minnesota Department of Transportation. Retrieved from https://www.dot.state.mn.us/trafficeng/safety/docs/sinusoidalrumblestripdesignoptimizationstudy.pdf.
Torbic, D. J. (2001). Comfort and controllability of bicycles as a function of rumble strip design. The Pennsylvania State University. Retrieved from https://search.proquest.com/openview/cfb03bde848e4abdbff393965cd4ca53/1?pq-origsite=gscholar&cbl=18750&diss=y.

Torbic, D. J., Hutton, J. M., Bokenkroger, C. D., Bauer, K. M., Harwood, D. W., Gilmore, D. K., Dunn, J. M., Ronchetto, J. J., Donnell, E. T., Sommer III, H. J., Garvey, P., Persaud, B., & Lyon, C. (2009). Guidance for the design and application of shoulder and centerline rumble strips (Vol. 641). NCHRP Report 641. Retrieved from http://www.cmfclearinghouse.org/studydocs/nchrp_rpt_641-GuidanceRumbleStrips.pdf.

Olson, D., Manchas, B., Glad, R. W., & Sujka, M. (2011). Performance analysis of centerline rumble strips in Washington state (No. WA-RD 768.1). Retrieved from https://wsdot.wa.gov/research/reports/fullreports/768.1.pdf.

Watts, G.R., et al. (2001). Optimization of traffic calming surfaces. Transport Research Laboratory.

Appendix A Agency Interview Questionnaire

Interview Questionnaire for Agencies on Sinusoidal Rumble Strip Implementations on Arterials and Collectors

This interview is part of the data collection efforts to support the Florida Department of Transportation's (FDOT) decision related to the selection of the appropriate type of sinusoidal rumble strips for reducing noise pollution, addressing safety issues, and accommodating bicyclists. The USF-CUTR research team is interested in understanding and learning from your agency or state regarding the motivation for and implementations of sinusoidal rumble strips, the specifications of your sinusoidal rumble strip designs, evaluation results of different designs, installations and maintenance experience, and associated costs. The research team is also interested in the details related to noise pollution reduction, safety evaluations, and bicyclist accommodations. The main objective of this interview is to obtain your agency's experiences with implementing sinusoidal rumble strips and lessons learned from your state that could benefit future sinusoidal rumble strip implementation in Florida.

Name of Agency:

Name and Title of Respondent:

Contact Email:

Office Phone:

<u>Sinusoidal Rumble Strip Design</u>

1. Has your agency or state used or adopted any sinusoidal rumble strip designs?
    a. Yes or No
    b. if Yes –
        i. Why did your agency or state use that design?
        ii. What are the specifications or dimensions of your chosen design?
        iii. Has your agency or state performed any noise and safety studies to compare your selected design with other sinusoidal designs?

<u>Noise Evaluations</u>

2. Has your agency or state conducted noise studies of different sinusoidal rumble strips in your state?
    a. Yes or No
    b. if Yes –
        i. Do you have any noise study documents to share with us?

3. Were the implemented sinusoidal rumble strips in your state able to reduce the exterior noise while still providing enough interior noise to alert the driver?
    a. Yes or No
    b. if Yes –
        i. Could you share more information or documents on how the sinusoidal rumble strips you used compared to other sinusoidal rumble strips you considered that helped to reduce the exterior noise and provided enough interior noise to alert the driver?

<u>Safety Evaluations</u>

4. Has your agency or state conducted any before and after safety evaluations on sinusoidal rumble strips regarding roadway departure crash, injury, and fatality reduction?
    a. Yes or No
    b. if Yes –
        i. How many years of data has your agency or state collected for the before-after study?
        ii. What were the main findings from the evaluations? Are there any documents available to share?

5. Has your agency or state performed any other safety evaluations of sinusoidal rumble strips in your state?
    a. Yes or No
    b. if Yes –
        i. Could you please explain more, or can you share any documents of the results?

<u>Bicyclist Accommodations</u>

6. Does your agency or state consider bicyclists during shoulder sinusoidal rumble strip installation?
    a. Yes or No
    b. if Yes –
        i. Does your agency or state have separate standards for bicycle locations and non-bicycle locations?
    c. if No –
        i. Do you only accommodate bicyclists when they request?

7. What are specific bicycle accommodations of rumble strip implementation for your state?

Not applicable
Rumble strip gaps for bicyclists: _______
Minimum shoulder width for bicyclists: ______
Other (please explain): _______

Overall Guidelines

8. Does your agency or state follow the national guidelines (i.e.: NCHRP 641, FHWA Rumble Strip Guideline) for the sinusoidal rumble strips installations, or do you have different guidelines for your state? If there is a state guideline available, would you please provide the guideline document or a web link to the document if it is available online?

9. Do you have a required minimum shoulder width for implementing shoulder or edgeline sinusoidal rumble strips?
    a. Yes or No
    b. if Yes –
        i. What is the minimum required width for shoulder rumble strips?
        ii. What is the minimum required width for edgeline rumble strips?

10. Does your state have weather-related guidelines for sinusoidal rumble strips, such as guidelines related to poor visibility, snow removal, excess rain, and hydroplaning?
    a. Yes or No
    b. if Yes –
        i. Would you please provide the guideline document or a web link to the document if it is available online?

11. What was the estimated cost of the sinusoidal rumble strips installations, including labor, for your state? Is this less expensive than the implementations of other strip types? (Yes/No)

12. How often does your state maintain the sinusoidal rumble strips and what is the maintenance process? Are there guidelines to instruct the maintenance process?

13. What are some success factors and lessons learned from implementing sinusoidal rumble strips in your state? Please share.

Appendix B Focus Group Questionnaire

<u>Study Site: US-301</u> Name of Participant: _______________________ Driver___ or Passenger___

Email Address of Participant: ____

On a scale of 1 to 10, with 1 being the least effective and 10 being the most effective to alert you that your vehicle is departing from the main roadway lane, please rate each of the sinusoidal rumble strips related to **<u>noise, vibration, and overall</u>**. For a driver, you can drive **<u>up to two times for each scenario if necessary</u>**. Two sites are included in the study: US-301 and SR-100. Sketches of the sites are available at the end. For each site, a separate trip for shoulder and edgeline is required.

Study Site: US-301 *(southbound is required and second round only if needed)*

Shoulder

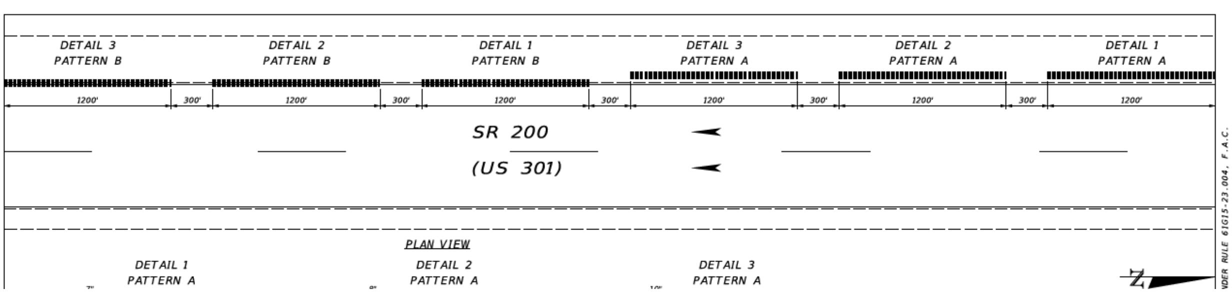
Order of sinusoidal rumble strips	Scenario 1: 65 mph			Scenario 2: 70 mph		
	Noise	***Vibration***	***Overall***	***Noise***	***Vibration***	***Overall***
First						
Second						
Third						

Comments: ____

Edgeline

Order of sinusoidal rumble strips	Scenario 1: 65 mph			Scenario 2: 70 mph		
	Noise	***Vibration***	***Overall***	***Noise***	***Vibration***	***Overall***
First						
Second						
Third						

Comments: ____



Focus Group Discussion for US-301

1. Please describe why you feel your selection was the **best overall** to alert when you departed from the roadway.

2. Please describe why you feel your selection was the **best related to noise** to alert when you departed from the roadway.

3. Please describe why you feel your selection was the **best related to vibration** to alert when you departed from the roadway.

4. Does **driving speed** make a difference on how effective the sinusoidal rumble strips are to alert you as a driver or a passenger? Why?

5. Do you have any other comments, suggestions, or feedback?

<u>Study Site: SR-100</u> Name of Participant: ______________________ Driver___ or Passenger___

Email Address of Participant: ____

On a scale of 1 to 10, with 1 being the least effective and 10 being the most effective to alert you that your vehicle is departing from the main roadway lane, please rate each of the sinusoidal rumble strips related to **<u>noise, vibration, and overall</u>**. For a driver, you can drive **<u>up to two times for each scenario if necessary</u>**. Two sites are included in the study: US-301 and SR-100. Sketches of the sites are available at the end. For each site, a separate trip for shoulder and edgeline is required.

Study Site: SR-100 *(Eastbound is required and westbound for second round only if needed)*

Shoulder

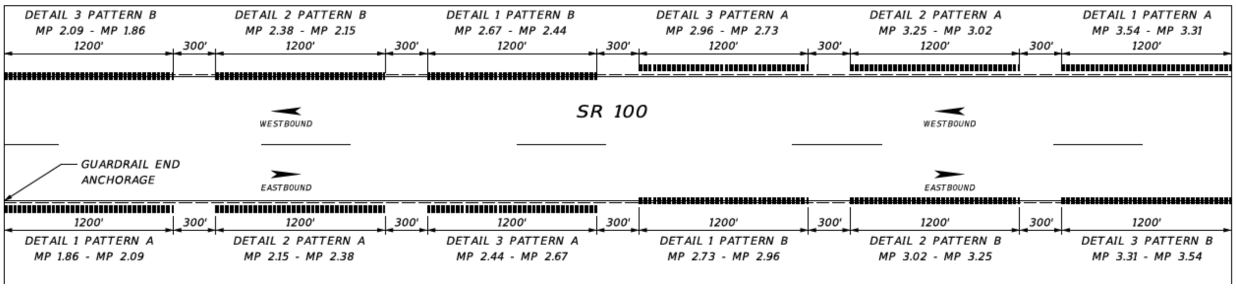
Order of sinusoidal rumble strips	**Scenario 1: 45 mph**			**Scenario 2: 50 mph**		
	Noise	***Vibration***	***Overall***	***Noise***	***Vibration***	***Overall***
First						
Second						
Third						

Comments: ____

Edgeline

Order of sinusoidal rumble strips	**Scenario 1: 45 mph**			**Scenario 2: 50 mph**		
	Noise	***Vibration***	***Overall***	***Noise***	***Vibration***	***Overall***
First						
Second						
Third						

Comments: ____



Focus Group Discussion for SR-100

1. Please describe why you feel your selection was the **best overall** to alert when you departed from the roadway.

2. Please describe why you feel your selection was the **best related to noise** to alert when you departed from the roadway.

3. Please describe why you feel your selection was the **best related to vibration** to alert when you departed from the roadway.

4. Does **driving speed** make a difference on how effective the sinusoidal rumble strips are to alert you as a driver or a passenger? Why?

5. Do you have any other comments, suggestions, or feedback?

Appendix C Summary of Focus Group Results

Table C 1. Site US-301 Average Ratings

Drivers	**65 mph**			**70 mph**		
Shoulder	***Noise***	***Vibration***	***Overall***	***Noise***	***Vibration***	***Overall***
First	5.57	5.43	5.57	6.00	5.43	5.86
Second	6.57	7.14	7.07	7.21	7.14	7.07
Third	6.71	7.14	7.14	7.14	7.00	7.14
Drivers	**65 mph**			**70 mph**		
Edgeline	***Noise***	***Vibration***	***Overall***	***Noise***	***Vibration***	***Overall***
First	7.14	7.00	7.07	7.29	7.00	7.14
Second	7.79	8.07	8.21	8.36	8.07	8.61
Third	7.57	8.00	7.93	8.00	7.71	8.00
Passengers	**65 mph**			**70 mph**		
Shoulder	***Noise***	***Vibration***	***Overall***	***Noise***	***Vibration***	***Overall***
First	6.00	6.13	6.25	6.63	6.38	6.63
Second	6.88	7.13	7.25	7.50	7.13	7.38
Third	7.00	7.00	7.06	7.25	7.38	7.38
Passengers	**65 mph**			**70 mph**		
Edgeline	***Noise***	***Vibration***	***Overall***	***Noise***	***Vibration***	***Overall***
First	7.75	7.56	7.75	7.81	7.69	7.94
Second	7.56	7.75	7.56	8.19	8.06	8.31
Third	8.13	8.06	8.25	8.00	7.75	7.88

Table C 2. Site SR-100 Average Ratings

Drivers	60 mph			65mph		
Shoulder	***Noise***	***Vibration***	***Overall***	***Noise***	***Vibration***	***Overall***
First	4.57	4.71	4.86	5.14	4.43	5.43
Second	6.29	6.00	6.71	6.86	6.43	7.29
Third	7.29	7.00	7.43	7.57	7.14	7.71
Drivers	**60 mph**			**65 mph**		
Edgeline	***Noise***	***Vibration***	***Overall***	***Noise***	***Vibration***	***Overall***
First	5.14	5.14	5.57	5.14	5.14	5.57
Second	6.86	7.29	7.43	7.29	7.00	7.43
Third	7.71	7.57	7.86	8.14	7.86	8.29
Passengers	**60 mph**			**65 mph**		
Shoulder	***Noise***	***Vibration***	***Overall***	***Noise***	***Vibration***	***Overall***
First	4.75	4.88	4.88	5.50	5.13	5.63
Second	6.25	6.50	6.50	7.00	6.75	7.00
Third	7.50	7.63	7.50	8.00	7.50	7.63
Passengers	**60 mph**			**65 mph**		
Edgeline	***Noise***	***Vibration***	***Overall***	***Noise***	***Vibration***	***Overall***
First	5.88	5.50	6.25	5.56	5.56	5.94
Second	7.13	6.50	7.25	7.00	6.75	7.50
Third	7.44	7.56	7.56	8.00	8.00	8.38

Appendix D Focus Group Photos