AN ABSTRACT OF THE DISSERTATION OF

Dylan Ross Horne for the degree of Doctor of Philosophy in Civil Engineering presented on November 12, 2019.

Title: Sound and Vibration Analysis of Alternative Rumble Strips.

Abstract approved: ____

David S. Hurwitz

Roadway departure crashes accounted for 18,275 fatal crashes in 2017 across the United States (Jones et al. 2017). Rumble strips (RS) provide audible and haptic interior alert when a vehicle is departing the roadway reducing run-off-the road crashes. Although inexpensive to install, and easy to maintain, RS are not installed on many roadways due to noise concerns. This Dissertation evaluated using a shallower sinusoidal RS as a quieter alternative to rounded milled RS. Rumble strip strikes by the passenger car and van generated less exterior noise with the sinusoidal than with the rounded design.

To be an effective safety countermeasure, the RS must generate an interior alert, through an increase in the interior noise and haptic feedback. The sinusoidal and rounded RS do generate a sufficient interior sound alert across passenger vehicles. The radio and climate control were tested, showing that these typical ambient conditions did increase the ambient interior noise reducing the interior alert to only a detectable level. The haptic feedback during all strikes generated a sufficient amount of vibration for all vehicle types. The heavy vehicle bridged its dual-tires over the narrower rounded RS, while the wider sinusoidal RS generated sufficient interior alert. Quieter sinusoidal RS installed in more locations extends the benefits of this safety countermeasure reducing roadway departure crashes.

The feasibility of using shallower epoxy-filled transverse rumble strips (TRS) as a quieter alternative for traditional TRS was also evaluated. Compared to the traditional TRS, the shallower epoxy filled TRS had a detectable reduction in roadside noise during probe vehicle strikes. Paving over the TRS clearly reduces roadside noise, but does not provide any driver alert.

Sound and Vibration Analysis of Alternative Rumble Strips

by

Dylan Ross Horne

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APPROVED:

Major Professor, representing Civil Engineering

Head of the School of Civil and Construction Engineering

Dean of the Graduate School

I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

Dylan Ross Horne, Author

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1.0 INTRODUCTION

1.1 Motivation

Crashes due to departure from the roadway accounted for 18,275 fatal crashes in 2017 across the United States (Jones et al. 2017). In Oregon, roadway departure crashes accounted for 54% of all highway fatalities, most of which happen on rural highways (Jones et al. 2017). In Oregon between 2009 and 2015 roadway departure crashes annually accounted for only 20% of crashes, indicating higher severity of these crashes. Rumble strips (RS) are a low-cost safety countermeasure that significantly reduce the incidence of roadway departure crashes. RS generate noises and vibrations that alert drivers when they are departing the roadway. RS are either milled into the road surface or installed with raised durable striping. Typical RS cross sections are shown in Figure 1.1.

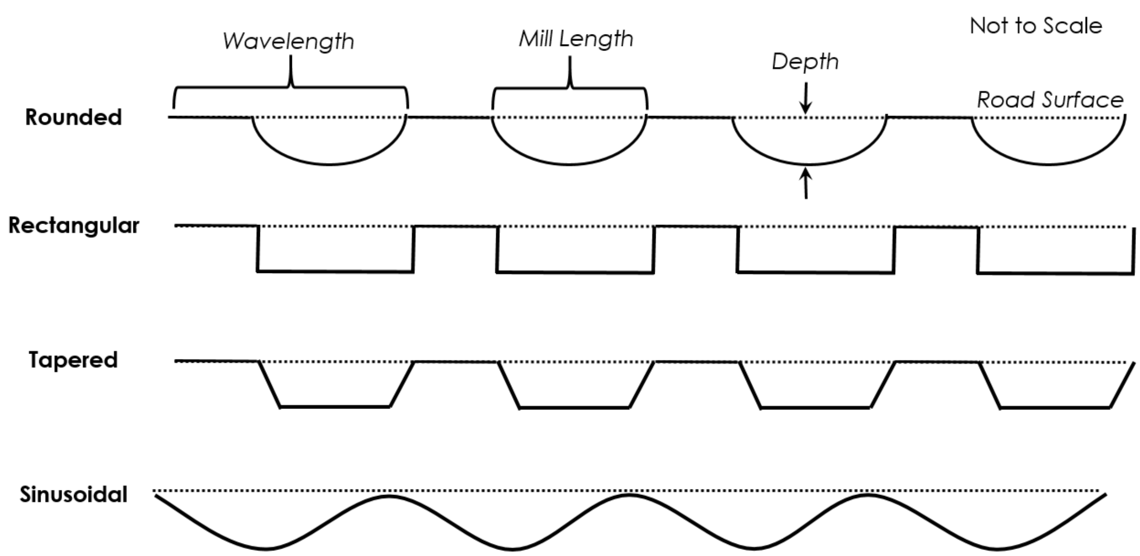

Figure 1.1 Typical Rumble Strip Cross Sections

This safety countermeasure is typically installed in the centerline rumble strips (CLRS) to reduce rates of head-on and sideswipe crashes. The Oregon Department of Transportation (ODOT) estimates that CLRS can annually reduce 87 rural crashes, 19 of which would be fatal crashes (Jones et al. 2017). On Oregon rural roadways, shoulder rumble strips (SRS) annually reduce 6 fatal injury crashes and all roadway departure crashes by 192 (Jones et al. 2017).

Considering their effectiveness as a safety countermeasure, RS are inexpensive to install ($1,800 per 0.5-mile segment), easy to maintain, and last as long as the roadway surface (Jones et al. 2017). The Oregon Roadway Departure Implementation Plan 2015 notes that RS are generally restricted to rural areas due to environmental noise externality generated during strikes (Jones et al. 2017). However, residents living adjacent to rural highways have complained to ODOT about the disturbing noise of RS. As a result, RS have been removed by repaving. Across Oregon, an effective safety countermeasure is not installed on many roadway segments, even though they could effectively reduce the rate of lane-departure crashes.

Furthermore, environmental noise, especially noise from traffic, has been shown to negatively impact the health of adjacent people, primarily through stress and sleep loss (Can, 2018; Kaddoura et al., 2017; Murphy, 2018; Soares, 2017). About half of urban noise is generated by transportation (Calvo et al., 2012). Modifying the characteristics of roadway features like rumble strips have been shown to reduce roadside noise (Donavan & Buehler, 2018).

1.2 Research Objectives

State agencies are investigating a shallower sinusoidal pattern RS that produces less noise than the traditional rounded RS. However, there is a tradeoff of the sound the RS generates, and the effectiveness of it as a safety countermeasure. Therefore it is necessary to evaluate the interior alert as well as the exterior roadside noise to fully understand the safety implications of this noise mitigation strategy. Furthermore, it is necessary to summarize and compare the work across the various state agencies to determine if there is consensus of the roadside noise reduction, and sufficient interior alert.

1.3 Benefits

If the research confirms that sinusoidal RS can be used as a substitute for rounded RS, then the research will provide important crash reduction benefits to ODOT and other Departments of Transportation. Highway safety would be improved by reducing the rates of roadway-departure crashes and associated fatalities and injuries, while nearby residences would not experience as much roadside noise. The cost to install RS treatments are estimated to be \$0.32 Million per life for saved (Jones et al. 2017). Quieter RS could be installed in more locations, extending this countermeasure to further reduce road departure crashes.

1.4 Background

1.4.1 Noise Detectability

Sound is the propagation of vibration through the air (Wee Sit, 2017). The pressure differential created by a specific vibration compared to the baseline atmospheric pressure determines the intensity and frequency of the sound. The human ear is a pressure transducer, and is able to interpret these different pressure intensities and frequencies as specific sounds. These pressures are generally measured using Pascal (Pa), where 6,895 Pa is equivalent to one pound per square inch. Human hearing responds to changes in sound levels in a logarithmic nature, instead of a linear scale. Therefore, sound is often measured using a decibel scale (dB), which is a logarithmic scale of the ratio of the observed sound divided by the threshold for human hearing (reference value: 20 e-6 Pa) as shown in Equation 1-1 (Wee Sit, 2017).

$$dB = 10 \log \frac{Pa_{Measured}}{Pa_{Reference}} \quad (1.1)$$

Noise detectability is a measure of a sound level compared to the amount of background noise (Terhaar et al., 2016). If a noise is audible (able to be heard) but not louder than the ambient noise, then it will not be distinguishable to a listener. Continuous noise (steady or background) is more comfortable than impulsive noise, which is more noticeable and, in turn, more annoying (Caltrans, 2012). Time of day influences noise perception, with loud noises at night being more annoying because there is less ambient noise, and people are more likely to be resting (Caltrans, 2012). The volume and frequency of sound determine the loudness and propagation of noise, with low-frequency noises travelling further due to lower energy losses, thereby affecting a wider audience of people (Sexton, 2014). In regards to human hearing, differences of 3 decibels (dB) between noises are necessary for detecting the distinct sounds. A difference of 6 dB is readily noticeable as shown in Table 1.1 (Torbic et al., 2009).

Table 1.1 Human perception of changes in sound levels (Torbic et al., 2009)

Change in sound level (dBA)	Change in apparent intensity
1	Imperceptible
3	Detectable
6	Clearly noticeable
10	About twice – or half as loud
20	About four times – or one-fourth as loud

Humans generally hear frequencies between 400-20k Hz as audible sounds (Stuart, 2011). Low-frequency noises in the 10–250 Hz frequency range are still noticeable as vibrations and may contribute to disturbed sleep, stress, and heart-rhythm disorders (An et al., 2016). The A-weighted decibel (dBA) scale is a weighted scale describing the intensity of noise as interrupted by the human ear and is based on the range of human hearing, as shown with example sounds in Table 1.2 (Terhaar et al., 2016). The dBA scale is used throughout this research to better match the measured sounds to human hearing.

Table 1.2 Typical sound levels expressed in dBA (Terhaar et al., 2016).

Sound source or location	Level (dBA)
Rocket Launching Pad	180
Artillery at Shooter Ear	170
Rifle at Shooter Ear	160
Loud Trumpet at 5 in	150
Jet Takeoff 200 ft	140
Jet Aircraft Workers on Tarmac	130
20 ft from Rock Band Speakers	120
Nightclub, Diesel Generator Room	110
Subway, Chain Saw, Stereo Headphones	100
Noise Appliances, Lawn Mower at Users Ear	90
Typical Home Stereo Level, Inside Factory	80
Freeway at 200 ft	70
Speech at 3 ft or Air Conditioner at 20 ft	60
Typical Urban Ambient	50
Typical Rural Ambient, Quiet Office	40
Quiet Rural Ambient, Quiet Library, Soft Whisper	30
Winter with no wind, Concert Hall	20
Wilderness in Winter	10
Threshold of Hearing	0

1.4.2 Environmental Noise Impact

Macroscopic noise evaluations are available based on the characteristics of traffic, such as speed, vehicle type and volume of vehicles, and can be used to determine the expected peak sound pressure (Can, 2018; Makarewicz, 2011). Congestion can reduce the amount of traffic noise, as vehicles travel slower during congestion events (Makarewicz, 2011). Road surface materials have a large impact on the level of annoyance generated by traffic (Soares et al., 2017). Noise maps can be developed that consider the configuration and location of buildings to better understand the general spatial distribution of noise impact at specific locations (Kaddoura et al., 2017). These maps are highly dependent on temporal conditions, as noise levels are higher during the day due to more activity, and noise sensitivity is higher during the night due to people resting (Kaddoura et al., 2017). The type of land use is also important in noise mapping, as people at workplaces, schools or hospitals may be more sensitive to noise disturbance, while most models focus on residential impacts (Kaddoura et al., 2017). These models can estimate the background level of noise generated by traffic, which can serve as a baseline for understanding the implications of noise mitigation strategies. Noise levels above 55 dBA have been shown to adversely disturb sleep, causing health impacts (Murphy, 2018).

Macroscopic models of noise impact often reflect homogenous, steady state conditions, using variables like annual average daily traffic, and average speed values to predict the daily noise impact (Can, 2018). More specific dynamic microscopic models have also been developed to better estimate urban traffic noise, which includes a wider variety of speed distribution, vehicle types, as well as acceleration and deceleration events (Can, 2018). Other factors, such as how aggressive a driver is and if the engine is gasoline or diesel, have been included microscopic models, with more aggressive driving or diesel engines increasing noise (Calvo et al., 2012). These microscopic models offer better estimates of peak noise levels, and can be used with real time traffic data to provide monitoring of noise levels based on current conditions (Can, 2018).

1.4.3 Rumble Strips

RS can be placed on either the right or left edge of the roadway. RS on the left edge are placed on the shoulder of one-direction roadways or on the centerline or paved median separating opposite-direction traffic. As summarized by Hawkins et al. (2016), SRS are located at the edge of lane or road, to reduce the incidence of run-off-road crashes. Edge-line RS are placed at the edge of the lane with a pavement marking on top. A narrow offset between the lane edge and the SRS improves correction rates, as drivers are alerted sooner and have a wider recovery area (Hawkins et al., 2016). However, narrow RS (<8 in) may be ineffective for alerting heavy vehicles because the wider tires of these vehicles may bridge the strip, reducing driver feedback (Terhaar & Braslau, 2015).

Centerline rumble strips (CLRS) are located between opposing lanes to reduce the incidence of head-on or cross-over crashes (Hawkins et al., 2016). The most common type of CLRS, milled RS are cut into the roadway and can be installed in asphalt or concrete at any time (Hawkins et al., 2016). Other CLRS types include rolled-in CLRS, which are applied to fresh construction and used primarily in non-snowy climates (Hawkins et al., 2016). CLRS typically separate 2- or 4-lane undivided roads. They may be cut across or on either side of the centerline pavement joint. Installation along as much of a corridor as possible increases the effectiveness of RS and does not decrease passing maneuvers (Hawkins et al., 2016).

Milled RS typically create more vibration and noise than other design options, such as raised or rolled RS (Hawkins et al., 2016). Increasing the groove depth or width of the RS increases interior noise (Caltrans, 2012). A 2007 study by the New Hampshire Department of Transportation (DOT) found a 1–2 dB increase in exterior noise when RS depth increased from 3/8 to 1/2 inches (Caltrans, 2012). Vehicle type and tire type have a large influence on the intensity of sound of a vehicle (Caltrans, 2012).

The sinusoidal RS, or mumble strips, are designed to decrease the amount of exterior noise generated with a RS strike while providing sufficient interior noise and haptic feedback to alert the driver (Himes et al. 2017). Caltrans suggests that sinusoidal RS produce less exterior noise because a vehicle's tire transitions more smoothly into the tapered mill and more smoothly between mills with the sinusoidal RS compared to the rectangular drop off that is found in traditional RS designs (Bucko, 2001).

1.4.4 Federal Guidelines

Released in 2009, the National Cooperative Highway Research Program (NCHRP) Report 641 provides extensive guidance on the design and application of RS (Torbic et al., 2009). This report provides information on crash mitigation, standardized dimensions, state agency practices, noise thresholds, safety effectiveness, application and design criteria, as well as recommendations for future research, including studies to mitigate the noise pollution aspect of RS.

In March 2017, the Federal Highway Administration (FHWA) released its *State of Practice* document (Himes et al. 2017). This report provides case studies of RS practices and tabulates RS design specifications from various state agencies. The document outlines an action plan to address deficiencies within the current state of practice. "Goal 1: Establish Safety Effects of Rumble Strips" specifically identifies the need for better understanding the relationship between quieter RS and safety.

These two reports provide different ranges of acceptable interior noise alerts. NCHRP 641 recommends a 6–12 dBA difference between the alert noise level and the background condition for urban facilities, and recommends an alert of 10–15 dBA for rural freeways. Alerts should not be >15 dBA, which is a painful level that could be frightful for drivers. The FHWA *State of Practice* summary states that alerts will vary based on the vehicle type, speed, pavement surface, tires, and suspension characteristics. This document recommends that alerts be ≥3 dBA (normally perceptible level) and preferably ≥5 dBA (readily perceptible level).

1.4.5 Previous Road Noise Evaluations

A 2014 study sponsored by Washington State DOT evaluated the exterior noise generated by RS using the AASHTO SIP Method (Sexton, 2014). Between 3 and 10 passes were made on each RS type, depending on weather conditions and the absence of other vehicle noise. Measurements were recorded for 10 s per pass. The test vehicle maintained contact with the RS for the whole duration during strike measurements. Nine facilities with previously existing RS of various dimensions were tested across Washington State. Maximum sound level (dBA) and 1/3-octave band measurements were recorded. Maximum sound level varied depending on location, (range: 76–96 dBA, mean ~ 80 dBA). The most common, loudest frequency was 800 Hz, with similar designs producing similar sound spectrums. Similar methodology will be used in the exterior roadside noise evaluation.

The Minnesota DOT (MnDOT) performed exterior and interior vehicle noise testing on 3 SRS designs – California, Pennsylvania, and Minnesota designs – using 3 vehicle types at 3 speed thresholds (Terhaar & Braslau, 2015). RS strike and pass-by sound levels were recorded at 50 ft and 75 ft from the edge of roadway along with video recording at 50 ft. Sound levels (in dB) were measured between 31.5 and 16,000 Hz and were converted to dBA. Maximum Leq was recorded for each pass inside the vehicle and on roadside, indicating that the highest observed sound level is reported. The average of 3 passes was used for comparison and compared to a baseline pass-by without a strike for each vehicle type. A further study a year later evaluated variations of the RS designs on a closed course, and evaluated the performance of the RS for people riding bicycles and motorcycles (Terhaar et al., 2016). Similar methodology will be used in this research to evaluate the RS.

An et al. (2016) evaluated the interior and exterior noises and vibrations for transverse RS using microphones and one accelerometer. They tested 4 transverse designs and used correlations to compare interior and exterior noise measurements. A linear relationship between interior and exterior noise was strongest for the sedan vehicle and decreased with vehicle size. The truck had the worst fit, likely due to the higher ambient noise generated in heavy vehicles. Methodology regarding the accelerometer will be used for this research.

In 2018, the Kansas DOT sponsored a study of how highway noise relates to high-friction surfaces (Linden et al., 2018). The research team used a modified version of the AASHTO Statistical Isolated Pass-by (SIP) method. Compared to other noise-evaluation methods, the SIP Method generates large samples of a diverse traffic mix because it is relatively easy to implement with roadside sensors. Data were collected in evenings to minimize the effects of traffic and wind. Weather information was collected during the experiment. A 3-section window was used to evaluate exterior noise measurements. Single-vehicle passes on normal pavement (baseline) were compared to passes on high-friction surfaces. The study found that high-friction surfaces slightly reduce roadside noise, but not by the originally desired 5 dB reduction. A modified version of the SIP method will be used in the exterior roadside noise evaluation.

In April 2018, CalTrans published a study comparing sinusoidal, conventional rounded, and raised pavement marker RS (Donavan & Buehler, 2018). The study described the development of the sinusoidal design based on tire dimensions to create a quieter RS that still generates a sufficient alert for the driver. Noise was evaluated using a modification of the AASHTO SIP Method. Accelerometers were used to capture haptic feedback in the steering column using the SAE J1447 standard (SAE International, 2000). Five test vehicles were evaluated at a 60 mph pass-by speed. The sinusoidal RS design decreased exterior sound levels by 3 dBA (for heavy vehicles) to 6 dBA (for light-duty vehicles). Interior sound and vibration measurements were comparable, with both RS types generating alerts ~13 dB higher than baseline.

1.4.6 Summary of Literature Review

Despite sufficient research discussing the dimensioning and noise generation of various RS designs, research is lacking concerning the safety implications and implementation of sinusoidal and other quieter RS designs (Himes et al. 2017). Areas where RS would be most effective and the relationship between noise level and safety need to be identified (Himes et al. 2017). Furthermore, interior noise evaluations have only been performed under minimal ambient noise conditions (windows closed, radio off, climate control off). Thus, previous studies suggest noise levels of RS are sufficient to alert drivers, but these studies have not been performed under common conditions of daily driving. Both interior and exterior sound measurements should use full-spectrum (1/3-octave) analysis to understand which frequencies are most prevenient during RS strikes, as each frequency propagates differently. Industry standards (AASHTO and SAE) should be used to ensure data quality and improve comparison with other studies.

Most previous studies focused on the sound interior alert for driver feedback. Two studies found limited differences between background vibration and RS strikes, but there are stark differences in methodology across the studies. No Federal guidance exists for minimum thresholds of haptic feedback levels (Torbic et al., 2009). Considering the size of the body of literature regarding sinusoidal RS, a comparison of state agencies reports is in order to verify that they do reduce roadside noise while providing sufficient driver interior alert.

1.5 Organization of the Manuscripts

This work is comprised of four related manuscripts that address the scope of this dissertation. The first (Chapter 2), entitled "Mitigating roadside noise pollution: a comparison between rounded and sinusoidal milled rumble strips" evaluates the exterior noise generated during rounded and sinusoidal RS strikes to determine if sinusoidal RS do reduce roadside noise. The units in Chapter 2 are shown in metric, as this was required by the research journal in which it is published. The original research for the Oregon Department of Transportation was conducted and reported in English units, and the other manuscripts keep that convention. "Evaluation of interior noise and vibration of sinusoidal rumble strip alert," the second manuscript in the sequence (Chapter 3), evaluates the interior alert generated by rounded and sinusoidal RS strikes by measuring the interior noise and vibration to confirm the sinusoidal design does in fact provide sufficient driver alert to be an effective safety countermeasure. The third manuscript (Chapter 4), "Quantifying the performance of low-noise transverse rumble strips", evaluates the exterior noise generated at traditional milled and epoxy filled transverse RS to prove this mitigation strategy does reduce roadside noise. A conclusion (Chapter 5) summarizes the major findings and discusses practical applications for the findings of this dissertation. Table 1.3 contains definitions found throughout this dissertation.

Table 1.3 Definitions of abbreviations and acronyms

Acronym / Abbreviation	Definition
Pa	Pascal
dB	Decibel
dBA	A-weighted Decibel
Maximum Leq	Maximum Equivalent Sound Level
RS	Rumble Strip
SRS	Shoulder Rumble Strip
CLRS	Centerline Rumble Strip
TRS	Transverse Rumble Strip
SIP	Statistical Isolated Pass-By Method
HV	Heavy Vehicle
PC	Passenger Car
ANOVA	Analysis of Variance
SD	Standard Deviation
μ	Mean
ODOT	Oregon Department of Transportation
MnDOT	Minnesota Department of Transportation
Caltrans	California Department of Transportation
OSU	Oregon State University
AASHTO	American Association of State Highway Transportation Officials
FHWA	Federal Highway Administration

2.0 MITIGATING ROADSIDE NOISE POLLUTION: A COMPARISON BETWEEN ROUNDED AND SINUSOIDAL MILLED RUMBLE STRIPS

Dylan Ross Horne, Hisham Jashami, David S. Hurwitz,
Christopher M. Monsere, and Sirisha Kothuri

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2.1 Abstract

Shoulder or centerline rumble strips (RS) generate noise and vibration to alert drivers when they are departing the travel lane. Although inexpensive to install, easy to maintain, and having documented safety benefits, RS are not installed on many roadway segments primarily due to noise concerns of nearby property owners. This study evaluated the feasibility of using sinusoidal RS as a substitute for rounded milled RS on roadway segments in Oregon with lane-departure crash problems. Exterior sound levels generated by rounded and sinusoidal RS strikes were compared to baseline sound levels for three vehicle types (passenger car, van, and heavy vehicle) to establish sound generation and alerts of the two designs. A total of 39 vehicle strikes of RS were recorded in a controlled field experiment. Rumble strip strikes by the passenger car and van generated less exterior noise with the sinusoidal (3.1 dBA) than with the rounded (passenger car: 5.4 dBA, van: 4.6 dBA) design. Results for the heavy vehicle were complicated due to bridging of the narrower rounded rumble strip by the tires. The wider cut of the sinusoidal RS generated a clearly detectable increase in exterior roadside noise for the heavy vehicle.

Keywords:

Shoulder rumble strips; Sinusoidal rumble strips; Rounded rumble strips; Traffic noise

Acknowledgements:

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2.2 Introduction

Environmental noise exposure has been linked to health effects such as sleep disturbance (Can, 2018; Kaddoura et al., 2017; Murphy, 2018; Soares, 2017; Muzet, 2007; de Kluizenaar et al., 2009), annoyance (Miedema and Oudshoorn, 2001; Fredianelli et al., 2019), cardiovascular effects (Babisch et al., 2005), learning impairment (Lercher et al., 2003; Chetoni et al., 2016), and hypertension ischemic heart disease (Van Kempen and Babisch, 2012). Thus, it is important to avoid unwanted sound and particularly to reduce the noise exposure from road traffic. About half of urban noise is generated by transportation (Calvo et al., 2012). Mitigating environmental noise can happen at the source by reducing the amount of noise generated, or at the receiver by reducing the amount of noise experienced (Murphy, 2018). Environmental noise impact is difficult to predict however, as the physical environment is complex, and individual buildings have different sound insulating conditions (Murphy, 2018). Therefore, it is necessary to mitigate noise at the source as well as the receiver to achieve holistic reductions in environmental noise impact (Murphy, 2018).

One mitigation strategy is to reduce the amount of noise generated by roadway features, such as rumble strips (RS), to reduce infrequent impulsive noise. RS generate noises and vibrations that alert drivers when they are departing the roadway reducing the incidences of run-off-road fatal injury crashes by 33% and all run-off-road crashes by 15% (Torbic et al., 2009). Although inexpensive to install, easy to maintain, and long-lasting, RS generate noise. In many areas with run-off road crashes that could be mitigated by RS, concerns about noise impacts limit their widespread application.

The sinusoidal RS is an alternative design that decreases the amount of exterior noise generated with a vehicle strike while providing sufficient interior noise and haptic feedback to alert the driver that they are leaving the travel lane (Himes et al. 2017). Sinusoidal RS are milled into the pavement similar to traditional, rounded RS but use a continuous cut that changes depth following a sinusoidal wave.

Sinusoidal RS were first developed in Europe and evaluated in the Netherlands, Sweden and Britain before being investigated in the United States in California by the California Department of Transportation (Caltrans) (Kragh, 2007; Caltrans, 2012). The

Minnesota Department of Transportation (MnDOT) then evaluated the proposed California sinusoidal design versus a Pennsylvania and Minnesota design (Terhaar & Braslau, 2015). The Oregon Department of Transportation (ODOT) and Caltrans then simultaneously evaluated sinusoidal RS in 2018 (Donavan & Buehler, 2018).

This paper summarizes the results of field research in Oregon that evaluated the feasibility of using sinusoidal RS as a substitute for rounded milled RS on roadway segments with lane-departure crash problems. Exterior sound levels generated by rounded and sinusoidal RS strikes were compared to baseline sound levels for three vehicle types (passenger car, van, and heavy vehicle) to establish sound generation of the two designs. The study benchmarks the existing noise generation of the rounded RS, and tests if the sinusoidal RS generates less noise. A total of 39 vehicle strikes of RS were recorded in a controlled field experiment for comparison. The results are compared to other evaluations of sinusoidal RS in the United States.

2.3 Background

The FHWA *State of the Practice* document has an extensive literature review regarding exterior noise evaluation of RS (Himes et al. 2017). Six studies have been identified from this document that evaluate the exterior noise associated with RS through a variety of road materials, RS sizes, RS spacing and vehicle types (Finley & Miles, 2007; Rys et al., 2010; Kragh, 2007; Datta et al., 2012; Sexton, 2014). Key findings indicate that exterior noise is related to the speed of the vehicle, as well as the depth of the RS (Rys et al., 2010; Datta et al., 2012).

MnDOT performed exterior vehicle noise testing on 3 sinusoidal RS designs – California, Pennsylvania, and Minnesota designs – using 3 vehicle types at 3 speed thresholds (Terhaar & Braslau, 2015). The dBA levels increased proportionally with vehicle speed and vehicle weight. The California and Minnesota designs produced similar exterior sound levels, with the Minnesota design being slightly louder at the highest speed. Noise with the California RS design was generally at a lower frequency, which improved the exterior sound level, while providing sufficient driver feedback.

In April 2018, CalTrans published a study comparing sinusoidal, conventional rounded, and raised pavement marker RS (Donavan & Buehler, 2018). The study described the development of the sinusoidal design based on tire dimensions to create a quieter RS that still generates a sufficient alert for the driver. Noise was evaluated using a modification of the AASHTO SIP Method. Five test vehicles were evaluated at a 96.6 kph pass-by speed. As the study methodology in this research and the MnDOT and Caltrans studies are very similar, the results of this study are compared to reports from other state agencies to verify the effectiveness of sinusoidal RS.

2.4 Methods

2.4.1 Site Selection

The experimental design was based on the AASHTO SIP Method (AASHTO, 2013). SIP criteria require a clear area free of trees and other reflecting surfaces. Figure 2.1, created by the authors, summarizes the key criteria of the SIP method. To explore sinusoidal and rounded RS, sites were selected on the same route, US-26, for comparability. Based on the criteria and using online maps, test sites were selected on US-26, southwest of Gresham OR, to measure sound levels.

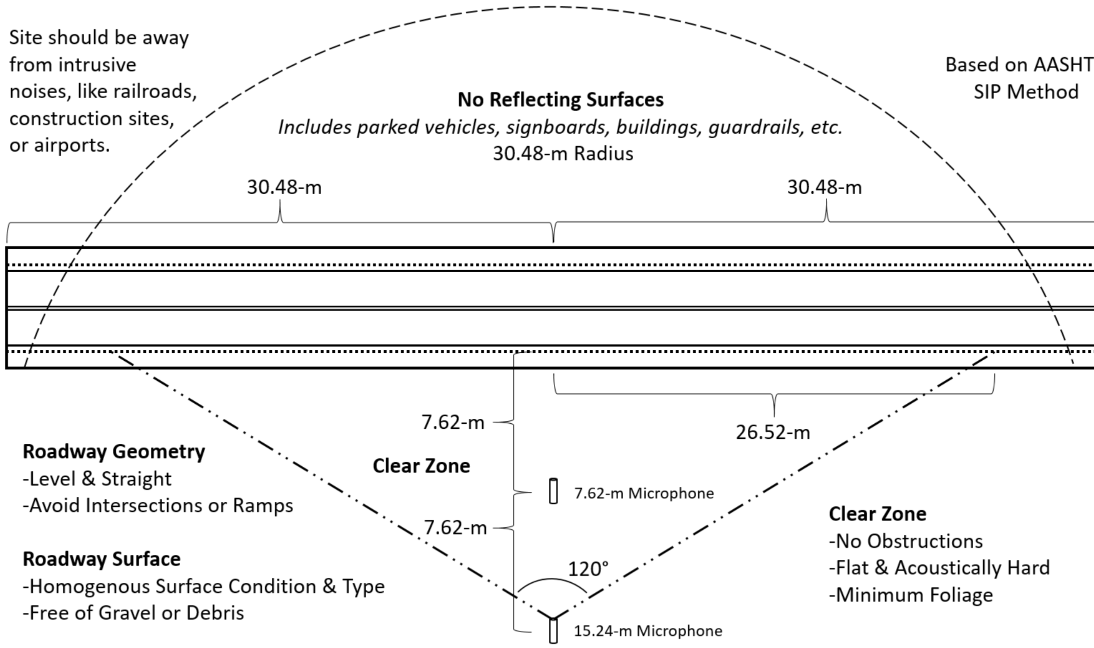

Figure 2.1 Site selection guidelines based on AASHTO SIP method

Site A is the location of the sinusoidal RS test site, located in Boring, OR. At this location, US 26 is a 4-lane divided highway, with left- and right-shoulder RS. Site B is the location of the rounded RS test site, located east of Sandy, OR. At this location, US 26 is a 4-lane highway with a 2-way left-turn lane with both centerline and shoulder RS. Only the shoulder RS were tested.

2.4.2 Exterior Noise Measurement

The setup for exterior measurements is shown in Figure 2.2 and 2.3. The near microphone was mounted 1.52 m above the ground, and the far microphone was mounted at 3.66 m. Equipment was selected based on SIP Method guidelines (AASHTO, 2013). The literature recommends a strike time of 10 s (Terhaar & Braslau, 2015). To alert the driver of the test vehicle to the required length to start and end the RS strike, two cones were placed 243.84 m apart on the shoulder. This distance is based on an 88.5-kph vehicle speed, which was verified for each strike using a radar gun. During each RS strike, the recording was monitored on a laptop to ensure that the event was 6 dB louder than the background noise. This decibel difference ensures that the strike event is detectable and independent from the influence of other noise. Additional runs were recorded if there was excess background noise.

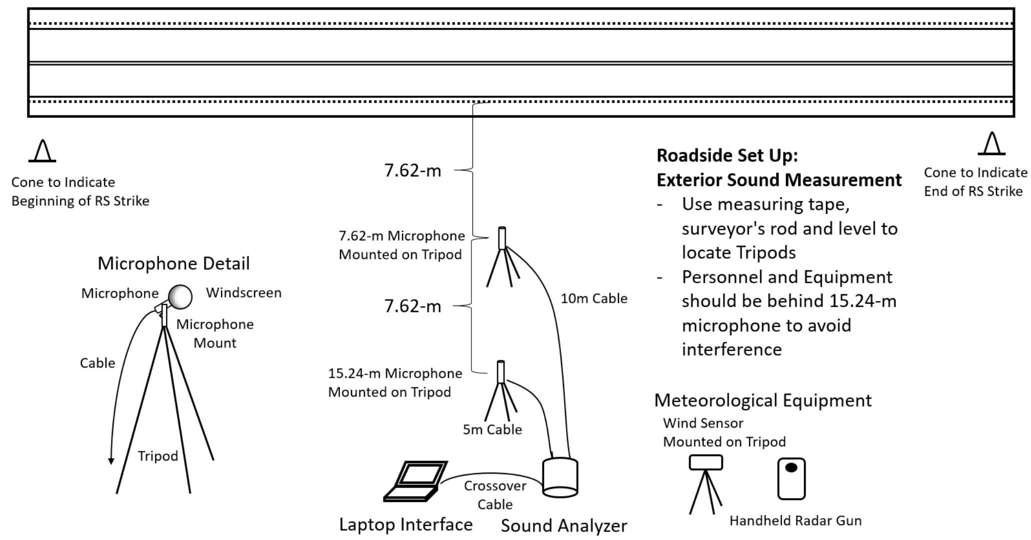

Figure 2.2 Exterior sound measurement diagram

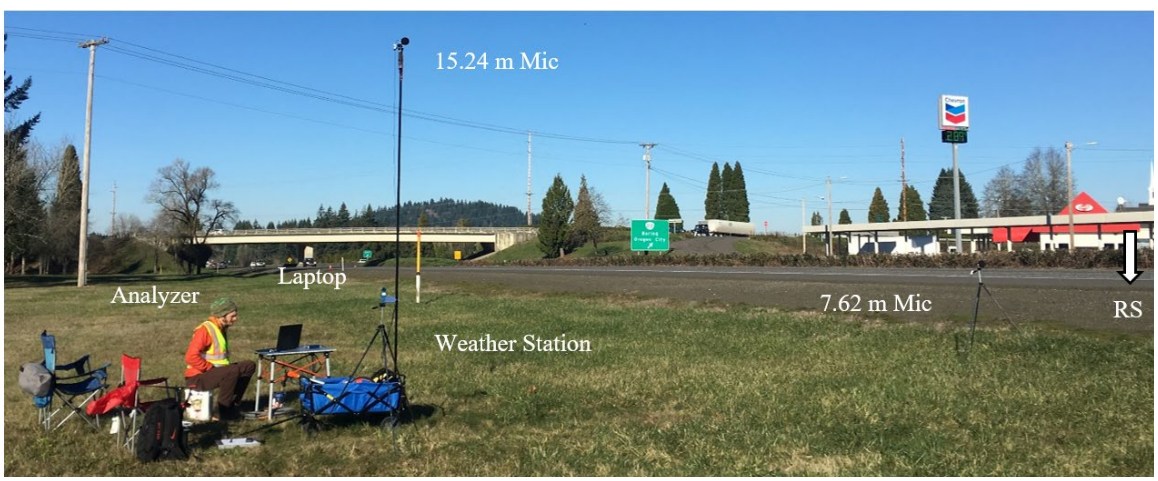

Figure 2.3 Exterior sound measurement setup

2.4.3 Meteorological Conditions

Meteorological conditions were recorded before the experiment and at one hour intervals during testing. If wind speed exceeded 17.7 kph at the time of measurement, the maximum threshold to avoid interference, additional vehicle passes were performed. Wind direction was noted, to explain potential data discrepancies. Temperatures should be within ±13.9 °C between measurements to minimize the influence of temperature on data. Sky conditions were recorded as clear, scattered clouds, partly cloudy, mostly cloudy, or overcast. Pavement was visibly dry; tests were not performed during wet conditions to avoid damaging the sound equipment.

2.4.4 Vehicle Types Evaluated

A 2015 Dodge Grand Caravan (Figure 2.4-Left) and 2017 Ford Focus Hatchback passenger car (Figure 2.4-Center) were rented from Oregon State University's motor pool and driven by licensed graduate students. A heavy vehicle was also tested, a Volvo VHD dump truck (Figure 2.4-Right), which was supplied by the Oregon Department of Transportation (ODOT) and driven by an ODOT equipment operator with a Commercial Driver's License from the Sandy Maintenance Division. Drivers were instructed to drive at the posted speed at a safe operating distance from other vehicles on the roadway.

Figure 2.4 Left: Van striking a RS; Center: Passenger car; Right: Heavy vehicle

In the Caltrans sinusoidal RS study, two types of tires (SRTT and GDY) were tested on a Ford Fusion to determine the sensitivity of tires on RS noise (Donavan & Buehler, 2018). Tire characteristics do influence the amount of sound generated in RS strikes, as much as 5 dB for certain frequencies. However, the interior sound and vibration alert was sufficient to warn the driver for both tires. For this study, the tires on the vehicles were held constant across the experiment. Therefore, a sensitivity analysis of the impact of the tire characteristics is not included. The van was equipped with Uniroyal Tiger Paw 225/65 R17. The passenger car was equipped with Continental ContiProContact 215/55 R16 93 H tires. The heavy vehicle was equipped with Bridgestone M854 385 R-22.5 in the front and Bridgestone L320 11 R-22.5 in the rear.

2.4.5 Rumble Strip Characteristics

Geometric characteristics of each RS type were measured and recorded to document the general properties of the tested RS. Average field geometric characteristics of the sinusoidal RS are shown in Figure 2.5, and the rounded RS is shown in Figure 2.6. Mill depth was measured several times at different mills due to slight variances in milling, and the average of these measurements is presented.

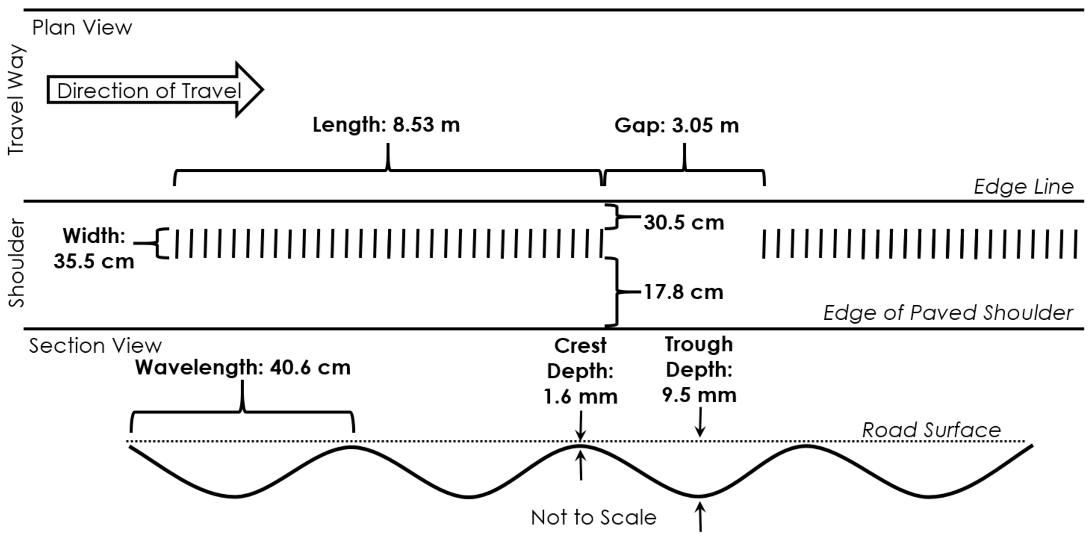

Figure 2.5 Sinusoidal RS geometric characteristics

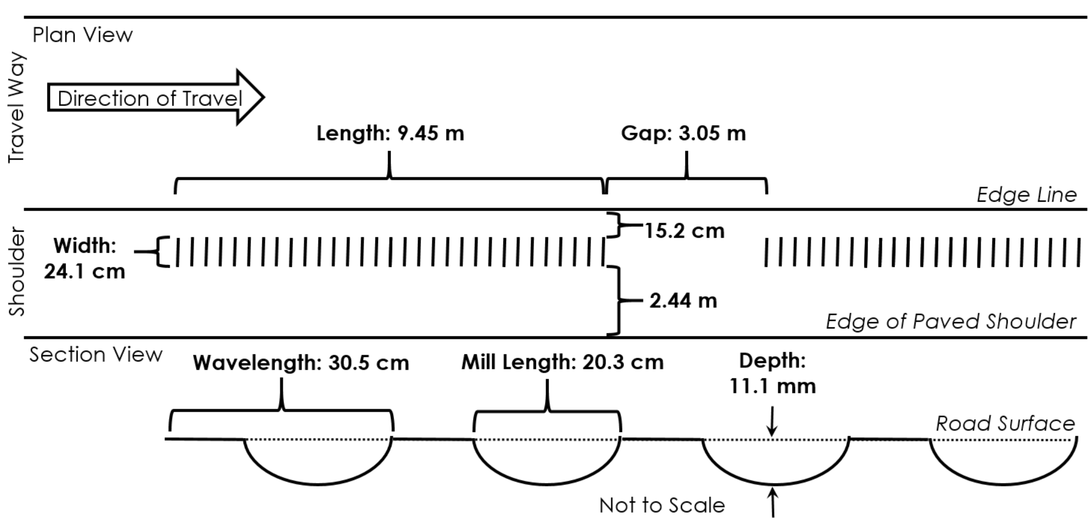

Figure 2.6 Rounded RS geometric characteristics

Figure 2.7 shows a photograph from each site. Irregularities in pavement aggregates caused some variation in mill depth, as larger aggregate chunks chipped away. The sinusoidal RS (on the left) had a slightly wider and more scalloped shape to the edge of the mill. The mills were continuous, with the maximum mill depth at the trough of the wave and the minimum at the crest. The maximum depth of the sinusoidal mill was less noticeable than that of the rounded design. The rounded RS (on the right) had a distinctive separation between each of the mills. The shape was generally rectangular (in plan view), with more defined edges. The maximum depth of the rounded mill was deeper than that of the sinusoidal design. The sinusoidal RS design is wider and shallower than the rounded RS design as shown in Figure 2.7.

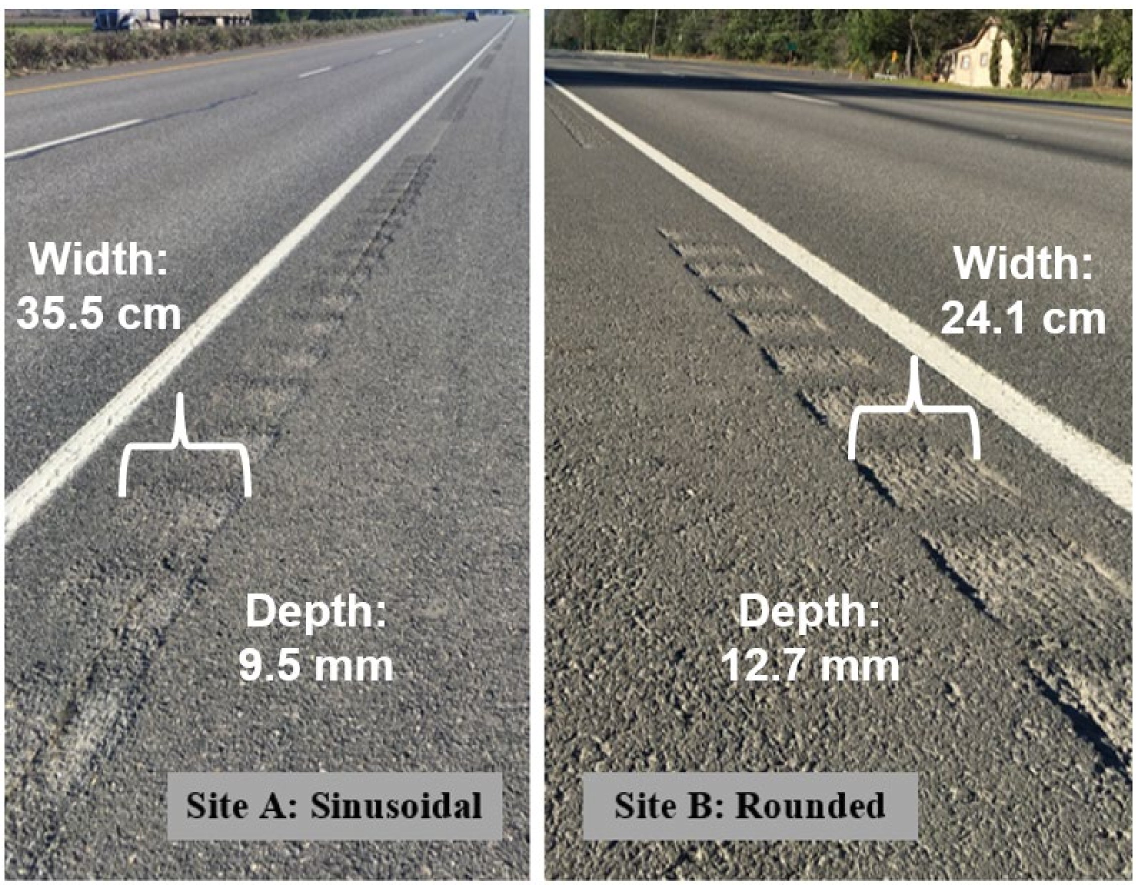

Figure 2.7 Visual comparison of RS designs

2.4.6 Experimental Data Collected

Sound levels generated by rounded and sinusoidal RS strikes were compared against baseline conditions across 3 vehicle classes (passenger car, van, and heavy vehicle). Starting at the sinusoidal RS location, exterior noise was measured for the baseline and strike conditions. After exterior measurements at the sinusoidal RS location, the research team moved to the rounded RS location. Equipment was then set up on the roadside for measurements for the rounded RS. Based on the literature, at least 3 recordings were made for each experimental case. If excessive background noise, high wind speeds, or partial RS strikes occurred, additional runs were collected. A total of 39 exterior measurements were collected (breakdown by factor groups of vehicle type, rumble strip type, and condition in Table 2.1).

Table 2.1 Number of Measurements for each Factor Group

Vehicle type	Rumble strip type	Condition	Exterior noise samples
Passenger Car	Sinusoidal	Baseline	3
		Strike	3
	Rounded	Baseline	3
		Strike	3
Van	Sinusoidal	Baseline	3
		Strike	3
	Rounded	Baseline	4
		Strike	5
Heavy Vehicle	Sinusoidal	Baseline	3
		Strike	3
	Rounded	Baseline	3
		Strike	3
		Total	**39**

2.4.7 Performance Measures

Performance measures for this study were chosen based on previous research and standards. Terhaar's framework plots the sound pressure level (SPL) against the 1/3-octave band for the ambient and RS strike noise levels (Terhaar, 2016). This method shows the frequencies at which the RS strike exceeds the background noise, indicating the distinguishable noise generated by the RS strike. The weighted average of the factor group values were used as the performance measure. Figure 2.8 shows how the RS strike frequencies were compared to the baseline conditions. For both RS types, the noise observed for the baseline condition was subtracted from the strike condition (Equations 2.1 and 2.2), to obtain the amount of additional noise that was generated from the strike when all other variables were held constant for each factor group.

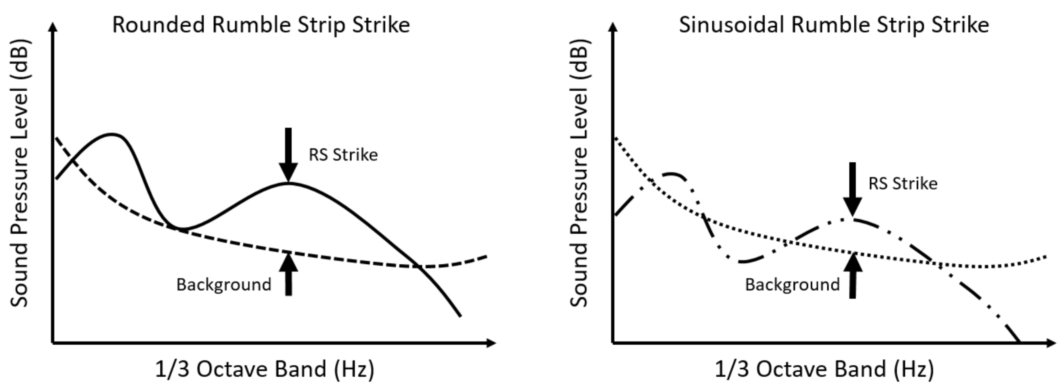

Figure 2.8 Framework for sinusoidal noise reduction during sound measurement

$$\Delta \text{ Rounded dB} = \text{RS Average Strike dB} - \text{Average Background dB} \quad (2.1)$$

$$\Delta \text{ Sinusoidal dB} = \text{RS Average Strike dB} - \text{Average Background dB} \quad (2.2)$$

2.5 Results

2.5.1 Meteorological Conditions

Average values for meteorological conditions at each site during data collection are shown in Table 2.2. Despite some variability between conditions, baseline and strike conditions for each factor group were recorded near each other to minimize variability and to obtain consistent deltas between measurements. Observed dBA differences between factor groups could vary slightly due to weather conditions, particularly wind speed. Based on the experimental set up, NCHRP 882 suggests that the measurement would be 1 dBA louder than the ideal condition based on the 12/7/17 Site B conditions (Kaliski et al., 2018). However, this increase would affect both the baseline and strike conditions, resulting in a very similar magnitude difference between the measurements.

Table 2.2 Measurements of Meteorological Conditions

Date	**Site**	**Average wind speed (KPH)**	**Average wind Direction**	**Average temperature (˚C)**	**Sky condition**
12/7/17	A	15.3	114˚	10	Clear
12/7/17	B	17.2*	156˚	7.2	Clear
12/12/17	A	4.8	74˚	3.3	Scattered Clouds
12/12/17	B	9.0	89˚	5.6	Scattered Clouds
12/13/17	A	3.9	90˚	5	Clear
12/13/17	B	7.9	88˚	2.8	Clear

**Windspeeds sometimes exceeded 17.7 kph threshold, necessitating 3 additional runs.*

2.5.2 Noise Measurement

A t-test was used to identify differences in central tendencies between the 7.6- and 15.2-m microphones for the sinusoidal RS with the passenger car. A statistically significant difference between these microphones was observed ($p < 0.05$). Higher noise was captured at 7.6 than at 15.2 m; this result was expected because the sound intensity decreases with distance from the source. Measurements from both microphones were averaged before further analysis was conducted.

To verify that RS measurements actually contained the additional noise profiles of the RS strikes, the frequency of sound pressure was evaluated. Based on the relationship between the speed of the vehicle and the size of the rumble strip, a specific frequency is expected. Previous research has predicted 80 Hz based on the conditions of the studied RS (Kalathas et al., 2019, Donavan & Buehler, 2018). For this study, the expected frequency is explained by vehicles traveling at 88.5 kph (24.60 m/s) striking a 40.6-cm (0.41-m) wavelength RS. Dividing the speed by the RS wavelength provided 60.5 strikes/s (Hz), which were transferred through the body of the vehicle producing the characteristic noise.

Figure 2.9 compares exterior measurements for the passenger car during the rounded RS strike condition (in blue) and the baseline condition (in red). This comparison shows the intensity of each frequency for the total measurement and does not relate to time. The expected peak demonstrating additional sound intensity ~80 Hz is present, confirming the presence of the RS noise recorded in the strike condition.

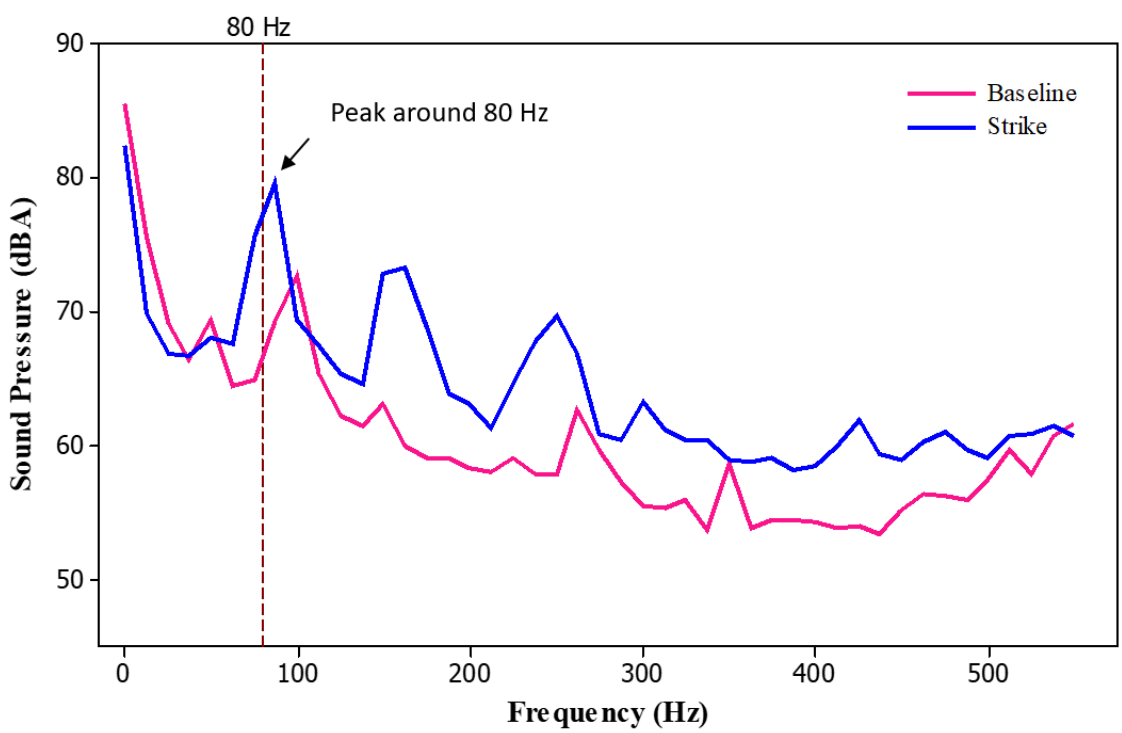

Figure 2.9 Exterior sound measurement frequency comparison

A dB histogram was analyzed to compare conditions for the same exterior passenger car measurement, without the influence of time. Figure 2.10 shows the sum of the observed dB measurements across the total measurement and does not relate to a time series. The strike condition for the rounded RS is shown in blue, and the baseline condition for the passenger car is in red. Two features are apparent. The first feature is a large increase in a specific dB related to the RS strike, around 73 dB. This dB corresponds to the amount of noise present at that sound level, and is not an indication of the frequency of the sound intensity. The second feature is an increase in the highest dB levels on the right tail of the distribution. The highest dB levels are the basis of the analysis, indicating how much the sound intensity is increased by the addition of the RS strike. The highest dB level for the baseline (red) is ~86 dB, whereas the highest dB level for the strike is 91 dB, with a peak of ~89 dB. The strike condition has a noticeable increase in the highest dB levels (increase in sounds with the most energy).

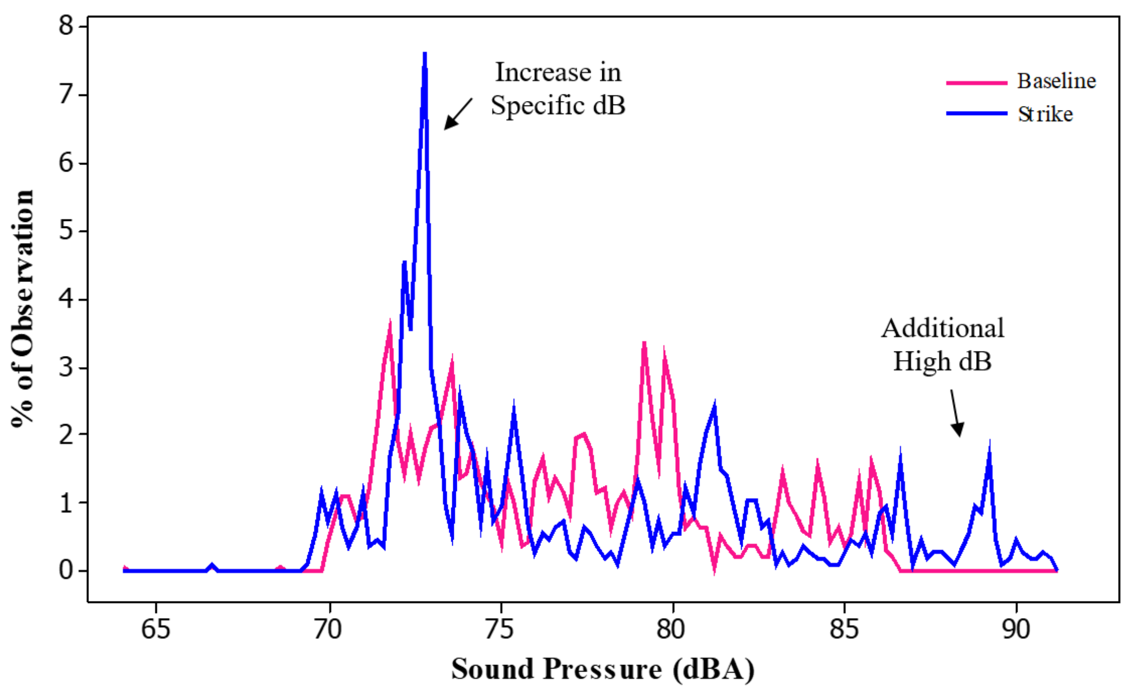

Figure 2.10 Exterior dB histogram for baseline and strike conditions

After confirming measurement of the RS strikes, specific strike and baseline events were isolated in the datasets. During field measurements, recordings began as the vehicle approached and continued as the vehicle passed the RS (~15 s). The probe vehicles (PC, van, and HV) were noticeable above the background noise for a shorter period (~3 s). Individual recordings were reviewed to identify when the peak noise intensity occurred.

As dBA is a logarithmic scale, a weighted average was used to average the 3 strike and 3 baseline conditions for each factor group (see Table 2.1) across the time series. Figure 2.11 shows the strike and baseline exterior sound measurements of the passenger car at the rounded RS site, and the weighted average values for the strike and baseline conditions. A total weighted average was calculated to determine the difference between the strike and baseline conditions for the total measurement. For this rounded strike, the strike average was 90.3 dBA (vs. 83.9 dBA for baseline). The difference (6.4 dBA) is sufficiently large to be noticeable to human hearing (>5 dBA), confirming that the RS strikes produce a clearly noticeable increase in road noise.

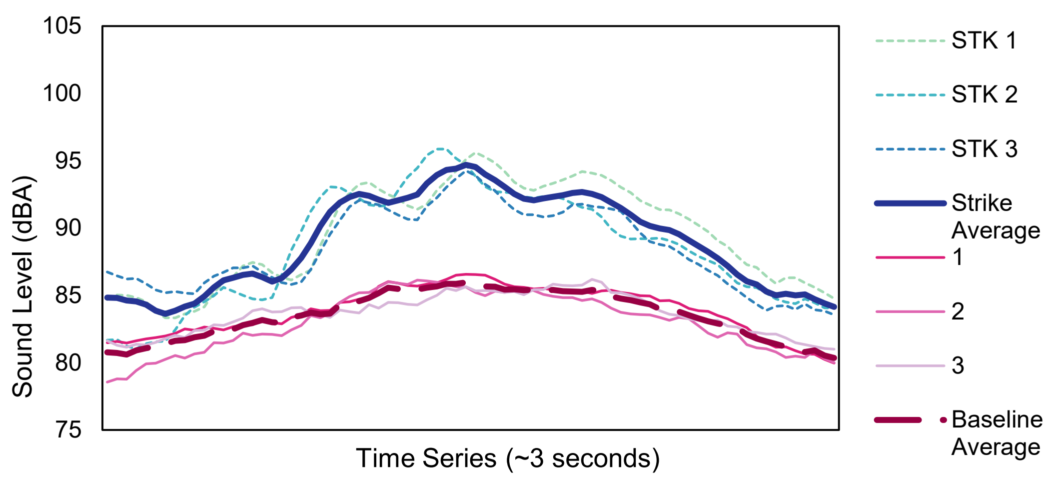

Figure 2.11 Sound measurements from passenger car striking the rounded RS

The procedure was repeated for each factor group. Figure 2.12 shows exterior measurements for the passenger car at the sinusoidal location. The baseline average was 85.3 dBA compared to the strike average of 87.1 dBA. The difference (1.8 dBA) was barely detectable (<3 dBA), indicating that the perception of road noise would be nearly the same for the baseline and strike conditions. As this measurement was taken immediately adjacent to the road, noise propagation should follow the same relationship, with the RS strike being perceived as normal road noise.

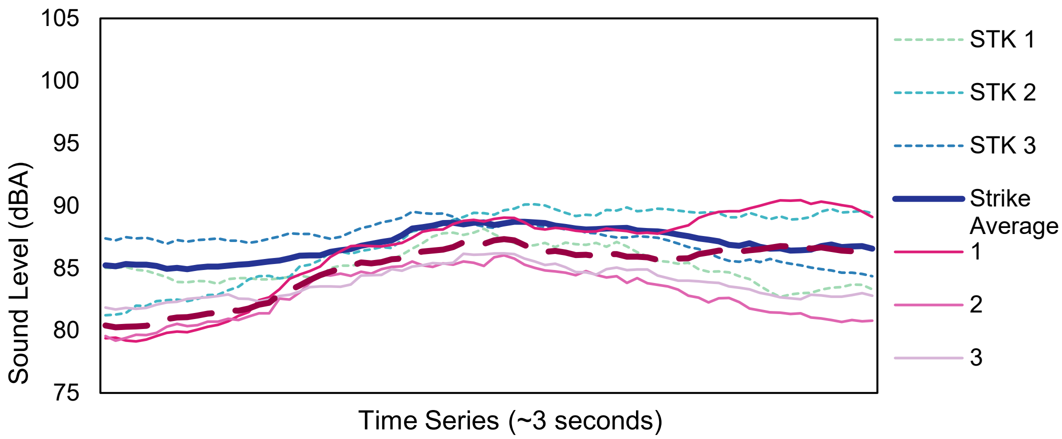

Figure 2.12 Sound measurements for the passenger car striking the sinusoidal RS

Table 2.3 Average dBA Magnitudes for the Factor Groups

Vehicle type	RS Type	Condition	Exterior Average dBA
Passenger Car	Sinusoidal	Baseline	84.6
		Strike	87.1
	Rounded	Baseline	83.9
		Strike	90.3
Van	Sinusoidal	Baseline	85.9
		Strike	86.0
	Rounded	Baseline	89.4
		Strike	94.2
Heavy Vehicle	Sinusoidal	Baseline	88.5
		Strike	94.5
	Rounded	Baseline	91.6
		Strike	95.0

Table 2.3 shows average measurements for the baseline and strike conditions for each factor group. Baseline measurements were generally within the barely detectable range (<3 dBA) for each vehicle type, indicating similar pavement, weather, and ambient noise conditions between the two locations.

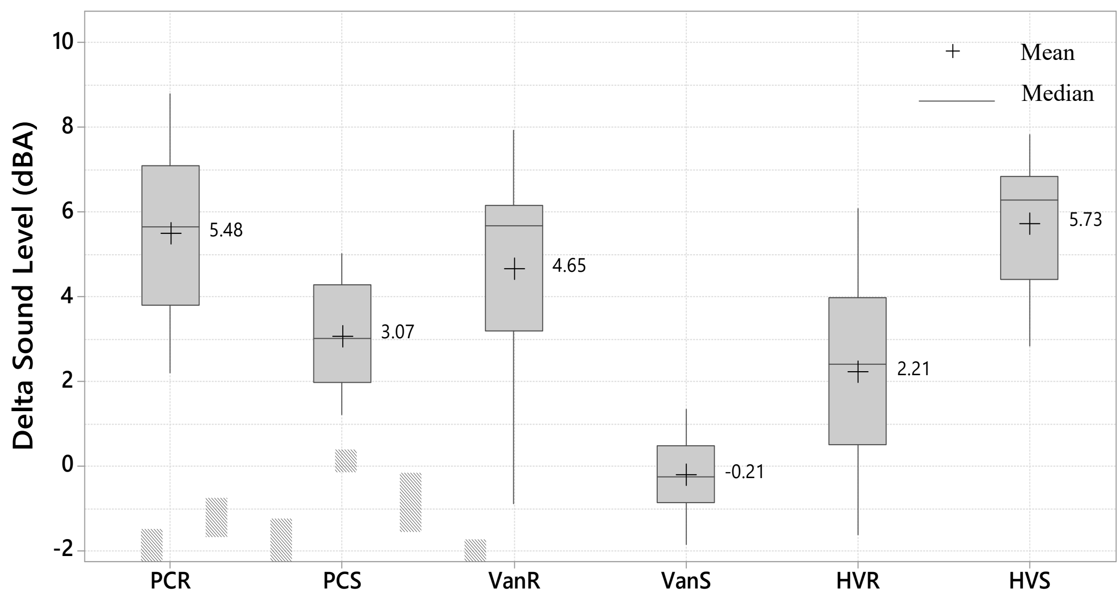

Figure 2.13 Boxplots by vehicle and RS type for exterior delta sound measurements. PC, passenger car; HV, heavy vehicle; R, rounded RS; S, sinusoidal RS.

Figure 2.13 shows boxplots for differences between the observed time series of strike and baseline conditions, indicating the increase in road noise, for each factor group. The figure labels denote the vehicle type and the type of strike (e.g. passenger car, rounded strike (PCR). Differences in the rounded RS strike over baseline for the passenger car and van were in the clearly noticeable range (5 dBA). The sinusoidal RS strike for the passenger car was detectable (3 dBA) over baseline, whereas the sinusoidal RS strike for the van was imperceptible from baseline road noise (0 dBA). The heavy vehicle had a barely detectable noise for the rounded RS strike compared to baseline, which increased to a noticeable noise for the sinusoidal RS strike. This increase was likely due to the wider RS of the sinusoidal RS, which allowed the dual-tires of the heavy vehicle to interact with the RS instead of bridging over it. This conclusion is supported by previous studies of RS width.

2.5.3 Statistical Analysis

Data were analyzed in the Minitab statistical software package (version 18). All tests were performed at a 95% confidence level. Two-way ANOVA was performed on the strike and baseline exterior sound measurement deltas to determine whether average sound differed between the 2 RS types (rounded and sinusoidal) and between the 3 vehicle types (passenger car, van, and heavy vehicle). Table 2.4 shows that there was a statistically significant difference for RS type ($p < 0.001$) and between the means for at least 1 vehicle type ($p < 0.001$).

Table 2.4 The ANOVA summary table for exterior sound measurement

Source of variance	**df**	**MS**	***F***	***P***
RS Type (R, S)	1	12.36	19.02	<0.001*
Vehicle Type (PC, Van, HV)	2	9.80	15.07	<0.001*
RS Type * Vehicle Type	2	27.56	42.40	<0.001*
Error	12	0.65		

**Significance level of 0.01*

To identify where differences between group means occurred, a Tukey HSD post hoc pairwise comparison test was performed, and main effect plots were used as shown in Figure 2.14. In this graph, the differences are observed between specific factors with all other factors held constant. For RS type, the noise of the rounded RS was ~1.3 dBA higher than that of the sinusoidal RS. For vehicle type, both the passenger car and heavy vehicle generated more noise than the van, with the passenger car producing the highest delta ($p < 0.0001$).

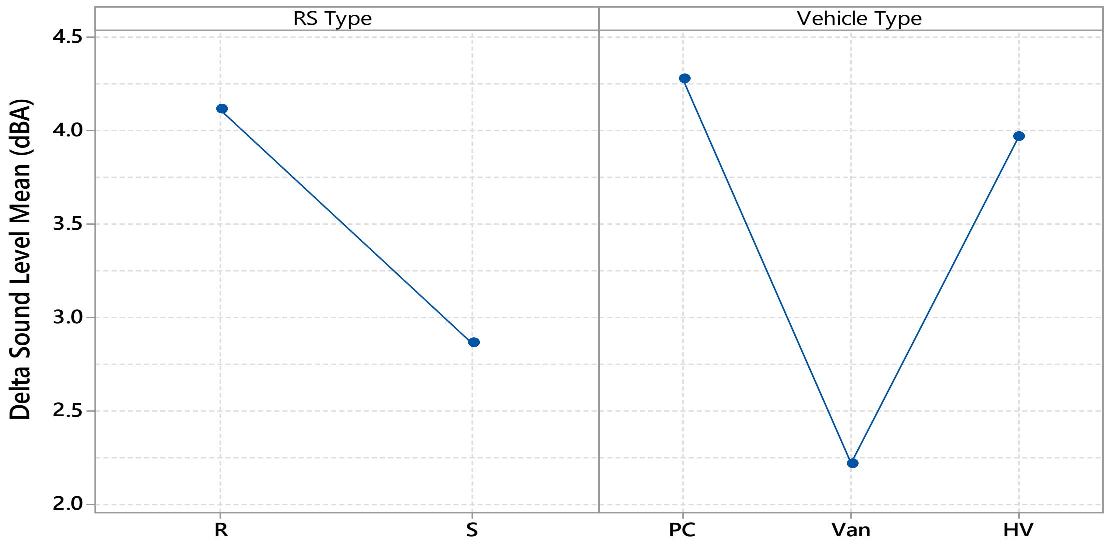

Figure 2.14 Main effect factors of exterior sound measurement

There was a statistically significant interaction between the combined effects of RS type and vehicle type on sound measurement ($p < 0.001$) (Table 6). Figure 2.15 plots the delta mean sound at each level of RS and vehicle type, as well as pairwise comparisons. The heavy vehicle generated more noise when striking the sinusoidal RS than when striking the rounded RS ($p < 0.001$). The passenger car and van generated less noise while striking the sinusoidal RS compared to the rounded RS ($p < 0.001$ for both).

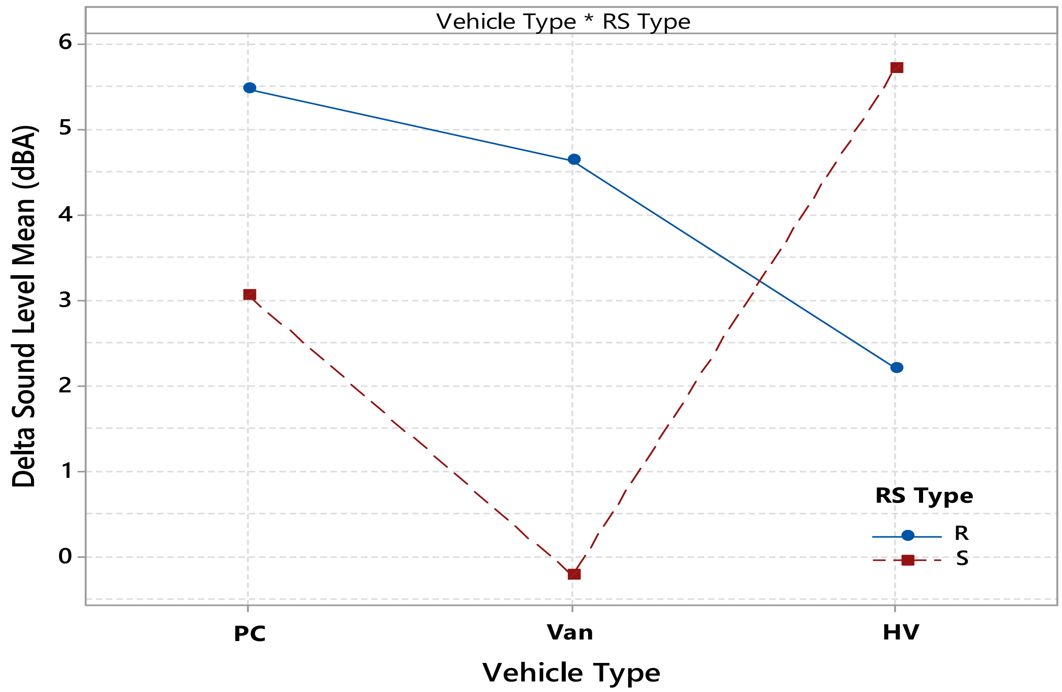

Figure 2.15 Factor interactions for exterior sound measurement

2.6 Discussion

For the passenger car or van, the exterior noise measured at 7.62 and 15.24 m from the roadside was less when striking the sinusoidal design compared to the rounded design. Rounded RS strikes generated a clearly noticeable increase in roadside noise of ~5 dBA over baseline (passenger car: 5.4 dBA, van: 4.6 dBA). The sinusoidal RS strike produced a detectable increase in roadside noise for the passenger car (3.1 dBA) but an imperceptible change from baseline for the van (-0.2 dBA). Differences between vehicle types were expected, as the suspension, tire characteristics, and vehicle weight influence noise generation. Both vehicles showed similar decreases in exterior sound, indicating that the sinusoidal design did in fact reduce roadside noise. This provides further evidence of the sound reduction potential of the sinusoidal design, confirming the results of other state agencies.

The dual-tire heavy vehicle did not generate high exterior (2.2 dBA) noise with the rounded RS strike. The MnDOT study suggested that RS be wider than 20.32 cm to address heavy vehicle tire bridging (Terhaar & Braslau, 2015). This was confirmed by the observational data that indicated bridging of the dual-tires over the narrow RS reduced the rounded RS noise. As the dual-tires are much wider than the width of the RS, noise and vibration are significantly reduced. The sinusoidal RS generated a detectable increase in exterior noise of 5.7 dBA. The dual-tires interacted with the wider sinusoidal RS increasing the exterior noise, generating additional noise. The heavy vehicle sinusoidal RS strike is similar to the exterior noise of the passenger car striking the rounded RS. Thus, installing a wider (sinusoidal or rounded) RS would likely extend the effectiveness of this countermeasure to heavy vehicles.

The results from this research compare well to two recent evaluations of sinusoidal rumble strips. Minnesota Department of Transportation (MnDOT) evaluated exterior vehicle noise from three sinusoidal RS designs (Terhaar & Braslau, 2015). The study compared three vehicle types and three different speeds groups. It found that the exterior sound levels for the Minnesota and California designs similar, and both generated a sufficient interior alert. The Pennsylvania design generated the lowest exterior noise, but did not generate a sufficient interior alert (Terhaar & Braslau, 2015).

The California Department of Transportation (Caltrans) preformed a similar sinusoidal RS study simultaneously with the Oregon study (Donavan & Buehler, 2018). The Caltrans sinusoidal RS design decreased exterior sound levels by 3 dBA (for heavy vehicles) to 6 dBA (for light-duty vehicles) (Donavan & Buehler, 2018). For exterior sound measurements of light-duty vehicles, baseline passes produced sound levels of 79.9–81.8 dBA (Donavan & Buehler, 2018). Rounded RS passes ranged 92.6–96.7 dBA, and sinusoidal RS passes ranged 85.6–90.0 dBA. Peak frequencies were observed at 80 and 160 Hz for the sinusoidal RS. The 80 Hz frequency is explained by vehicles traveling at 96.6 kph (26.8 m/s) striking a 35.6-cm (0.36-m) wavelength RS. Dividing the speed by the RS wavelength provided 75.4 strikes/s (Hz), which were transferred through the body of the vehicle producing the characteristic noise. Interior sound and vibration measurements were comparable, with the both RS types generating alerts ~13 dB higher than baseline insure a sufficient alert to the driver (Donavan & Buehler, 2018).

Table 2.5 compares some of the results from the MnDOT and Caltrans study to the present study. The passenger car data reported for both the external studies was a

Chevy Malibu, but the heavy vehicles were different, with Caltrans using a 4 yard dump truck and MnDOT a tractor and trailer. The physical geometry of the sinusoidal RS designs varies across the studies. The MnDOT design was the widest and deepest, though the shortest wavelength. The Caltrans design was the most narrow, and shallow. The ODOT design has the longest wavelength. The rounded designs were also compared between Caltrans and ODOT, with similar wavelengths, but slightly deeper for ODOT. The speeds were the same between the MnDOT and Caltrans study, but ODOT was slightly slower, which is expected to reduce the intensity of the noise.

In Table 2.5, the delta between the baseline measurement and the strike value is reported to show the relative increase of the sound during a RS strike. This comparison to the baseline helps to control the differences in pavement materials, vehicle types, speeds and other characteristics. The delta for the Caltrans sinusoidal RS was 3 dB less than the rounded design for the passenger vehicle. A decrease (2.4 dB) was also found for the ODOT passenger vehicle between the RS types. The Caltrans study found lower noise from the sinusoidal RS and traditional RS for the heavy vehicle. Whereas the ODOT sinusoidal RS increased the exterior noise compared to the rounded RS. The lower noise for the rounded RS is related to the tire bridging over the narrower rounded RS for the dual-tire truck. The Caltrans study did suggest that tire bridging may have reduced the response for the heavy vehicle. The MnDOT study did not compare against a rounded design, but the MnDOT sinusoidal RS produced the highest delta (18.5 dB) of the three RS studies (Terhaar & Braslau, 2015).

A RS is only effective if the interior alerts to the driver are noticeable. The interior alerts, or the difference between the background and strike sound levels measured inside the vehicle, are also presented in Table 2.5. The two other studies found the sinusoidal RS produce a readily noticeable increase in interior noise. Caltrans reported a larger alert for the sinusoidal design compared to their rounded design, though both are large enough to alert the driver. The MnDOT design produced a large alert of 15.5 dB for the passenger car (Terhaar & Braslau, 2015). For the heavy vehicle, Caltrans reported an insufficient interior alert (< 5 dB) for the sinusoidal RS compared to the sufficient alert for the rounded. Heavy vehicle data was not presented for the MnDOT sinusoidal design

(Terhaar & Braslau, 2015). The present study also included an experimental analysis of interior noise but the methods, sampling approach, and data analysis are significantly different than the exterior evaluation and are not reported in this paper for brevity. However, the results were generally consistent with those from MnDOT and Caltrans.

Table 2.5 Comparison of results to similar studies (Terhaar & Braslau, 2015; Donavan & Buehler, 2018)

		Sinusoidal Designs			**Rounded Designs**		**Units**
		MnDOT	Caltrans	Present Study	Caltrans	Present Study	
Geometry	Wavelength	30.5	35.6	40.6	30.5	30.5	cm
	Depth	9.5 - 12.7	7.9	1.6 - 9.5	7.9	11.1	mm
	Width	40.6	20.3	35.5	n/a	24.1	cm
	Speed	96.6	96.6	88.5	96.6	88.5	kph
Exterior Delta	PC	18.5	7.1	3.1	10.5	5.5	dBA
	HV	n/a	3.7	5.7	5.9	2.2	dBA
Interior Delta	PC	15.5	19.1	5.8	16	11.4	dBA
	HV	n/a	2.6	6.8	7.6	0.8	dBA

Note: PC – Passenger Car; HV – Heavy Vehicle

Constructability, cost and maintenance are also important considerations in selection of RS type. A survey of RS contractor experience and equipment was developed to better understand the state of practice of RS installation. Contractors provided information about best practices from their experiences, installation cost, equipment type, and performance. Contractors suggested that sinusoidal rumble strips take three times longer to cut than traditional due to the continuous nature of the cuts. This increase in cutting time would increase the marginal cost of sinusoidal RS compared to the rounded RS. Asphalt pavement is generally preferred, as concrete cuts are even slower, though concrete can be cut if it has been recently poured. Specific cutting heads may be required for sinusoidal cuts depending on the milling machine, increasing initial capital cost.

2.7 Conclusions

This research study compared exterior sound levels of three typical vehicle classes striking traditional rounded and sinusoidal rumble strips (RS) to baseline conditions. The values are based on the average difference between the baseline and strike conditions over a 3 second period for at least 3 strikes. This study compared the results of the exterior noise evaluation to similar studies. The results of this study are similar to other studies, showing a decrease in exterior noise with the sinusoidal RS design.

The sinusoidal RS strike generated less exterior noise than the rounded RS for the passenger car and van. This statistically significant reduction varied for the vehicles, with the passenger car having a detectable reduction (2.3 dBA), while the van had clearly noticeable reduction in roadside noise (4.8 dBA). This reduction in roadside noise is an indication that switching to a sinusoidal RS design could be used as a mitigation method for reducing source environmental noise.

The exterior noise increased 3.5 dBA for the heavy vehicle striking the sinusoidal RS compared to the rounded RS. This increase is related to the dual-tires of the heavy vehicle bridging over the narrower rounded RS, but interacting with the wider sinusoidal RS. This conclusion is also supported by the Minnesota Department of Transportation study, which indicated that RS should be wider than 20.32 cm to address tire bridging (Terhaar & Braslau, 2015). Installing wider RS of all types could help to extend the effectiveness of this safety countermeasure to heavy vehicles.

RS are designed to alert the driver that they are leaving the travel lane with an intense short duration noise which can wake nearby sleeping residents. Reducing the intensity of this noise could allow for wider adoption of this effective safety countermeasure. Changing the RS design is a relatively low cost alternative, compared to cost of crashes due to avoiding the countermeasure, or installing sound walls. The results of this study are generally consistent with two other independent state agency studies, confirming that sinusoidal RS are an effective safety countermeasure while reducing roadside noise.

3. EVALUATING INTERIOR ALERT INSIDE THE VEHICLE DURING INCURSIONS ON SINUSOIDAL RUMBLE STRIPS

Dylan Ross Horne, Hisham Jashami, David S. Hurwitz,
Christopher M. Monsere, and Sirisha Kothuri

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3.1 Abstract

Roadway departure crashes accounted for 18,275 fatal crashes in 2017 across the United States (Jones et al. 2017). Rumble strips (RS) provide audible and haptic feedback when a vehicle is departing the roadway, to reduce run-off-the road crashes. The shallower and scalloped sinusoidal RS is a quieter alternative to traditional rounded designs reducing environmental noise externalities. However, to be an effective safety countermeasure, the RS must generate a sufficient interior alert through an increase in the interior noise and additional haptic feedback.

To better represent typical driving conditions, the radio and climate control were tested to understand how this additional interior noise effected the interior alert. The ambient conditions did increase the interior noise reducing the interior alert from clearly noticeable to detectable in the passenger car.

The rounded RS did not generate a noticeable alert for the heavy vehicle, while the sinusoidal RS generated a sufficient interior alert. The wide dual-tires of the heavy vehicle bridged over the narrower rounded RS (tire bridging), whereas the wider sinusoidal RS generated the interior alert, indicating that wider RS of any type could extend the effectiveness of RS to heavy vehicles.

This research study confirms that the sinusoidal RS does generate a sufficient interior sound alert across the passenger vehicles. The traditional rounded RS also generated sufficient interior alert. The haptic feedback was evaluated, showing an increase over the human perception threshold for vibration for all vehicle types. The quieter sinusoidal RS could be installed in more locations, especially noise sensitive ones, providing safety benefits by reducing run-of-the-road crashes.

Keywords:
SRS, Shoulder Rumble Strips, Audible Alert, Instrumented Vehicle Study

Acknowledgment:
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3.2 Introduction

Run off the road crashes are responsible for over half of highway fatalities in Oregon (Jones et al. 2017). Many of these crashes are on rural highways. Rumble strips (RS) are a proven safety countermeasure that alert the drivers that they are leaving the roadway through noise and vibration caused by milled grooves or raised striping on the roadway. Shoulder rumble strips (SRS) have been shown to reduce fatal rural highway lane departure crashes by 33% (Torbic et al., 2009). Similarly, Centerline rumble strips (CLRS) have been shown to reduce head on and sideswipe crashes due to lane departure by 30% (Torbic et al., 2009).

While RS are a proven safety countermeasure, they are also associated with highway noise concerns, especially from people living near roadways where they are installed. Long term exposure to road noise has been shown to have negative health impacts, including disturbed sleep (Can, 2018), annoyance (Fredianelli et al., 2019), learning impairment (Chetoni et al., 2016), and hypertension ischemic heart disease (Van Kempen & Babisch, 2012). A new RS design that uses a shallower sinusoidal pattern has been shown to reduce roadside noise (Terhaar & Braslau, 2015; Donavan & Buehler, 2018; Hurwitz et al., 2019a). The interior alert, or the noise and vibration generated from an incursion with the RS, must be sufficient to alert the driver they are departing the lane. Evaluating this noise and vibration of the sinusoidal RS is necessary to ensure this new design is still an effective safety countermeasure. If the interior alert is adequate, sinusoidal RS could be installed in more locations where noise concerns have prevented their use. Compared to other safety countermeasure in Oregon, RS have a low cost per life saved ($320,000 per life), so extending the application of this countermeasure has the potential to reduce road departure crashes (Jones et al. 2017).

3.3 Literature Review

3.3.1 Rumble Strip State of Practice

RS are installed at the edges of the roadway, either on the shoulder (SRS) to reduce run-off-road crashes, or along the centerline (CLRS) to reduce head-on crashes (Hawkins et al., 2016). Across the United States, departments of transportation have a variety of standard RS dimensions and application practices, which are compiled in the FHWA's *State of Practice for Shoulder and Center Line Rumble Strip Implementation on Non-Freeway Facilities* document (hereinafter referred to as the FHWA *Standard of Practice* document) (Himes et al. 2017). The report includes an action plan to address deficiencies within the current state of practice and specifically identifies the need for better evaluation of the safety tradeoffs of quieter RS.

The National Cooperative Highway Research Program (NCHRP) also provides design and application guidance for RS in NCHRP Report 641 (Torbic et al., 2009). This report provides information on crash mitigation strategies, typical dimensions, best practices from state agencies, interior alert thresholds, safety countermeasure effectiveness, and application and design criteria (Torbic et al., 2009). The report also includes recommendations for future research, including the need for studies to mitigate the noise pollution aspect of RS.

The amount of necessary interior alert from a RS strike differs between these two research summaries. A 6 to 12 dBA increase in interior noise is recommended by NCHRP 641 for urban facilities. Guidelines are higher for rural freeways, where 10 to 15 dBA is the target. NCHRP 641 also recommends that alerts not be over 15 dBA, as this may startle the driver. The FHWA State of Practice report suggest the interior alert be at least 3 dBA and preferably at least 5 dBA. Both documents recognize the lack of standards or minimum thresholds on the amount of haptic or vibration feedback.

Based on the FHWA Standard of Practice report, the average SRS has mills that are 16” wide (perpendicular to roadway), 7” long (along roadway), between 0.5” to 0.625 in deep, with a spacing of 12” between mills (Himes et al. 2017). Many studies have shown that the depth of RS mill is a key factor correlated with noise generation with deeper mills producing more noise (Elefteriadou et al., 2000; Bucko, T., & California, 2001; Torbic et al., 2009; Caltrans, 2012). The speed of the vehicle is also correlated with the amount of noise generated, with faster speeds creating more noise during strikes (Finley & Miles, 2007; Terhaar & Braslau, 2015). Some states use narrower RS (<8 in), however these may be bridged over by the wide dual-tires of heavy vehicles, reducing driver feedback, and rendering them ineffective for alerting the driver of lane departure (Torbic et al., 2009; Terhaar & Braslau, 2015).

3.3.2 Sinusoidal Rumble Strips

The motivation behind sinusoidal RS is to mitigate the roadside noise generated during RS strikes to reduce complaints about RS noise. RS strikes have a characteristic frequency around 80 Hz (Donavan & Buehler, 2018; Hurwitz et al., 2019a). Exposure to low frequency vibrations between 10-250 Hz have been shown to disturb sleep, contribute to stress, and have negative cardiovascular effects (An et al., 2016). These low frequency vibrations generally travel further than other noises, affecting people further from the road (Sexton, 2014). To detect a noise, the intensity of the sound must be higher than the ambient background noise (Terhaar et al., 2016). Therefore, time of day plays a critical role in noise disturbance, as there is less background noise at night, and that people are often resting (Caltrans, 2012). Similarly, impulsive noise, such as RS strikes, are more noticeable than continuous noise (Caltrans, 2012).

Sinusoidal RS are a modification of traditional RS design, using a sinusoidal waveform that is shallower with smoother transitions, reducing the amount of noise generated during a strike (Bucko, 2001). This design was initially developed and evaluated in Europe, by the Netherlands, Sweden and Britain, before being studied in California (Kragh, 2007; Caltrans, 2012). In 2015 Minnesota Department of Transportation (MnDOT) evaluated three sinusoidal RS designs: California, Pennsylvania, and Minnesota, finding the California Design most effective (Terhaar & Braslau, 2015).

In 2018 Caltrans reevaluated the California sinusoidal RS with an updated and expanded sinusoidal RS study (Donavan & Buehler, 2018). The newer study documented the development of the California design, and evaluated the interior noise and vibration of sinusoidal, conventional rounded and raised pavement markers RS (Donavan & Buehler, 2018). Initial research suggests that the sinusoidal RS do reduce the roadside noise while providing sufficient interior alert (Torbic et al., 2009; Terhaar & Braslau, 2015; Himes et al. 2017; Donavan & Buehler, 2018). But variations in the shape of the RS, especially the depth, can have a large influence on the noise and vibration generated during a strike.

3.3.3 Interior Sound Alert

Sinusoidal RS have most recently been evaluated in the United States in Minnesota and California and Oregon (Terhaar & Braslau, 2015; Donavan & Buehler, 2018; Hurwitz et al., 2019a). The research methodologies of these studies are similar and consistent with the FHWA & NCHRP recommendations with two parts (Himes et al. 2017 & Torbic et al., 2009). A microphone placed in the vehicles records sound levels and frequencies collecting the noise. An accelerometers captures vibration of a variety of vehicles striking sinusoidal RS (Caltrans, 2012; Himes et al. 2017). A comparison between the baseline normal road driving noise and vibration during vehicle RS strikes evaluates the magnitude of the interior alert. SAE International provides guidance for consistently measuring noise on the interior of vehicles in Standard J1477 (SAE International, 2000). Both the California and Oregon studies used Standard J1477 in their evaluation (Donavan & Buehler, 2018; Hurwitz et al., 2019a)

For the MnDOT study, interior noise was similar for the passenger car and pickup truck for the California and Minnesota designs. The Pennsylvania design produced lower interior sound levels, with a marked reduction in driver feedback (Terhaar & Braslau, 2015). Noise with the California RS design was generally at a lower frequency, which improved the exterior to interior sound level, while providing sufficient driver feedback.

In the Caltrans study, the sinusoidal RS design decreased exterior sound levels by 3 dBA for heavy vehicles to 6 dBA for light-duty vehicles confirming that the sinusoidal design reduces roadside noise (Donavan & Buehler, 2018). For interior sound measurements of light-duty vehicles, baseline passes produced sound levels of 62.8–72.8 dBA (Donavan & Buehler, 2018). Rounded RS passes ranged 79.3–89.8 dBA, and sinusoidal RS passes ranged 81.5–90.6 dBA. Three of the four vehicles produced higher sound levels with the sinusoidal than with the rounded RS.

3.3.4 Haptic Feedback Interior Alert

The haptic feedback generated by RS strikes has been evaluated in several studies, with mixed results. In 2001, Caltrans used 4 accelerometers attached to the steering wheel to evaluate the haptic feedback generated by traditional RS designs (Bucko, T., & California, 2001). The results were inconclusive however, as the steering wheel mounting added significant motion to the measured forces.

Future studies would attach the accelerometers to the steering column or seat track. Dulaski and Noyce (2006) evaluated the haptic feedback of CLRS using 2 accelerometers mounted to the steering column and to the clutch pedal. The average acceleration, variance, and standard deviation were calculated for each axis (X, Y, Z), and values were similar across CLRS and SRS strikes, but noticeably different than background driving (Dulaski & Noyce, 2006). Analysis of variance (ANOVA) tests only found statistically significant differences between the background and strikes in one direction. This caused the researches to conclude that differences in waveforms are what are detected in haptic feedback, not the magnitude of the vibration.

MnDOT used C-weighted analysis of the sound measurements as a surrogate of the vibration generated on the interior and exterior, but did not offer any conclusions other than these measurements did not correlate with the sound measurements (Terhaar & Braslau, 2015). Caltrans evaluated haptic feedback on the steering column as well as on the seat track using accelerometers (Donavan & Buehler, 2018). Caltrans measured interior vibration on the seat track and steering column, with baseline steering columns levels of 111.0–127.4 $\mu m/s^2$. Rounded RS passes ranged 117.8–136.6 $\mu m/s^2$, and sinusoidal RS passes ranged 127.7–139.7 $\mu m/s^2$. These values were converted to a dB scale, showing increases in vibration of 10 dB during the strikes compared to the baseline (Donavan & Buehler, 2018).

Morioka and Griffin (2005) discussed different levels of perception thresholds of vibration based on the hand, seat, and foot. Perception thresholds generally follow a logarithmic pattern known as Weber's law, which applies to many psychophysical laws. Very small changes in stimuli are detectable. For sound measurement, 3 dB is typically associated with a detectable change in sound level. A similar detectable change for vibration (in terms of acceleration) is around 0.011 m/s^2 for vibrations ~80 Hz.

3.4 Method

The literature review and industry standards were used to develop the experimental design. Sound and vibration are measured in the interior of three vehicles using a microphone, a triaxial accelerometer and a sound analyzer while striking rounded and sinusoidal RS. The results are then compared to federal guidelines and similar studies to verify that the sinusoidal RS generates a sufficient interior alert.

3.4.1 Equipment

The equipment used in this study was calibrated to insure accurate measurements of the noise and vibration. A GRAS 42AG sound calibrator was used to verify that the sound equipment accurately measured 2 tones (250 and 1000 Hz) at two intensities (94 and 114 dB), with an acceptable margin of error of 0.5 dB. Similarly, the triaxial accelerometer was calibrated using a Meggitt Ref2500 handheld shaker at three different frequencies (61.44, 100.0, and 159.2 Hz).

3.4.2 Site Selection

Potential RS locations were examined in Oregon along US-26, where both types of RS are installed. Four potential sinusoidal sites and 2 rounded sites were evaluated based on site access, pavement condition, and a field visit. Site A is the sinusoidal RS site on US 26, a 4-lane divided highway, with left- and right-shoulder RS. Site B is the rounded RS site also on US-26, a 4-lane highway with a 2-way left-turn lane with CLRS and SRS. The locations are shown in Figure 3.1.

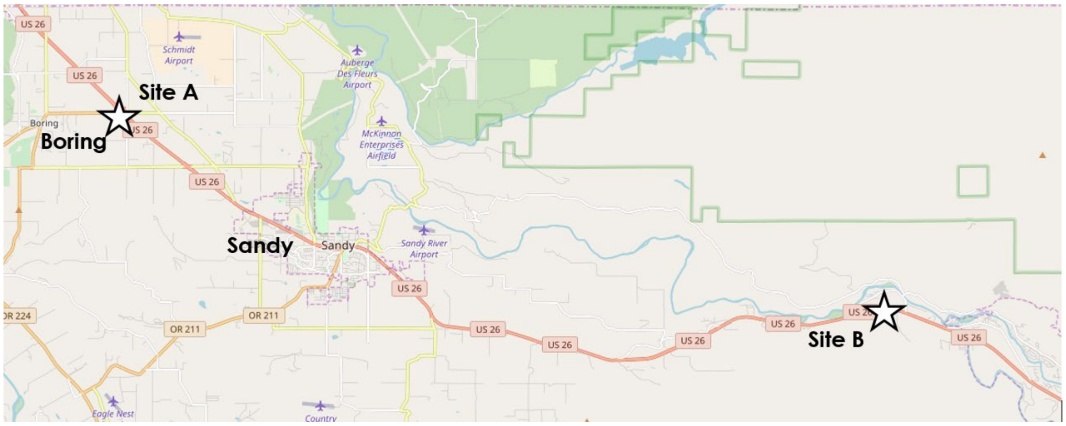

Figure 3.1 Site Locations for Testing (© OpenStreetMap contributors)

3.4.3 Interior Alert Vibration Measurement

To measure the haptic feedback of the RS strikes, a triaxial accelerometer was attached to the steering column of the vehicles as shown in Figure 3.2. For consistency, the following convention was used for the directions of the three axis. The Y axis faced the driver, the X axis was oriented in the horizontal direction, and the Z axis was oriented in the vertical direction.

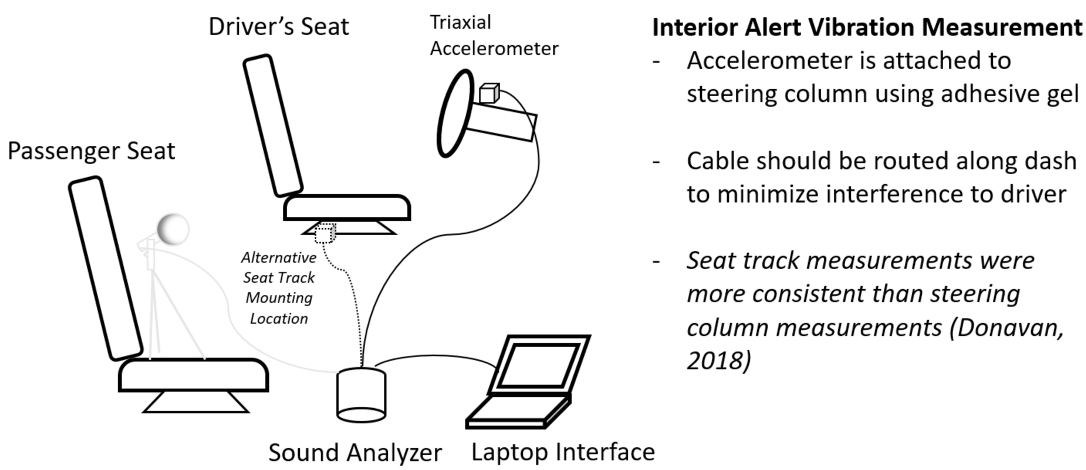

Figure 3.2 Interior Alert Vibration Measurement Diagram

3.4.4 Interior Alert Sound Measurement

To record the sound generated during the RS strikes, a microphone was placed on the front seat of the vehicles. The microphone was positioned based on SAE Standard J1477 which is an industry standard for measuring interior sound inside light-duty vehicles (SAE International, 2000). Figure 3.3 was created to highlight the general specifications of this standard. The microphone recorded simultaneously with the triaxial accelerometer.

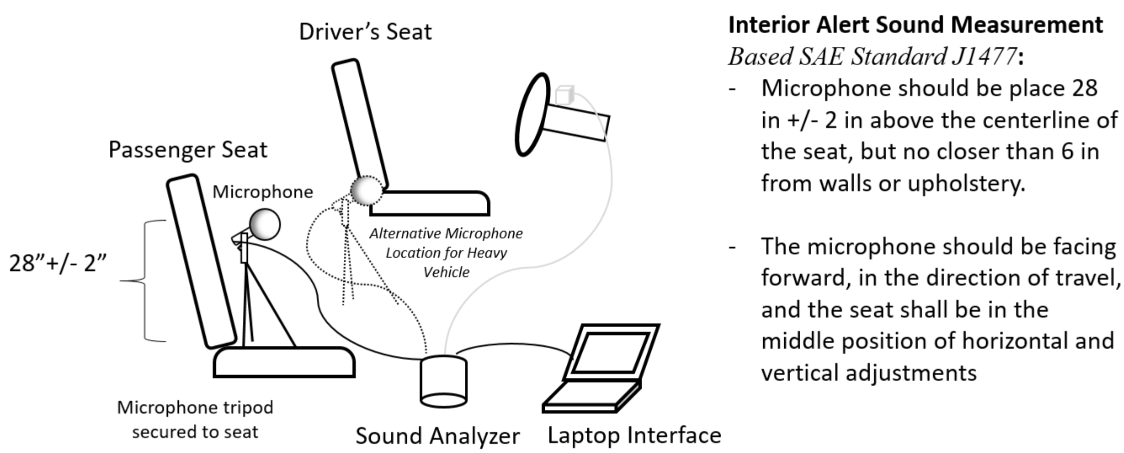

Figure 3.3 Interior Alert Sound Measurement Diagram

3.4.5 Passenger Car Ambient Interior Alert Measurements

In previous studies, interior sound levels were collected under controlled conditions, with windows closed, the radio off, and climate control off. However, these controlled conditions do not reflect typical driving conditions. Additional ambient noise could reduce the effectiveness of the alert. A sensitivity analysis of interior noise was performed to understand the impact of these other conditions compared to the control conditions for the interior alert levels. Three conditions were evaluated, the radio on set to a 3 dB increase in interior noise, the climate control fan on (settings shown in Figure 3.4), and both radio and fan simultaneous. These ambient noise conditions were collected independently, but the factors were not completely counterbalanced to reduce the number of required measurements.

Additional cases were collected for the passenger car to examine the influence of conflicting ambient noise on interior sound measurements. Three conditions – Radio, Fan, and Both – will be compared against the baseline condition of no conflicting ambient noise to evaluate the effectiveness of the RS strike during typical driving conditions. These factors have the potential to wash out the audible noise generated by a RS strike. Each ambient noise factor was measured independently. While this approach does not provide a complete counterbalancing of factors, it does significantly reduce the number of required runs.

For the ambient noise factors, the sound analyzer was used to measure the noise generated by the radio and fan. While parked with the engine running, the baseline ambient noise of the car cabin was measured. The radio was then turned on and adjusted until a 3-dB increase in sound was observed (3 dB is the sound level increase that is typically detectable to the human ear). A similar procedure was used to determine the fan speed setting. Using the sound analyzer, various configurations of climate control settings were evaluated to determine the highest sound output. The fan speed was set at the highest level and directed through the windshield defrost vents, as shown in Figure 3.4. These same settings were used in tandem for the Both case (radio on and fan on at high speed).

Figure 3.4 Climate Control Settings for Fan Ambient Noise

3.4.6 Vehicle Types Evaluated

A van, a 2015 Dodge Grand Caravan, (Figure 3.5.a) and passenger car, a 2017 Ford Focus Hatchback, (Figure 3.5.b) were evaluated. A Volvo VHD dump truck was used for the heavy vehicle as shown in Figure 3.5.c. The vehicles were driven at the posted speed of 55 mph while maintaining a safe distance from other vehicles.

Figure 3.5 a) Van Striking the Sinusoidal RS; b) Passenger Car c) Heavy Vehicle

In the Caltrans study, five test vehicles including a dump truck were evaluated for interior and exterior noise and vibration at a 60 mph pass-by speed (Donavan & Buehler, 2018). Additional measurements were made with one vehicle, a Chevy Malibu, to better understand the relationship of speed to RS noise and vibration generation (Donavan & Buehler, 2018). The MnDOT study evaluated three vehicles, a passenger car, pickup truck and an empty semi-trailer truck (Terhaar & Braslau, 2015).

Individual vehicle characteristics, including suspension features, tire dimensions and air pressure, and type, age, and weight of vehicle, all influence the noise that is generated when the vehicle strikes a RS. Interior characteristics also influence how much of the sound propagates into the cab of the vehicle for the driver alert. Across the 3 studies, 8 passenger vehicles and 3 heavy vehicles have been evaluated while striking RS for interior and exterior performance (Terhaar & Braslau, 2015; Donavan & Buehler, 2018). In general, the passenger vehicle results are similar, confirming the effectiveness of the sinusoidal RS, whereas the heavy vehicle results differ across the studies, suggesting a need for more research for heavy vehicle RS design.

3.4.7 Measuring Rumble Strip Characteristics

The physical dimensions of the RS were measured in the field to document the actual geometric characteristics of the tested RS. The sinusoidal RS dimensions are shown in Figure 3.6, with the depth measured at the crest and trough of the sinusoidal cut. The rounded RS dimensions are shown in Figure 3.7.

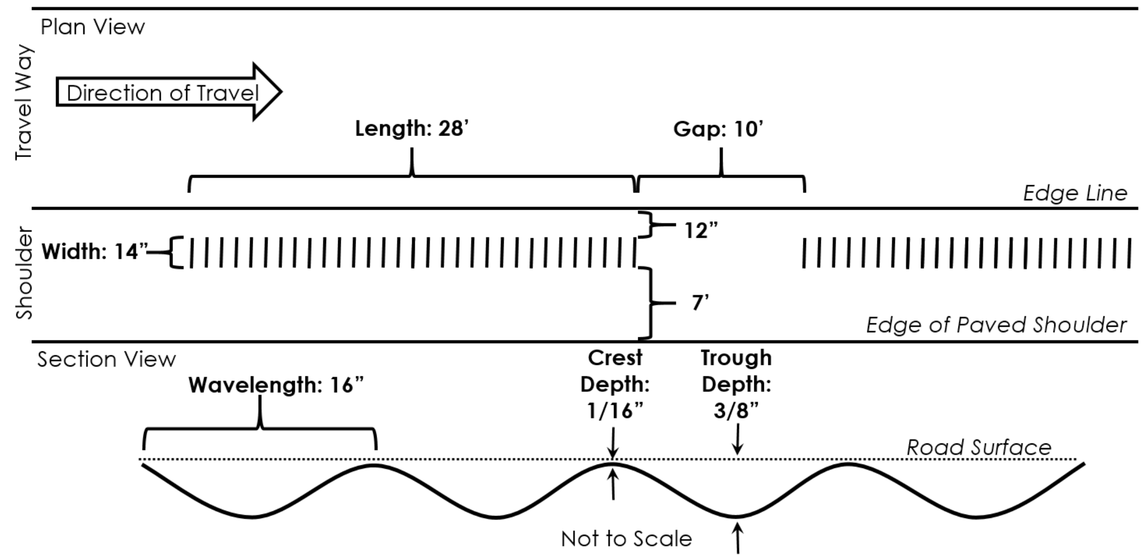

Figure 3.6 Sinusoidal RS geometric characteristics

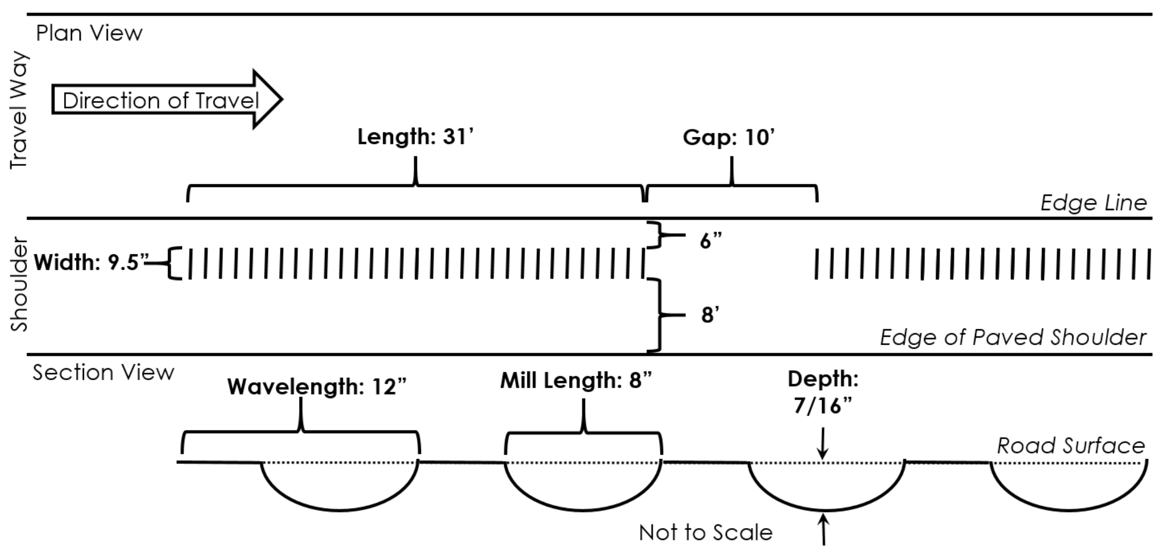

Figure 3.7 Rounded RS geometric characteristics

3.4.8 Experimental Data Collected

The sound levels generated by the strikes were compared to baseline sound levels of the three vehicle types driving at speed within the lane to determine the increase in interior noise during the strike. This comparison was conducted for the sinusoidal and rounded RS locations. A minimum of 3 recordings were captured for each experimental case. Additional runs were captured if the vehicle did not maintain good contact with the RS, or for excessive background noise as shown in Table 4-3. Additional runs were collected for the passenger car for the ambient noise evaluation, for a total of 75 measurements.

Table 3.1: Number of measurements for each factor group

Vehicle Type	Rumble Strip Type	Condition	Interior
Passenger Car	Sinusoidal	Baseline	12
		Strike	13
	Rounded	Baseline	13
		Strike	12
Van	Sinusoidal	Baseline	3
		Strike	4
	Rounded	Baseline	3
		Strike	3
Heavy Vehicle	Sinusoidal	Baseline	3
		Strike	3
	Rounded	Baseline	3
		Strike	3
		Total	**75**

3.4.9 Performance Measures

The performance measures are based on previous research and standards. For the sinusoidal RS and rounded RS, the baseline condition was subtracted from the strike condition to generate a delta (Equations 3-1 and 3-2). This represents the increase of noise that was generated from the strike when all other variables are held constant. The final performance measure is the weighted average of the difference. NCHRP 641 recommends a 6-dBA increase in the interior noise to alert drivers that they are leaving the roadway (Torbic et al., 2009). The delta, representing the interior alert that is generated by the RS strike, was compared to the recommended alert levels established in NCHRP 641 and by FHWA (Torbic et al., 2009; Himes et al. 2017).

$$\Delta \text{ Rounded dB} = \text{RS Strike dB} - \text{Baseline dB} \quad (3\text{-}1)$$

$$\Delta \text{ Sinusoidal dB} = \text{RS Strike dB} - \text{Baseline dB} \quad (3\text{-}2)$$

Calculating the interior haptic feedback was based on the Dulaski and Noyce study (2006). Acceleration for the three axis's (X, Y, and Z) was resolved into a single resultant vector using Equation 3-3 for each time step. Each component vector is orthogonal to the others, simplifying calculation of the resultant. Acceleration was calculated in terms of acceleration due to gravity (*g*). Resultant vectors for baseline condition were subtracted from the strike condition, to estimate the change in haptic alert due to the strike as shown in Equation 3-4. These values were compared to the haptic perception threshold (0.011 m/s^2) identified in the literature to insure the haptic alert was detectable (Morioka and Griffin, 2005). ANOVA was used to understand the statistical difference between the strike and background conditions.

$$\left|\overrightarrow{Resultant}\right| = \sqrt{x^2 + y^2 + z^2} \quad (3\text{-}3)$$

$$\text{Strike Vibration Level} - \text{Baseline Vibration Level} = \Delta \text{ Haptic Alert} \quad (3\text{-}4)$$

3.5 Results

3.5.1 Interior Sound Measurement

The amount of interior alert was measured by comparing the interior sound levels during normal flat road conditions (baseline) and striking the various RS (strike). Drivers maintained steady conditions for a 10-s period while the data was gathered. The interior alert was calculated for each of the vehicle types and the two RS types. An example of this data (dashed lines) is shown in Figure 3.8, the interior sound measurements for the passenger car striking the rounded RS compared to the baseline. The average value for the three runs was then calculated to estimate the average amount of interior noise for the strike (111.8 dBA) and baseline (100.4 dBA) conditions as solid lines in Figure 3.8. The interior alert for the rounded RS (11.4 dBA) more than doubled the noise (> 10 dBA) on the interior of the passenger car.

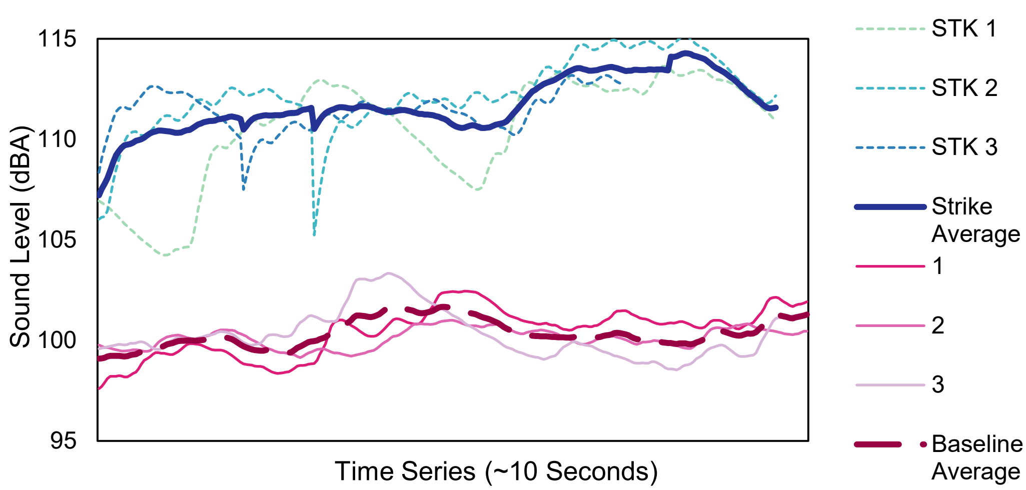

Figure 3.8 Interior sound comparison for the passenger car on the rounded RS

The procedure was repeated for the sinusoidal RS with the passenger car data shown in Figure 3.9 with the baseline average (99.0 dBA) and strike average (104.8 dBA) identified by the thick lines. The amount of interior alert is 5.8 dBA for the sinusoidal RS, indicating a clearly noticeable increase in interior noise (>5 dBA). Interior alert values for all vehicles are located in Figure 3.10.

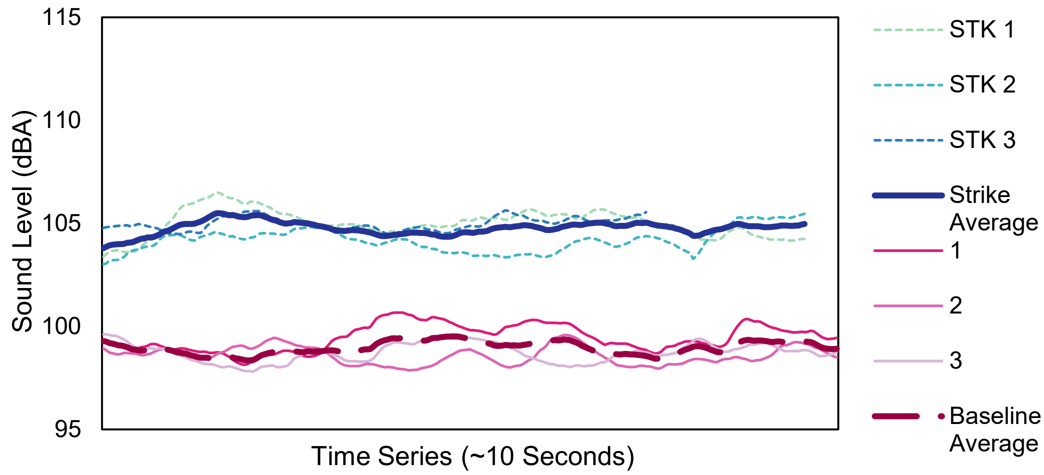

Figure 3.9 Interior sound comparison for the passenger car on the sinusoidal RS

3.5.2 Statistical Analysis

The procedure was repeated for the three vehicles (PC: passenger car, Van, HV: Heavy Vehicle) and the two RS types (R: Rounded, S: Sinusoidal), with the average values shown as boxplots in Figure 3.10. The values are in the clearly noticeable range (> 5 dBA), with the exception of the HV striking the Rounded RS. Tire bridging of the dual-tires of the HV over the narrower rounded RS is suspected, as found in the literature, nullifying the interior alert.

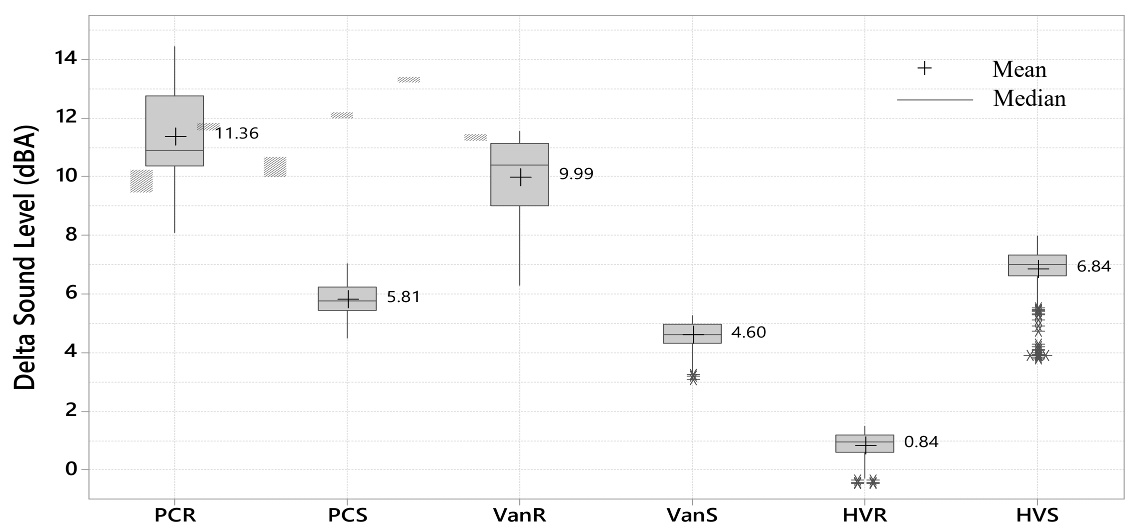

Figure 3.10 Boxplots by vehicle and RS type for interior delta sound measurements

A two way ANOVA test was used to statistically measure the difference between the interior alert means based on the three vehicle types and two rumble strip types. RS type tested as statistically significant ($p < 0.001$), as well as one of the vehicles being statistically different ($p < 0.001$). A Tukey HSD post hoc pairwise comparison was used to calculate the group means for each of the main effects as shown in Figure 3.11. This comparison shows the influence of each factor with all other factors held constant. Across the vehicle types, the rounded RS was about 2 dB louder than the sinusoidal RS. Across the RS types, the PC and van had noticeably more interior noise than the HV with the PC the loudest ($p < 0.0001$).

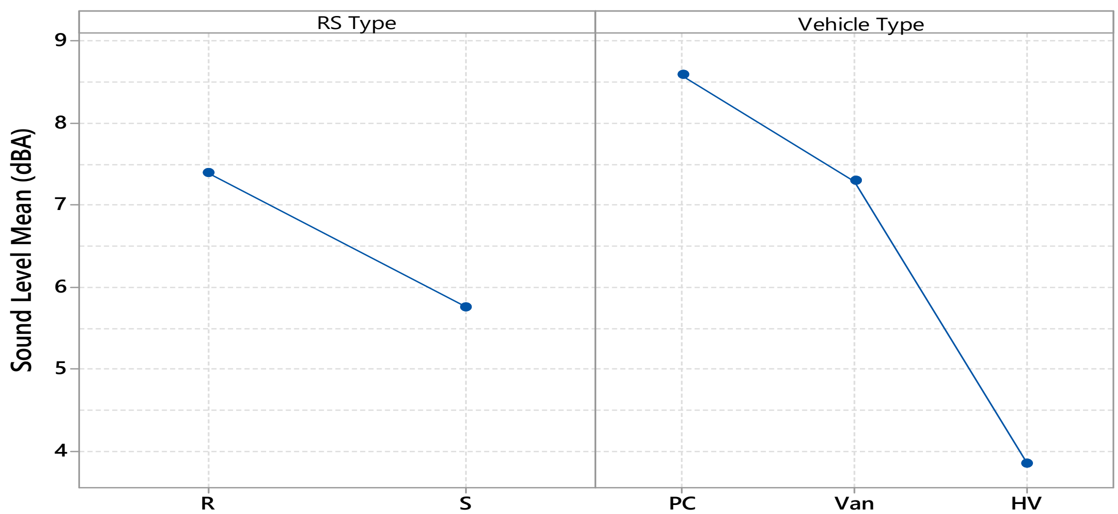

Figure 3.11 Main effect factors of interior sound measurement

The combined effects of RS type and vehicle type on mean sound level have a statistically significant interaction ($p < 0.001$) as shown in Figure 3.12. Pairwise comparisons indicate that the interior sound levels are significantly less for the PC and van for the sinusoidal RS ($p < 0.001$). The heavy vehicle has the opposite pairwise comparison ($p < 0.001$), with the rounded RS generating less interior sound.

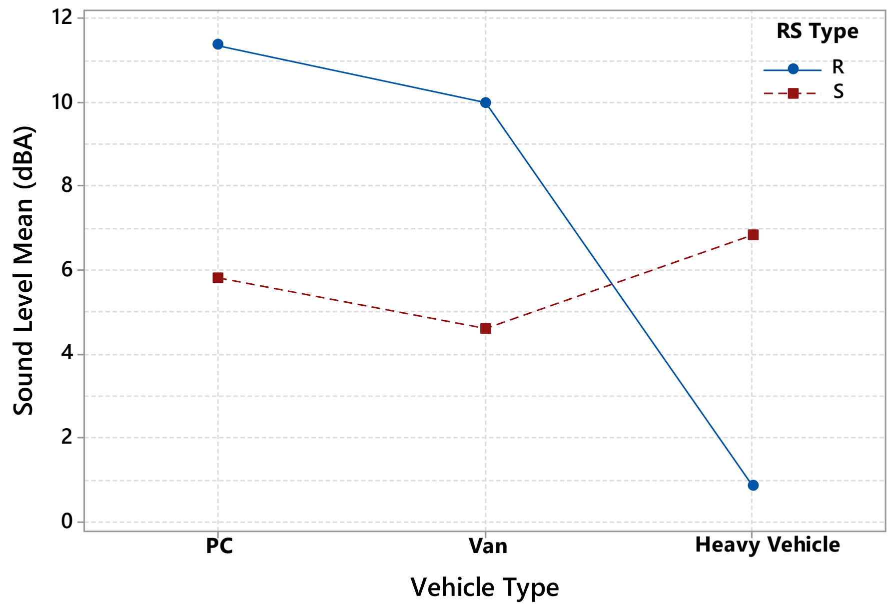

Figure 3.12 Interaction comparison of interior sound measurement

3.5.3 Interior Noise Measurements: Ambient Noise Levels

To better understand the influence of ambient noise conditions on the interior alert level, additional interior sound levels were measured in the passenger car. In typical driving conditions, climate control and the radio are often used, increasing the sound levels inside the vehicle. Three additional conditions were tested, with the radio on, the fan on, and both the radio and fan on simultaneously. The average sound levels are shown in a boxplot in Figure 3.13, with the baseline conditions for both RS types being very similar (< 3 dBA difference). The strike conditions have similar clusters, with the rounded interior sound higher than the sinusoidal.

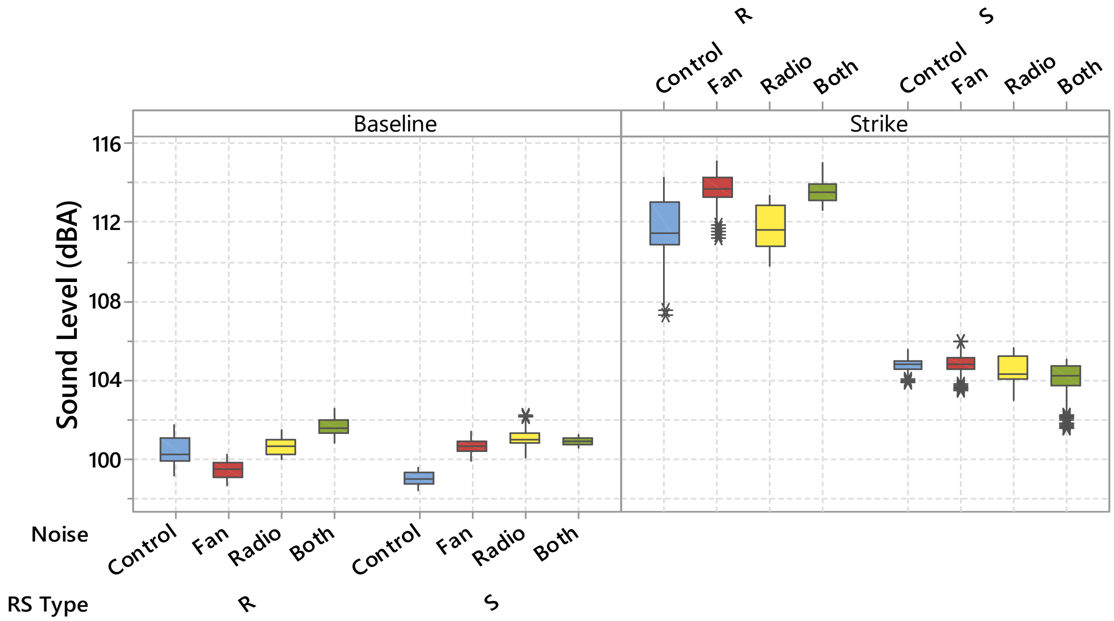

Figure 3.13 Boxplot comparison of ambient interior sound measurements

3.5.4 Statistical Analysis of Ambient Conditions

To evaluate the difference between the factors, a three-way ANOVA test was used. RS type has statistically significant differences ($p < 0.001$), as well as strike condition ($p < 0.001$). At least one of the four ambient noise conditions was different ($p < 0.001$). The main effects were estimated using a Tukey HSD post hoc pairwise comparison to find the differences for each factor with the other factors held constant. The ambient conditions, strike levels, and RS type were all significantly different ($p < 0.001$). The statistically significant interactions of the combined effects ($p < 0.001$) are shown as in Figure 3.14. For the combined effects of the RS type (Noise * RS Type) show a consistently higher sound level for the rounded RS. The combined effects of the ambient condition (Noise * Strike) show a slight increase in interior sound for the Fan, Radio and Both for the baseline and strike condition. The baseline conditions were similar for each RS, while the rounded RS strike had a higher sound level than the sinusoidal, as shown in the combined effects for the RS type (RS Type * Strike).

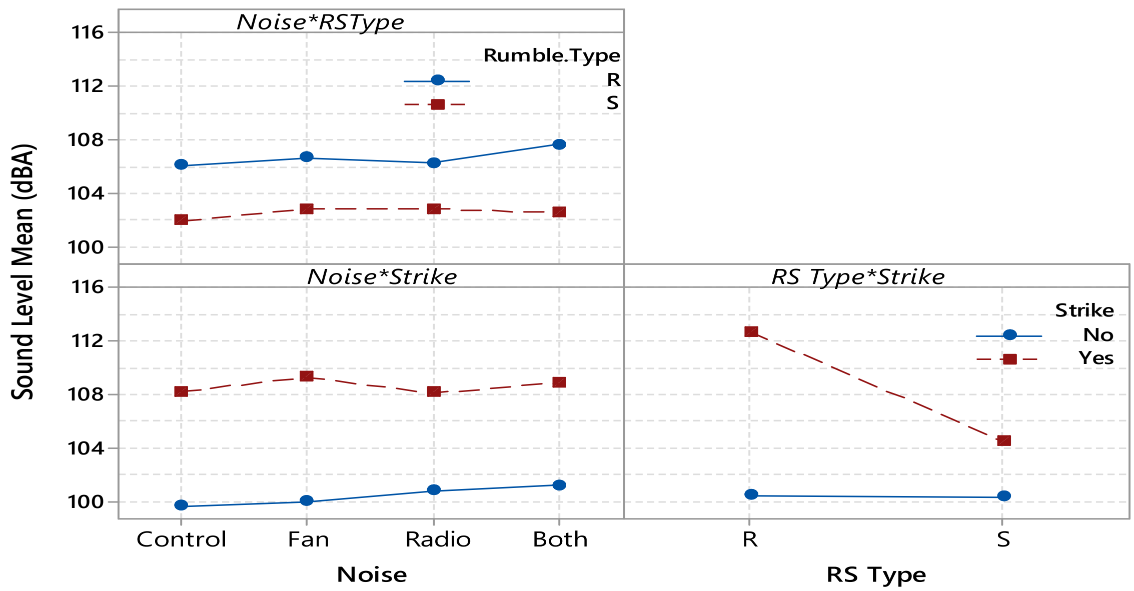

Figure 3.14 Two-way interaction plots for interior vehicle measurements

3.5.5 Interior Vibration Measurement

The interior vibration was recorded by three accelerometers. A resultant vector was calculated using Equation 4-3 to estimate the total steering column acceleration, or the haptic feedback. The resultant haptic feedback was calculated for the baseline and strike conditions. The resultant vector for the three runs were averaged together to estimate the average haptic feedback. Figure 3.15 shows an example of this average haptic feedback for the HV sinusoidal RS strike and baseline conditions. The strike value often exceeds the perception threshold of 0.00112 g, indicating a detectable amount of vibration, compared to the baseline condition that is under the perception threshold.

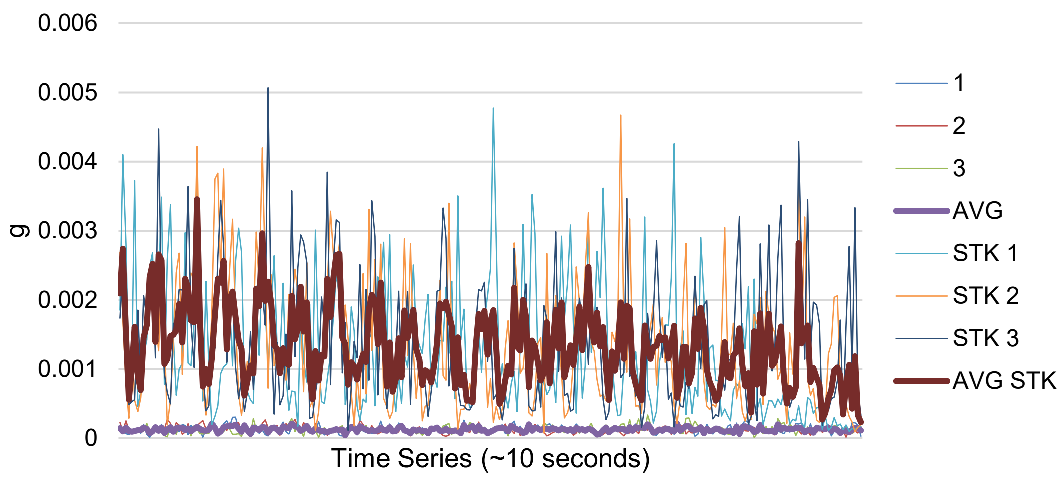

Figure 3.15 Vibration measurements for the heavy vehicle striking the sinusoidal RS

Figure 3.16 shows a boxplot of the various vehicle types interacting with 2 RS types in the baseline and strike conditions. These values indicate the increase in vehicle vibration due to the RS strike for each factor group. Acceleration values were converted to milli- (10^{-3}) g to simplify interpretation of the results. A change of 1 milli-g represents the necessary vibration to exceed the perception threshold.

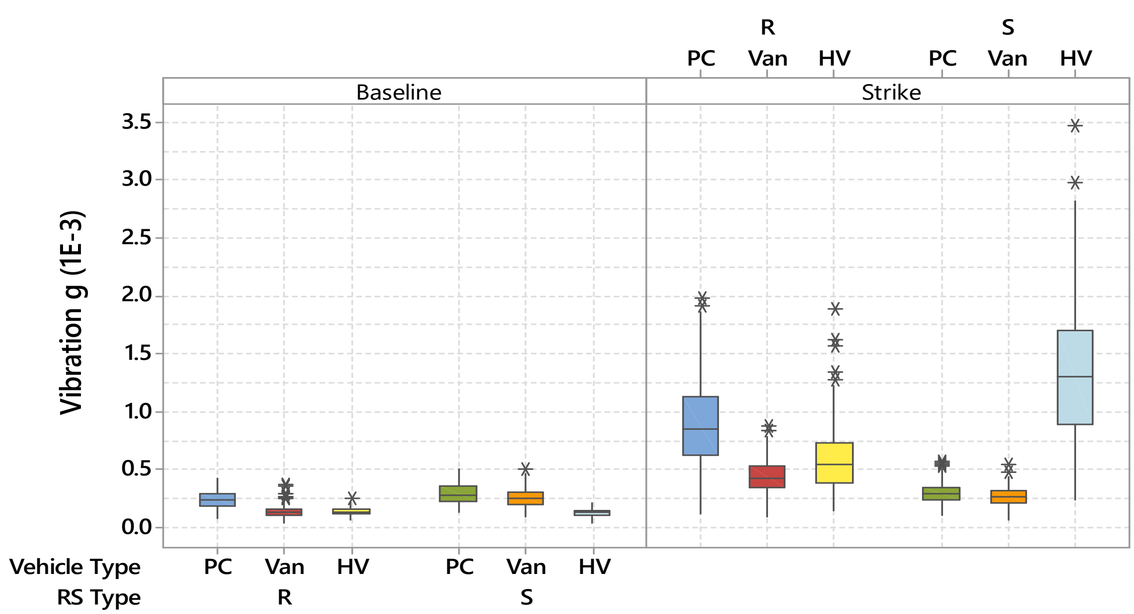

Figure 3.16 Boxplot comparison of vibration measurements

The interior vibration generated by the rounded RS strike was higher than the baseline for all vehicle types. The interior vibration generated by the sinusoidal RS strike for the passenger car or van was similar to that of the baseline. These values represent the average of 3 out-of-phase strikes; therefore, the means are expected to be lower than the observed measurements.

3.5.6 Statistical Analysis

A 3-way ANOVA test was performed on vibration measurements to determine whether average vibration differed between the baseline and strike conditions, the 2 RS types (rounded and sinusoidal), or the 3 vehicle types (passenger car, van, and heavy vehicle). There were statistically significant differences for RS type ($p = 0.004$) and strike condition ($p < 0.001$). Additionally, there was a statistically significant difference between the means for at least 1 vehicle type ($p < 0.001$).

To identify where differences between group means occurred, a Tukey HSD post hoc pairwise comparison test was performed. Main effect plots are shown in Figure 3.17, in which differences are observed between specific factors with all other factors held constant. The strike condition showed an increase of ~0.44 milli-g between baseline and strike conditions for all strikes (sinusoidal and rounded). For RS type, the vibration for the sinusoidal RS was ~0.02 milli-g higher than the rounded RS, due to the large increase in vibration for the heavy vehicle for the sinusoidal RS. For vehicle type, the passenger car and heavy vehicle generated higher vibration magnitudes than the van. In the Caltrans RS study, they noted that different vehicles had noticeably different vibration signatures, especially for the steering column (Donavan & Buehler, 2018). The low differences for the van observations were likely due to individual vehicle suspension characteristics.

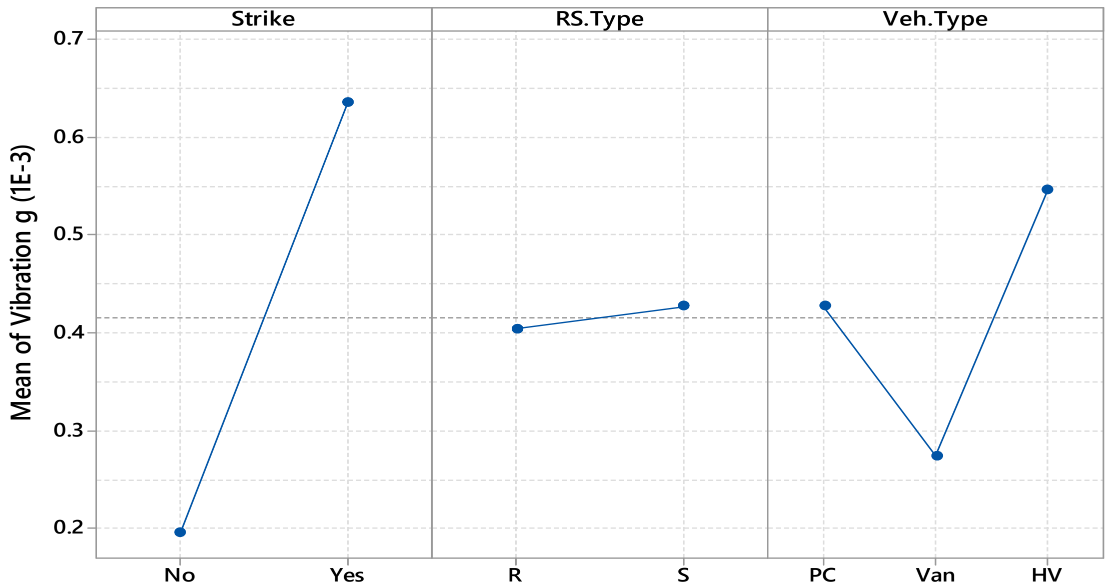

Figure 3.17 Main effect factors of interior vibration measurements

There was a statistically significant interaction between the combined effects of strike condition with RS type ($p < 0.001$) and with vehicle type ($p < 0.001$) on the vibration measurements, and between RS type and vehicle type ($p < 0.001$). Figure 3.18 plots the mean vibration at each level of each factor. Results of pairwise comparisons show that, regardless of vehicle type, striking the sinusoidal or rounded RS generated significantly higher vibrations than the baseline condition ($p < 0.001$). Regardless of the strike condition, the heavy vehicle generated significantly greater vibration (0.3 milli-*g*) while striking the sinusoidal RS than striking the rounded RS ($p < 0.001$), whereas the passenger car had a lower vibration level for the sinusoidal RS ($p < 0.001$). There was no statistically significant difference in vibration for the van between RS types ($p > 0.05$).

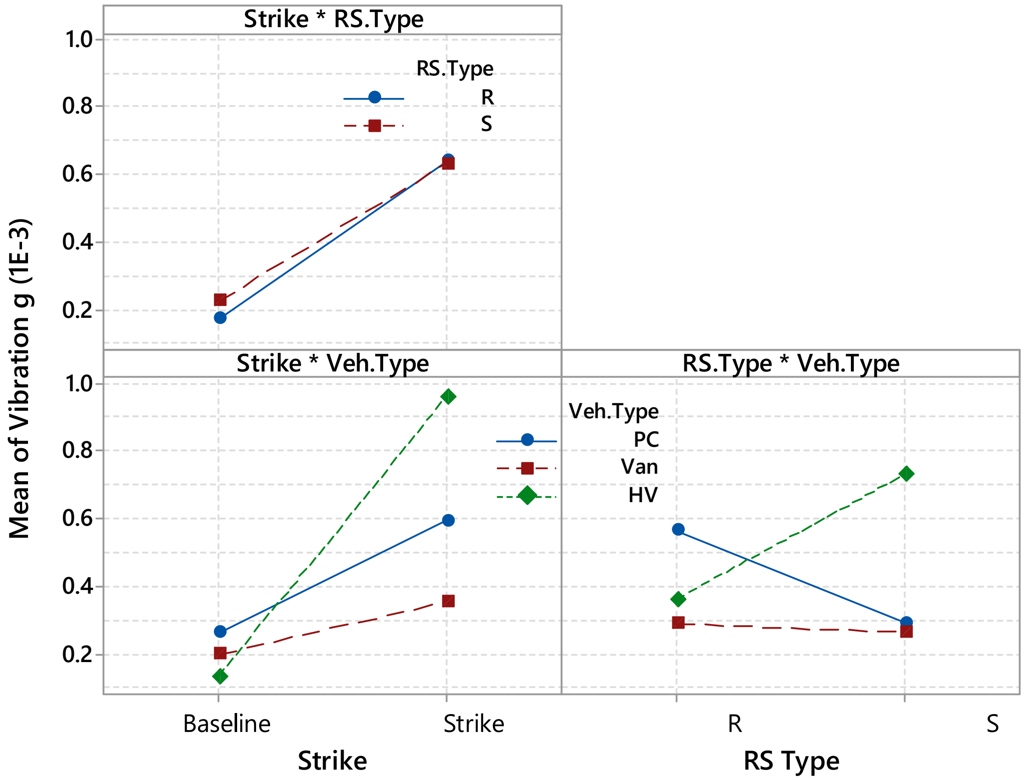

Figure 3.18 Two-way interaction plot of mean vibration

3.6 Discussion

This research study compared interior sound levels of 3 vehicle classes striking traditional rounded and sinusoidal RS to baseline conditions. Steering column vibration in the vehicle interior was measured by triaxial accelerometer to quantify the haptic feedback generated by RS strikes. An effective RS design must provide sufficient auditory and vibratory alerts in the vehicle interior, while limiting the exterior noise produced during lane departure. The framework for the experiment was based on previous studies of RS noise and effectiveness and SAE Standard J1477 (SAE International, 2000). Interior measurements ensure that RS strikes generate a sufficient alert to the driver that they are leaving the roadway.

Frequency analysis determined that the RS strikes generated noise at the expected specific frequency and increased the highest sound energy levels. Based on the geometry of the RS, the other studies found specific frequencies of 80 Hz across the vehicle types

(Terhaar & Braslau, 2015, Donavan & Buehler, 2018). Similarly, in this study, a specific frequency of 80 Hz was observed for the RS strikes. At least 3 passes were recorded for each factor group, and weighted averages were used to calculate differences between strike and baseline conditions. These delta measurements provided an estimate of the increased noise generated by the strike while holding other factors as constant as possible. According to the literature, humans can detect differences in noise levels at 3 dB, with 5 dB being easily noticed.

Many roadway conditions were controlled for between test locations to minimize differences between measurements during the experiment. The results reflect the pavement type and condition, mill quality, type of sound-absorbing materials at the site (foliage, trees, etc.), and atmospheric conditions at the time of observation. Other locations may generate more or less noise, as these factors will vary across the built environment. However, it is expected that the differences observed between the baseline and strike conditions would be similar, as these variables would have a similar effect on both conditions in other locations.

Noise generated by the rounded RS strike doubled the interior noise levels for the passenger car and van (10 dBA). The sinusoidal RS strike created a noticeable alert in these vehicles; although the levels were less than the 6-dBA guidance provided in NCHRP 641. FHWA suggests that 5 dBA is sufficient to alert the driver, which the van and passenger car met. The interior alert generated by the vehicle striking the sinusoidal RS design was sufficient to warn drivers under test conditions (Himes et al. 2017). The rounded RS doubled interior noise for the passenger car and van (11.3 dBA, 10.0 dBA). The sinusoidal RS generated a clearly noticeable interior alert for the passenger car and van (5.8 dBA, 4.6 dBA). According to the Tukey HSD post hoc pairwise comparison, the rounded RS was about 2 dB louder than the sinusoidal RS across all vehicle types. The sinusoidal RS design generates an effective interior alert, confirming the sinusoidal RS as an effective safety countermeasure for passenger vehicles.

Ambient interior noise conditions while the radio and climate control system are on influenced detectability of the RS alert in the passenger car. Statistical analysis showed that addition of each factor resulted in a barely detectable (1 dBA) increase in background noise, which decreased the relative size of the alert. A Tukey HSD post hoc pairwise comparison found the ambient conditions, strike levels, and RS type all significantly different ($p < 0.001$). The sinusoidal alert decreased from 5.8 to 3.2 dBA with both radio and fan on. The interior alert was detectable and within the FWHA acceptable range, but is not clearly noticeable (5 dBA). Alert levels for the rounded RS were >10 dBA, doubling the amount of interior noise for all ambient factor groups (11.2–14.4 dBA), which exceeds the NCHRP and FHWA thresholds. This shows that the sinusoidal RS design generates a detectable alert under normal driving ambient noise conditions. However, this alert is lower than the NCHRP standard for a clearly noticeable alert.

For the heavy vehicle, the sinusoidal RS generated a clearly noticeable interior alert (6.8 dBA). The rounded RS interior alert for the dual-tire heavy vehicle was imperceptible (0.8 dBA). Literature suggest that this result was due to bridging of the dual-tires over the narrow rounded RS (Terhaar & Braslau, 2015). Figure 3.19 demonstrates the tire bridging phenomena. The sinusoidal RS generated a significant increase in haptic feedback of the heavy vehicle as well. These results indicate that the wider RS design allowed the tires of the heavy vehicle to interact with the RS, inducing more vibration than the rounded design.

This indicates that wider RS trigger an effective response for heavy vehicles. Thus, installing a wider (sinusoidal or rounded) RS would extend the effectiveness of this countermeasure to heavy vehicles. Evaluating a wider variety of RS widths would provide a more comprehensive understanding of the relationship of this characteristic to the performance of RS alerting heavy vehicles of roadway departures. Other RS configurations, like rumble stripes, thermoplastic pavement markings, or raised pavement markers, could be evaluated using this methodology to understand the effectiveness of these countermeasures as well.

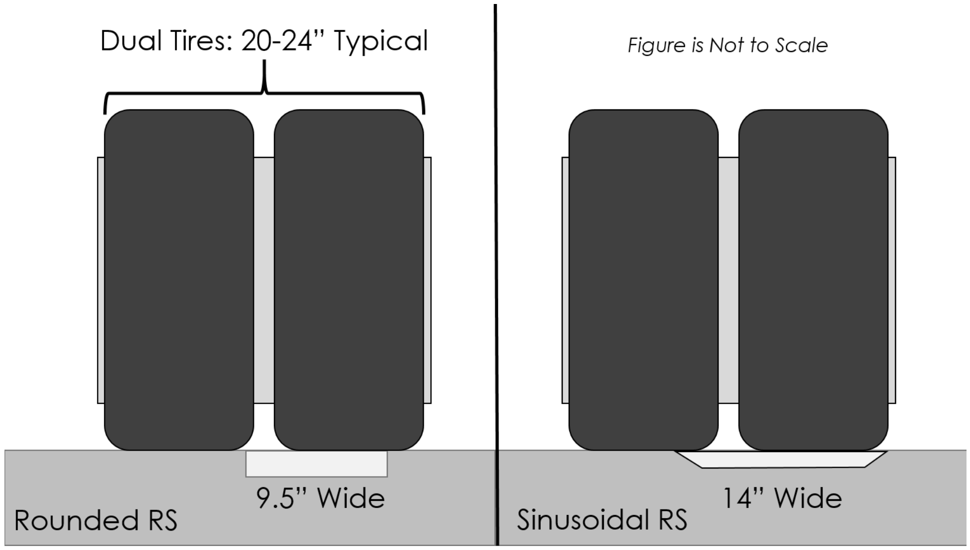

Figure 3.19 Bridging Effect for Dual-tire Heavy Vehicles

Analysis of data from steering column accelerometers showed that the rounded RS generated sufficient vibration for all vehicle types (>0.002 *g*). The passenger car and van have similar vibration levels for both RS. Caltrans suggests that the seat track provides improved consistency of measure haptic feedback (Donavan & Buehler, 2018). However, two-way interaction analysis for the vibration data showed an increase in vibration values for all vehicle types for both RS strikes. The heavy vehicle sinusoidal RS strike recorded the highest values for any of the factor groups.

The results of this study are compared two similar state agency reports. The sinusoidal RS evaluated in the MnDOT study had interior sound level increases of ≥10 dBA, with peaks at ~80 and 160 Hz (Terhaar & Braslau, 2015). In the Caltrans study, interior sound and vibration measurements were comparable, with the both RS types generating alerts ~13 dB higher than baseline (Donavan & Buehler, 2018). Interior alert levels were ≥10 dB across the vehicle types and RS types, with larger alerts at the 80 Hz frequency (up to 32.6 dBA). The interior sound alerts from this study are somewhat lower than the reported values from MnDOT and Caltrans. However, the values are at or above the standard thresholds, providing an effective interior alert. The other studies provided the maximum sound levels generated during the strikes, whereas this study averaged the values over a 10 second window, a more conservative measurement. In general, the three studies agree that sinusoidal RS generate a sufficient interior sound alert, confirming that this RS design is an effective safety countermeasure.

MnDOT used a C weighted analysis of the sound measurements as a surrogate for vibration measurements, but offered no conclusions regarding the haptic feedback for the RS (Terhaar & Braslau, 2015). Caltrans measured interior vibration on the seat track and steering column (Donavan & Buehler, 2018). They reported the absolute value results of the vibration, as well as converting the results into a dB scale showing increases in vibration of 10 dB for all vehicle types during the strikes compared to the baseline (Donavan & Buehler, 2018). Comparing the haptic feedback results across these studies is difficult, as each study provided different units and techniques for measurement. However, the general conclusions are similar, that the sinusoidal RS generated sufficient haptic feedback. The lack of federal guidance about haptic feedback for RS, as well as the sparse literature concerning haptic feedback for RS, indicate that more research is needed to better standardize the evaluation vibration during RS strikes.

The MNDOT study and contractor survey suggested that cyclists (bicyclists and motorcyclists) preferred sinusoidal RS because they are easier to traverse (Terhaar et al., 2016). The scalloped edges of the sinusoidal design provide a smoother transition than the abrupt edges of the traditional rounded design. Although wider RS will extend the effectiveness of the RS, wider RS are likely to reduce the amount of useable shoulder for cyclists. Although not directly evaluated in this research study, using the sinusoidal design would provide a less disruptive alternative for cyclists.

3.7 Conclusions

Rumble strips (RS) provide audible and haptic feedback when a vehicle is departing the roadway to reduce run-off-the road crashes. Typically, grooves are cut into the pavement to generate this response. However, RS are associated with noise complaints, and are often removed, or not installed near residential land use. The shallower and scalloped sinusoidal RS is a quieter alternative to traditional rounded designs. To be an effective safety countermeasure, the RS must generate a sufficient interior alert, through an increase in the interior noise and additional haptic feedback.

This study confirms that the sinusoidal RS does generate a sufficient interior sound alert across the passenger vehicles. This conclusion is supported by two similar research studies by the Minnesota Department of Transportation (MnDOT), and the California Department of Transportation (Caltrans). Across the studies, the sinusoidal RS generated a clearly noticeable increase in interior sound levels. The traditional rounded RS also generated sufficient interior alert.

An additional evaluation of ambient noise conditions was conducted to better represent typical driving conditions. The radio and climate control were tested to understand how this additional interior noise effected the interior alert. While the ambient conditions did increase the interior noise, they did not reduce the interior alert below the acceptable levels for the passenger car.

The results from the heavy vehicle were different from the passenger vehicles. The rounded RS did not generate a detectable alert while the sinusoidal RS generated a sufficient interior alert. As discussed in the MnDOT study, the wide dual-tires of the heavy vehicle bridged over the narrower rounded RS (tire bridging), whereas the wider sinusoidal RS generated the interior alert. Further evaluation of the width of RS and the tire bridging phenomena are necessary but from the initial results wider RS of any type could extend the effectiveness of RS to heavy vehicles.

The haptic feedback was evaluated, showing an increase over the human perception threshold for vibration for all vehicle types. This result is similar to the Caltrans study, which found the sinusoidal RS were found to provid sufficient haptic feedback (Donavan & Buehler, 2018). However, there is a lack of federal guidance regarding haptic feedback thresholds and significant variation across the studies in how haptic feedback is evaluated.

The quieter sinusoidal RS could potentially be installed in more locations, especially noise sensitive ones, providing safety benefits by reducing run-off-the-road crashes. The cost of this design is marginally more than the traditional rounded RS, providing a high benefit to cost ratio.

4.0 QUANTIFYING THE PERFORMANCE OF LOW-NOISE TRANSVERSE RUMBLE STRIPS

Dylan Ross Horne, Hisham Jashami, and David S. Hurwitz

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4.1 Abstract

This study evaluated the feasibility of using shallower epoxy filled transverse rumble strip (TRS) as a substitute for traditional TRS to address noise concerns. A total of 24 vehicle strikes of TRS were recorded and exterior sound levels generated by TRS strikes were compared to baseline and epoxy filled sound levels for a probe vehicle. The experimental framework was based on previous RS studies, and the AASHTO SIP Method. Humans can detect differences in noise levels at 3 dB, with 5 dB being easily noticed. Compared to the traditional TRS, the shallower epoxy filled TRS average sound level measurements dropped from 87.6 dBA to 84.1 dBA, a detectable 3.5 dBA difference. When both measurements are compared based on their peak (max value), the difference in sound measurement was 6.0 dBA, or a clearly noticeable change. Additionally, the sound level generated from the epoxy TRS is higher than the paved condition, with a 95% confidence interval (CI) [0.1 dBA, 4.8 dBA]. This CI range indicates that the epoxy filled TRS was indiscernible at least, and clearly noticeable at most compared to a baseline vehicle pass, meaning that the epoxy TRS is still noticeable compared to background traffic. Comparing the before condition TRS to the after paved TRS, the average sound level measurement dropped from 89.4 dBA to 81.6 dBA, a clearly noticeable 7.8 dBA difference. However, the peak difference in sound measurement is approximately 18 dBA. This indicates that the original TRS is nearly four times louder than the same passing vehicle on flat pavement.

Keywords:

Transverse rumble strips, roadside noise, SIP method

Acknowledgments:

The research was sponsored by the Oregon Department of Transportation (SPR 829A).

4.2 Introduction

Transverse rumble strips (TRS) have been shown to reduce crashes by 20 to 30% and generally reduce vehicle speeds (Thompson et al., 2006; Yang et al., 2016), but are associated with noise concerns (Finley & Miles, 2007). Unlike shoulder or centerline rumble strips that are installed at the edge of the travel lane to reduce lane departure crashes by alerting the driver with noise and vibration, TRS are installed across the travel lane to alert the driver of a stop ahead. Residents living adjacent to roadways have complained to the Oregon Department of Transportation (ODOT) about the noise generated by TRS. Previous research suggests that modifying the shape of the TRS can reduce the sound levels associated with TRS, reducing noise pollution and nearby resident complaints (An et al., 2016).

Human perception of sound is dependent on how intense or strong a noise is against other background sounds (Terhaar et al., 2016). All sounds have a sound level or volume, as well as a specific frequency profile (Sexton, 2014). Some sounds are more irritating than others, such as short impulsive noises, compared to steady sounds (Caltrans, 2012). Generally, people are more sensitive to noise at night, when they are resting (Caltrans, 2012). Low frequency noises between 10-250 Hz have been shown to interrupt sleep, add to stress, and potentially cause heart-rhythm disorders (An et al., 2016). Also, low frequency noises travel further, potentially affecting more people.

One solution to this noise problem is a shallower TRS, which produces a lower noise profile than the traditional TRS. There is a need to quantify scientifically the noise differential between traditional and shallow TRS. Research suggests that shallower RS generate the necessary in-vehicle noise and reduced roadside noise (Finley & Miles, 2007; Hurwitz et al., 2019a). The objective of this study is to evaluate the feasibility of using an epoxy to reduce the depth of traditional milled rumble strips in transverse applications post-installation. A quantitative and empirical comparison of the roadside noises of epoxy filled and traditional transverse rumble strips will give an indication as to whether the epoxy retrofit can potentially be used to resolve roadside noise complaints associated with transverse applications. The research question is “do epoxy retrofit applied to transverse rumble strips effectively reduce roadside noise?”

4.3 Methods

This section documents the research design, which is based on previous RS sound evaluations (Terhaar & Braslau, 2015; Donavan & Buehler, 2018; Hurwitz et al., 2019a). The experiment measures the resultant noise of a probe vehicle striking a traditional and shallow TRS.

4.3.1 Experimental Design

One experimental location was evaluated, the NB ramp terminal of the S. Jefferson Interchange (Exit 238) as shown in Figure 1.a. The before observation focuses on the traditional TRS, and the after observation focuses on the shallower TRS. A passenger car probe vehicle was used to collect at least 3 isolated TRS strikes at 45 mph, which is lower than posted speed limit 55 mph. This speed was used as the TRS are close to an intersection. Probe vehicle strikes have been used previously to evaluate rumble strips (Linden et al., 2018; Hurwitz et al., 2019a).

The TRS site was located on Jefferson Highway (OR 164) at the NB Interstate 5 exit and entrance ramp, near Millersburg, OR as shown in Figure 4.1. The weather was clear, sunny, and warm on both days. Wind was calm, and the road surface was dry. All way stop signs were added to the intersection of OR 164 and the I-5 ramp, which was previously stop controlled on the ramp only. TRS were installed on the approaches to warn drivers of the new stop condition in addition to stop ahead signs (W3-1) equipped with flashing yellow warning lights as shown in Figure 4.2.

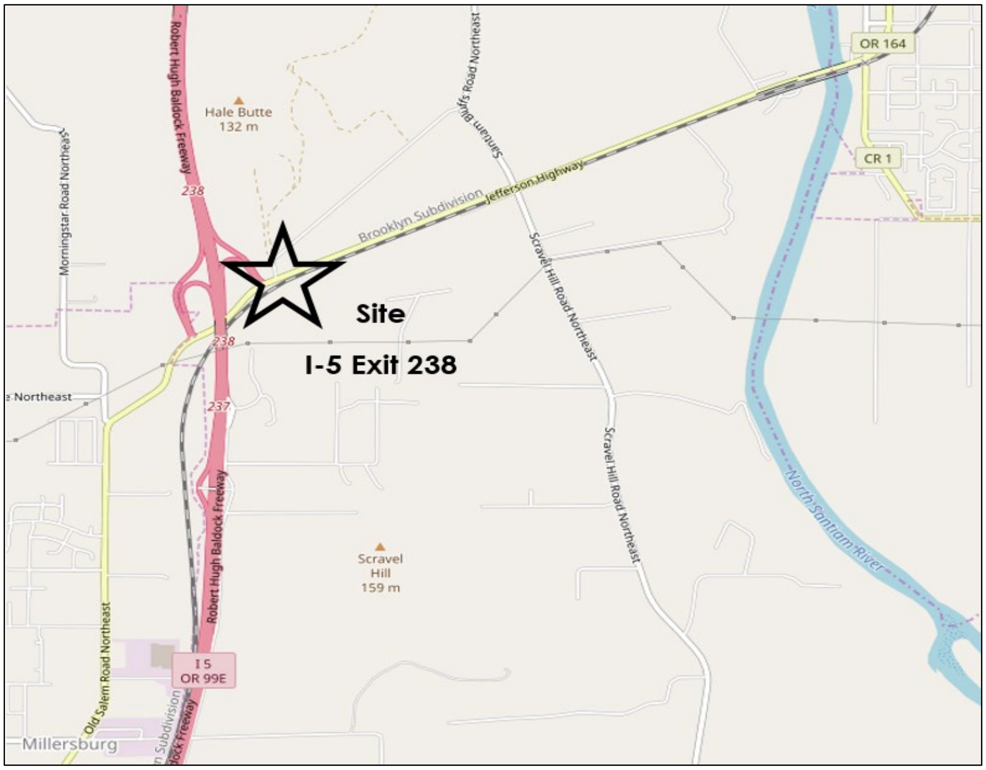

Figure 4.1 Site location for testing (© OpenStreetMap contributors)

The SIP Method is a standard method for measuring the sound pressure levels of road surfaces (AASHTO, 2013). The maximum A-weighted sound level (dBA) for a given vehicle type is calculated and compared to a baseline ambient sound level to determine the effect of road surface variations. This method establishes standards for equipment, test sites, traffic conditions, microphone positions, calibration, experimental procedures, and data calculations. If excessive background noise or high wind speeds occur, additional runs were collected. A modified version of this method has been applied by several agencies for evaluating RS using probe vehicles instead of ambient traffic (Terhaar & Braslau, 2015; Donavan & Buehler, 2018; Hurwitz et al., 2019a).

4.3.2 Exterior Noise Measurement

The setup for exterior measurements is shown in Figure 4.2. Due to site constraints, microphones were located closer than prescribed in AASHTO's SIP Method (AASHTO, 2013). The microphones were centered on each TRS group, and the microphone was located above the road surface as shown in Figure 4.2. The microphone closer to the stop sign is referred to as the near microphone throughout this report, and the other is termed the far microphone. During each TRS strike, the sound level was monitored on the laptop to ensure that the event was 6 dB louder than the background noise ensuring the strike event is detectable. Each pass was monitored to insure that the captured sound was independent from the influence of other traffic noise. Additional runs were recorded if there was excess background noise, usually due to traffic in the opposing direction.

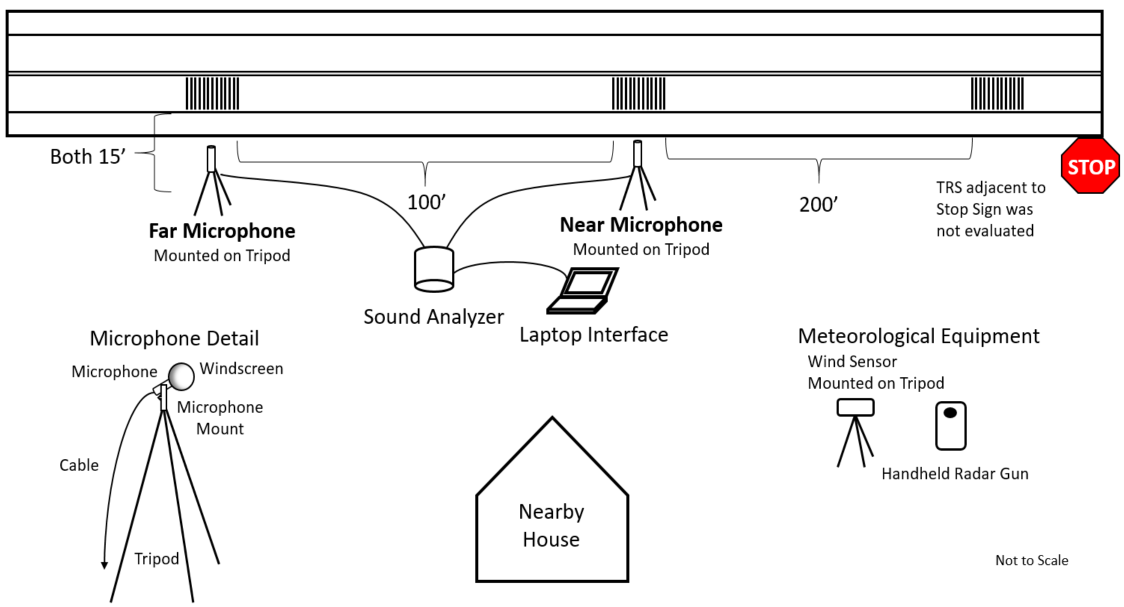

Figure 4.2 TRS Sound Measurement Diagram

4.3.3 Probe Vehicle

A passenger car was rented from Oregon State's motor pool and driven by licensed graduate research assistants. Drivers were instructed to drive at the posted speed at a safe operating distance from other vehicles on the roadway. Two-way radios were used to communicate between the vehicle assistant and the roadside team at the measurement location. The passenger car was a 2017 Ford Focus Hatchback. The tires were Continental ContiProContact 215/55 R 16 93 H. Tire pressures are shown in Table 4.1. The probe vehicle data is used as an estimate the noise generated for a passenger car striking the TRS, and is used as a surrogate to understand the relative noise generating characteristics of the various TRS designs. Compared to other RS studies with several vehicle types, the results are less broad, but still provide insight into the performance of the TRS.

Table 4.1 Tire pressure (psi) for probe vehicle

psi	Front	Rear
Driver Side	28.5	34
Passenger Side	34.5	32

4.3.4 Rumble Strip Characteristics

Geometric characteristics of each TRS type were measured and recorded to document the general properties of the tested TRS in the before and after data collection. Average field geometric characteristics of the before TRS are shown in Figure 4.3. The epoxy filled shallow TRS at the near location is dimensioned in Figure 4.4, and the paved TRS at the far location is shown in Figure 4.5. Large characteristics, such as the total length of the TRS group, were measured to the nearest half foot. Smaller characteristics, such as the mill depth, were measured to the nearest 1/16”. Mill depth was measured several times at different mills due to slight variances in milling, and the average of these measurements is presented.

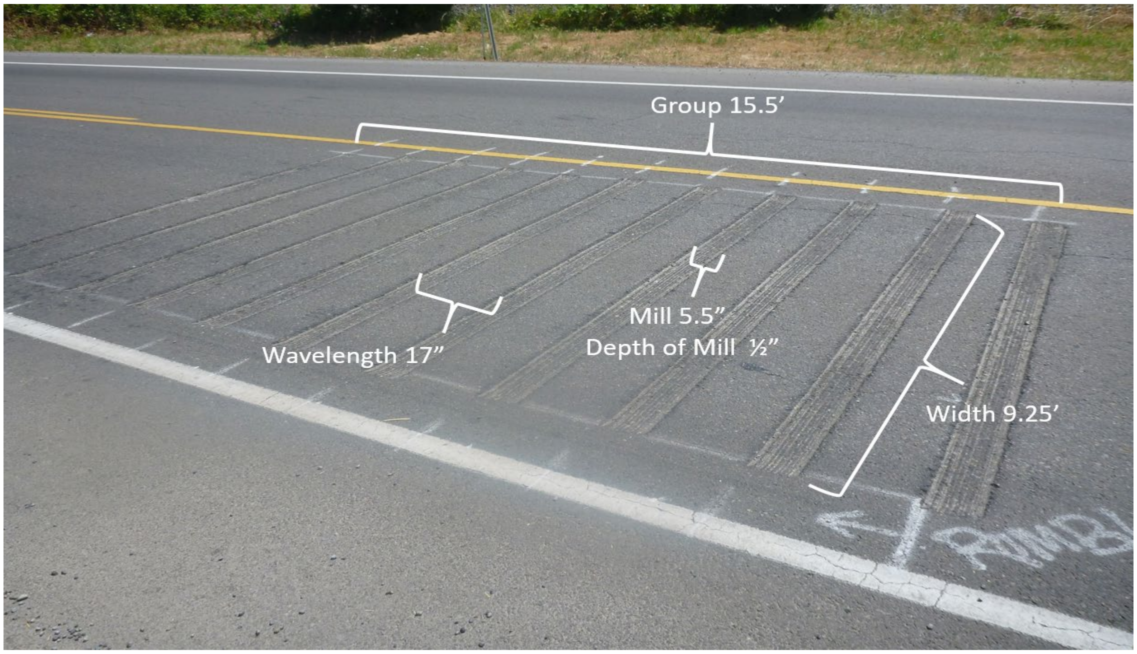

Figure 4.3 Before condition: TRS Geometric Characteristics

Figure 4.4 After condition: Epoxy filled TRS at near location

Figure 4.5 After condition: Paved TRS at far location

The TRS appeared to be installed as specified. Irregularities in pavement aggregates caused some variation in mill depth, as larger aggregate chunks chipped away. Similar variation exists across the epoxy TRS, but the fill appeared consistent. The new pavement at the paved TRS is likely to influence the sound slightly, as the pavement has a generally rougher surface when new.

4.3.5 Traffic Volumes

Traffic volumes were gathered with a manual count recorded from 2:15 to 3:25pm during the before data collection at milepost 8 on OR-164. A total of 211 vehicles (11 % heavy vehicles) passed the TRS. Vehicles were classified using Federal Highway Administration (FHWA) standard vehicle classification groups. These classifications were used to estimate the total number of axles that pass over the TRS per minute. As each axle strikes the TRS, multi axle trucks produce many TRS strikes with each vehicle. During the before data collection, over 9 axles per minute were observed, indicating 9 TRS strikes per minute. Compared to shoulder RS which are only struck if a vehicle is leaving the roadway, TRS generate a significant number of strikes, further increasing the annoyance of these RS for nearby people.

4.4 Results and Discussion

Exterior sound noise was recorded and evaluated. Data were analyzed and visualized using Minitab software for Windows (version 18.1) and Excel software (version 14.0.1), respectively.

4.4.1 Exterior Sound Measurement

A total of 24 sound measurements were collected from the probe vehicle strikes (10 before, 14 after). Several of the measurements were not used as they had additional ambient traffic noise from other vehicles passing at the time of the strike. Ultimately, 5 measurements were used at the near location for the before and after conditions. Similarly, 3 measurements were used at the far location for the before and after conditions. The measurements were combined using a weighted averaged, as dBA is a logarithmic scale as shown in the time series documented in Figure 4.6. In this figure, the three before far TRS individual measurements are shown as dashed lines, and the overall average is shown with the solid line.

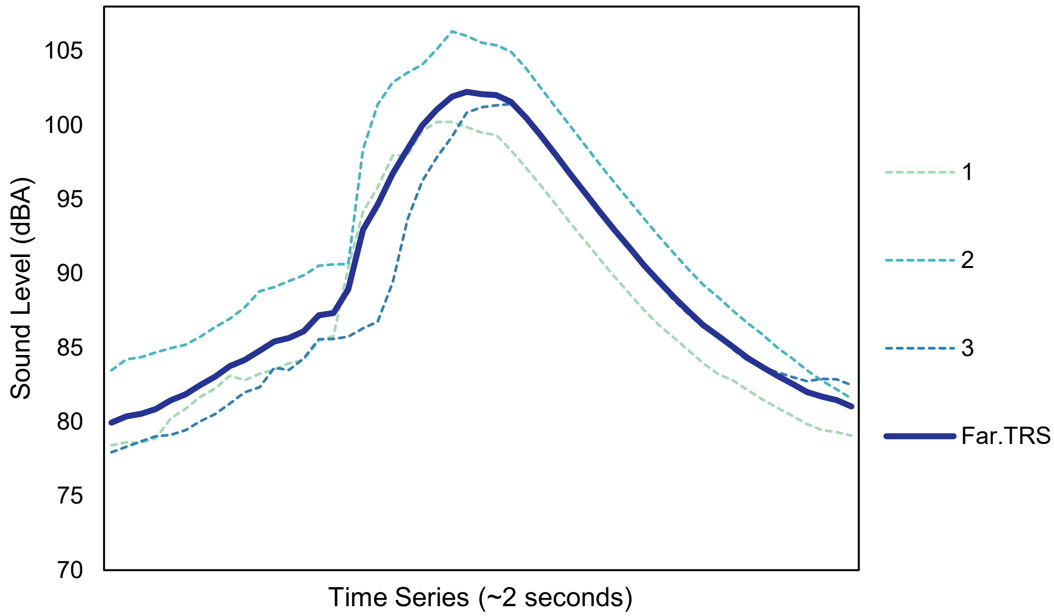

Figure 4.6 Exterior Sound Measurements from Passenger Car Striking the Far TRS

Figure 4.7 shows the overall time series weighted averages for the probe vehicle. The far TRS value is the weighted average value shown in Figure 3. This is the highest sound level, which corresponds to the deep TRS, as well as the highest vehicle speeds. The near TRS value has similar depth as the far, but vehicle speeds are lower as drivers decelerate in response to the stop sign. The next highest signal comes from the near epoxy filled TRS. The depth of the TRS has a large influence on the amount of additional noise generated by rumble strip strikes (Finley & Miles, 2007; Hurwitz et al., 2019a). The lowest sound levels were recorded at the far paved location, where the TRS was removed with new pavement. This value was used as a baseline for comparison of the other TRS measurements that describe the sound of a vehicle passing the location.

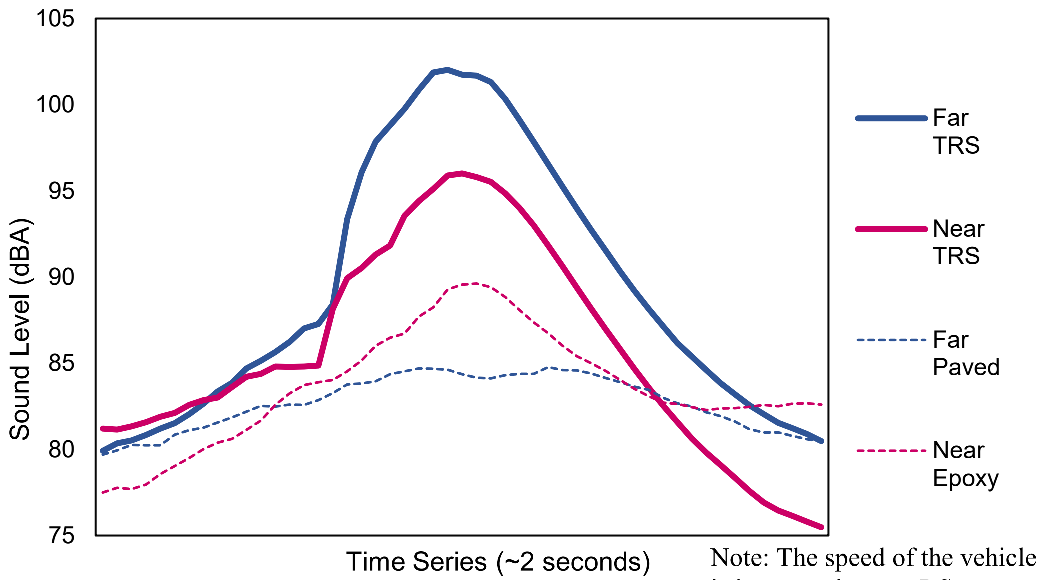

Figure 4.7 Exterior Sound Measurement from Passenger Car Striking the TRS

4.4.2 Descriptive Analysis

Data were analyzed in the Minitab statistical software package (version 18). All tests were performed at a 95% confidence level. Table 4.2 shows the mean (μ), standard deviation (SD), minimum, and maximum sound level in dBA for a milled TRS in each factor group. As shown in Table 4.2, TRS in the before scenario generated the highest average sound level based on the observed field measurements. The sound levels are higher in the presence of milled TRS for both locations. The far location in the before scenario reported the highest mean sound level (μ = 89.40, SD = 7.40) with a maximum value of 102.3 dBA. This higher sound measurement is likely related to the fact that the speed of vehicles is higher at the far location than at the near location. Drivers tend to decrease their speed during the approach to an intersection; those lower speeds generate less noise.

In the after scenario, when the far location was paved, the average sound level measurement dropped from 89.4 dBA to 81.6 dBA, a 7.8 dBA difference. For human hearing, this is a clearly noticeable change in the sound level (>5 dBA). When both measurements are compared based on their peak (max value), the difference in sound measurement is approximately 18 dBA. When the near TRS in the after scenario was treated with epoxy, the average sound level measurements dropped from 87.6 dBA to 84.1 dBA, a 3.5 dBA difference. This is a detectable change in sound level. However, the peak difference in sound measurement was 6.0 dBA, or a clearly noticeable change.

Table 4.2 Descriptive statistics dBA magnitudes for the factor groups

RS Type	Scenario	Location/Treatment	Mean	SD	Min	Max
Transverse	Before	Far/TRS	89.40	7.40	79.95	102.25
		Near/TRS	87.58	5.90	78.18	97.92
	After	Far/Paved	81.64	1.94	78.34	84.35
		Near/Epoxy	84.09	4.10	78.11	91.88

Figure 4.8 shows a boxplot of sound levels for the two scenarios (before-after) by location (far-near) and treatment type. Roadside noise generated by the TRS strike was higher in the before condition. Alternatively, the alert generated by the TRS strike was reduced when the treatments were applied.

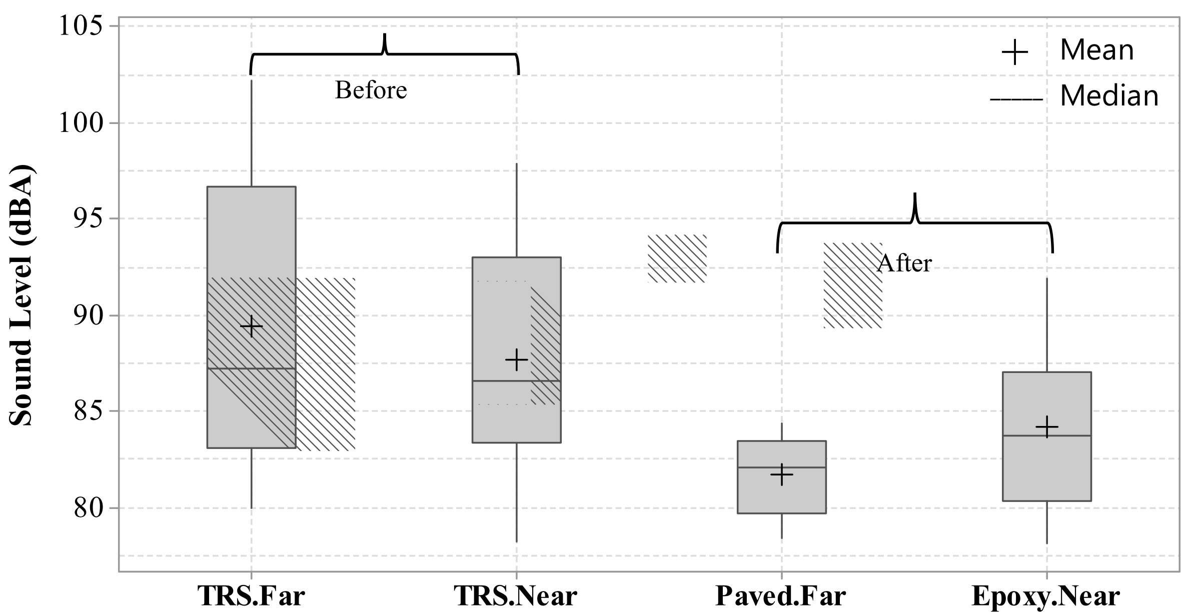

Figure 4.8 Boxplots by treatment and location for Sound Measurements

4.4.3 Statistical Analysis

Researchers performed a one-way ANOVA test on the sound measurements to determine whether the average sound levels differed between the 3-treatment procedure (TRS, epoxy, and paved). A statistically significant difference between means was found for at least 1 treatment type, $p < 0.001$. To identify where differences between group means occurred, a Dunnett multiple comparison test with paved as the control treatment was performed. Regardless of location, the sound level generated from a TRS strike (*Mean* = 88.5 dBA) is higher than the paved condition (*Mean* = 81.6 dBA), p-value < 0.001, 95% CI [4.9 dBA, 8.9 dBA]. This CI range indicates that the TRS is readily noticeable at least, and nearly doubling the roadside noise at most. Additionally, the sound level generated from the TRS treated with epoxy (*Mean* = 84.1 dBA) is higher than the paved condition, p-value = 0.03, 95% CI [0.1 dBA, 4.8 dBA], but is significantly lower when compared to the TRS strike. This CI range indicates that the epoxy filled TRS was indiscernible at least, and clearly noticeable at most compared to a baseline vehicle pass on the roadside.

Then, a two-way ANOVA test was performed on sound measurements to determine whether the average sound levels differed between the before and after scenarios, or between the near and far locations. The main effect results were obtained, where differences can be observed between specific factors while all other factors are held constant. A statistically significant difference between means was found for the before and after scenarios, $p < 0.001$, 95% CI [4.2 dBA, 7.1 dBA]. This makes sense as the TRS were modified between these conditions. In the after scenario, the far TRS was paved, and the near TRS was partially filled with epoxy. This is consistent with previous research that shows TRS add 7 to 11 dBA to roadside noise compared to flat road pavement (An et al., 2016).

The noise generated from the far TRS and near TRS were not statistically significant, $p = 0.66$, [-1.1 dBA, 1.8 dBA]. This finding was expected as in the before scenario both TRS locations had the same depth treatment. This also indicates that the speed difference between the two locations did not significantly influence the amount of noise generated. The near is slightly higher, as it has the shallow epoxy TRS in the after condition. In terms of interaction factors, there was a statistically significant interaction between the scenario (before/after) and the TRS location ($p < 0.001$).

Figure 4.9 plots the mean noise at each level of each factor. Results of pairwise comparisons showed that, the far TRS in the before scenario generated significantly more noise than when the TRS was paved over in the after scenario, $p < 0.001$, 95% CI [5.1 dBA, 10.5 dBA]. Similarly, the near TRS in the before scenario generated more noise than with the epoxy filled TRS in the after scenario, $p = 0.005$, 95% CI [0.8 dBA, 6.2 dBA].

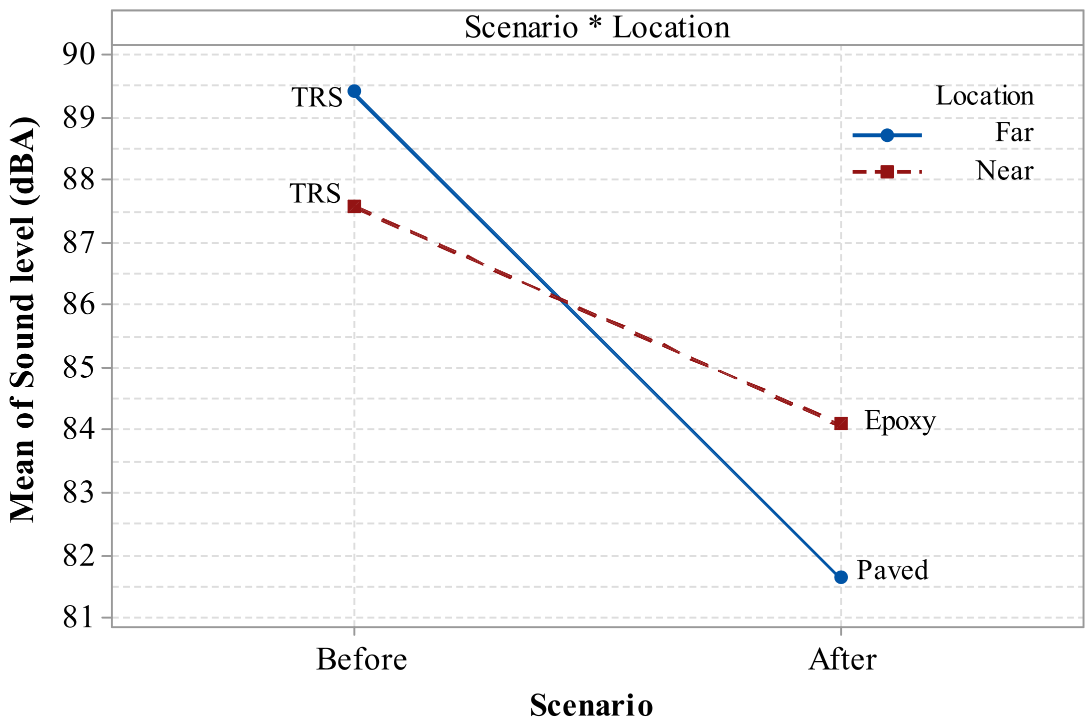

Figure 4.9 Interaction comparison of probe vehicle sound measurements

This study only evaluated the exterior sound levels of the probe vehicle striking the various transverse RS. While the exterior noise for the epoxy TRS was a detectable amount more than the paved condition, this does not confirm the effectiveness of the epoxy TRS at generating a sufficient interior alert. Additional research on the interior of the vehicle to estimate sound and vibration of the interior alert is necessary.

4.5 Conclusion

This research study compared exterior sound levels for a probe vehicle striking traditional deep and shallow epoxy filled TRS in a before and after study. The framework for the experiment was based on previous studies of TRS noise and effectiveness, and the AASHTO SIP Method (AASHTO, 2013). At least 3 passes were recorded for each factor group, and weighted averages were used to calculate differences between TRS conditions. These delta measurements provided an estimate of the increased noise generated by the strike while holding other factors as constant as possible. According to the literature, humans can detect differences in noise levels at 3 dB, with 5 dB being easily noticed. A difference of 3 dBA between noise sources is the minimum amount needed for a typical human to perceive a difference in sound level. From the results, the research team developed 3 conclusions concerning the use of epoxy to modification of TRS as an alternative to traditional TRS.

Compared to the before condition of the deep TRS, the epoxy filled TRS average sound level measurements dropped from 87.6 dBA to 84.1 dBA, a 3.5 dBA difference. This is a detectable change in sound level. However, the peak difference in sound measurement was 6.0 dBA, or a clearly noticeable change. Additionally, the sound level generated from the epoxy TRS is higher than the paved condition, p-value = 0.03, 95% CI [0.1 dBA, 4.8 dBA], but is significantly lower when compared to the TRS strike. This CI range indicates that the epoxy filled TRS was indiscernible at least, and clearly noticeable at most, compared to a baseline vehicle pass, meaning that the epoxy TRS is still detectable compared to background traffic on the roadside.

Comparing the original TRS to the after paved TRS, the average sound level measurement dropped from 89.4 dBA to 81.6 dBA, a 7.8 dBA difference. This is a clearly noticeable change in sound level on the roadside. When both measurements are compared based on their peak (max value), the difference in sound measurement is approximately 18 dBA. This indicates that the original TRS is nearly four times louder than the same passing vehicle on flat pavement.

In terms of practice, the research results confirmed an epoxy retrofit applied to transverse rumble strips can effectively reduce roadside noise. Filling TRS with Epoxy provides an intermediary treatment between full depth TRS and repaving the road. The TRS can be used to mitigate roadside noise for nearby residences.

4.5.1 Limitations

Only one speed was tested for all factor groups, the free flow speed limit of 45 mph. Increasing the speed has been shown to increase the noise generated in a RS strike, but the consistency of that relationship is unclear. Only one vehicle was used as the probe vehicle, differences between vehicle types were expected, as the suspension, tire characteristics, and vehicle weight influence noise generation. Only 2 TRS designs were tested (traditional deep, and shallow epoxy). Small changes in RS dimensions, especially mill depth, have a large influence on noise generation. Other mill depths could be used to further reduce noise (shallower), or increase driver alert (deeper).

Many roadway conditions were controlled for between test locations, to minimize differences between measurements during the experiment. The results reflect the pavement type and condition, mill quality, type of sound-absorbing materials at the site (foliage, trees, etc.), and atmospheric conditions at the time of observation. Other locations may generate more or less noise, as these factors will vary across the built environment. However, it is expected that the differences observed between the baseline and strike conditions would be similar, as these variables would have a similar effect on both conditions in other locations.

Further interior alert research is needed to verify the effectiveness of the TRS as a safety countermeasure. Both interior sound levels and haptic feedback should be measured to confirm the interior alert levels. However, the epoxy filled TRS did generate a detectable difference in exterior noise, indicating the potential for a successful alert.

5.0 CONCLUSIONS

Rumble strips (RS) are used to alert drivers of various road conditions. Shoulder RS alert drivers when they are leaving the travel way and are a very efficient and effective safety countermeasure. Transverse RS alert drivers of changes in traffic control devices or can be used to alert drivers of stop controlled intersections on rural facilities. The noise generated during RS strikes contributes to roadside noise concerns as the strikes generate a louder, distinctive, short duration sound compared to background road noise. Due to these noise concerns, RS are often not installed near residential dwellings or are removed after complaints. However, new RS designs have been shown to mitigate some of the noise concern while continuing to offer safety benefits to the driving public.

This research evaluated two different types of alternative RS designs, sinusoidal shoulder RS, and epoxy filled transverse RS across three papers. In the first paper, exterior noise generated during sinusoidal RS strikes was measured to confirm that the sinusoidal design reduces roadside noise compared to traditional rounded RS. The second paper evaluated the interior alert generated during the sinusoidal RS strikes to insure that the sound and haptic feedback were sufficient to alert a driver that they are leaving the roadway. The third paper measured the exterior roadside noise generated during transverse RS strikes with full depth mills, epoxy filled mills and repaved pavement, confirming that the modified transverse RS can be used as a quieter alternative.

5.1 Roadside Noise

The evaluation of exterior roadside noise compared 3 vehicle classes striking traditional rounded and sinusoidal RS to baseline conditions. The framework for the experiment was based on previous studies of RS noise and effectiveness and the AASHTO SIP Method. Frequency analysis determined that the RS strikes generated noise at the expected specific frequency and increased the highest sound energy levels. At least 3 passes were recorded for each factor group, and weighted averages were used to calculate differences between strike and baseline conditions. These delta measurements provided an estimate of the increased noise generated by the strike while holding other factors as constant as possible.

Roadside noise levels are a combination of vehicle noises from the tire, engine, and aerodynamics, as well as other environmental noises such as wind, wildlife and other non-transportation related human activities. The RS strike adds a distinctive new sound to this profile, and humans interpret that variation from the background condition as the sound of the RS strike. In addition to these measurements concerning the highest noise levels generated, the experiment found that the specific frequency of the RS strike was also present. The RS strike increased the total sound level on the roadside and introduced a specific new noise (the rumble).

The sinusoidal design reduced the exterior noise produced during RS strikes for the passenger car and van compared to the rounded design. Rounded RS strikes generated a clearly noticeable increase in roadside noise of ~5 dBA over baseline (passenger car: 5.4 dBA, van: 4.6 dBA). The sinusoidal RS strike produced a detectable increase in roadside noise for the passenger car (3.1 dBA) but an imperceptible change from baseline for the van (-0.2 dBA). Differences between vehicle types were expected as the suspension, tire characteristics, and vehicle weight influence noise generation. Both vehicles showed similar decreases in exterior sound, indicating that the sinusoidal design did in fact reduce roadside noise. Exterior measurements were made immediately adjacent to the roadway. Relationships between sound levels will be similar further from the road but at a lower sound levels; as the sound energy generated from a strike propagates away from the strike location, the sound intensity will decrease as the energy diffuses with distance.

The results from this research are compared with two recent evaluations of sinusoidal rumble strips. Minnesota Department of Transportation (MnDOT) evaluated exterior vehicle noise from three sinusoidal RS designs (Terhaar & Braslau, 2015). They found that the exterior sound levels for the Minnesota and California designs similar, and both generated a sufficient interior alert. The Pennsylvania design generated the lowest exterior noise, but did not generate a sufficient interior alert (Terhaar & Braslau, 2015). The California Department of Transportation (Caltrans) preformed a similar sinusoidal

RS study simultaneously with the Oregon study (Donavan & Buehler, 2018). The Caltrans sinusoidal RS design decreased exterior sound levels by 3 dBA (for heavy vehicles) to 6 dBA (for light-duty vehicles) (Donavan & Buehler, 2018). The results from the other agencies support the conclusions drawn from this study, that sinusoidal RS do decrease roadside noise compared to traditional RS.

5.2 Interior Alert

The interior alert was evaluated by measuring the steering column vibration using a triaxial accelerometer to quantify the haptic feedback as well as a microphone to capture interior sound levels during strike and baseline conditions. An effective RS design must provide sufficient auditory and vibratory alerts in the vehicle interior to alert the driver that they are leaving the roadway. This experiment was based on previous evaluations of interior alert during RS strikes as well as SAE Standard J1477. The vehicle types, number of passes, and performance measures were similar to the exterior evaluation, with the addition of the vibration analysis. Additional analysis of interior ambient noise during typical driver conditions was also conducted, with the radio and climate control on. Interior alert generated by the vehicle striking the sinusoidal RS design was sufficient to warn drivers. Although the rounded RS doubled interior noise for the passenger car (11.3 dBA) and van (10.0 dBA), the sinusoidal RS still produced a clearly noticeable alert over baseline (passenger car: 5.8 dBA, van: 4.6 dBA). This alert was very close to the 6–12 dBA range for interior alerts recommended in the NCHRP Report 641 and exceeded the 2017 FHWA *State of Practice* recommendations that an alert be ≥3 dBA and ideally ≥5 dBA (Himes et al. 2017). The rounded design met both guidelines, but the sinusoidal design only met the FHWA recommended levels. The sinusoidal design is still an effective countermeasure for interior noise.

The sinusoidal RS evaluated in the MnDOT study had interior sound level increases of ≥10 dBA, (Terhaar & Braslau, 2015). In the Caltrans study, interior sound and vibration measurements were comparable, with the both RS types generating alerts ~13 dB higher than baseline (Donavan & Buehler, 2018). The interior sound alerts from this study are somewhat lower than the reported values from MnDOT and Caltrans.

However, the values are at or above the standard thresholds, providing an effective interior alert. The other studies provided the maximum sound levels generated during the strikes, whereas this study averaged the values over a 10 second window, a more conservative measurement. In general, the three studies agree that sinusoidal RS generate a sufficient interior sound alert, confirming that this RS design is an effective safety countermeasure.

As expected, additional ambient interior noise (generated by the radio, fan, or both) influenced detectability of the RS alert in the passenger car. Statistical analysis showed that addition of each factor resulted in a barely detectable (1 dBA) increase in background noise, which decreased the relative size of the alert. The sinusoidal alert decreased from 5.8 to 3.2 dBA with both radio and fan on, but the alert level was still detectable and within the FWHA acceptable range (although closer to the lower bound). Alert levels for the rounded RS were >10 dBA, doubling the amount of interior noise for all ambient factor groups (11.2–14.4 dBA), which exceeds the NCHRP and FHWA thresholds.

According to the literature, the threshold of human perception for vibration is 0.00112 *g* (Morioka and Griffin, 2005). Analysis of data from steering column accelerometers showed that both RS types generated sufficient vibration (>0.002 *g*) to alert drivers. The analysis method averaged vibration profiles. Because vibrations oscillate between positive and negative magnitudes, passing through zero each time, the vibration averages were lower than the individual observations; thus, the calculated vibration alert is a conservative estimate. Higher vibration values were observed in the raw data. Two-way interaction analysis for the vibration data showed an increase in vibration values for all vehicle types for the strikes. As was the case with the sound data, the heavy vehicle had the highest vibration response for the sinusoidal RS. The wider sinusoidal design allowed the tires of the heavy vehicle to interact with the RS, inducing more vibration than the rounded design.

MnDOT used a C weighted analysis of the sound measurements as a surrogate for vibration measurements, but offered no conclusions regarding the haptic feedback for the RS (Terhaar & Braslau, 2015). Caltrans reported the absolute value results of the vibration, as well as converting the results into a dB scale showing increases in vibration of 10 dB for all vehicle types during the strikes compared to the baseline (Donavan & Buehler, 2018). Comparing the haptic feedback results across these studies is difficult, as each study provided different units and techniques for measurement. However, the general conclusions are similar, that the sinusoidal RS generated sufficient haptic feedback. The lack of federal guidance about haptic feedback for RS, as well as the sparse literature concerning haptic feedback for RS, indicate that more research is needed to better standardize the evaluation vibration during RS strikes.

5.3 Heavy Vehicle Tire Bridging

The dual-tire heavy vehicle did not generate high exterior (2.2 dBA) or interior (0.8 dBA) noise with the rounded RS strike. Literature and observational data suggest that this result was due to bridging of the dual-tires over the narrow RS. The wider sinusoidal RS generated a sufficient interior alert (6.8 dBA), indicating that wider RS trigger an effective response for heavy vehicles. Sinusoidal RS also generated a detectable increase in exterior noise of 5.7 dBA, which is similar to the exterior noise of the passenger car striking the rounded RS. Thus, installing a wider (sinusoidal or rounded) RS would extend the effectiveness of this countermeasure to heavy vehicles.

5.4 Transverse Rumble Strips

The average original transverse RS roadside noise (89.4 dBA) increased compared to the paved condition (81.6 dBA) for a clearly noticeable difference of 7.8 dBA. At the peak sound level the difference is approximately 18 dBA, nearly four times the amount of roadside noise. The epoxy filled transverse RS noise (84.1 dBA) had a detectable decrease of 3.5 dBA in sound level compared to the original TRS (87.6 dBA), with a clearly noticeable peak difference of 6.0 dBA. The epoxy filled TRS strike was also statistically higher than the paved conditions p-value = 0.03, 95% CI [0.1 dBA, 4.8 dBA] indicating a sound loud enough for a driver alert. Compared to the paved condition (81.6 dBA), the epoxy filled TRS decreased the roadside noise (84.1 dBA) to a just detectable sound level difference of 2.5 dBA. This confirms that epoxy filled TRS decreases roadside noise significantly. This design should be used as an intermediate step between full depth TRS and repaving the road to mitigate roadside noise. Further interior vehicle testing is needed to confirm the effectiveness as a safety countermeasure.

5.5 Economic Comparison of Safety Countermeasures

Compared to other roadway departure crash countermeasures, RS are extremely cost efficient. Table 5.1 shows the number of improvements planned in Oregon of each type of countermeasure over a 5 year planning period at an annual cost of $6.2 million (Jones et al. 2017). The table also shows construction cost, crash reduction rates, and the estimated cost per life saved. RS have high crash reduction rates, and very high fatal and sever injury reduction rates as well. The estimated cost per life saved for RS is dramatically lower than other countermeasure to reduce roadway departure crashes.

Table 5.1 Oregon Roadway Departure Plan strategy summary (Jones et al. 2017)

Countermeasure	**2009-17 Crashes**	**Number of Improvements**	**Construction Cost ($ Million)**	**Annual Crash Reduction**	**Annual Fatal Reduction**	**Sever Injury Reduction**	**Cost / Life Saved ($Million)**
Curve treatment - Signs	6,810	842	$10.53	238.35	7.72	19.58	$1.36
Curve treatment – Beacons	861	18	$1.80	29.06	0.94	2.39	$1.91
Center Line Rumble Strips	**2,366**	**249**	**$0.45**	**86.75**	**18.78**	**35.27**	**$0.02**
Edge Rumble Strips	**10,664**	**654**	**$1.96**	**191.95**	**6.06**	**14.53**	**$0.32**
Delineation	1,346	164	$1.23	46.66	1.2	2.53	$1.02
High Friction Surface Treatment	386	12	$0.98	24.13	0.56	1.53	$1.75
Wider Shoulders (2 ft.)	1,395	25	$0.86	4.07	0.13	0.31	$6.62
Tree Management	507	21	$0.26	8.45	0.54	0.92	$0.48
Rural Alcohol Enforcement	15	1	$0.02	0.2	0.05	0.05	$0.53
Urban Alcohol Enforcement	25	2	$0.03	0.33	0.03	0.04	$1.05
Rural Speed Enforcement	414	8	$0.15	4.14	0.09	0.23	$1.67

Considering that RS are only installed in rural locations, quieter RS could extend this cost effective safety countermeasure to urban locations. The marginal increase in construction cost for the sinusoidal design would not significantly change the relative effectiveness of RS a countermeasure. Considering the number of RS projects planned, switching to the sinusoidal design could significantly reduce the amount of environmental noise disturbance experienced during RS strikes.

In summary, sinusoidal RS have been found to reduce roadside noise while still providing sufficient interior sound alert and haptic feedback to be an effective safety countermeasure to reduce road departure crashes. This conclusion supports similar conclusions from other state agencies of the effectiveness of sinusoidal RS. Narrow RS of any design may be bridged by dual-tire heavy vehicles, so wider RS have the potential to extend the effective of RS to heavy vehicles. This conclusion is supported by other research, though more research regarding the necessary width is needed to confirm this for a wider variety of heavy vehicles. Epoxy filled transverse RS significantly reduced roadside noise while still providing a driver alert and can be used as a roadside noise mitigation strategy for TRS.

5.6 Primary Contribution

The unique contribution of this Dissertation to the body of human knowledge, is the evaluation of sinusoidal RS strike interior alert during typical ambient road conditions. The radio and climate control both increase the interior noise of the vehicle, reducing the effectiveness of the RS interior alert. While the RS interior alert is still detectable, conservative safety standards suggest at least a clear detectable alert. Other research studies have only confirmed the safety effectiveness of sinusoidal RS.

This Dissertation complies and compares the results from three state agencies generating a synthesis of sinusoidal RS literature in the United States. The sinusoidal Rs has been shown to effectively reduce roadside noise while still providing a sufficient interior alert across the three agencies. The identification of dual tire bridging of RS for heavy vehicles has been noted in other state agency reports but is not recorded in scientific literature. The methodology of this Dissertation exceeds the current state of practice from the literature, offering detailed experimental design and statistically significant data analysis. The experiments outlined in this Dissertation are repeatable and transparent.

5.7 Future Research

Many roadway conditions were controlled for between test locations, to minimize differences between measurements during the experiment. The results reflect the pavement type and condition, mill quality, type of sound-absorbing materials at the site (foliage, trees, etc.), and atmospheric conditions at the time of observation. Other locations may generate more or less noise, as these factors will vary across the built environment. Future research could focus on these factors, especially if sinusoidal RS were to be installed in urban areas where roadway conditions are significantly different than the rural conditions tested here. However, it is expected that the differences observed between the baseline and strike conditions would be similar, as this is most related to the RS dimension.

Only previously installed RS designs were tested. Small changes in RS dimensions, especially mill depth, have a large influence on noise generation. In this study, the RS width had a large influence on the RS effectiveness for the heavy vehicle. Evaluating a wider variety of RS dimensions would provide a more comprehensive understanding of the relationship of these characteristics to their performance. Other RS configurations, such as rumble stripes, thermoplastic pavement markings, or raised pavement markers, could be evaluated using this methodology to understand the effectiveness of these countermeasures.

Although not directly evaluated in this research study, the literature review and contractor survey suggested that cyclists (bicyclists and motorcyclists) preferred sinusoidal RS because they are easier to traverse. The scalloped edges of the sinusoidal design provide a smoother transition than the abrupt edges of the traditional rounded design. Although wider RS will extend the effectiveness of the RS, wider RS are likely to reduce the amount of useable shoulder for cyclists. Using the sinusoidal design could provide a less disruptive alternative for cyclists, but understanding the tradeoff between a narrower shoulder and a smoother rumble strip needs more study.

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