QUANTIFYING THE PERFORMANCE OF LOW-NOISE RUMBLE STRIPS

Final Report

PROJECT SPR 800

Oregon Department of Transportation

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16. Abstract: Shoulder or centerline rumble strips (RS) generate noise and vibration to alert drivers when they are departing the lane of travel. Although inexpensive to install, easy to maintain, and very long-lasting, 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 and interior sound levels and interior vibrations generated by rounded and sinusoidal RS strikes were compared to baseline and no-strike sound levels for 3 vehicle classes (passenger car, van, and heavy vehicle) to establish sound generation and alerts of the 2 designs. A total of 114 vehicle strikes of RS were recorded. Rumble strip strikes by the passenger car and van generated less exterior noise with the sinusoidal than with the rounded design. Interior noise generated by striking the sinusoidal design generated a clearly noticeable alert, suggesting that the sinusoidal rumble strip is still an effective countermeasure. Based on thresholds of human perception for vibration, both rumble strip types generated sufficient vibration to alert the driver. Results for the heavy vehicle were complicated due to bridging of the harrower 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. Likewise, the sinusoidal design created a noticeable interior alert for the HV but the rounded design did not.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	millimeters squared	mm^2
ft^2	square feet	0.093	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometers squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	ml
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3
~NOTE: Volumes greater than 1000 L shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit	(F-32)/1.8	Celsius	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
m^2	meters squared	1.196	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME		
ml	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius	1.8C+32	Fahrenheit	°F

*SI is the symbol for the International System of Measurement

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DISCLAIMER

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1.0 INTRODUCTION

This report meets the deliverable requirement of the *Draft Final Report* identified in the Project Work Plan. This report documents the findings of the literature review, the state of practice, and the methodology, results, and conclusions of the study.

1.1 PROBLEM STATEMENT

Crashes due to departure from the roadway account for 66% of all highway fatalities in Oregon, most of which happen on rural highways (FHWA, 2010). Rumble strips (RS), whether on the shoulder or centerline, are a low-cost countermeasure that significantly reduce the incidence of roadway departure crashes. RS generate noises and vibrations that alert drivers when they are departing the roadway. In Oregon, RS are either milled or installed with raised durable striping. On rural 2-lane roadways, shoulder rumble strips (SRS) reduce the incidences of run-off-road fatal injury crashes by 33% and all run-off-road crashes by 15%. Centerline rumble strips (CLRS) reduce rates of head-on and sideswipe crashes by 30% (Torbic et al., 2009). However, although inexpensive to install, easy to maintain, and very long-lasting, RS are associated with noise concerns. Residents living adjacent to highways have complained to ODOT about the noise generated by rounded milled RS. As a result, RS are not currently installed on many roadway segments, even though they could reduce the rate of lane-departure crashes.

One solution to this noise problem is a newer sinusoidal pattern design of RS, which produces a lower noise profile than the traditional rounded RS. There is a need to quantify scientifically the noise differential between rounded and sinusoidal milled RS. Initial research suggests that sinusoidal RS generate the necessary in-vehicle noise and reduced roadside noise. The haptic feedback generated by sinusoidal RS also warrants additional study.

1.2 RESEARCH OBJECTIVES

The proposed study will evaluate the feasibility of using sinusoidal RS as a substitute for rounded milled RS on roadway segments with lane-departure crash problems. In-vehicle noises and vibrations as well as roadside noises will be quantitatively and empirically compared between sinusoidal and rounded RS to indicate whether the sinusoidal pattern can potentially be used as a substitute for the rounded pattern.

1.3 BENEFITS

If the research project results confirm that sinusoidal RS can be used as a substitute for rounded RS, then the research will provide important benefits to ODOT and other jurisdictions within the state of Oregon. 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. As RS treatments have a high cost: benefit ratio (the ODOT Roadway

Departure Plan estimates an upwards of 90:1 cost: benefit ratio, considering only fatal and serious injuries), this improvement would mean possible installation at more sites (FHWA, 2010).

1.4 ORGANIZATION OF FINAL REPORT

This report contains 1) a literature review examining previous research on the safety and operational performance of sinusoidal RS; 2) results from a contractor survey on experiences with sinusoidal RS and a summary of the current nationally recommended best practices; 3) the experimental design and procedure for the data collection effort; 4) analysis of experimental data; and 5) conclusions and recommendations based on findings of the experiment.

2.0 LITERATURE REVIEW

This chapter documents the literature review. Design manuals, guidance documents, and published literature were reviewed, with a focus on sinusoidal RS design and measurement of the resultant noise and vibration upon vehicle incursions with RS. Rather than a comprehensive review of rounded RS, this chapter focuses on topics most relevant to ODOT SPR 800. The chapter is organized by topical area and concludes with a summary of relevant literature findings.

2.1 RUMBLE STRIP APPLICATIONS

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. 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 and Braslau, 2015).

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. Other CLRS types include rolled-in CLRS, which are applied to fresh construction and used primarily in non-snowy climates. 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).

Figure 2.1 shows the standardized dimensioning of RS (length, width, spacing, depth) as discussed throughout the literature (Sexton, 2014). Gaps between RS sections are common, to allow vulnerable road users to cross from the shoulder to the travel lane. In some studies, a double RS is used, with a longitude gap in the length direction, resulting in two parallel groups of RS.

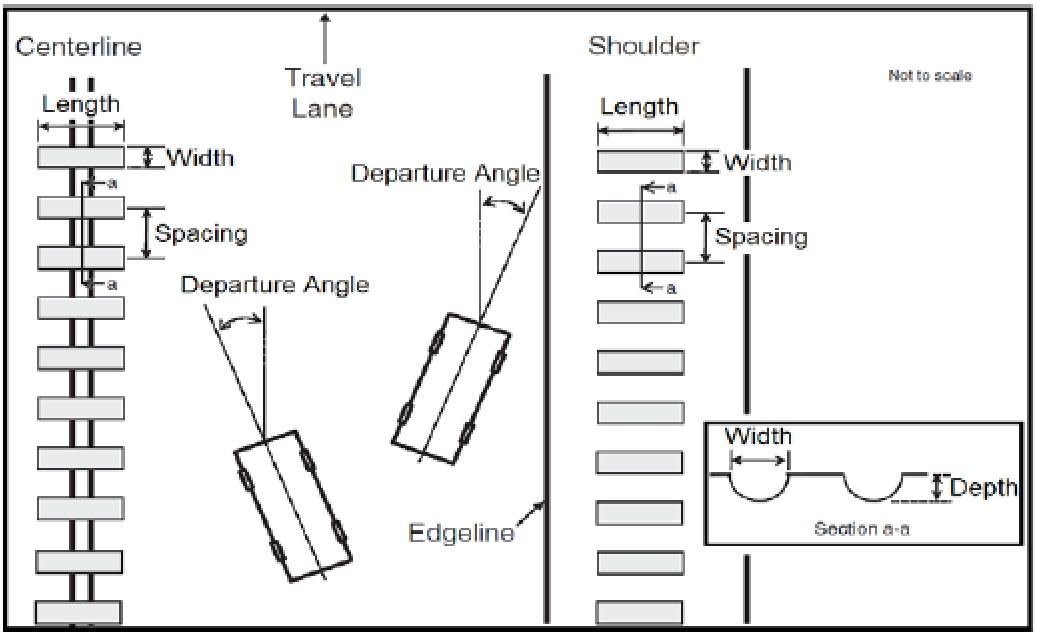

Figure 2.1: Standardized dimensioning of RS designs (Sexton, 2014)

Table 2.1 shows the national average dimensions for SRS and CLRS based on FHWA research. Each state has different standard RS dimensions, which are available 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 FWHA *Standard of Practice* document) (Himes et al., 2016).

Table 2.1: National Average Dimensions (in Inches) for SRS and CLRS (Himes et al., 2016)

TYPE	WIDTH	LENGTH	DEPTH	SPACING
Traditional SRS	7	16	0.5 to 0.625	12
Traditional CLRS	7	12 or 16	0.5	12

2.2 SINUSOIDAL RUMBLE STRIPS

The sinusoidal RS is a recently developed technology, 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., 2016)(Himes et al., 2016). 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). Sinusoidal RS are milled into the pavement like traditional RS but use a continuous cut that changes depth following a sinusoidal wave. Figure 2-2 shows a comparison of sinusoidal RS (labeled "California" and "Pennsylvania") to traditional RS (labeled "Minnesota"), as shown in Figure 2 of the FHWA's *State of Practice* document (Himes et al., 2016)(Himes et al., 2016).

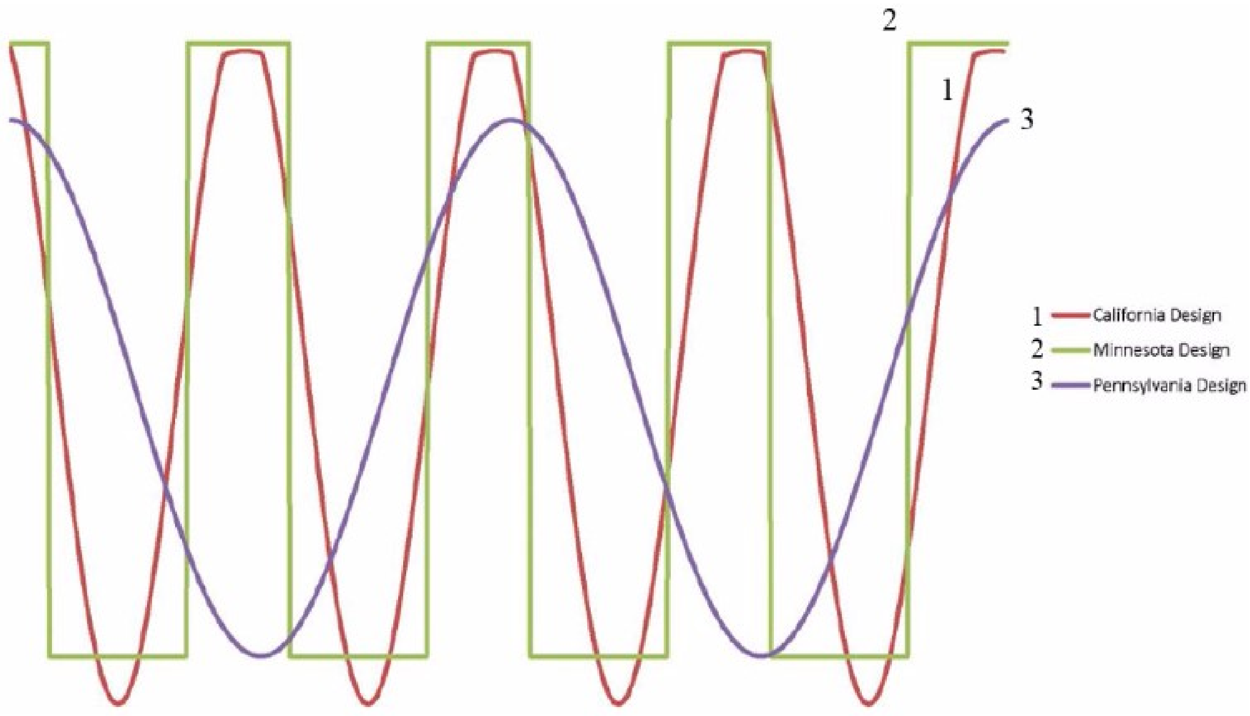

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Figure 2.2: Comparison of sinusoidal to traditional RS sections (from figure 2 in FHWA, 2017)

Figure 2.3 shows the plan and cross-section of a sinusoidal RS installed in Oregon along I-205. This RS features a wavelength of 16 in, width of 12 or 16 in, and depth of 3/8 to 1/2 in (See Appendix E). The edges are tapered, with continuous installation on the left shoulder and 30-ft installation with a 10-ft gap on the right shoulder. The RS edge is installed 12 in outside of the edge of lane striping.

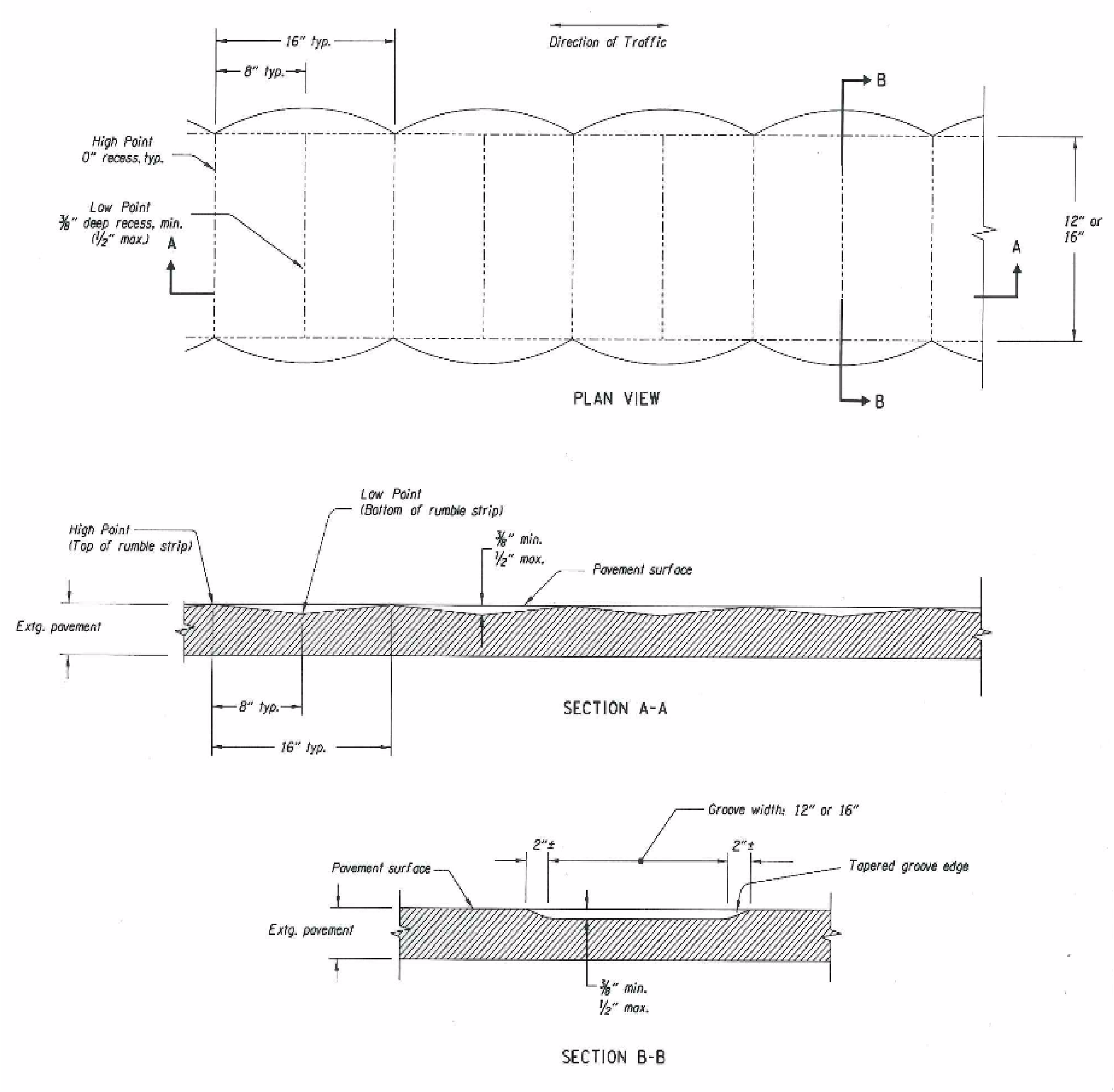


Figure 2.3: Sinusoidal RS design ODOT sheet 2A (See Appendix E)

2.3 NOISE DETECTABILITY

Noise detectability is a measure of the intensity of a sound 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). Appendix A contains a glossary of sound terminology.

Humans can discern differences in noise levels at 3 decibels (dB), with 5 dB being easily noticed. The most common range of frequencies heard by humans is 400–2000 Hz (Himes et al., 2016)(Himes et al., 2016). Changes in sound levels and the related perceived intensity are shown in Table 2.2 (Table 75, Torbic et al., 2009). NCHRP 641 recommends a noise level increase of 6–12 dBA to alert drivers that they are encroaching on a RS (Torbic, 2009). The A-weighted decibel (dBA) scale is based on the range of human hearing, as shown with example sounds in Table 2.3 (FHWA, 2015).

Table 2.2: Approximate Human Perception of Changes in Sound Levels (from Table 75 in Torbic et al., 2009)

CHANGE IN SOUND LEVEL (DBA)	CHANGE IN APPARENT INTENSITY
1	Imperceptible
3	Barely noticeable
6	Clearly noticeable
10	About twice – or half as loud
20	About four times – or one-fourth as loud

Table 2.3: Typical sound levels expressed in dBA (Terhaar et al., 2016).

SOUND SOURCE OR LOCATION	LEVEL (DBA)
Rocket Launching Pad	180
Artillery at Shooters Ear	170
Rifle at Shooters Ear	160
Loud Trumpet at 5 in	150
Jet Takeoff 200 ft	140
Jet Aircraft Workers on Tarmac	130
20 feet 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 feet or Air Conditioner at 20 ft	60
Typical Urban Ambient	50
Typical Rural Ambient (35-40), 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

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). Low-frequency noises in the 10–250 Hz frequency range are the most noticeable noises and may contribute to disturbed sleep, stress, and heart-rhythm disorders (An et al., 2016). For each doubling of distance away from the source, sound intensity decreases by 6 dB for point sources or 3 dB for line sources (FHWA, 2015).

Figure 2.4 shows the sound pressure and frequency levels for distinguishing noise, with the threshold for audible noise in red, the background ambient noise in blue, and the RS-generated noise in purple. Only frequencies in yellow can be heard; these are the frequencies at which the intensity of RS-generated noise (purple) exceeds the ambient noise (blue). This figure shows a full-spectrum analysis, using the 1/3-octave band, indicating the intensity of each measured frequency.

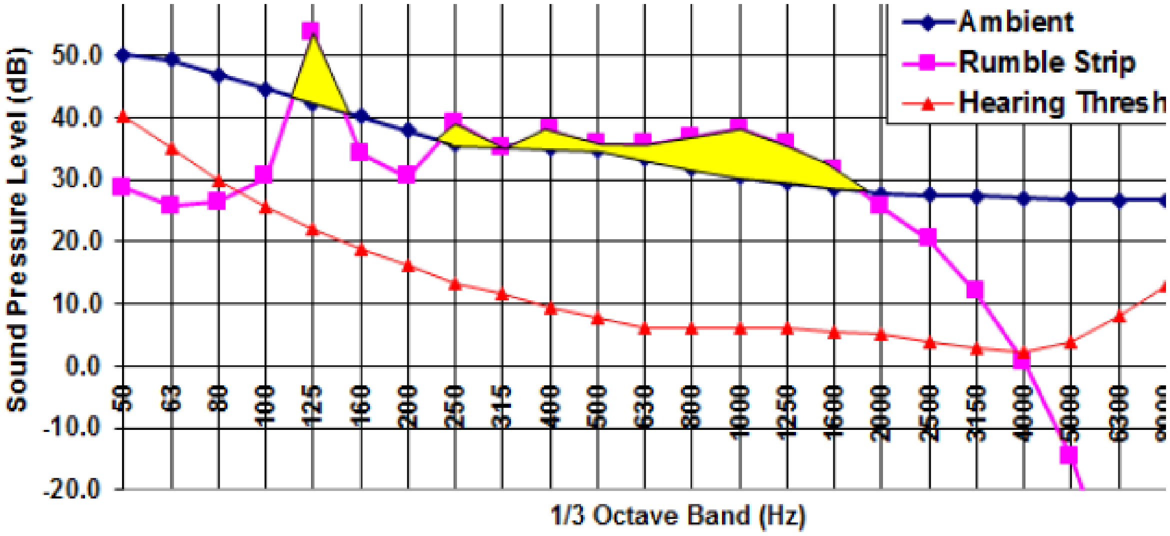


Figure 2.4: Sound pressure and frequency levels for distinguishable noise (Terhaar et al., 2016)

2.4 PREVIOUS INTERIOR AND EXTERIOR NOISE EVALUATIONS

The FHWA *State of the Practice* document has an extensive literature review regarding interior and exterior noise evaluation of RS (Himes et al., 2016). Table 2.4 summarizes differences between various studies in the literature and a short summary of the key findings.

Table 2.4: Summary of the FHWA (2017) Literature Review

STUDY	TYPE	RS QUALITIES	EQUIPMENT	FINDING
Bucko & Khorashadi, 2002*	Interior noise, vibration	Rolled & milled traditional, various sizes & spacing	Accelerometers, sound level meter	Maximum noise is proportional to RS depth.
Torbic et al., 2009	Interior noise, multiple states	Milled traditional, various sizes & spacing	GPS, sound level meter	Increased RS dimension leads to increased noise; increased spacing leads to decreased noise.
Miles & Finley, 2007	Interior noise, 3 vehicle types & various speeds	Milled traditional, various sizes & spacing	Sound level meter	Speed relates to ambient noise but not RS noise.
Elefteriadou et al., 2000	Interior noise, 3 speeds	Milled traditional: bike-friendly, various depths & spacing	Sound level meter	Deepest RS are loudest.
Terhaar & Braslau, 2015*	Interior & exterior noise, 3 vehicle types, 3 speeds	Milled traditional vs. sinusoidal, various sizes & spacing	Meteorological data, sound level meter (spectrum analysis)	Interior sound increases with speed & vehicle weight. Sinusoidal RS produce less exterior noise with similar interior noise.
Finley & Miles, 2007	Exterior noise, various speeds, 2 vehicle types	Milled traditional, various sizes & spacing	Sound level meter 50-ft offset	Increased length increases noise. Chip seal produces less noise than hot-mix asphalt.
Rys et al., 2010	Exterior noise, various speeds, 2 vehicle types	Milled traditional: rectangular & football-shaped	Sound level meter 50-, 100- & 150-ft offsets	Exterior noise relates to speed, vehicle type & distance from RS.
Danish Road Institute, 200	Exterior noise	Milled traditional vs. sinusoidal: various sizes & spacing	Sound level meter 25-ft offset	Sinusoidal noise is 0.5–1 dB louder than ambient; unclear if change from design or dimensions.
Datta et al., 2012	Exterior noise	Milled traditional: various depths, location & pavement types	Sound level meter 50-ft offset	10-dBA noise increase for SRS; depths of 0.25–0.5 in minimize exterior noise.
Sexton, 2014*	Exterior noise	Milled traditional: various sizes & spacing	Sound level meter 25- & 50-ft offsets SIP Method	Design with minimum exterior noise: 0.375–0.5 in depth; 6–6.9 in width; 8 in length; 12 in spacing.

*Studies are discussed in more depth elsewhere in this literature review.

Milled RS typically create more vibration and noise than other design options, like 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 in (Caltrans, 2012). Vehicle type and tire type have a large influence on the intensity of sound of a vehicle (Caltrans, 2012).

A 2001 study by the New York State DOT (Caltrans, 2012) found that RS increase the maximum sound level (LAmax) for short periods of time but do not increase the loudest-hour equivalent sound level (LAeq1h). The LAeq1h represents the background sound level adjusted by vehicle volume and speed, distance to the roadway, and attenuation due to absorption. By contrast, LAmax represents one pass of an individual vehicle. The study used various vehicle types, recorded sound levels from immediately proximate to the road to 300 feet away, and tested 3 sound-deterrence treatments (e.g., sound walls).

The Minnesota DOT (MnDOT) performed exterior and interior vehicle noise testing on 3 SRS designs – California, Pennsylvania, and Minnesota designs (see Figure 2.2) – using 3 vehicle types at 3 speed thresholds (Terhaar and 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. Interior noise was similar for the passenger car and pickup truck for those two designs. The Pennsylvania design produced lower interior and exterior sound levels, with a marked reduction in driver feedback (difference between ambient and RS interior noise). 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.

Sinusoidal RS sound levels were recorded at 50 feet and 75 feet from the edge of roadway along with video recording at 50 feet (Terhaar et al., 2016). Sound levels (in dB) were measured between 31.5 and 16,000 Hz and were converted to dBA. The Leq or equivalent sound level captures the average acoustical energy for a given time. Maximum Leq was recorded for each pass inside the vehicle and on roadside. The average of 3 passes was used for comparison and compared to controls with no RS for each vehicle type. Data were also collected for a traditional RS design (16-in wavelength). All of the sinusoidal RS in the MnDOT study had interior sound level increases of ≥10 dBA, with peaks at ~80 and 160 Hz (Terhaar et al., 2016). Use of milled RS increased exterior noise levels by 5–19 dB and interior noise levels by 5–19 dB (Caltrans, 2012).

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 2014 study sponsored by Washington State DOT (WSDOT) 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 (Figure 2.5).

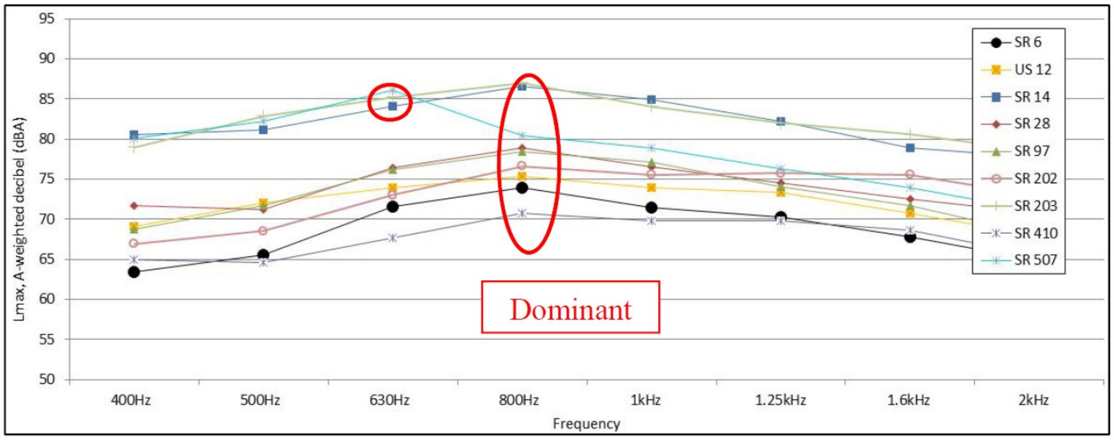


Figure 2.5: Frequency spectrum at 50-ft measurement location (Sexton, 2014)

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 (Figure 2.6). 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.

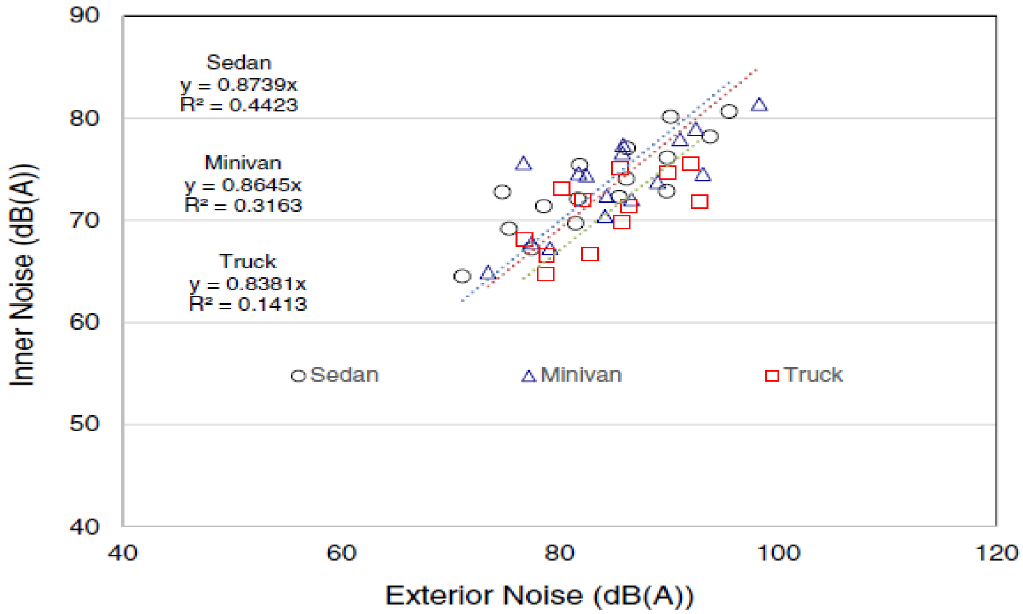


Figure 2.6: Correlation between interior & exterior noise (An et al., 2016)

2.5 VULNERABLE ROAD USER PREFERENCE

Vulnerable road users, like motorcyclists and bicyclists, can have issues traversing RS due to the lower stability associated with having only 2 wheels. Seven CLRS designs were tested for motorcyclist and bicyclist comfort at a pavement test track (MnROAD). Design dimensions are shown in Table 2.5 (Terhaar et al., 2016). Six of the designs were sinusoidal with various wavelengths and widths. Two of the designs consisted of 2 adjacent RS with a 4-in gap. Three groups of voluntary motorcyclists (52 total riders) tested the design performance by completing a survey before and after the experiment. The 11 Likert-scale items on the survey asked questions about comfort, control, and function. Most motorcyclists reported extensive experience riding motorcycles. They indicated that Design 2 had the highest levels of control and function, and Design 6 had the highest level of comfort, whereas Designs 3 and 7 were the least desirable designs due to the longitudinal gap between the strips.

Table 2.5: MnDOT Sinusoidal RS Designs (from Figure 3.1 in Terhaar et al., 2016)

DESIGN	TYPE	EDGE TYPE	WAVELENGTH (in)	WIDTH (in)	DEPTH (in)
1	Sinusoidal	Tapered	16	14	1/16 to 3/8
2	Sinusoidal	Straight	16	14	1/16 to 3/8
3	Sinusoidal	Straight	16	2× 8 in w/ 4-in gap	1/16 to 3/8
4	Non-Sinusoidal	Straight	12	14	3/8
5	Sinusoidal	Tapered	14	14	1/16 to 3/8
6 ◊	Sinusoidal	Straight	14	14	1/16 to 3/8*
7 ◊	Sinusoidal	Straight	14	2× 6 in w/ 4-in gap	1/16 to 3/8*

◊Additional field installation and testing.

*Also field-tested with a maximum depth of 1/2 in.

Three bicyclists repeated the performance evaluation with the same RS designs (Terhaar et al., 2016). The sample size was limited by scheduling and weather constraints. Bicyclists preferred Designs 3 and 7 because they could ride between the strips. They considered the sinusoidal design to be more comfortable and easier to traverse than the traditional design. Gaps between lengths of SRS (typically 10–12 foot gaps between 40–60 foot lengths of RS) enabled bicyclists to move from the shoulder to the travel lane (Hawkins et al., 2016).

2.6 IN-VEHICLE VIBRATION MEASUREMENT

2.6.1 In-Vehicle Haptic Feedback

A 2001 study by Caltrans used a series of 4 accelerometers to measure haptic feedback and a sound level meter to evaluate traditional RS designs (Bucko and Khorashadi, 2001). Accelerometers capture translation and rotation of the steering wheel and can be used to calculate the resultant force or haptic feedback. The setup is shown in Figure 2.7.

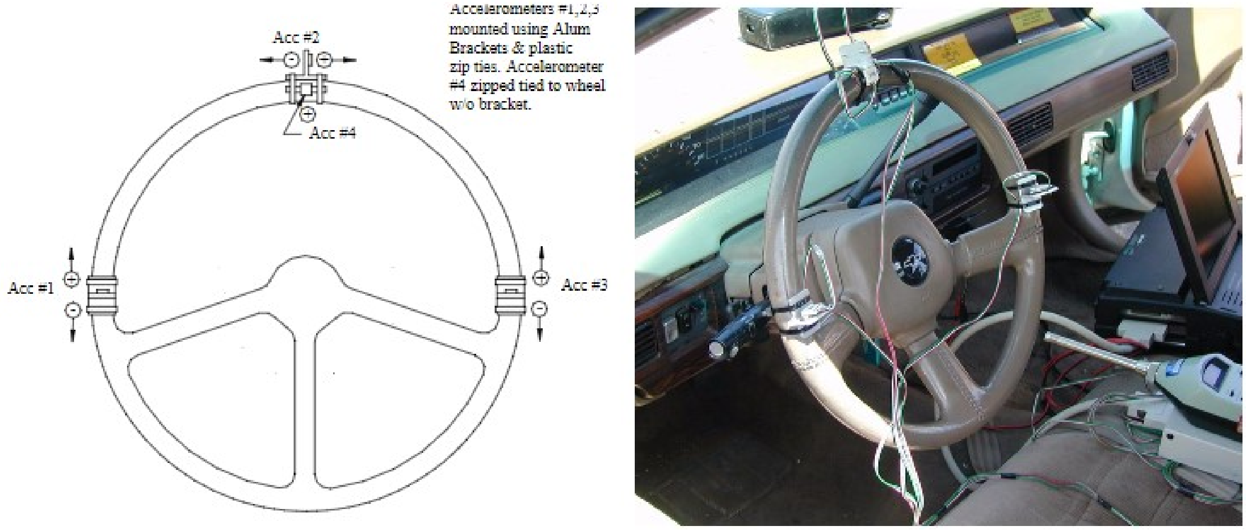
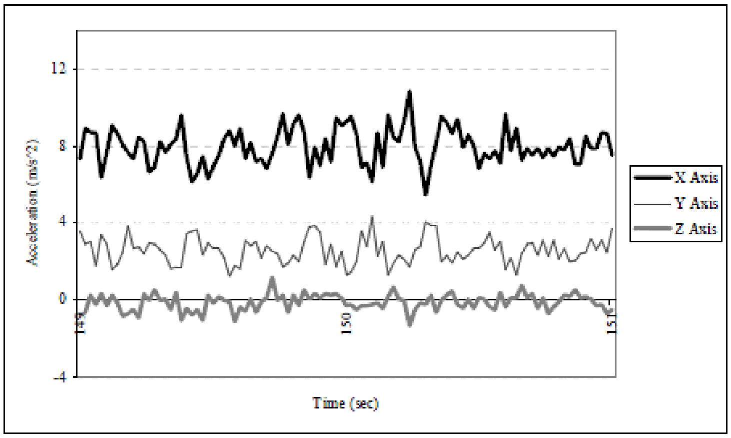
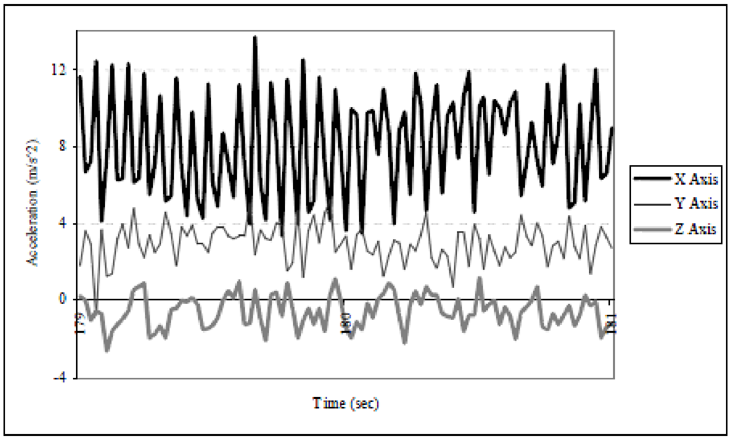


Figure 2.7: Accelerometer placement for measuring haptic feedback (Bucko and Khorashadi, 2001)

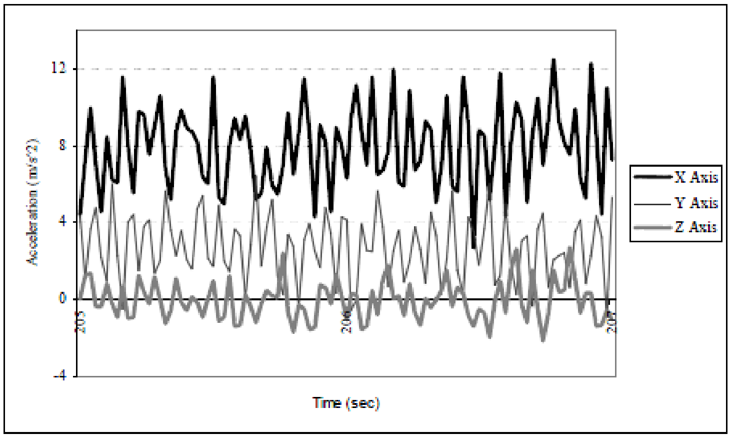
Dulaski and Noyce (2016) studied the haptic feedback of CLRS using 2 accelerometers, which were mounted to the top of the steering column or to the clutch pedal. Three distinct acceleration signatures were observed: background driving, striking the SRS, and striking the CLRS (Figure 2.8). The average acceleration, variance, and standard deviation were tabulated for each axis (X, Y, Z) for each acceleration signature. Average values for CLRS and SRS strikes were very similar, with a notable difference from the background level. Analysis of variance (ANOVA) tests showed that the only statistically significant difference was along the X axis between the RS and background. The researcher concluded that drivers must rely on the differences in waveform instead of differences in magnitude to perceive haptic feedback from RS strikes.



Background Acceleration



Shoulder Incursion



Centerline Incursion

Figure 2.8: Steering column accelerometer results (Dulaski and Noyce, 2006)

2.6.2 In-Vehicle Noise Sensors

In previous research studies that used a handheld noise monitor, the sensor was held near the driver's ear (Himes et al., 2016)(Himes et al., 2016). Caltrans mounted a microphone to the seat back in a similar position (Caltrans, 2012). NCHRP 641 recommends mounting the microphone in the center of the vehicle, facing forward, at approximately the same location as the driver's ear (Torbic et al., 2009). For each run, 10 s of data were collected, and ambient sound levels were based on the average sound level in the first 0.5 s. The angle of departure (angle at which the test vehicle left the travel lane) was recorded and ranged from 1 to 10 degrees.

SAE Standard J1477 establishes guidelines for measuring interior sound levels of light automotive vehicles (SAE International, 2000). This standard specifies requirements for the test site, equipment, and vehicle preparation. According to SAE Standard J1477, the microphone should be 28 ± 2 in above the centerline of the seat, but no closer than 6 in from walls or upholstery. The microphone should be facing forward, in the direction of travel. The seat should be in the middle position of the horizontal and vertical adjustments. A 30-s measurement is recommended.

2.7 ROADSIDE NOISE SENSORS

Caltrans and WSDOT used the AASHTO SIP Method to evaluate the noise performance of sinusoidal RS (AASHTO, 2013). The SIP Method is a standard method for measuring exterior sounds, such as the sound pressure levels (SPLs) of road surfaces. The maximum A-weighted SPL for a given vehicle type is calculated and compared to a baseline ambient sound level to determine the effect of road surface variations (e.g., RS). The method establishes standards for equipment, test sites, traffic conditions, microphone positions, calibration, experimental procedures, and data calculations. Microphones are placed at 25- and 50-ft horizontally and 5- and 12-ft vertically from the centerline of the travel lane. The test site should be in an open area along a tangent section of the roadway, away from intersections or areas with frequent acceleration or deceleration. The site should have minimum reflective surfaces, to reduce the incidence of noise obstructions.

NCHRP Report 882 discusses the effects of weather on highway noise measurement (Kaliski, 2018). This report shows how noise propagation is affected by various weather conditions, like wind, inversions, and temperature, and provides tables to adjust observed values based on weather conditions. Distance from the roadway plays a major role in the magnitude of these effects; thus, developing an experiment that locates the microphones close to the roadway minimizes the impact of weather.

2.8 SUMMARY

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., 2016)(Himes et al., 2016). Areas where RS would be most effective and the relationship between noise level and safety need to be identified (Himes et al., 2016). Furthermore, interior noise evaluations have only been performed under minimal ambient noise conditions (windows closed, radio off, climate control off). Thus, previous studies suggest that 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 portion of driver feedback. One study evaluated haptic feedback using a relative scale. Two studies found limited differences between background vibration and RS strikes. No minimum thresholds exist for haptic feedback levels (Torbic, 2009).

3.0 STATE OF PRACTICE SUMMARY

The extensive FHWA (2017) *State of Practice* document details milled-in RS patterns and provides federal and state best practices. NCHRP Report 641 provides information regarding the current state of practice of RS installation. In addition to drawing from these sources, the research team surveyed contractors to assess readiness to implement sinusoidal RS, including equipment and training. Findings from these documents and the contractor survey are summarized below.

3.1 AGENCY PRACTICES

Released in 2009, NCHRP Report 641 provides extensive guidance on the design and application of RS (Torbic, 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, FHWA released its *State of Practice* document (Himes et al., 2016). 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).

In April 2018, CalTrans published a study comparing sinusoidal, conventional rounded, and raised pavement marker RS (Donavan, 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. 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 the both RS types generating alerts ~13 dB higher than baseline.

For exterior sound measurements of light-duty vehicles, baseline passes produced sound levels of 79.9–81.8 dBA (Donavan, 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 60 mph (88 ft/s) striking a 14-in (1.167-ft) 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.

For interior sound measurements of light-duty vehicles, baseline passes produced sound levels of 62.8–72.8 dBA (Donavan, 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. Alert levels were ≥10 dB, with larger alerts at the 80 Hz frequency (up to 32.6 dBA). Interior vibration measurements were taken 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 $\mu m/s^2$. Specific frequencies were noted for each vehicle type. Seat track measurements were more consistent than steering column measurements. Additional measurements were made with one vehicle, a Chevy Malibu, to better understand the relationship of speed to RS noise and vibration generation.

3.2 CONTRACTOR SURVEY

To understand contractor capabilities, a survey about RS installation and equipment was developed (Appendix B). The phone-based survey focused on contractors' experience level with installing traditional and sinusoidal RS, as well as specifics regarding equipment type and performance. Contractors provided information about subcontractor use and best practices. One graduate student made the call, while another transcribed the conversation. Follow-up emails provided contact information, a copy of the survey, and information about the I-205 sinusoidal RS design. ODOT provided contact information for 4 contractors, chosen based on historic bids for RS projects within Oregon (Table 3.1). Two additional subcontractors were contacted after the initial interview process.

Table 3.1: Contractor Information and Experience

COMPANY	LOCATION	INSTALL RS	SINUSOIDAL RS EXPERIENCE
Specialized Pavement Marking (SPM)	Tualatin, OR	In-House / Subcontractor	Test location with ODOT (2015)
Apply-A-Line	Pacific, WA	In-House	I-205, Additional Project WA
Hicks Striping & Curbing	Salem, OR	Subcontractor Only	None
Nevada Barricade & Sign Co.	Sparks, NV	In-House	None
Diversified Concrete	Sparks, NV	Does Not Perform Work in OR	
Surface Preparation Technologies (SPT)	Mechanicsburg, PA	Specializes in RS	Extensive

Experience levels of contractors with sinusoidal RS ranged widely, from only using subcontractors to installing sinusoidal RS in Oregon on I-205. Two contractors had experience with traditional RS but had not cut sinusoidal strips. They were optimistic, however, that their equipment could be set up for this alternative design. All contractors with in-house equipment had automated, continuous-cut milling machines. Contractors suggested that sinusoidal RS take 3 times longer to cut than traditional RS due to the continuous nature of the cuts. Asphalt pavement was generally preferred over concrete for cutting RS. Concrete was slower to cut but could be used if recently poured. Specific cutting heads may be required for sinusoidal cuts depending on the milling machine. Effectiveness of the sinusoidal strips depends on the depth of the cut (deeper cuts are louder) and the accuracy (smoothness) of the cut to match the intended design.

Surface Preparation Technologies (SPT), a subcontractor that specializes in RS, was the preferred subcontractor of 2 of the original contractors. SPT has the most extensive experience with sinusoidal strips. They are currently installing 150 miles of sinusoidal RS in New Jersey and have created sinusoidal-specific milling machines for the international market over the last 6 years. They suggested that tapered edges in the sinusoidal design reduce water ponding and improve bicycle and motorcycle ride ability. They warned that cutting centerline sinusoidal strips removes existing centerline pavement markings, requiring temporary markings and restriping. They suggested that an 8-inch-wide design is too narrow to be very effective, especially for vehicles with wider tires.

3.3 SUMMARY

Extensive state of practice information is provided at the Federal level through NCHRP 641 and FHWA's *State of Practice* document. These references were reviewed but are not duplicated here. A survey of RS contractors provided insight on the current practice of the industry, to understand equipment capabilities and experience levels regarding the relatively novel sinusoidal design. In general, sinusoidal RS installation is very similar to conventional installations, with some modification to the operations and performance (primarily speed) of equipment. Contractors provided additional lessons learned and are a valuable knowledge base.

4.0 METHODOLOGY

This chapter documents the research design, which is based on studies from the literature review. The experiment measures the resultant noise and vibration of vehicle incursions with rounded and sinusoidal RS. The chapter is organized by topical area and concludes with a summary of the experimental design.

4.1 EXPERIMENTAL DESIGN

The experimental design was based on the AASHTO SIP Method (see Section 2.7 for details). Guidelines for the SIP Method are described in Table 4.1.

Table 4.1: AASHTO SIP Method Guidelines (AASHTO, 2013)

TYPE	STANDARD	DESCRIPTION
Location	7.1.1	Road extends 100 feet on both sides of microphone location
	7.1.2	Road should be level and straight, avoid horizontal curves. Note geometry.
	7.1.3	Homogeneous roadway surface. Take pictures.
	7.1.4	Sound characteristics for new pavement may change during first 6 months.
	7.1.5	Road surface should be free of gravel and debris.
	7.1.6	Open space free from large reflecting surfaces within 100 feet of microphone.
		Includes parked vehicle, signboards, buildings, guardrails, etc.
	7.1.7	Ground surface between microphone and road should be flat and acoustically hard. Note foliage.
	7.1.8	Line-of-sight of microphones should not be obscured in 120° arc.
	7.1.9	Vehicles should be in steady-state speed, not accelerating or decelerating for intersections or ramps.
	7.1.10	Mix of traffic should contain all vehicle types.
	7.1.11	Background Noise Requirements Section 8.2.1
	7.1.12	Site should be away from intrusive noises, like railroads, construction sites, or airports.
Background Noise	8.2.1	Background noise should be 10 dB below intended measured sound.
Meteorological	9.1	Wind speed shall be <11 mph regardless of wind direction and recorded once per hour.
	9.2	Air temperature shall be 40–95°F (*SAE) and recorded once per hour.
	9.3	Sky condition (clear, cloudy, overcast) shall be recorded once per hour.
	9.4	Pavement moisture: road must be visibly dry.

**SAE Interior Sound Level Guidelines are met by these specifications unless noted otherwise.*

After each RS strike, the SPL was analyzed to ensure that the event was 6 dB louder than the background noise immediately before and after the strike (Figure 4-1). Additionally, the strike should be ≥10 dB louder than the observed background noise from nonvehicle sources to ensure that the strike event is detectable and independent from the influence of other noise.

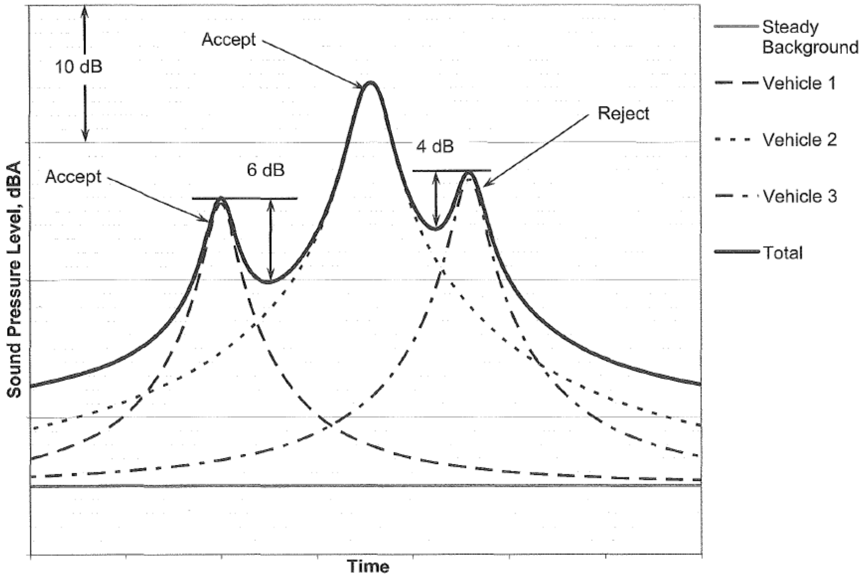


Figure 4.1: Event sound levels compared to background noise (AASHTO, 2013)

4.2 EQUIPMENT

Before equipment purchase or selection, sound recording and analysis equipment were checked against SIP Method Standards to ensure that standards were met or exceeded (Table 4-2). The sound analyzer exceeded minimum requirements and was higher fidelity than equipment used in previous studies. To measure vehicle speed during testing, the Pocket Radar Traffic Advisor radar unit was used, which met the required tolerance level. Meteorological conditions (wind, temperature, and sky conditions) were measured during sound measurements using the Windmate 200 handheld weather station, which met or exceeded SIP Standards.

Table 4.2: Equipment Standards (SIP Method)

Equipment	SIP Standard	Project Equipment	Meets Standard?
Sound Level Meter	IEC 61672-1	Spider-20E	Meets
Windscreen	Should be used	GRAS Windscreen	Meets
Frequency Analysis Range	50 to 10,000 Hz	Spider-20E	Exceeds
Frequency Analysis Standard	IEC 61260	Spider-20E	Meets
Calibration Instrument	IEC 60942	GRAS 42AG	Meets
Speed Measurement	±1 mph	Pocket Radar Traffic Advisor	Meets
Temperature Measurement	±2°F	Windmate 200	Meets
Wind Measurement: Speed	±2 mph	Windmate 200	Exceeds
Wind Measurement: Direction	±10°	Windmate 200	Meets

Sound and vibration measurements were verified by independent calibration devices. The GRAS 42AG sound calibrator emits 2 tones (250 and 1000 Hz) at 2 intensities (94 and 114 dB) with 0.02% variability. Tones were measured by the sound equipment to ensure that the sound analyzer correctly identified pitch and intensity. Before field data were collected, the research team verified that the sound analyzer operated to within 0.5 dB of the sound calibrator based on the requirements of the SIP Method. Vibration measurements were calibrated with a Meggitt Ref2500 handheld shaker, which generates 3 frequencies (61.44, 100.0, and 159.2 Hz). The triaxial accelerometer was validated similarly before field data collection. Sound and vibration calibrations were successfully performed with the project equipment in the lab setting.

4.3 SITE SELECTION

SIP criteria require a clear area free of trees and other reflecting surfaces (Figure 4.2). To explore sinusoidal and rounded RS, sites were selected on the same route, US-26, for comparability. Based on the criteria and using Google Streetview, 4 potential sites for sinusoidal and 2 sites for rounded RS tests were identified on US-26, southwest of Gresham, to measure sound levels.

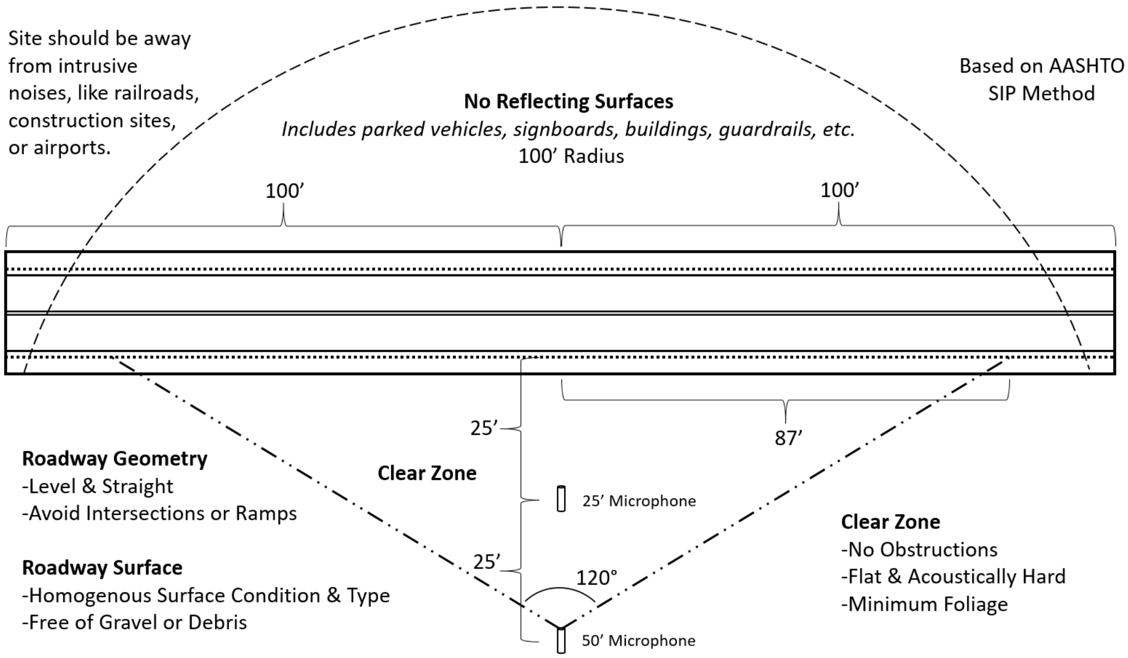


Figure 4.2: Site selection guidelines based on AASHTO SIP method

Site visits were made to evaluate sites based on their characteristics. Based on the literature, a 10-s strike at 55 mph is recommended to measure noise levels, thus requiring a segment of 807 feet (~0.15 miles) for a RS strike. Driving routes for each site were explored by considering the shortest path while maintaining a loop (to eliminate the need for turnaround maneuvers). Site selection also considered ease of access, pavement quality, length of the driving loop, and a preliminary field visit. ODOT's TransGIS website indicated good pavement quality for both locations, which are on US-26 near Sandy, OR (SE of Portland; Figure 4.3). Detailed driving directions used for the experiment are provided in Appendix B (Section 6-1).

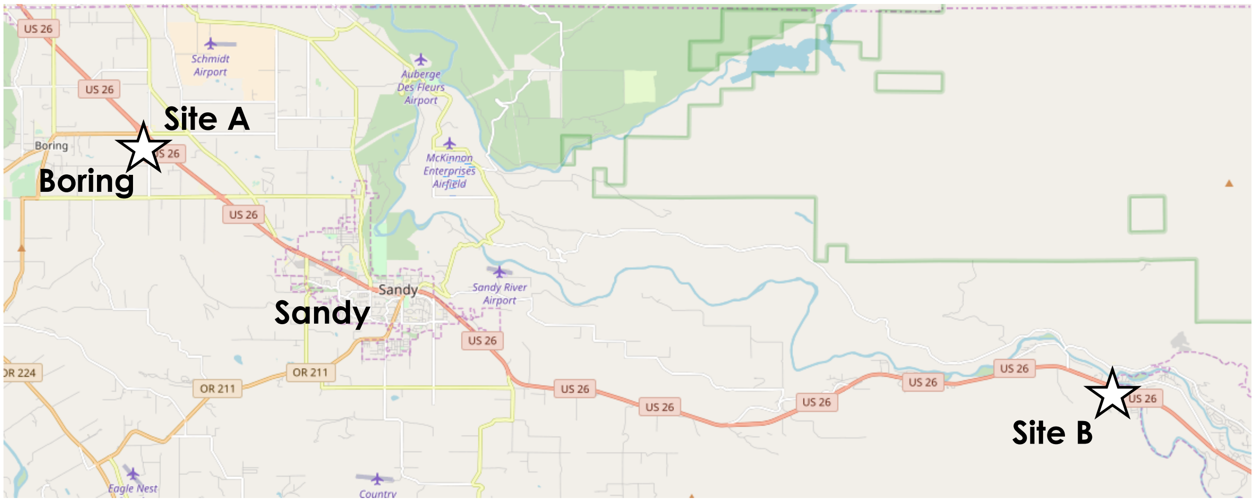


Figure 4.3: Site locations for testing (© OpenStreetMap contributors)

4.3.1 Traffic Volumes

Traffic volumes were gathered from an automatic traffic recorder at milepost 14.36 on US-26. The eastbound (EB) direction automatic traffic recorder indicated 17,253 vehicles. Figure 4.4 shows the average hourly traffic volumes in the EB direction. Weekday volumes were higher during the PM peak than during the AM peak.

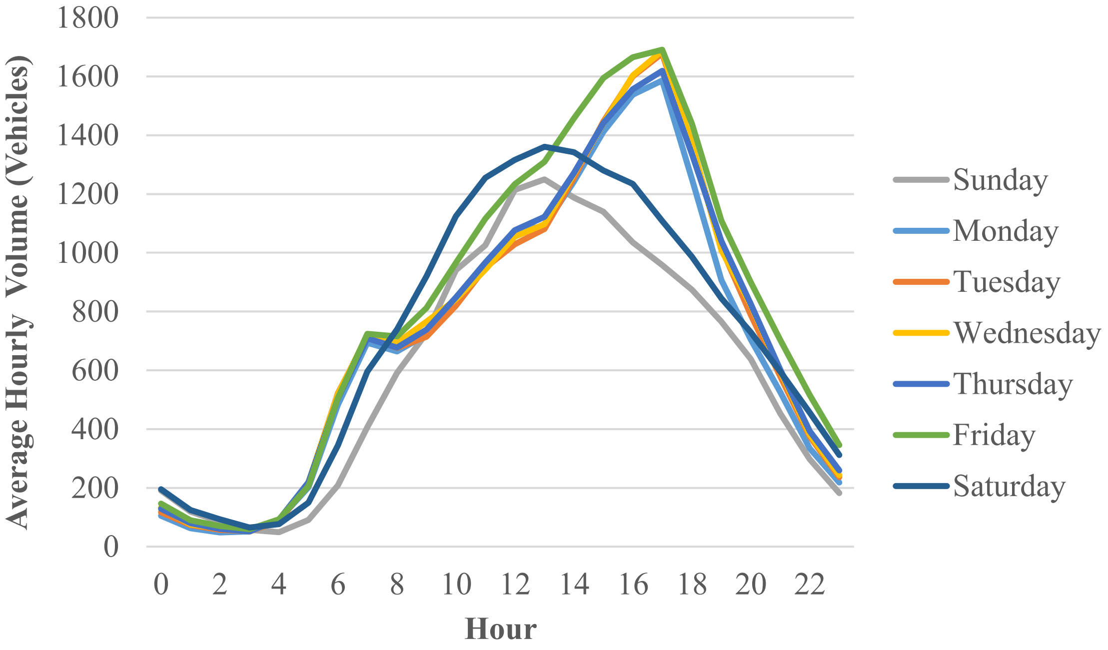


Figure 4.4: Average hourly volume (EB) at automatic traffic recorder 26-003.

4.3.2 Site A: Location

Site A is the sinusoidal RS site, located near Boring, OR at US-26 Mile Point (MP) 19.7 (Figure 4.5). At this location, US 26 is a 4-lane divided highway, with left- and right-shoulder RS.

Figure 4.5: Site A: Sinusoidal RS (© OpenStreetMap contributors)

4.3.3 Site B: Location

Site B is the rounded RS site, located east of Sandy, OR at US-26 MP 37.0 (Figure 4.6). At this location, US 26 is a 4-lane highway with a 2-way left-turn lane with CLRS and SRS.

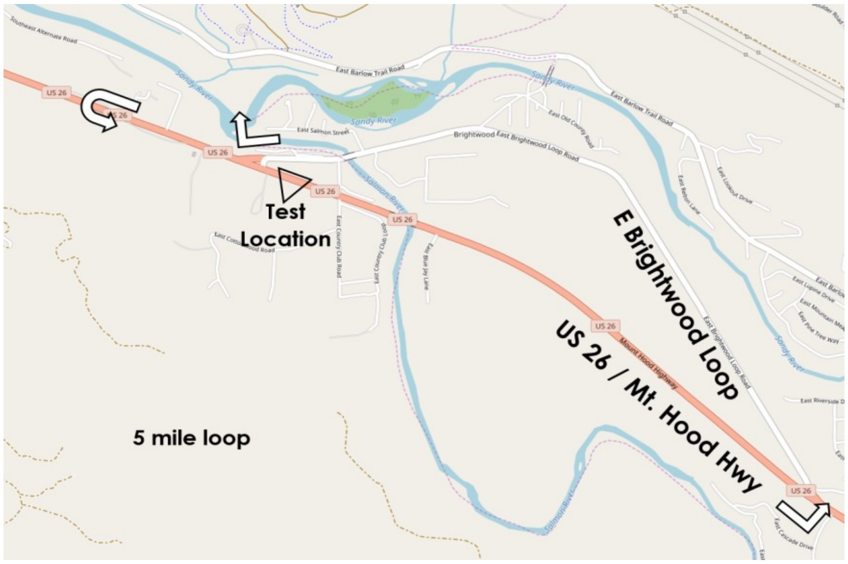


Figure 4.6: Site B: Rounded RS (© OpenStreetMap contributors)

4.4 EXTERIOR NOISE MEASUREMENT

The setup for exterior measurements is shown in Figure 4.7. Microphones and cones were located using a measuring wheel. Personnel and other equipment were located 50 feet behind the microphone to minimize interference with the sound measurements (Figure 4.8). The literature recommends a strike time of 10 s. To alert the driver of the test vehicle to the required length to start and end the RS strike, two cones were placed 800 feet apart on the shoulder. This distance is based on a 55-mph vehicle speed, which was verified for each strike using a radar gun. During each RS strike, the SPL 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.

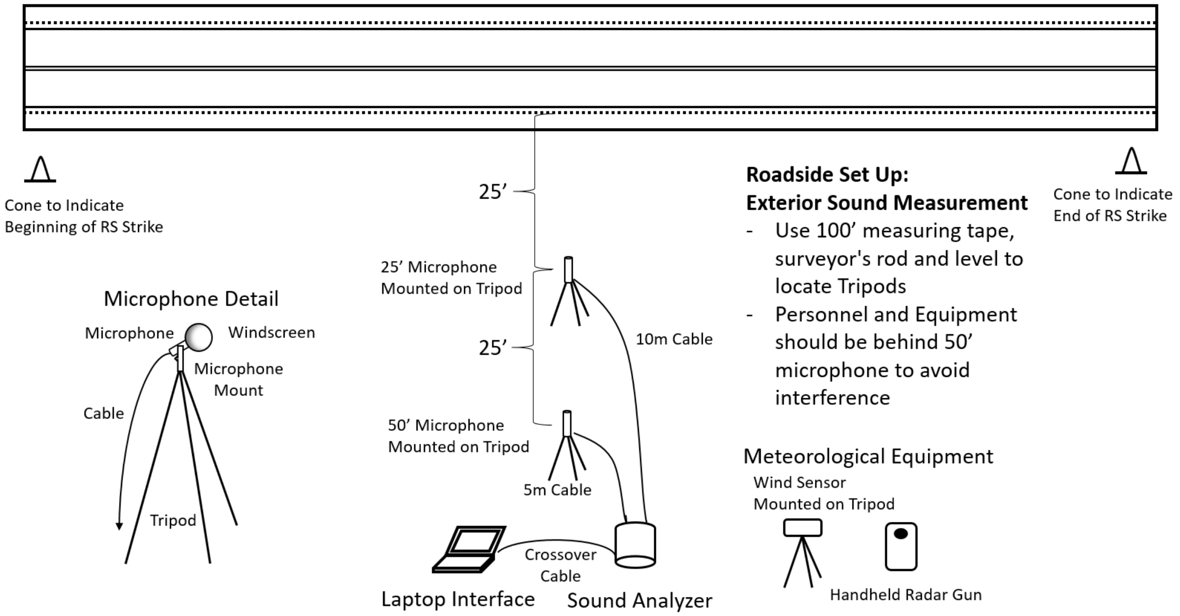


Figure 4.7: Exterior sound measurement diagram

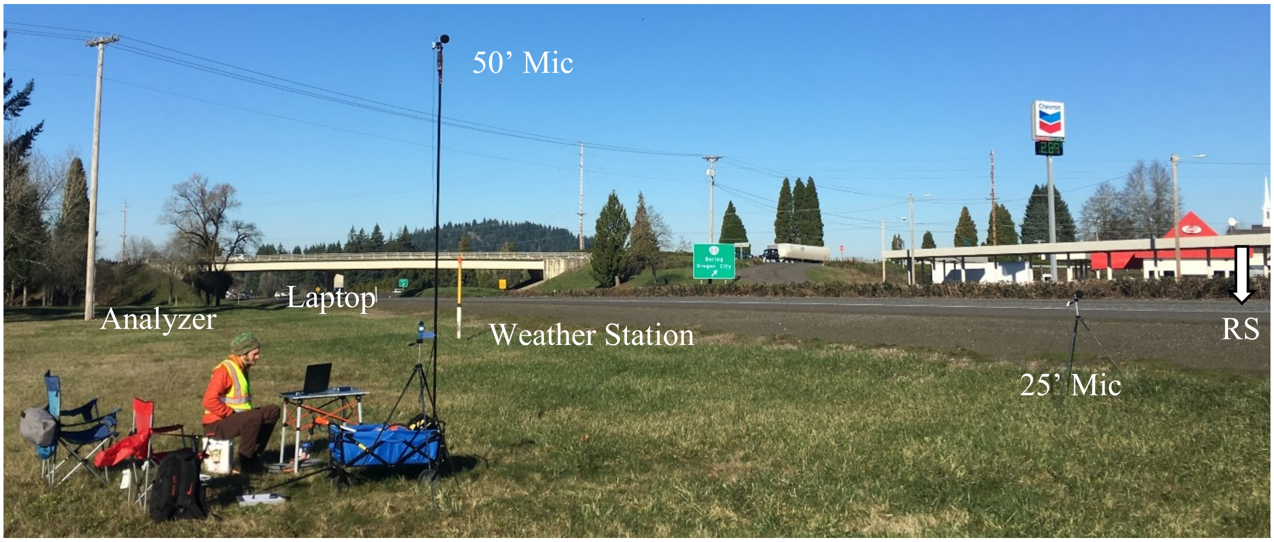
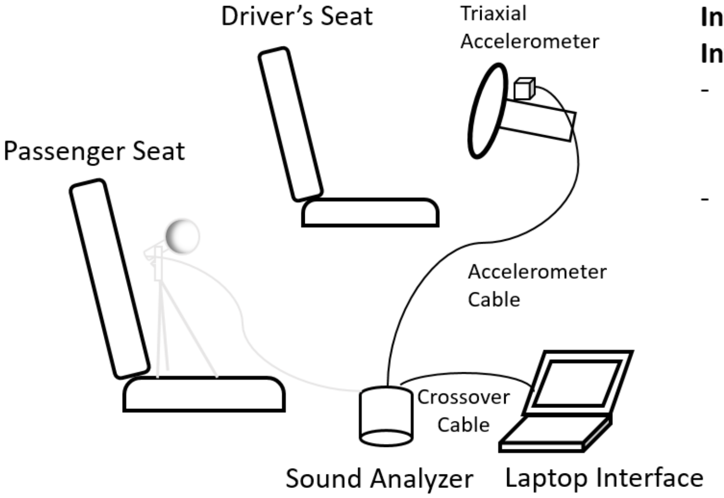


Figure 4.8: Exterior sound measurement setup

4.5 INTERIOR VIBRATION MEASUREMENT

A triaxial accelerometer was used to capture translation and rotation of the steering column, which will be used to calculate the resultant force or haptic feedback. The setup is shown in Figure 4.9. The triaxial accelerometer was attached to the steering column (Figure 4.10). The sound analyzer and laptop interface were onboard the vehicle during testing. The laptop was placed so the vehicle assistant could operate the EDM Waveform Editor software during the experimental runs. The 3 axes were recorded using 3 channels on the sound analyzer. The Y axis was pointed towards the driver, the X axis was aligned across the vehicle (parallel to the dash), and the Z axis was aligned in the vertical direction.



Interior Set Up:
Interior Vibration Measurement

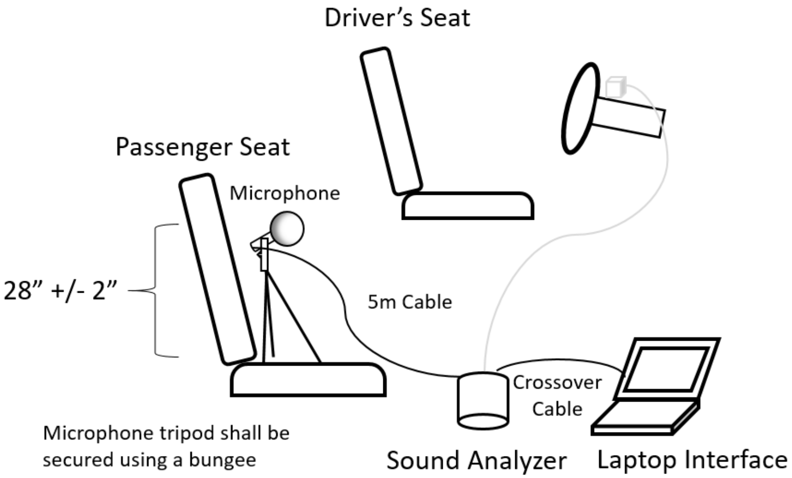
- Accelerometer is attached to steering column using adhesive gel
- Cable should be routed along dash to minimize interference to driver

Figure 4.9: Interior vibration measurement diagram

Figure 4.10: Accelerometer placement in passenger car

4.6 INTERIOR NOISE MEASUREMENT

SAE Standard J1477 establishes a framework for measuring the interior sound levels of light-duty vehicles (SAE International, 2000). The standard provides minimum equipment specifications, as well as requirements for the test site and vehicle preparation (Figure 4.11). One microphone, mounted on a tripod, was securely placed in the passenger seat (Figure 4.12). This microphone used the fourth channel of the sound analyzer, simultaneously measuring interior sound and vibration.



Microphone tripod shall be secured using a bungee chord or tie down strap

Interior Set Up:
Interior Sound Measurement

- Microphone should be place 28 in +/- 2 in above the centerline of the seat, but no closer than 6 in from walls or upholstery.

- The microphone should be facing forward, in the direction of travel, and the seat shall be in the middle position of horizontal and vertical adjustments

Figure 4.11: Interior sound measurement diagram

Figure 4.12: Microphone placement in passenger car

4.7 PASSENGER CAR AMBIENT NOISE 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 noticeable 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 4.13. These same settings were used in tandem for the both case (radio on and fan on at high speed).

Figure 4.13: Climate control settings for san ambient noise

4.8 METEOROLOGICAL CONDITIONS

Meteorological conditions were recorded before the experiment and at 1-h intervals during testing. If wind speed exceeded 11 mph 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 (Figure 4.14). Air temperature was recorded because temperature can influence sound propagation. Temperatures should be within ±7°F 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. Data were recorded using the worksheet provided in Appendix B (Section 6.5).

Figure 4.14: Instrument for measuring temperature, wind speed, and direction

4.9 VIDEO RECORDING

Two cameras (from a CountCam Duo) were used to capture video recordings of the data collection process (Figure 4.15). Cameras captured the test location for the total duration of the experiment. These videos can be observed and transcribed to determine background traffic volume during each strike event and to identify other confounding factors in sound recordings. The video is time stamped to enable identification of specific events. A sample video clip is shown in Figure 4.16, showing the van downstream of the sinusoidal test location.

Figure 4.15: Video camera setup

Figure 4.16: Video clip of van during experiment

4.10 VEHICLE TYPES EVALUATED

A van (Figure 4.17) and passenger car (Figure 4.18) were rented from Oregon State's motor pool and driven by licensed graduate students. 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 van was a 2015 Dodge Grand Caravan (license plate no. E2746636). The passenger car was a 2017 Ford Focus Hatchback (license plate number E269175).

Figure 4.17: Van striking the sinusoidal RS

Figure 4.18: Passenger car used in experiment

The heavy vehicle was a Volvo VHD dump truck (ODOT equipment number 15-0504, Figure 4.19), which was supplied by ODOT and driven by a CDL-licensed ODOT equipment operator from the Sandy Maintenance Division. The accelerometer was attached to the steering column using the magnetic base (Figure 4.20). The microphone was placed between the seats to allow the analyzer operator to sit in the cab, as shown in Figure 4.21.

Figure 4.19: Heavy vehicle used in experiment

Figure 4.20: Accelerometer placement in heavy vehicle

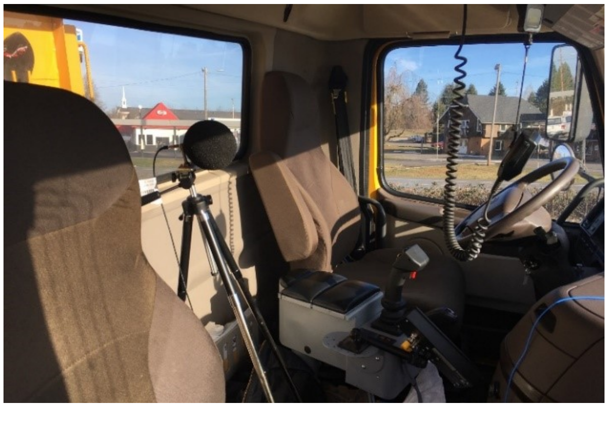


Figure 4.21: Microphone placement in heavy vehicle

4.11 MEASURING RUMBLE STRIP CHARACTERISTICS

Geometric characteristics of each RS type were measured and recorded to document the general properties of the tested RS. Various traditional RS designs with different mill shapes exist (Figure 4.22). Site B has the rounded RS pattern, which is the typical pattern used in Oregon.

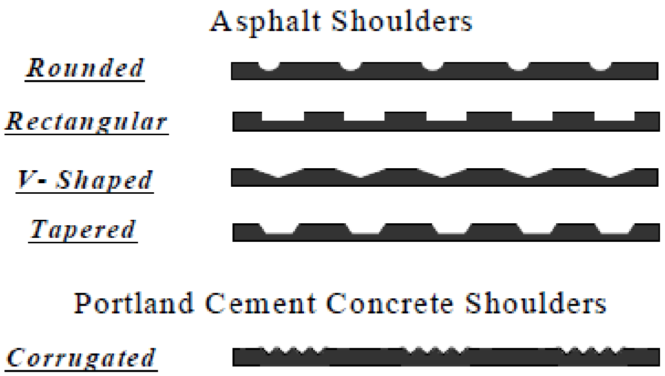


Figure 4.22: Rounded RS designs (Bucko and Khorashadi, 2001)

Specific measurements were made by following the framework established by Harwood in 1993, as shown in Figure 4.23 from Bucko and Khorashadi (2001).

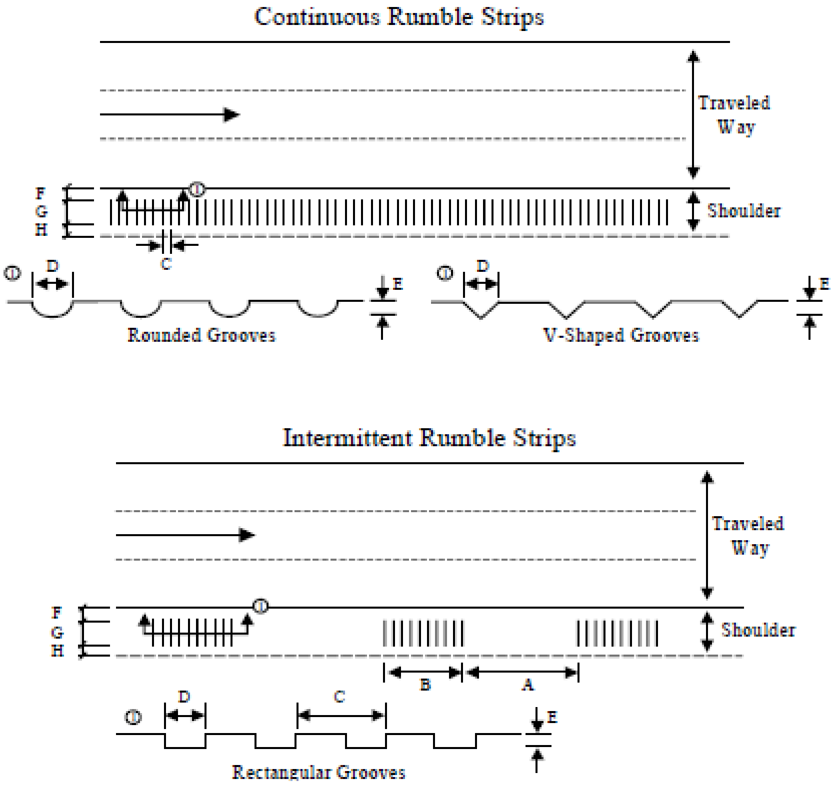


Figure 4.23: RS geometric characteristics (Bucko and Khorashadi, 2001)

Two depths of mill were measured for the sinusoidal RS: the depth at the trough of the wave, and the depth at the crest (Figure 4.24). Minimum and maximum values are based on the typical sinusoidal design drawings provided by ODOT (See Appendix E).

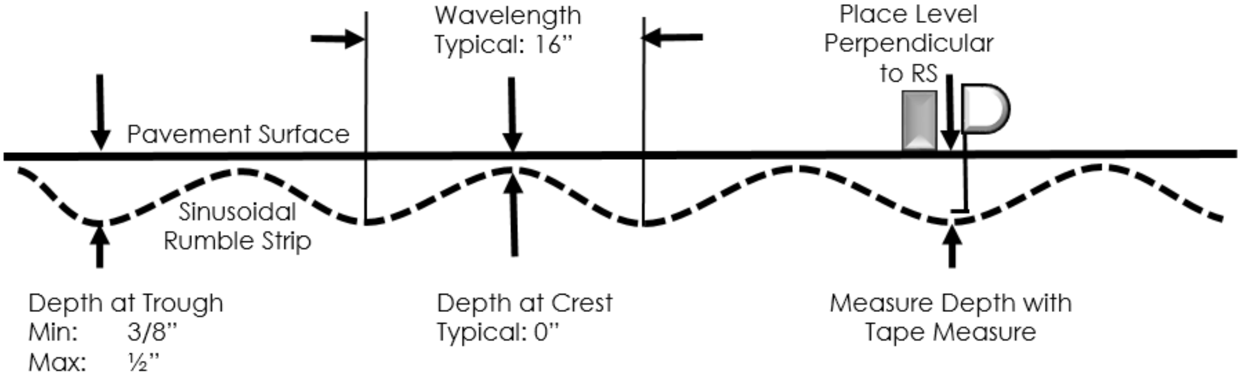


Figure 4.24: Depth measurements for sinusoidal RS

4.11.1 Measurement Procedure for Rumble Strip Characteristics

Three researchers measured the characteristics of the RS patterns (Figure 4.26). The first measured the characteristics using the tape measure, the second recorded the data, and the third stood upstream of the measurement site to serve as a lookout and alert drivers. The worksheet for RS characteristics is provided in Appendix B (Section 6.3). Measurements were quickly made during gaps in traffic to minimize the amount of time on the shoulder. Figure 4.25 shows a researcher measuring the depth of a mill, as described in Figure 4.24.

Figure 4.25: Measuring the depth of an individual mill

Figure 4.26: Measuring sinusoidal RS characteristics

4.12 RESEARCH TEAM ROLES

To ensure safety and efficient data collection, the following team roles were developed to prepare research assistants for the specific tasks during the experiment.

4.12.1 Equipment Set Up

- *Lead Researcher:* Led the team in equipment set up. Upon arriving at a test location, determined the exact location of the equipment during exterior measurement using the 100-ft measuring tape and surveyor's rod. Once the location was identified, focused on setting up the sound recording equipment. Calibrated equipment to ensure correct setup before the experiment began.

- *Research Assistant:* Assisted the lead researcher during equipment setup, especially in locating equipment. Set up atmospheric measurement tools and recorded initial conditions.

- *Vehicle Driver*: Inspected vehicles to ensure safe operations before experiments. Served as "lookout" during initial equipment setup and measurement of RS characteristics while the research team was near the shoulder of the highway.

- *Vehicle Assistant:* Assisted the lead researcher during equipment setup. Located the position for the beginning/end strike cones with the research assistant. Took photographs during setup to document the process.

4.12.2 Experimental Runs

- *Lead Researcher*: Team member in charge of safety and communication for all team members. Tracked experimental runs and led the team in equipment setup/tear down.

Answered questions from team and interfaced with public as necessary. Operated the sound analyzer equipment to ensure data quality.

- *Research Assistant:* Assisted research team as needed, primarily through tracking atmospheric data and recording vehicle speed on each pass using the radar gun. Operated the roadside 2-way radio. Took pictures during the experiment to track progress.

- *Vehicle Driver:* Operated various vehicles during experimental runs. To minimize distraction, were tasked only with operating the vehicle safely. Appropriate licenses were required for the driver (CDL for heavy vehicle).

- *Vehicle Assistant*: Provided an extra set of eyes for the driver to ensure that each RS strike began and ended at the correct location. Communicated with roadside team with a 2-way radio on the approach for each run. Communicated with lead researcher to confirm experimental runs.

4.12.3 Equipment Tear Down

- *Lead Researcher:* Led the research team during equipment tear down. Focused on placing clean and dry equipment back in storage bags.

- *Research Assistant:* Assisted lead research in collecting equipment.

- *Vehicle Driver*: Served as a “lookout” during equipment tear down while the research team was near the shoulder of the highway.

- *Vehicle Assistant:* Took photographs during tear down to document the process. Assisted lead researcher as necessary.

4.13 EXPERIMENTAL DATA COLLECTED

Sound levels generated by rounded and sinusoidal RS strikes were compared against baseline and no-strike conditions across 3 vehicle classes (passenger car, van, and heavy vehicle), to determine the influence of vehicle type on sound generation and to document the effectiveness of RS type on alerting the driver of impending roadway departure. Starting at the sinusoidal RS location, exterior noise was measured for the baseline and strike conditions. Sound measurement equipment was then reconfigured to capture noise and vibration within the vehicle. After interior measurements at the sinusoidal RS location, the research team moved to the rounded RS location and repeated interior measurements. Equipment was then set up on the roadside for exterior measurements for the rounded RS. A detailed schedule is provided in Appendix B (Section 6.2).

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 114 measurements were collected (breakdown by factor group in Table 4.3). Data were collected by team members on the worksheet provided in Appendix B (Section 6.4).

Table 4.3: Number of Measurements for each Factor Group

VEHICLE TYPE	RUMBLE STRIP TYPE	CONDITION	EXTERIOR	INTERIOR
Passenger Car	Sinusoidal	Baseline	3	12
		Strike	3	13
	Rounded	Baseline	3	13
		Strike	3	12
Van	Sinusoidal	Baseline	3	3
		Strike	3	4
	Rounded	Baseline	4	3
		Strike	5	3
Heavy Vehicle	Sinusoidal	Baseline	3	3
		Strike	3	3
	Rounded	Baseline	3	3
		Strike	3	3
		Subtotal	39	75
		Total	114	

4.14 PERFORMANCE MEASURES

Performance measures for this study were chosen based on previous research and standards. Terhaar's framework plots the 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.

Figure 4.27 shows how the sinusoidal RS strike frequencies were compared to the rounded RS strikes. For both cases, the baseline condition was subtracted from the strike condition (Equations 4-1 and 4-2), to obtain the amount of additional noise that was generated from the strike when all other variables were held constant for one time step. A time-series comparison allowed for a larger sample size for each pass event. The weighted average of the difference was used as the final performance measure. Equation 4-3 shows how the dB levels were converted to Pascals (a linear scale). The weighted average dB level based on multiple measurements of vehicle passes in Pascals is shown in Equation 4-4.

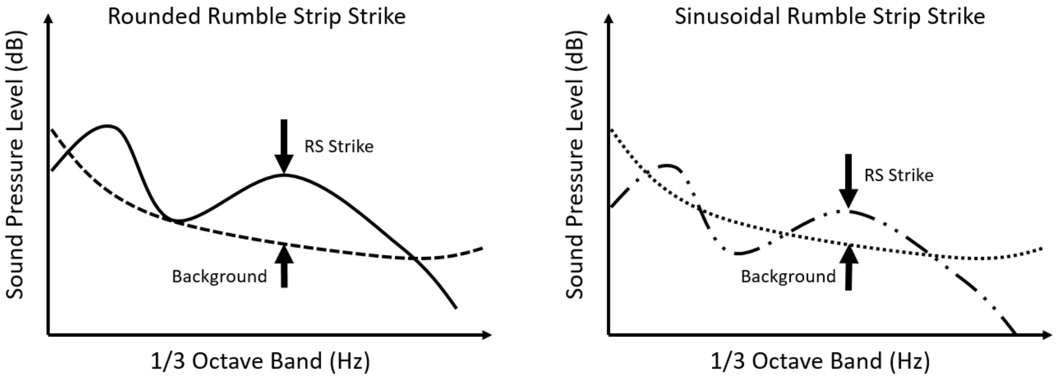


Figure 4.27: Framework for sinusoidal noise reduction during exterior sound measurement

$$\Delta\ \boldsymbol{Rounded\ dB = RS\ Strike\ dB - Background\ dB} \tag{4-1}$$

$$\Delta\ \boldsymbol{Sinusoidal\ dB = RS\ Strike\ dB - Background\ dB} \tag{4-2}$$

$$\frac{Pa_{Observed}}{Pa_{Reference}} = 10^{\frac{dB_{Observed}}{10}} \tag{4-3}$$

$$Avg\ dB = 10 * \log_{10}\left[\sum \frac{Pa_{Observed}}{Pa_{Reference_1}} + \frac{Pa_{Observed}}{Pa_{Reference_2}} + \frac{Pa_{Observed}}{Pa_{Reference_3}}\right] / 3 \tag{4-4}$$

For interior sound measurements, NCHRP 641 recommends a 6-dBA increase in noise threshold for alerting drivers that they are leaving the roadway (Torbic, 2009). This alert threshold was calculated by adding 6 dBA to the background noise level across all frequencies (Figure 4-28). A similar comparison between the baseline and strike conditions was calculated using subtraction (Equation 4-5 and 4-6). Delta, representing the audible alert that is generated by the RS strike, was compared to the recommended alert levels established in NCHRP 641 and by FHWA.

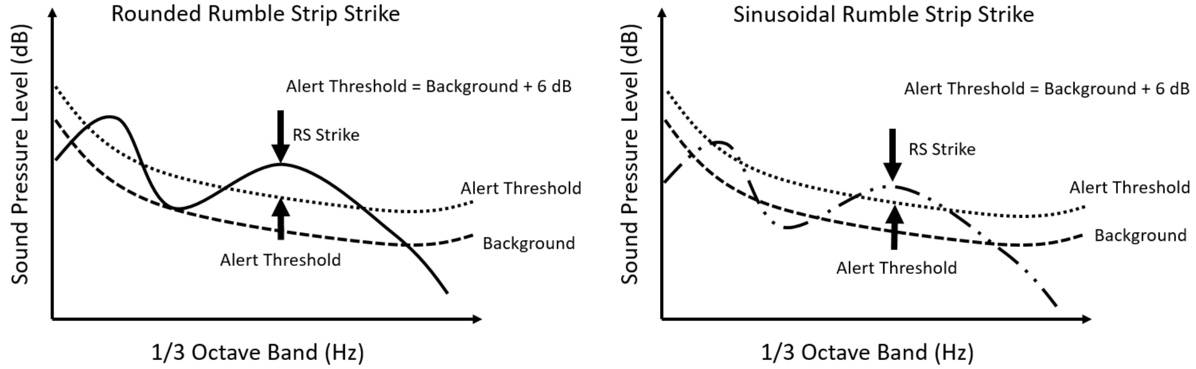


Figure 4.28: Framework for percent reduction in driver alert

Δertt n k for recommended alert levels established in

(4-5)

Δ-Sinusoidal Alert dB = RS Strike dB – Alert Threshold dB

(4-6)

Interior haptic feedback was evaluated based on the procedure developed by Dulaski and Noyce (2016). Acceleration for each axis (X, Y, and Z) was resolved into a vector using Equation 4-7 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 conditions were compared against the strike condition, to estimate the change in vibration due to the strike for the rounded and sinusoidal RS, using equations similar to Equation 1-2. The amplitude and frequency of steering column vibrations were expected to increase with the strikes. ANOVA was used to evaluate the difference between the strike and background condition to determine the statistical significance of the data.

$$\left|\overrightarrow{\boldsymbol{Resultant}}\right| = \sqrt{\boldsymbol{x}^2 + \boldsymbol{y}^2 + \boldsymbol{z}^2}$$

(4-7)

4.15 SUMMARY

The experimental procedure was based on previous research and industry standards (AASHTO, 2013; SAE International, 2000), as discussed in *Interim Report #2*. Noise generated from rounded and sinusoidal RS strikes were compared to background noise for 3 vehicle types (passenger car, van, and heavy vehicle). Interior and exterior sounds were measured with a signal analyzer connected to microphones. Haptic (vibrational) feedback was measured in the vehicle interior by a triaxial accelerometer connected to a signal analyzer. A total of 114 measurements were captured across all factor groups. Sinusoidal and rounded RS sites were described, and detailed driving directions were provided to the drivers. Geometric characteristics of the RS were carefully measured. Video cameras recorded ambient traffic, and meteorological conditions were measured throughout the experiment to ensure consistent data. Roles of team members were outlined before, during, and after the experiment. Ambient noises from the radio and fan within the passenger car were measured to advance the current state of practice in RS evaluation.

5.0 RESULTS

This chapter presents results of the field data collection experiment. Section 5.1 describes the RS characteristics. Section 5.2 provides context for the meteorological conditions during data collection. Sections 5.3 and 5.4 describe results of sound measurements collected inside the vehicle and at the roadside, respectively. Section 5.5 considers the influence of additional noise sources within the vehicle. Section 5.6 deals with the vibration observed internal to the vehicle.

5.1 RUMBLE STRIP CHARACTERISTICS

Average field geometric characteristics of the study sites are shown in Table 5.1. Large characteristics, such as the total length of the RS cluster (B), were measured to the nearest foot. Smaller characteristics, such as the mill depth (E), were measured to the nearest 1/16 in. Mill depth (E) was measured several times at different mills due to slight variances in milling, and the average of these measurements is presented.

Figure 5.1 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.

Table 5.1: Field Measurements of RS Geometry

DIMENSION*	DESCRIPTION	SITE A: SINUSOIDAL	SITE B: ROUNDED
A	Gap between RS clusters	10 ft	10 ft
B	Length of RS cluster	28 ft	31 ft
C	Wavelength	16 in	12 in
D	Length of individual RS mill	16 in	8 in
E-1	Depth of RS mill at trough (see Figure 4-24)	3/8 in	7/16 in
E-2	Depth of RS mill at crest	1/16 in	0 in
F	Distance between edge of lane line and inside edge of RS mill	12 in	6 in
G	Width of RS mill	14 in	9.5 in
H	Distance between outside edge of RS mill and edge of pavement	7 ft	8 ft

**Dimension values match characteristics described in Figure 4.23.*

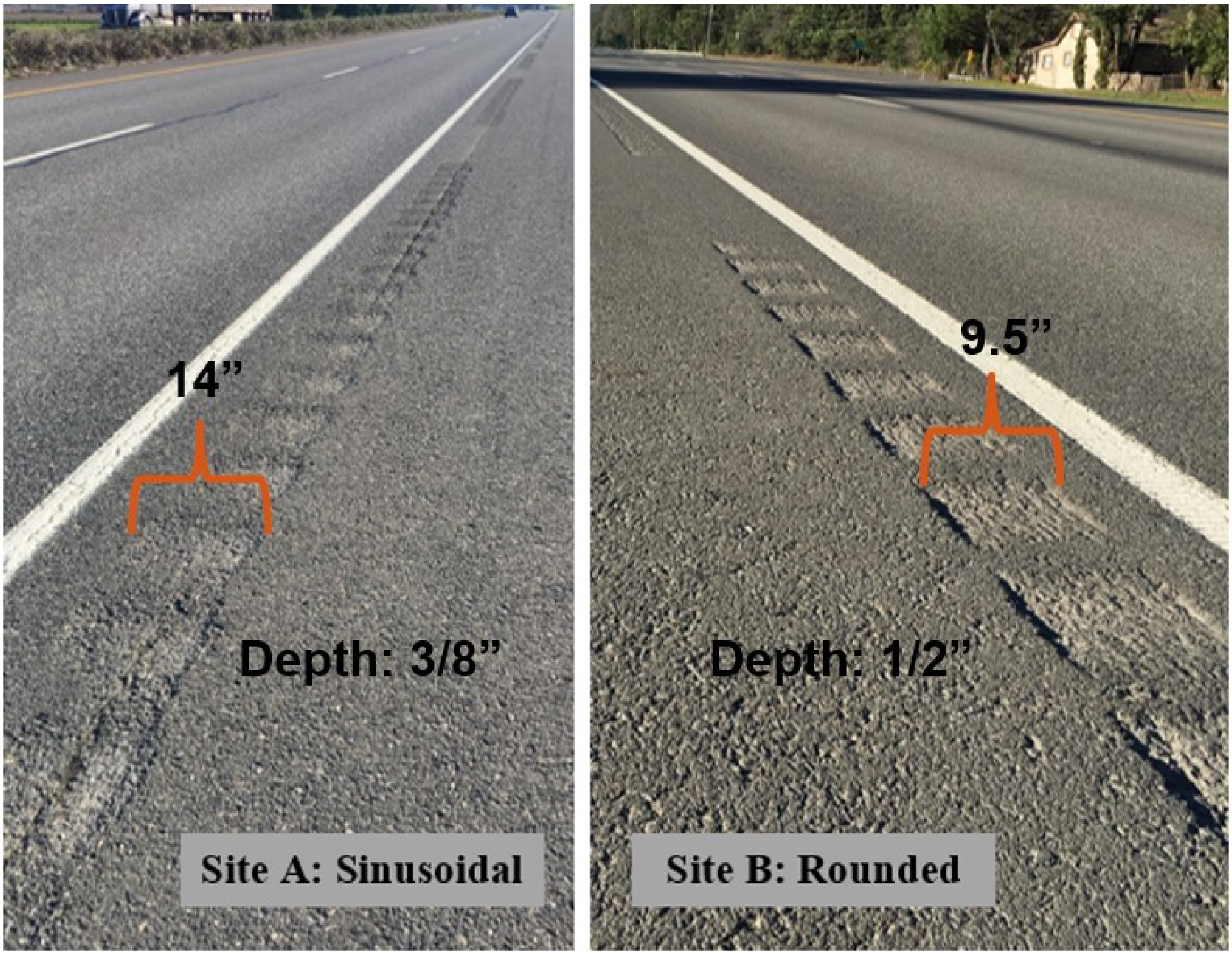


Figure 5.1: Visual comparison of RS designs

5.2 METEOROLOGICAL CONDITIONS

Average values for meteorological conditions at each site during data collection are shown in Table 5.2. 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 5.2: Measurements of Meteorological Conditions

DATE	SITE	AVERAGE WIND SPEED (MPH)	AVERAGE WIND DIRECTION	AVERAGE TEMPERATURE (˚F)	SKY CONDITION
12/7/17	A	9.5	114˚	50	Clear
12/7/17	B	10.7*	156˚	45	Clear
12/12/17	A	3	74˚	38	Scattered Clouds
12/12/17	B	5.6	89˚	42	Scattered Clouds
12/13/17	A	2.4	90˚	41	Clear
12/13/17	B	4.9	88˚	37	Clear

**Windspeeds sometimes exceeded 11 mph threshold, necessitating 3 additional runs.*

5.3 EXTERIOR NOISE MEASUREMENT

A t-test was used to identify differences between the 25- and 50-ft 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 25 than at 50 ft; 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. The research team discussed the data with Dr. Yue Zhang at Oregon State University, who has worked on developing theoretical designs for RS for ODOT (Agreement #31167 – Project 1). Dr. Zhang's simulation indicated that RS should generate a signal at ~80 Hz, which is consistent with the literature. Figure 5.2 compares exterior measurements for the passenger car during the rounded RS strike condition (in green) and the baseline condition (in blue). 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 in the strike condition.

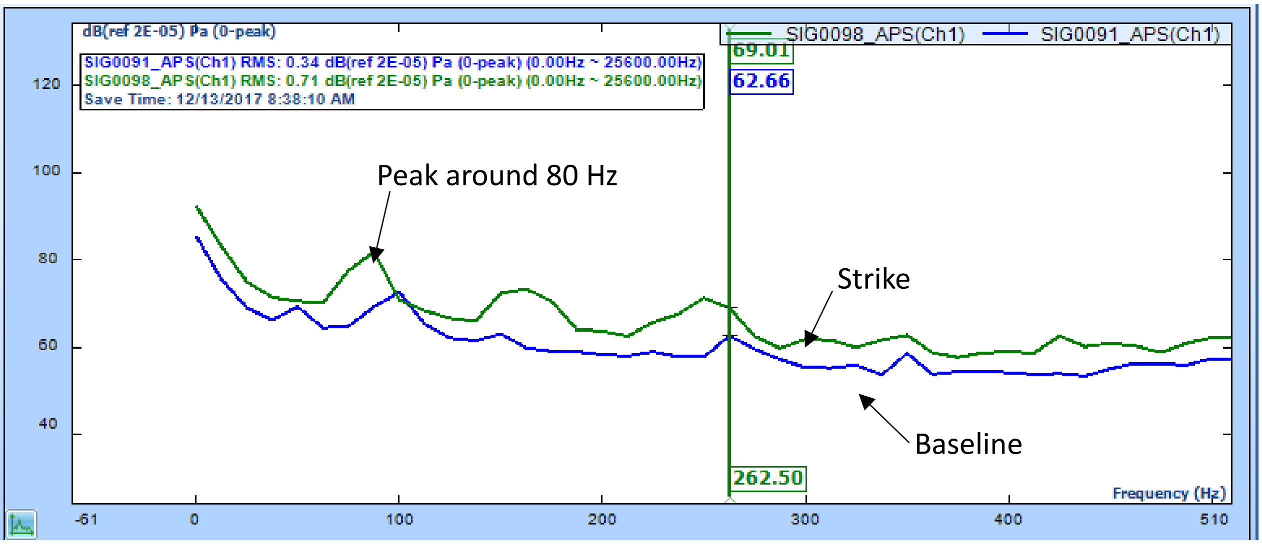


Figure 5.2: Exterior sound measurement frequency comparison

A dB histogram was analyzed to compare conditions for the same exterior passenger car measurement, without the influence of time. Figure 5.3 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 green, and the baseline condition for the passenger car is in blue. 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 (blue) 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).

To understand the noise generation of a RS strike, imagine the complex interaction of all the sounds on the roadside. Some noises are generated by vehicles, tires, engines, radios, aerodynamics or braking (especially from heavy vehicles). Other noises are produced by in-situ conditions, like wind, wildlife, or other non-transportation related human activities. Generally, most of these noises are similar between the baseline and strike condition. The RS strike introduces a new distinctive sound into the mix, that has a very specific frequency (the specific dB increase), as well as increasing the overall intensity of vehicle noises (particularly the tire noise). Tire noise is one of the largest contributors of roadside noise, especially at higher speeds, and as the RS strike intensifies this noise is the result of repeatedly hammering the tire into the RS mill.

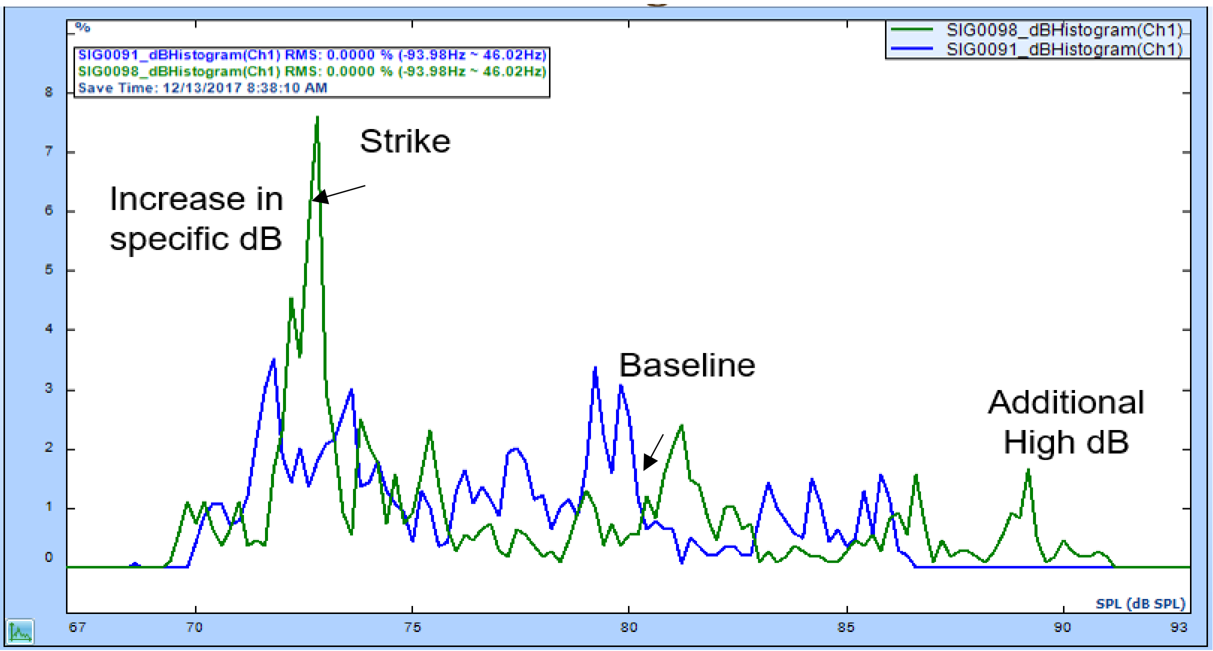


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Figure 5.3: Interior vibration measurement diagram

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. A sample was trimmed from the total recording, starting 1.5 s before and after the peak intensity. These 3-s measurements were used for analysis.

As dBA is a logarithmic scale, a weighted average was used to average the 3 strike and 3 baseline conditions for each factor group across the time series. Figure 5.4 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 factor group, 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.

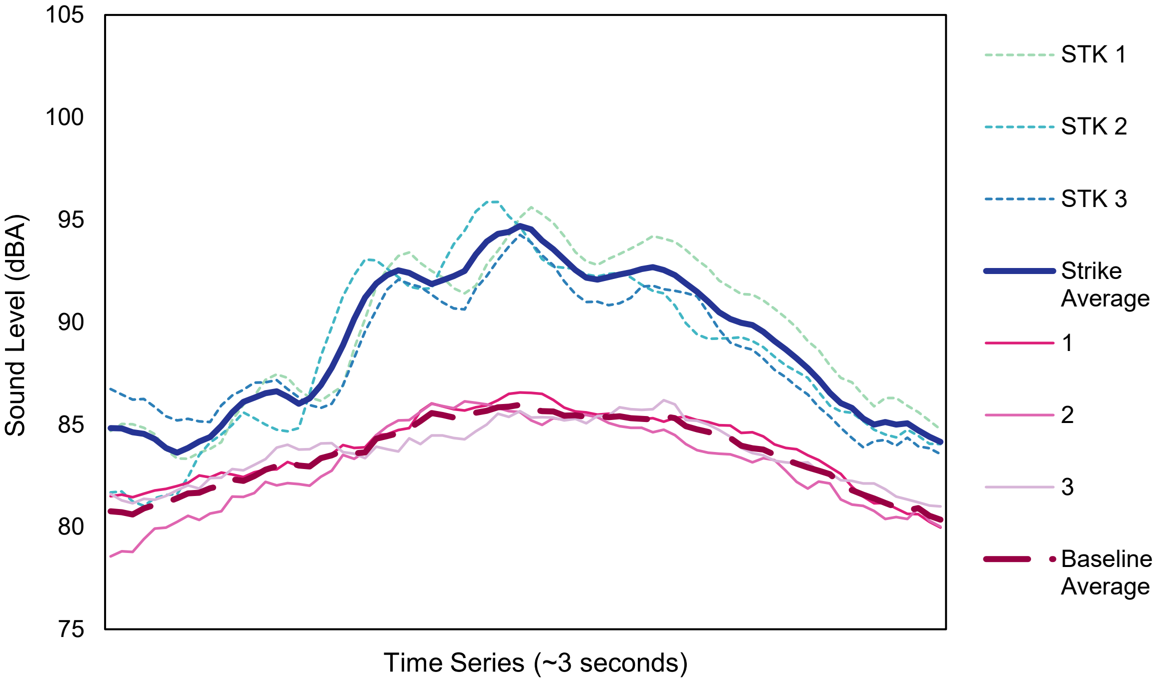

Figure 5.4: Exterior sound measurement from passenger car striking the rounded RS

The procedure was repeated for each factor group. Figure 5.5 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 noticeable (<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. Additional graphs about exterior measurements for the van and heavy vehicle can be found in Appendix C.

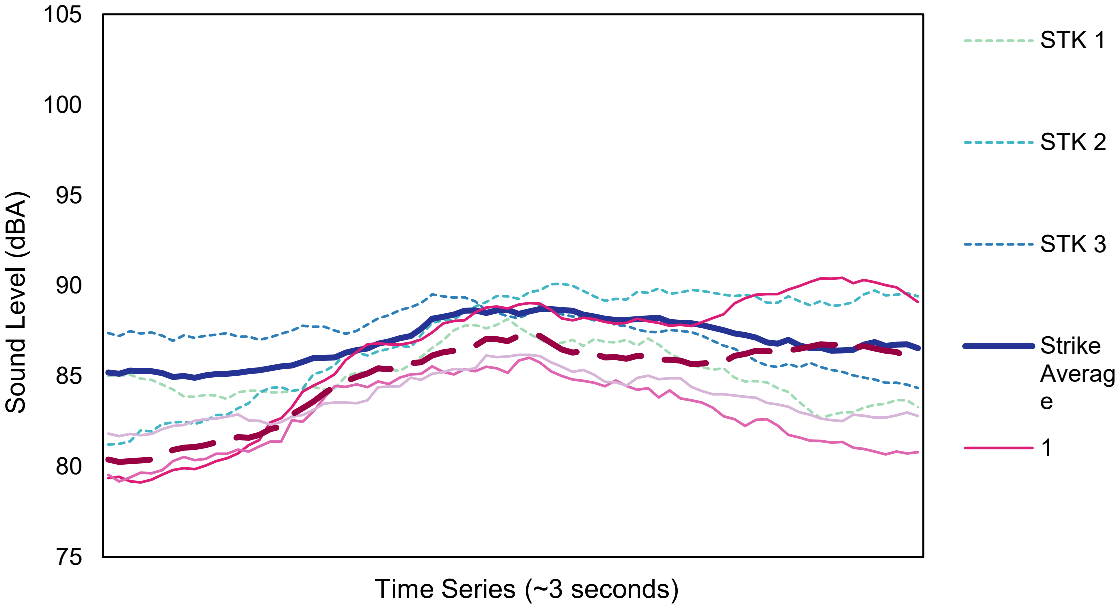

Figure 5.5: Exterior sound measurements for the passenger car striking the sinusoidal RS

5.3.1 Statistical Analysis

Data were analyzed in the Minitab statistical software package (version 18). All tests were performed at a 95% confidence level. Table 5-3 shows average measurements for the baseline and strike conditions for each factor group. Baseline measurements were generally within the barely noticeable range (<3 dBA) for each vehicle type, indicating similar pavement, weather, and ambient noise conditions between the two locations.

Table 5.3: Average dBA Magnitudes for the Factor Groups

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

Figure 5.6 shows boxplots for differences between strike and baseline conditions, indicating the increase in road noise, for each factor group. 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 noticeable (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 noticeable 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. A decrease in 6 dBA is comparable to doubling the physical distance between a sound and its observer. A difference of 3 dBA between noise sources is the minimum amount needed for a typical human to perceive a difference in sound intensity.

Road noise (tires, engines, aerodynamics) is considered a line source, as the noise is created along a linear road. Rumble strip noise is considered a point source, as the noise is created at a distinctive time and location. For each doubling of distance between the source of a sound and the observer, sound intensity decreases by 6 dB for point sources or 3 dB for line sources (FHWA, 2015). The decay rates of the baseline (line) and strike (point) noise levels are explored graphically in Appendix D.

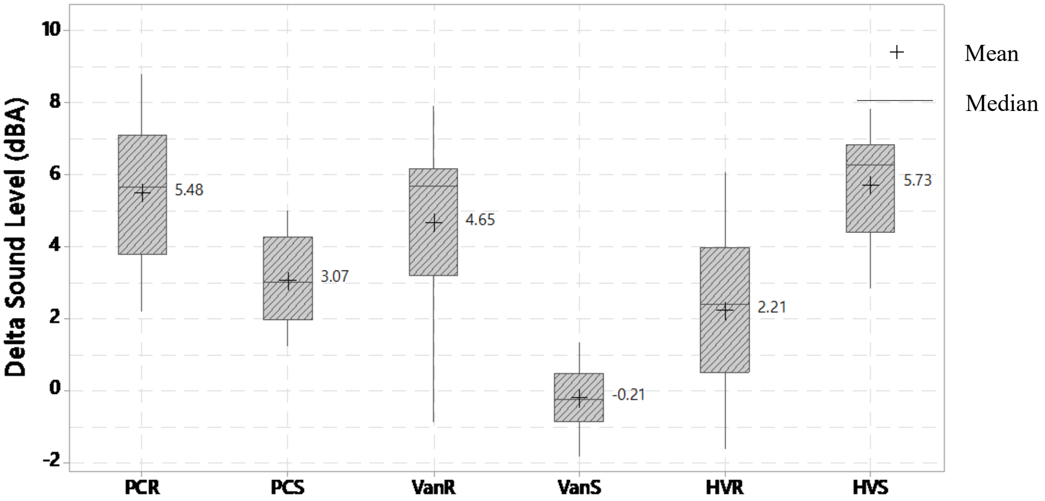

Figure 5.6: Boxplots by vehicle and RS type for exterior delta sound measurements. PS, passenger car; HV, heavy vehicle; R, rounded RS; S, sinusoidal RS.

Two-way ANOVA was performed on the strike/baseline exterior sound measurement deltas to determine whether average sound differed between the 2 RS types (rounded and sinusoidal) or between the 3 vehicle types (passenger car, van, and heavy vehicle). There was a statistically significant difference for RS type ($p < 0.001$) and between the means for at least 1 vehicle type ($p < 0.001$). To identify where differences between group means occurred, a Tukey HSD post hoc pairwise comparison test was performed, and main effect plots were used (Figure 5.7). 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 ~1.25 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 ($p < 0.0001$).

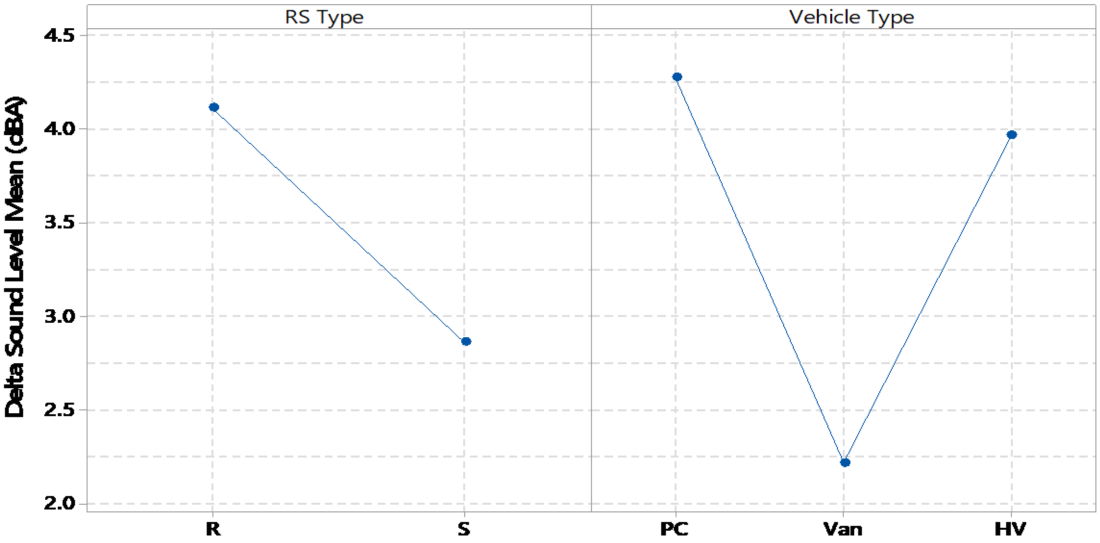

Figure 5.7: Main effect factors of exterior sound measurement

There was a statistically significant interaction between the combined effects of RS type and vehicle type on sound measurement ($p < 0.001$). Figure 5.8 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).

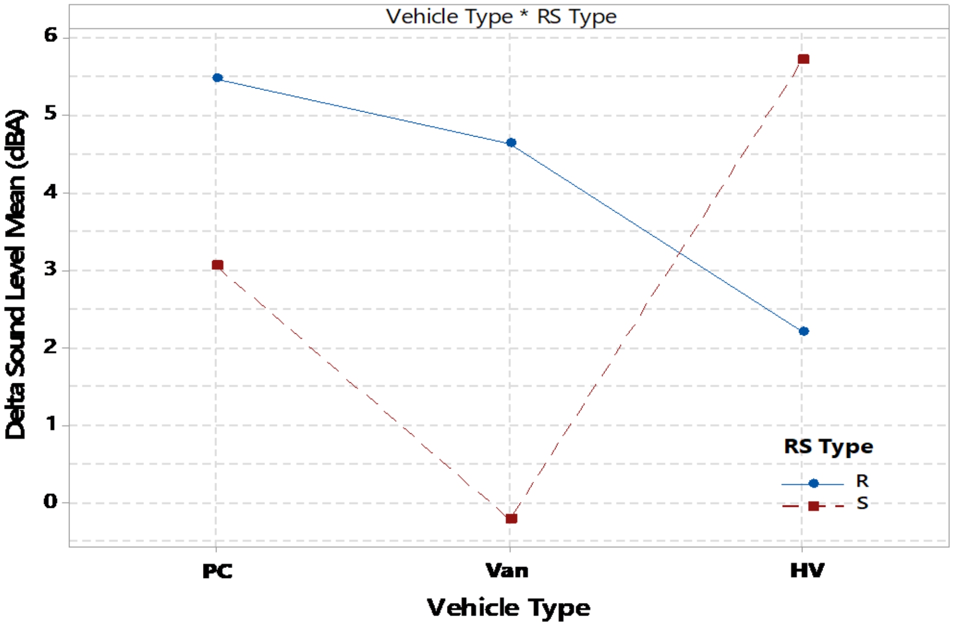

Figure 5.8: Factor interactions for exterior sound measurement

5.4 INTERIOR SOUND MEASUREMENT

Interior sound levels were measured by a procedure similar to that for the exterior sound. Because the sound analyzer was onboard the vehicle for the entire test run, a longer 10-s time interval was used for interior analysis. Data when the vehicle temporarily left the RS during the test run were removed, resulting in sound levels only during RS strikes. As shown in Figure 5.9, the baseline average interior sound level of the passenger car striking the rounded RS was 100.4 dBA, compared to a strike average of 111.8 dBA. The difference (11.4 dBA) is the audible alert that the RS generated inside the vehicle, which more than doubled the interior noise (i.e. >10 dBA).

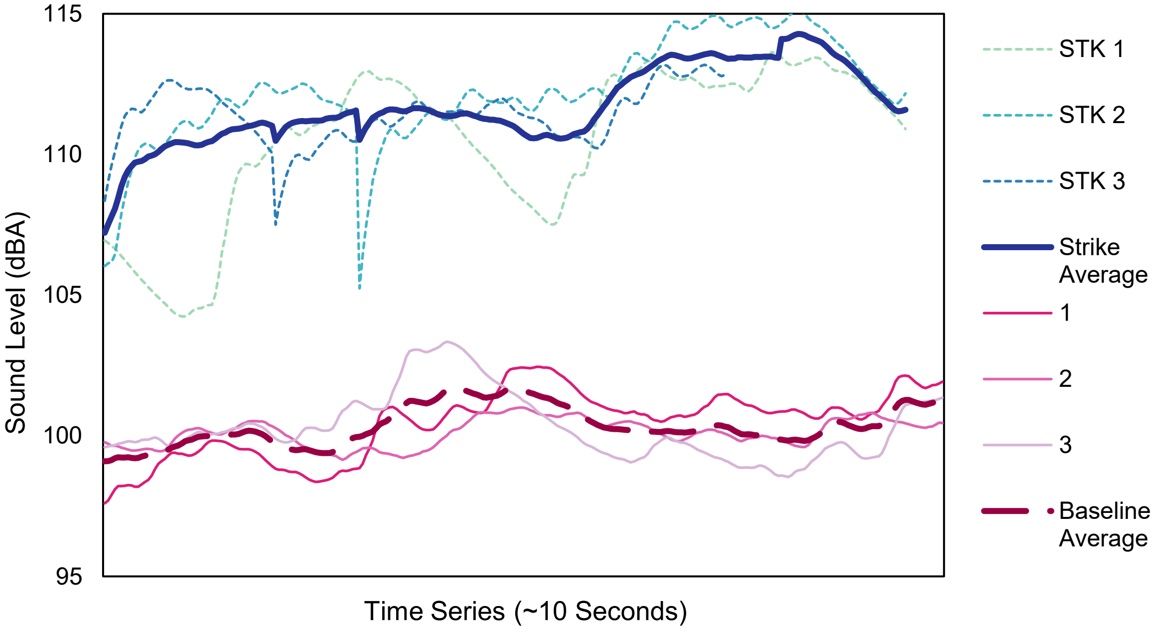

Figure 5.9: Interior sound measurement for the passenger car striking the rounded RS

Figure 5.10 shows interior sound measurements for the baseline and strike conditions of the passenger car with the sinusoidal RS. Baseline average was 99.0 dBA and strike average was 104.8 dBA, for a clearly noticeable (>5 dBA) difference of 5.8 dBA. This alert level is slightly less than the 6 dB recommended by NCHRP 641 but above the 5-dBA level recommended by the FHWA. Thus, the sinusoidal RS generated a clearly noticeable alert under ideal conditions. Appendix C provides additional graphs for interior measurements of the van and heavy vehicle.

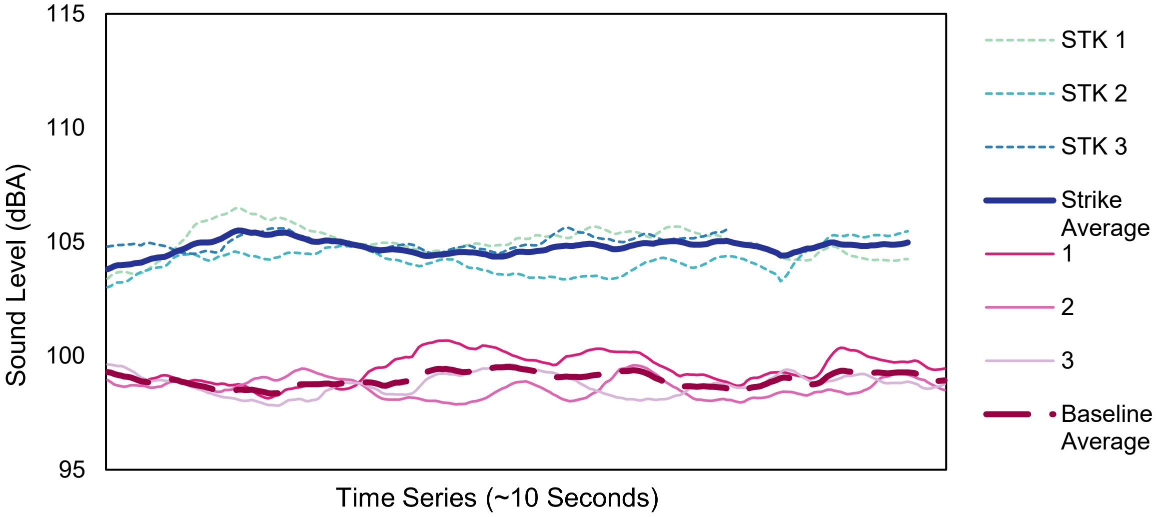

Figure 5.10: Interior sound measurement for the passenger car striking the sinusoidal RS

5.4.1 Statistical Analysis

Figure 5.11 shows the differences between the baseline and strike conditions using the same naming conventions as described in Figure 5.6. 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, the FHWA suggests that 5 dBA is sufficient to alert the driver. The heavy vehicle had a imperceptible alert (<1 dBA) with the rounded RS, but the sinusoidal RS alert was above the 6 dBA guideline. This improvement indicates that the extra width associated with the sinusoidal RS created an additional alert for heavy vehicles with dual tires, extending the effectiveness of the RS to that vehicle type.

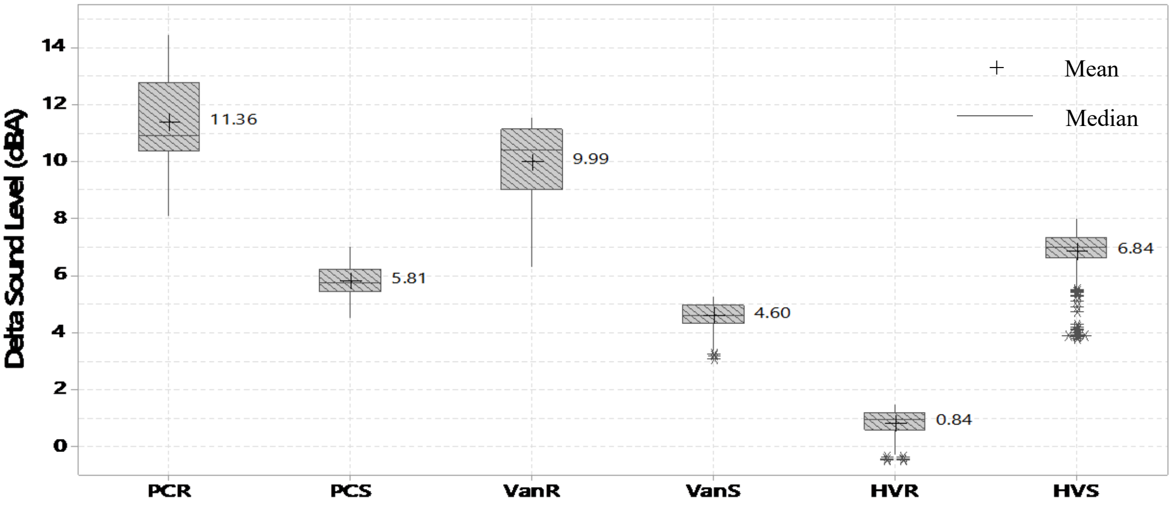

Figure 5.11: Boxplots by vehicle and RS type for interior delta sound measurements

Similarly to the exterior measurement, a 2-way ANOVA test was performed on the strike/baseline delta sound measurements to determine whether the average interior sound differed between the 2 RS types (rounded and sinusoidal) or between the 3 vehicle types (passenger car, van, and heavy vehicle). There was a statistically significant difference for RS type ($p < 0.001$) and between the means for at least 1 vehicle type ($p < 0.001$). To identify where differences between group means occurred, a Tukey HSD post hoc pairwise comparison test was performed, and main effect plots were used (Figure 5.12). Differences were observed between specific factors with all other factors held constant. Regarding RS type, the noise for the rounded RS was ~2 dBA higher than the noise for the sinusoidal RS. For vehicle type, both the passenger car and van generated more noise than the heavy vehicle; the passenger car produced the greatest noise ($p < 0.0001$).

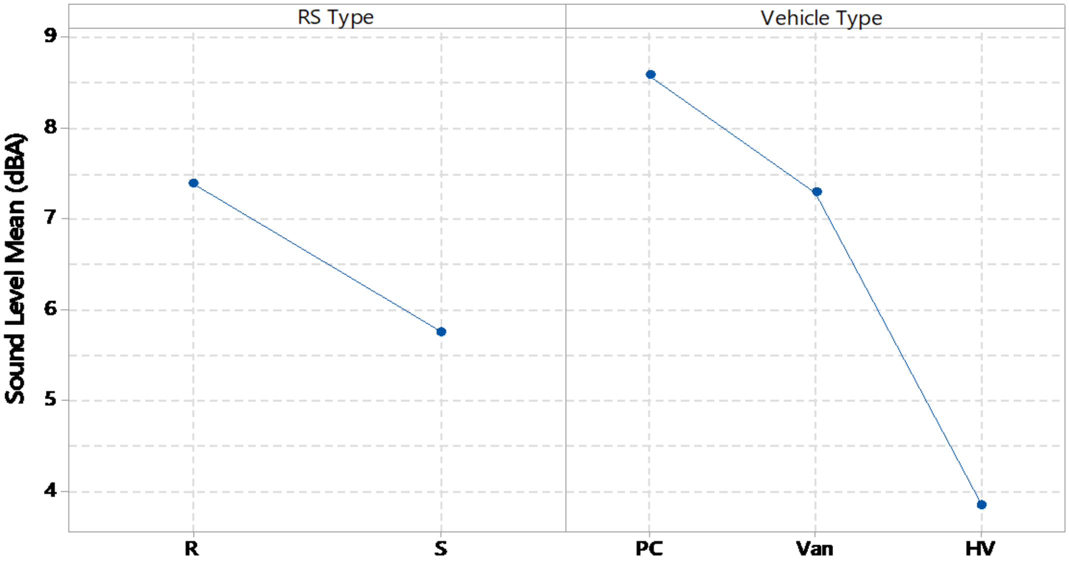

Figure 5.12: Main effect factors of interior sound measurement

There was a statistically significant interaction between the combined effects of RS type and vehicle type on sound measurement ($p < 0.001$). Figure 5-13 plots the delta mean sound at each level of RS and vehicle type. Pairwise comparisons showed that the heavy vehicle generated greater amounts of noise when striking the sinusoidal RS than striking the rounded RS ($p < 0.001$). The passenger car and van generated significantly less amounts of noise when striking the sinusoidal RS than the rounded RS ($p < 0.001$ for both).

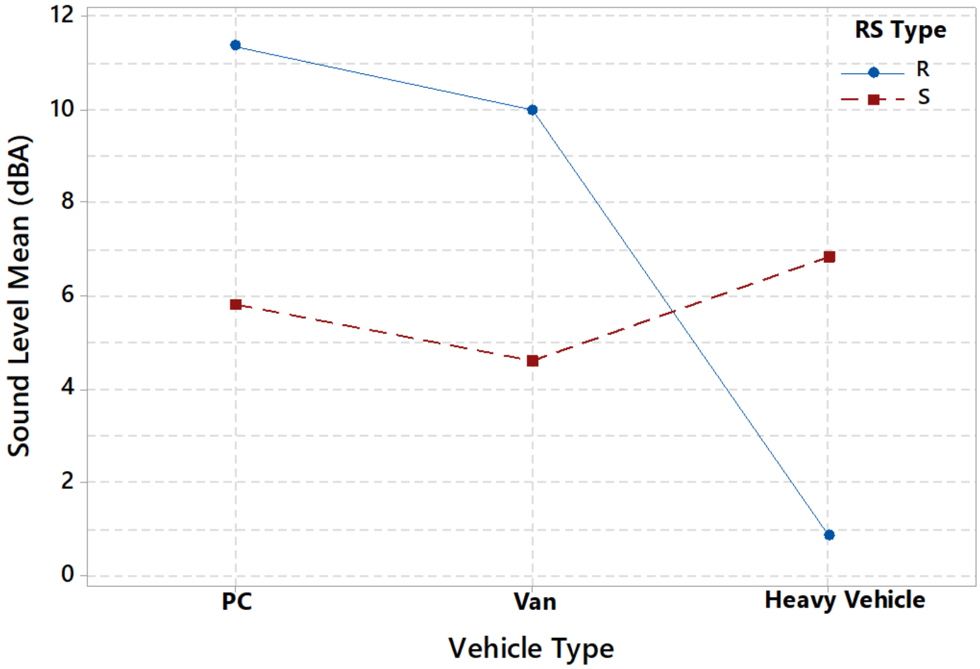

Figure 5.13: Interaction comparison of interior sound measurement

5.5 INTERIOR NOISE MEASUREMENTS: AMBIENT NOISE LEVELS

Additional interior measurements were recorded for the passenger car to observe the influence of ambient in-vehicle noise sources on detectability of RS strikes. Three conditions were recorded: 1) radio on, 2) fan (of the climate control system) on, and 3) both radio and fan on simultaneously. Average values for these measurements and the delta between the baseline and strike conditions are shown in Table 5.4.

Table 5-4: Ambient interior noise measurements for the passenger car

RS Type	Condition	Baseline	Radio	Fan	Both
Rounded	Baseline	100.4	100.6	99.4	101.6
	Strike	111.7	111.8	113.8	113.7
	Alert	11.3	11.2	14.4	12.1
Sinusoidal	Baseline	99.0	101.0	100.6	100.9
	Strike	104.8	104.5	104.8	104.1
	Alert	5.8	3.5	4.2	3.2

Figure 5.14 shows a boxplot of sound levels for the 3 scenarios over the baseline condition. Interior noise generated by the rounded RS strike was higher when the fan or fan and radio were on than for the baseline or when only the radio was on (2 dBA). On the other hand, the alert generated by the sinusoidal RS strike was reduced when any ambient noise condition was on compared to the baseline (<2 dBA).

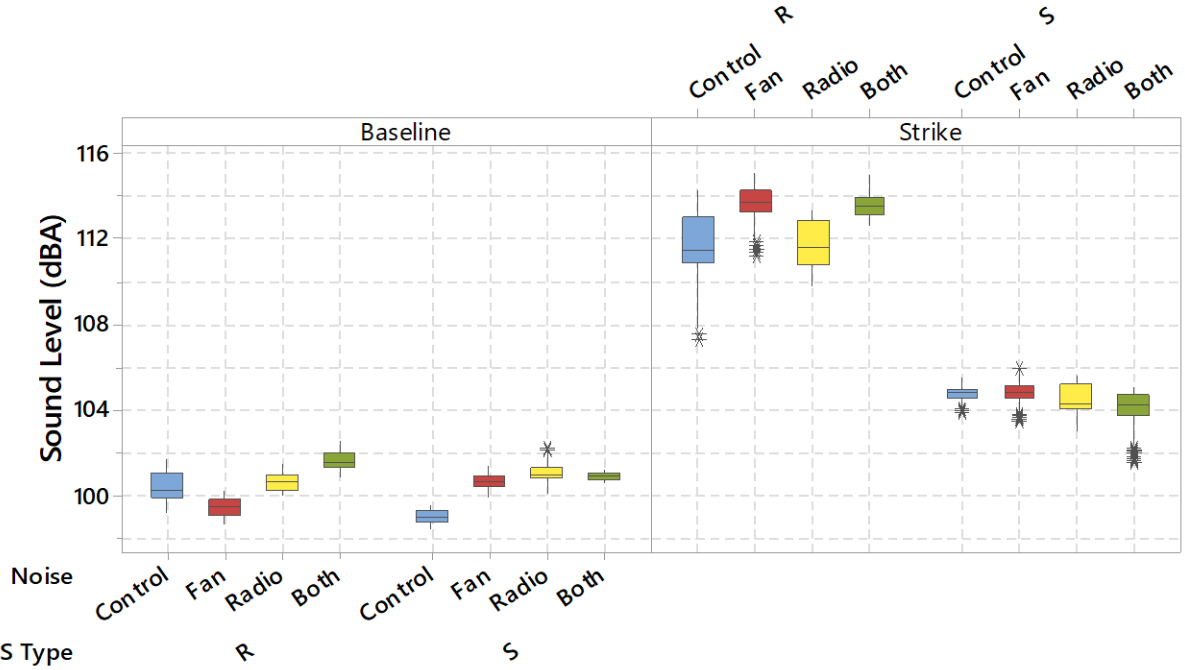

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Figure 5.14: Boxplot comparison of ambient interior sound measurements

5.5.1 Statistical Analysis

A 3-way ANOVA test was performed on sound measurements to determine whether the average sound levels differed between the baseline and strike conditions, the 2 RS types (rounded and sinusoidal), or the 4 ambient noise types (baseline, fan, radio, and both). Statistically significant differences were found for RS type ($p < 0.001$) and strike condition ($p < 0.001$). A statistically significant difference between means was found for at least 1 ambient noise 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 5.15, in which differences are observed between specific factors with all other factors held constant. The strike condition showed an increase of ~8 dBA between the baseline and strike conditions for all strikes (sinusoidal and rounded and combined) ($p < 0.001$). For RS type, the noise for the rounded RS was ~4 dBA higher than the noise of the sinusoidal RS ($p < 0.001$). For the ambient noise type, operating both the fan and radio had the highest noise level, followed by the fan, the radio, and the baseline condition ($p < 0.001$). These findings support the hypothesis that ambient noise factors will increase the interior baseline noise, thereby reducing the magnitude of the alert generated from a RS strike.

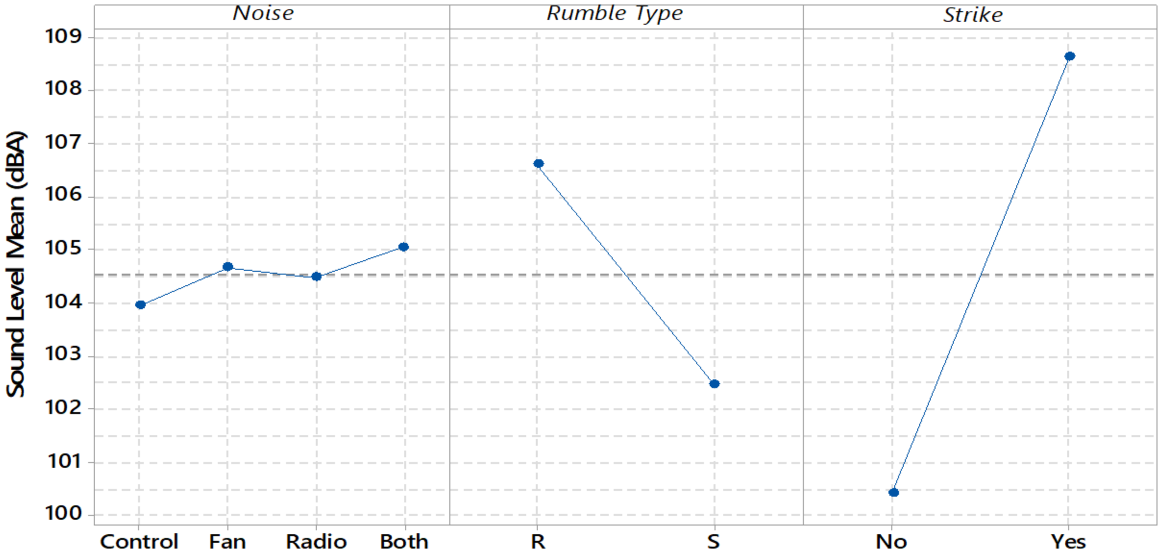

Figure 5.15: Main effect factors of ambient interior sound measurements

In terms of interaction factors, there was a statistically significant interaction between the combined effects of RS type with the strike condition ($p < 0.001$) and the ambient noise type on the sound measurements ($p < 0.001$), and between strike condition and ambient noise type ($p < 0.001$). Figure 5-16 plots the mean noise at each level of each factor. Results of pairwise comparisons showed that, regardless of strike condition, all ambient noise types generated significantly lower amounts of noise with the sinusoidal RS than with the rounded RS ($p < 0.001$). With the RS factor held constant, the strike condition generated higher noise for all ambient noise types than the no-strike condition ($p < 0.001$). Finally, regardless of ambient noise, the passenger car striking the sinusoidal and rounded RS generated significantly higher noise than the no-strike condition ($p < 0.001$).

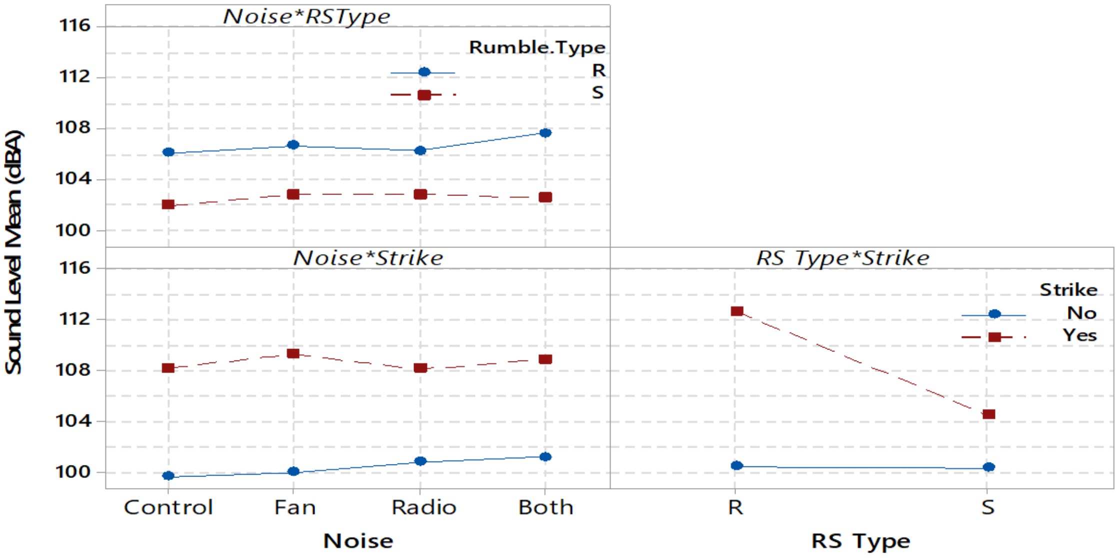

Figure 5.16: Two-way interaction plots for interior vehicle measurements

5.6 INTERIOR VIBRATION MEASUREMENT

Morioka and Griffin 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 noticeable. For sound measurement, 3 dB is typically associated with a noticeable change in sound level. A similar noticeable change for vibration (in terms of acceleration) is around 0.011 m/s^2 for vibrations ~80 Hz. Vibration measurements from this study are reported in terms of *g*, the English unit for acceleration (1 $g = 9.81\ m/s^2$). Conversion of this vibration threshold to *g*'s is shown in Equation 5-1.

$$\mathbf{0.011\,\frac{m}{sec^2} * \frac{1\,g}{9.81\ {}^{m}/_{sec^2}} = 0.00112\,g}$$

(5-1)

Figure 5.17 shows the raw accelerometer data for the heavy vehicle during the baseline rounded RS condition. The 3 accelerometer vectors are shown, with magnitudes of ~0.0002 *g*. Vibration was generally consistent because the vehicle travelled along at a steady speed on smooth pavement. Positive and negative values represent the direction of the acceleration, as the vibrations oscillate back and forth.

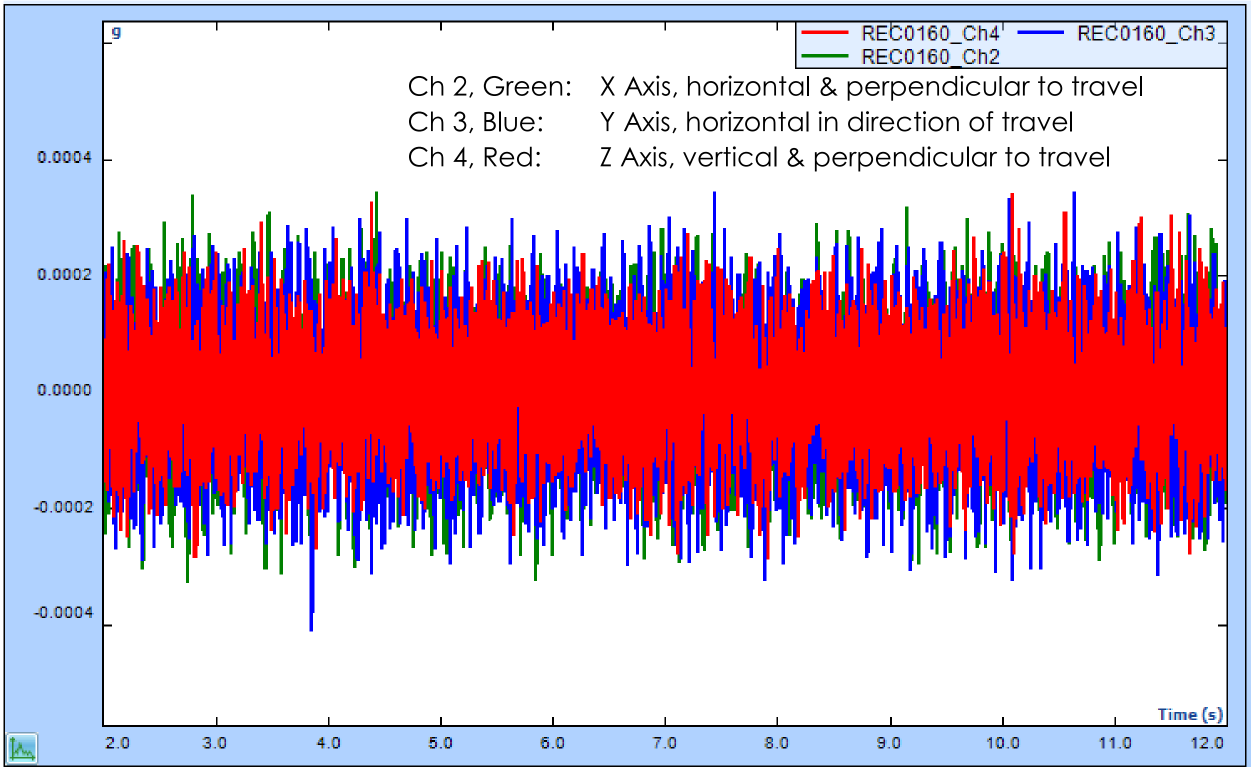

Figure 5.17: Baseline rounded RS raw accelerometer data for the heavy vehicle

Figure 5.18 shows similar data for the strike condition on the rounded RS for the heavy vehicle. Groups of much higher acceleration levels reached levels between 0.003 and 0.005, depending on the axis. These high acceleration events related to the vehicle striking the RS groups. Low acceleration levels between the groups related to the gaps between RS groups. Between the 12- and 14-s marks, the heavy vehicle was only partially striking the rounded RS.

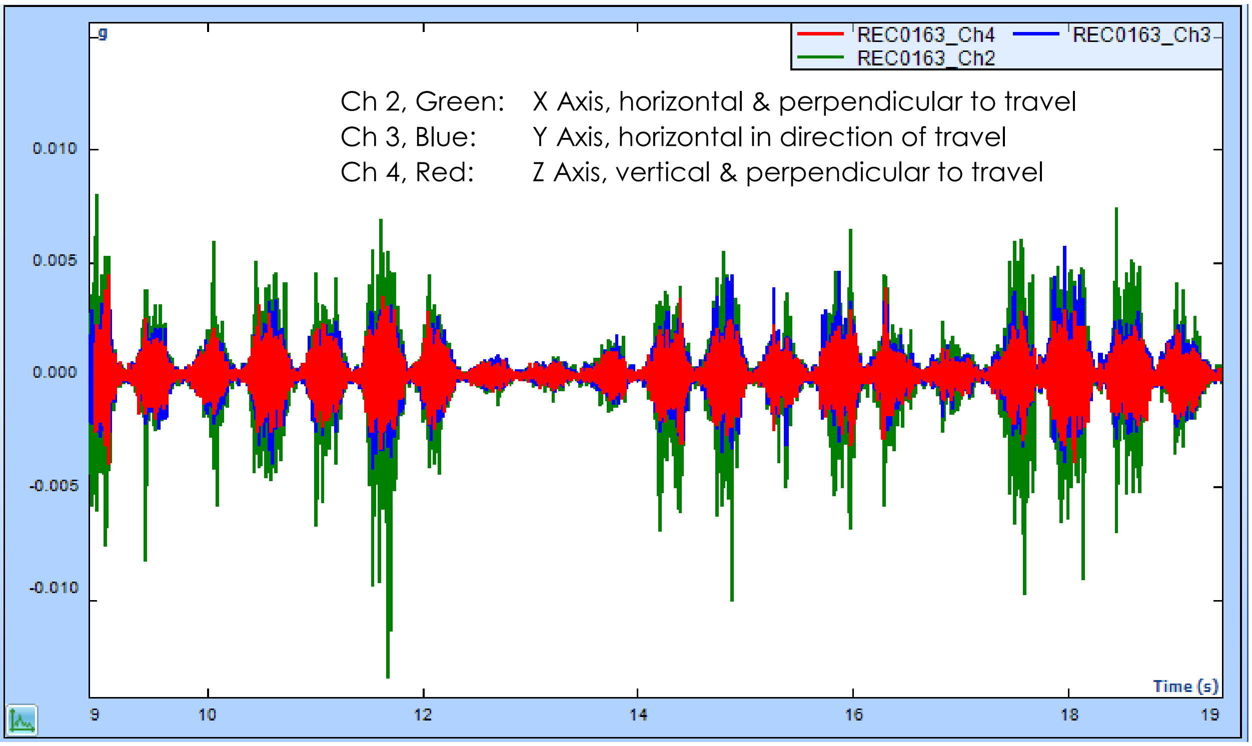

Figure 5.18: Raw accelerometer data for the heavy vehicle during the rounded RS strike

Equation 5-2 calculates the difference in vibration level. Equation 5-3 shows the calculation for the observed vibration levels relative to the perception threshold for vibration. Therefore, the strike-induced vibration in the steering column is readily perceptible to typical human hands.

$$\boldsymbol{Strike\ Vibration\ Level - \ Baseline\ Vibration\ Level = \Delta\ Vibration\ Level}$$

(5-2)

$$\mathbf{0.003}\ \boldsymbol{g} - \ \mathbf{0.0002}\ \boldsymbol{g} = \ \mathbf{0.0028}\ \boldsymbol{g}\ > \ \mathbf{0.00112}\ \boldsymbol{g\ Preception\ Threshold}$$

(5-3)

Figure 5.19 shows average values for the resulting vibration acceleration for the heavy vehicle for the baseline and strike conditions on the rounded RS. Average vibration values were lower than the individual strike vibration levels, because the passes were somewhat out of phase with one another. For example, a high RS vibration level was averaged with a lower vibration level when the vehicle was between RS clusters. Nonetheless, the vibration level often exceeded the perception threshold of ~0.001 g, alerting the driver that the vehicle was striking the RS.

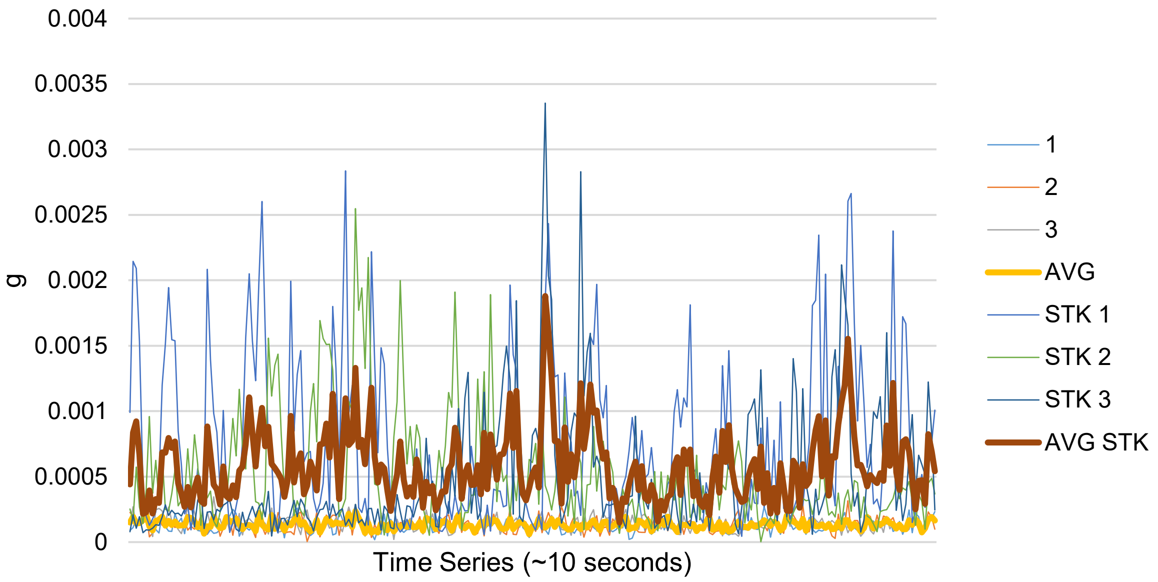

Figure 5.19: Vibration measurement for the heavy vehicle striking the rounded RS

Figure 5.20 shows the average vibration measurements for the heavy vehicle in contact with the sinusoidal RS. As in the rounded RS case, a central tendency bias was evident because the individual measurements were out of phase. Nonetheless, the average strike values often exceeded the 0.001 *g* perception threshold. Additional figures are provided in Appendix C for the passenger car and heavy vehicle.

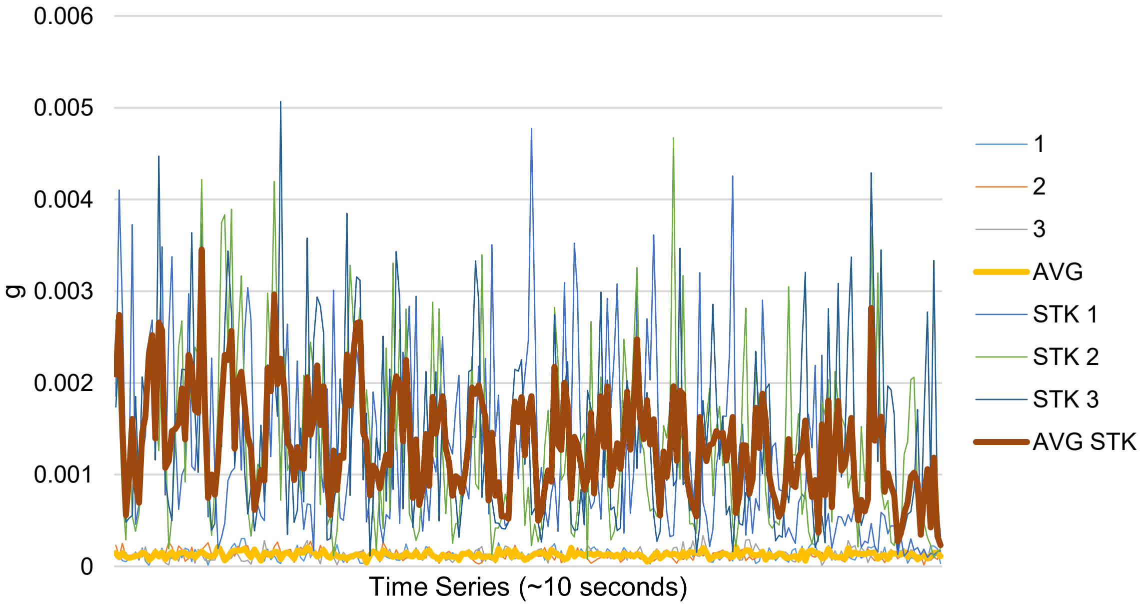

Figure 5.20: Vibration measurements for the heavy vehicle striking the sinusoidal RS

Figure 5.22 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. In the following graphs, a change of 1 milli-*g* represents the perception threshold. 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.

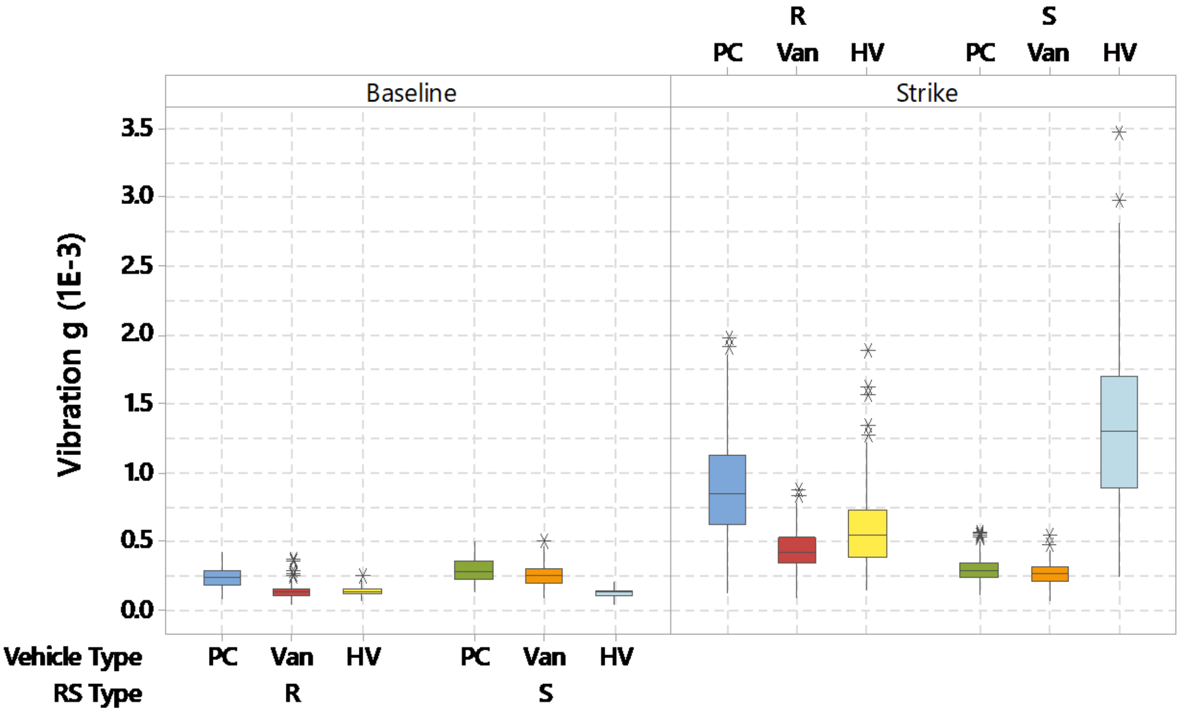

Figure 5.21: Boxplot comparison of vibration measurements.

5.6.1 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 5.23, 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, 2018). The low differences for the van observations were likely due to individual vehicle suspension characteristics.

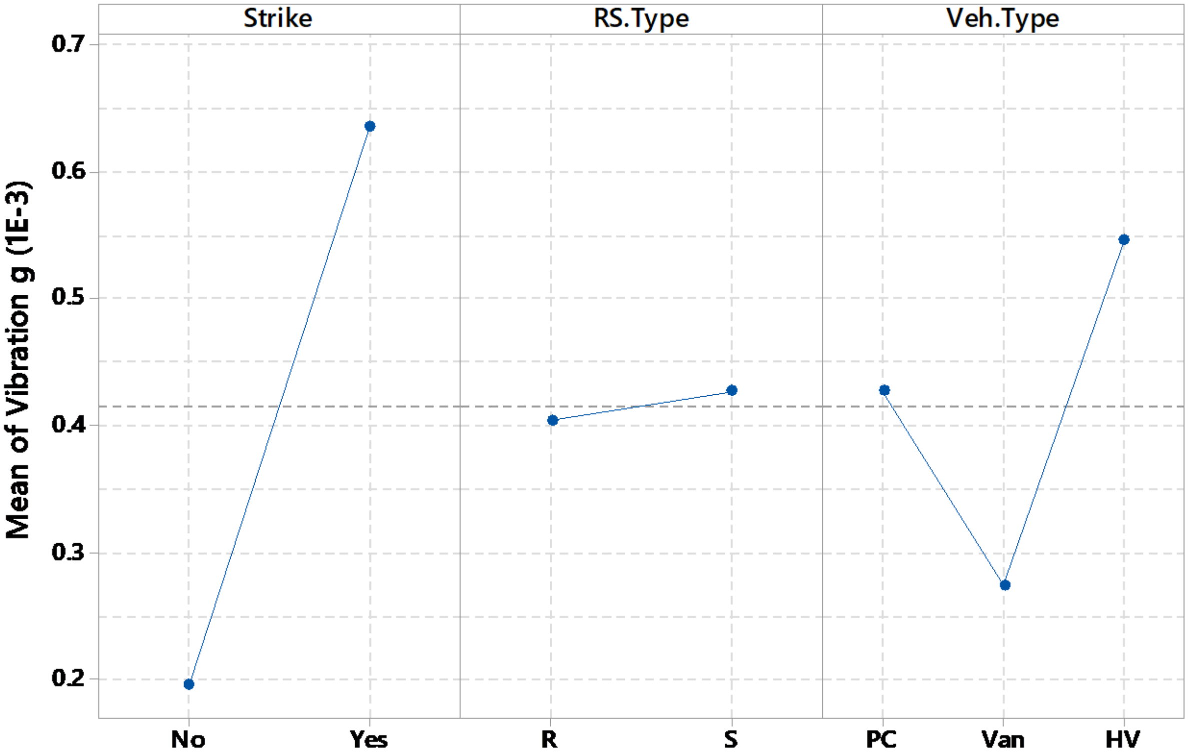

Figure 5.22: Main effect factors of interior vibration measurements

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 5-24 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 ($p > 0.05$).

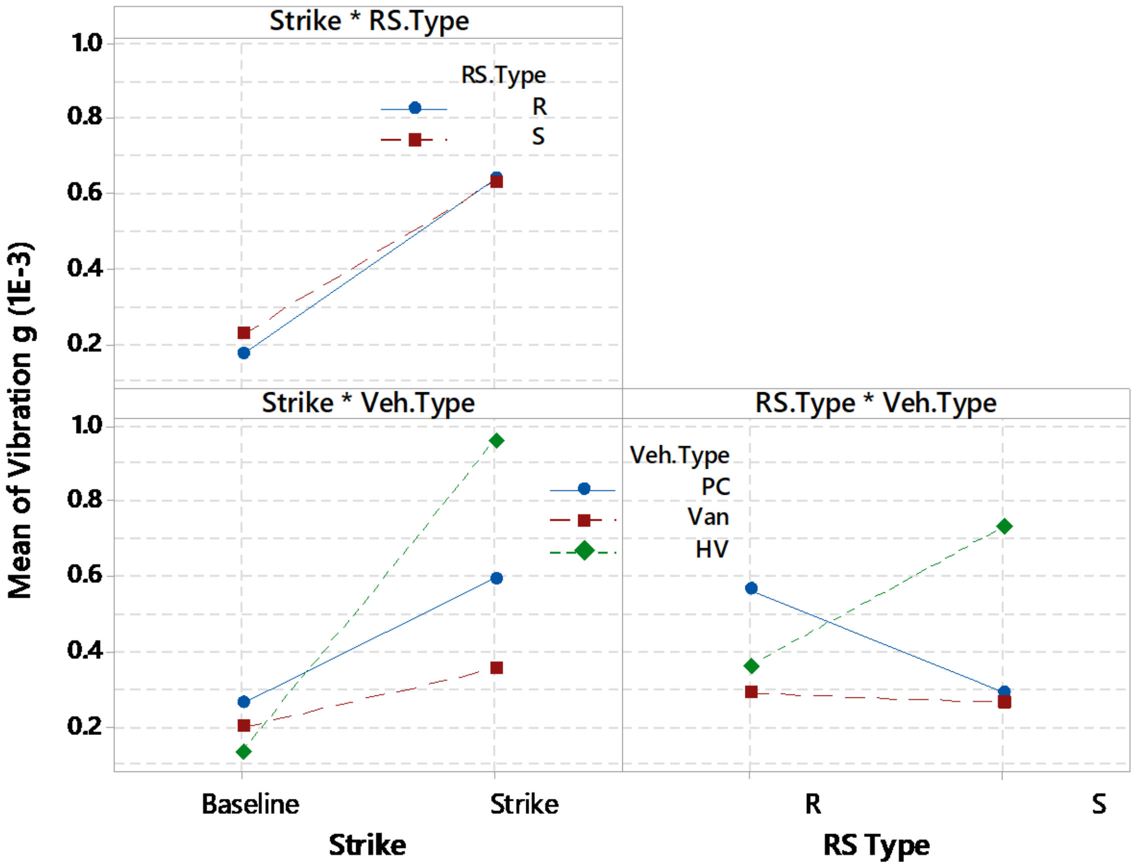

Figure 5.23: Two-way interaction plot of mean vibration

6.0 CONCLUSIONS AND RECOMMENDATIONS

This research study compared interior and exterior 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, the AASHTO SIP Method, and SAE Standard J1477. 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. 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. A decrease in 6 dBA is comparable to doubling the physical distance between a sound and its observer. A difference of 3 dBA between noise sources is the minimum amount needed for a typical human to perceive a difference in sound intensity.

From the results, the research team developed 5 key conclusions concerning the use of sinusoidal RS as an alternative to traditional rounded RS.

1. Roadside noise levels are a combination of vehicle noises from the tire, engine, and aerodynamics, as well as other environmental noises like 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. For the passenger car or van, the exterior noise measured at 25 and 50 feet 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 **noticeable** 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 lesser intensity; 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.

2. Additional interior noise 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. 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. In addition to these measurements concerning the highest noise levels generated, the experiments found that the specific frequency of the RS strike was also present. The RS strike increased the total sound level in the vehicle interior and introduced a specific new noise (the rumble) to the driver.

3. 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 noticeable (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.

4. 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.

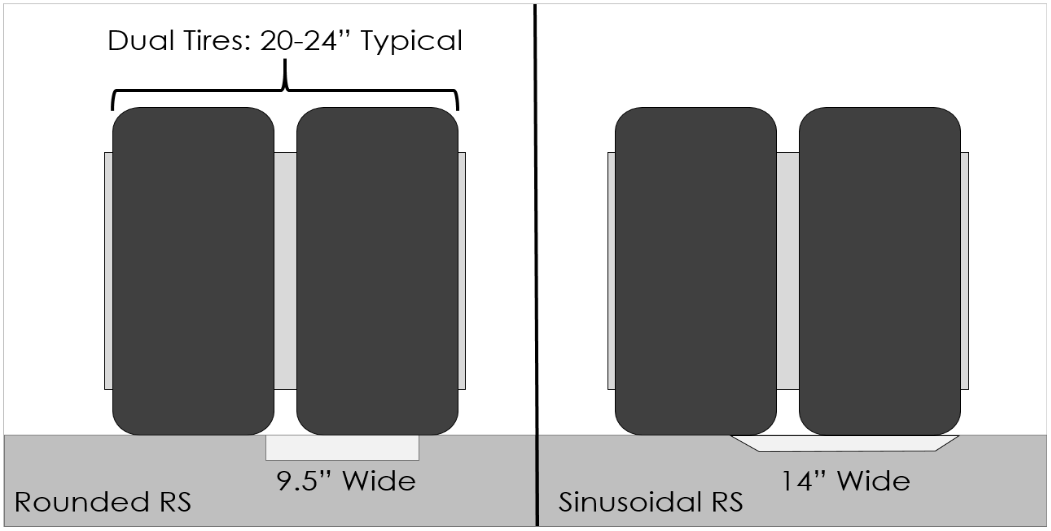

Figure 6.1: Bridging effect for dual-tire heavy vehicles

5. 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 date, 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.

6. Road noise (tires, engines, aerodynamics) is considered a line source, as the noise is created along a linear road. Rumble strip noise is considered a point source, as the noise is created at a distinctive time and location. For each doubling of distance between the source of a sound and the observer, sound intensity decreases by 6 dB for point sources or 3 dB for line sources (FHWA, 2015). Point sources decrease intensity quicker, resulting in a location where the background noise is more noticeable than the strike as shown graphically in Appendix D. The distance from the road where the baseline (line) and strike (point) noise levels are equal in intensity is shown in Table 6.1.

Table 6.1: Distance from Roadside where the Baseline and Strike Sound Intensities are Equal

Vehicle	RS Type	distance from roadside (feet)*
Passenger Car	sinusoidal	69
	rounded	170
van	sinusoidal	39
	rounded	120
Heavy Vehicle	sinusoidal	150
	rounded	85

* Distances are estimated. Actual sound propagation depends on terrain, vegetation, structures, weather conditions, etc.

6.1 LIMITATIONS OF THE RESEARCH

The primary limitation of this research study is the number of vehicles that were evaluated to determine the effectiveness of the sinusoidal RS. 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. The vehicles with the highest US market share in 2018 were not evaluated in this study and should be added to a study in the future. Interior characteristics also influence how much of the sound propagates into the cab of the vehicle for the driver alert. Only one speed was tested for all factor groups: the posted highway speed limit of 55 mph. Increasing the speed has been shown to increase the noise generated in a

RS strike, but the consistency of that relationship is unclear. From a fundamental physics perspective, the amount of kinetic energy in the vehicle is proportional to the velocity squared. At higher speeds, much more energy is involved, resulting in a louder sound being generated from a strike.

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.

Only 2 RS designs were tested (Section 5.1). 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, like 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 would provide a less disruptive alternative for cyclists.

6.2 RECOMMENDATION FOR PRACTICE

The following recommendations could be included in the ODOT *Traffic-Roadway Bulletin TR17-03(B)* regarding the policy on longitudinal RS, dated 09/01/2017. In the section regarding projects on “Rural Freeways and Divided Highways” (page 3), the Exceptions section could be expanded to include information generated from this study, specifically that:

- Option 1. The specification for measurements to a residence or campground could be clarified. It is not clear how the 600 and 200 feet are intended to be measured, either along the roadway length or directly to the residence or campground. A figure similar to Figure 4.2 from this technical report could be created.

- Mitigation option B could be revised to read: Installing sinusoidal rumble strips instead of rounded designs to minimize the generation of roadside noise.

In the Definitions section, add a definition of sinusoidal RS. A suggested definition is:

- Sinusoidal Rumble Strip – A milled rumble strip that follows a sinusoidal pattern, with a shallower depth of cut. These designs have been shown to decrease the amount of roadside noise generated from a strike, while providing a sufficient alert to warn the driver that they are leaving the lane of travel.

Finally, in the References section, a citation to this technical report could be added:

- Hurwitz, D., Horne, D., Jashami, H., Monsere, C. & Kothuri, S. (2018) SPR 800: Quantifying the performance to low-noise rumble strips (ODOT), Salem, OR, 95p.

Based on this research, several updates are suggested for the next update of the *ODOT Noise Manual* (Reference July 2011). In Section 7.1.2 "Highway Design," sinusoidal RS could be added to the list of highway design characteristics that can be modified to mitigate noise concerns. Sinusoidal RS reduce the roadside noise generated by RS strikes by as much as 5 dBA. In areas where noise is of particular concern, such as residential areas, sinusoidal RS could be used as an effective crash countermeasure without generating as much noise impact.

In Section 7.3 "Feasibility Criteria for Abatement," sinusoidal RS have been shown to decrease roadside noise by 5 dBA per strike. While this document generally discusses longer duration noise studies, switching to the sinusoidal design could offer an improvement for areas with known complaints about RS noise, while meeting FHWA criteria for abatement. In Section 7.8 "Federal Funding for Abatement," sinusoidal RS should be included in the list of alternatives. From 23 CFR Section 772.15 Federal participation, Item C2 does not specifically include or restrict use of RS countermeasures. This additional funding mechanism could be used to increase sinusoidal RS use, especially as a replacement for traditional rounded designs.

In Appendix D "Noise Measurement Methodology and Field Data Record," Figure 4.2 from this report could be added to item G, regarding noise measurements. This figure was developed for the site-selection process based on the AASHTO SIP Method and would provide a clear and concise framework of site section for other sound evaluations.

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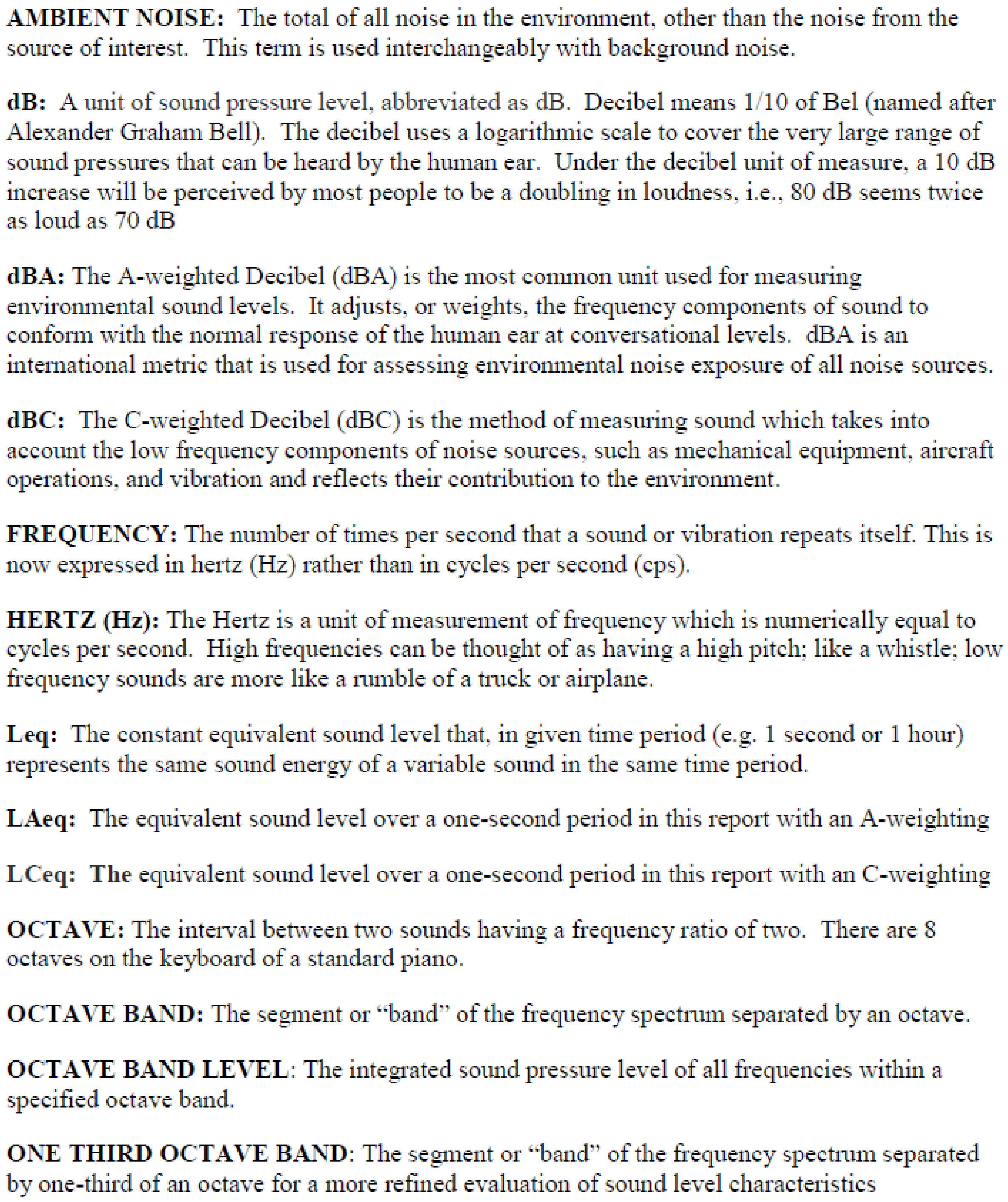
APPENDIX A

GLOSSARY

This glossary contains definitions of abbreviations, acronyms, and common terms.

Table A.1: Definitions of abbreviations and acronyms

ACRONYM/ABBREVIATION	DEFINITION
AASHTO	American Association of State Highway Transportation Officials
RS	Rumble Strip
SRS	Shoulder Rumble Strip
CLRS	Centerline Rumble Strip
SIP	Statistical Isolated Pass-By Method
ANOVA	Analysis of Variance
SPT	Surface Preparation Technologies
OSU	Oregon State University
PSU	Portland State University



AMBIENT NOISE: The total of all noise in the environment, other than the noise from the source of interest. This term is used interchangeably with background noise.

dB: A unit of sound pressure level, abbreviated as dB. Decibel means 1/10 of Bel (named after Alexander Graham Bell). The decibel uses a logarithmic scale to cover the very large range of sound pressures that can be heard by the human ear. Under the decibel unit of measure, a 10 dB increase will be perceived by most people to be a doubling in loudness, i.e., 80 dB seems twice as loud as 70 dB

dBA: The A-weighted Decibel (dBA) is the most common unit used for measuring environmental sound levels. It adjusts, or weights, the frequency components of sound to conform with the normal response of the human ear at conversational levels. dBA is an international metric that is used for assessing environmental noise exposure of all noise sources.

dBC: The C-weighted Decibel (dBC) is the method of measuring sound which takes into account the low frequency components of noise sources, such as mechanical equipment, aircraft operations, and vibration and reflects their contribution to the environment.

FREQUENCY: The number of times per second that a sound or vibration repeats itself. This is now expressed in hertz (Hz) rather than in cycles per second (cps).

HERTZ (Hz): The Hertz is a unit of measurement of frequency which is numerically equal to cycles per second. High frequencies can be thought of as having a high pitch; like a whistle; low frequency sounds are more like a rumble of a truck or airplane.

Leq: The constant equivalent sound level that, in given time period (e.g. 1 second or 1 hour) represents the same sound energy of a variable sound in the same time period.

LAeq: The equivalent sound level over a one-second period in this report with an A-weighting

LCeq: **The** equivalent sound level over a one-second period in this report with an C-weighting

OCTAVE: The interval between two sounds having a frequency ratio of two. There are 8 octaves on the keyboard of a standard piano.

OCTAVE BAND: The segment or "band" of the frequency spectrum separated by an octave.

OCTAVE BAND LEVEL: The integrated sound pressure level of all frequencies within a specified octave band.

ONE THIRD OCTAVE BAND: The segment or "band" of the frequency spectrum separated by one-third of an octave for a more refined evaluation of sound level characteristics

Figure A.1: Glossary of sound terminology (Terhaar, 2016).

APPENDIX B

Oregon Department of Transportation: Sinusoidal Rumble Strip Survey

Contractor Name ________________________________ Contact Name _________________
Contact Email ________________________________ Phone Number _________________
Date ________________

1. What is your experience installing milled centerline or shoulder rumble strips?
   a. How many projects have you completed? ___________________________________
   b. Percentage of projects completed in Oregon? ___________________________________

2. Are you familiar with sinusoidal rumble strips as shown in Figure 1?
   a. How many projects have you completed? ___________________________________
   b. Percentage of projects completed in Oregon? ___________________________________

3. What are your equipment capabilities?
   a. Automated or manual control? ________________________________
   b. Boundary Conditions: adjustments to width, length and depth of cuts ________________________________
   c. Gaps between rumble strips? ________________________________
   d. Asphalt and/or concrete? ________________________________
   e. Mill pattern
      Traditional rumble strips ________________________________
      Sinusoidal rumble strips ________________________________
   f. Mill speed
      Traditional rumble strips ________________________________
      Sinusoidal rumble strips ________________________________

RS CHARACTERISTICS WORKSHEET

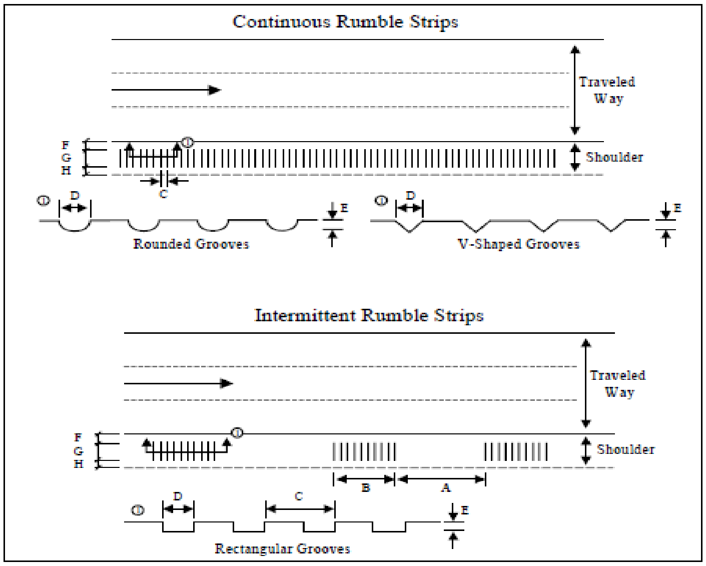


Figure 1B. Typical rumble strip applications on asphalt shoulders (Harwood 1993).

Circle Rumble Strip Type

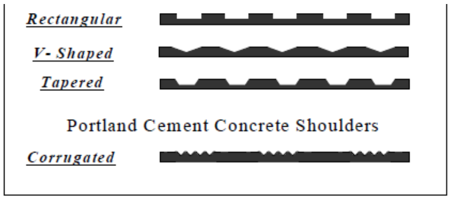
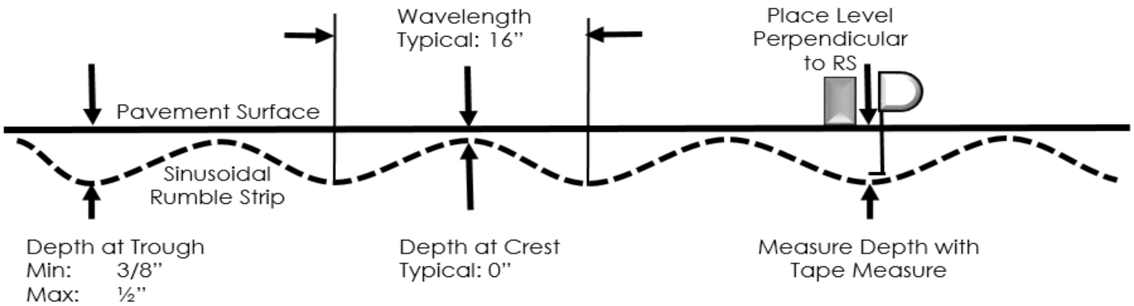


Figure 1A. Typical shapes of rumble strips along shoulders.

Dimension	Description	Measurement (Inches)
A	Gap between RS clusters	
B	Length of RS cluster	
C	Wavelength	
D	Length of individual RS mill	
E-1	Depth of RS mill at trough (see below)	
E-2	Depth of RS mill at crest	
F	Distance between edge of lane line and inside edge of RS mill	
G	Width of RS mill	
H	Distance between outside edge of RS mill and edge of pavement	

From the literature, the depth of the RS mill has the largest impact on the noise generated. Therefore, several mills (at least 5) should be measured to ensure consistent depth. **Measure to the nearest 1/8 in.**



RS DATA COLLECTION TABLE

Pilot Study: Passenger Van

Date ____________________

Location ____________________

Data Recorder ____________________

Run #	RUMBLE STRIP TYPE	TEST LOCATION	MEASUREMENT LOCATION	SUCCESSFUL STRIKE?	TRAFFIC VOLUME	HEAVY VEHICLES	TIME	PHOTO	SPEED
	None	A	Exterior						
	None	A	Exterior						
	None	A	Exterior						
	Sinusoidal	A	Exterior						
	Sinusoidal	A	Exterior						
	Sinusoidal	A	Exterior						
	None	A	Interior						
	None	A	Interior						
	None	A	Interior						
	Sinusoidal	A	Interior						
	Sinusoidal	A	Interior						
	Sinusoidal	A	Interior						
	None	B	Interior						
	None	B	Interior						
	None	B	Interior						
	Rounded	B	Interior						
	Rounded	B	Interior						
	Rounded	B	Interior						
	None	B	Exterior						

Run #	RUMBLE STRIP TYPE	TEST LOCATION	MEASUREMENT LOCATION	SUCCESSFUL STRIKE?	TRAFFIC VOLUME	HEAVY VEHICLES	TIME	PHOTO	SPEED
	None	B	Exterior						
	None	B	Exterior						
	Rounded	B	Exterior						
	Rounded	B	Exterior						
	Rounded	B	Exterior						

Extra Run #	RUMBLE STRIP TYPE	TEST LOCATION	MEASUREMENT LOCATION	SUCCESSFUL STRIKE?	TRAFFIC VOLUME	HEAVY VEHICLES	TIME	PHOTO	SPEED

Run #: Record the file name of the strike data file

Successful Strike: The strike began at the correct location through the end point. No evidence of significant conflicting traffic.

Traffic Volume: Rough estimate of the number of vehicles on both sides of the road during the strike in the area of interest.

Heavy Vehicles: Record the number of heavy vehicles, including tractor trailers, RVs, and other louder industrial trucks.

Time: Record approximate time of the strike (hour: minute).

Photo: Check if a photo of the strike was taken.

Speed: Radar measured speed of the traffic stream at time of the strike

RS METEOROLOGICAL CONDITIONS

Date ____________________

Location ____________________

Data Recorder ____________________

Time	Wind Speed	Wind Direction	Temperature	Sky Condition	Photo

Time: Conditions should be measured at the beginning of the experiment, and then once per hour.

Wind Speed: should be routinely monitored to ensure that it does not exceed 11 mph.

Temperature: ±7 °F between measurements

Sky Condition: Record as clear, scattered clouds, partly cloudy, mostly cloudy, or overcast

Photo: Take a photo of the road surface / sky conditions

APPENDIX C

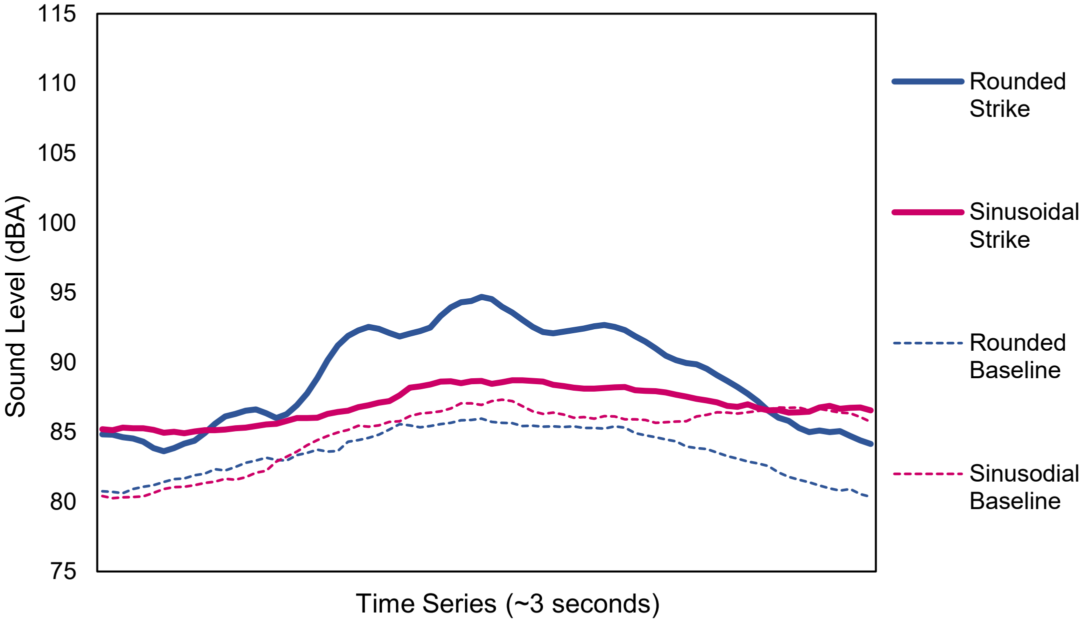


Figure C.1:Passenger car RS exterior comparison

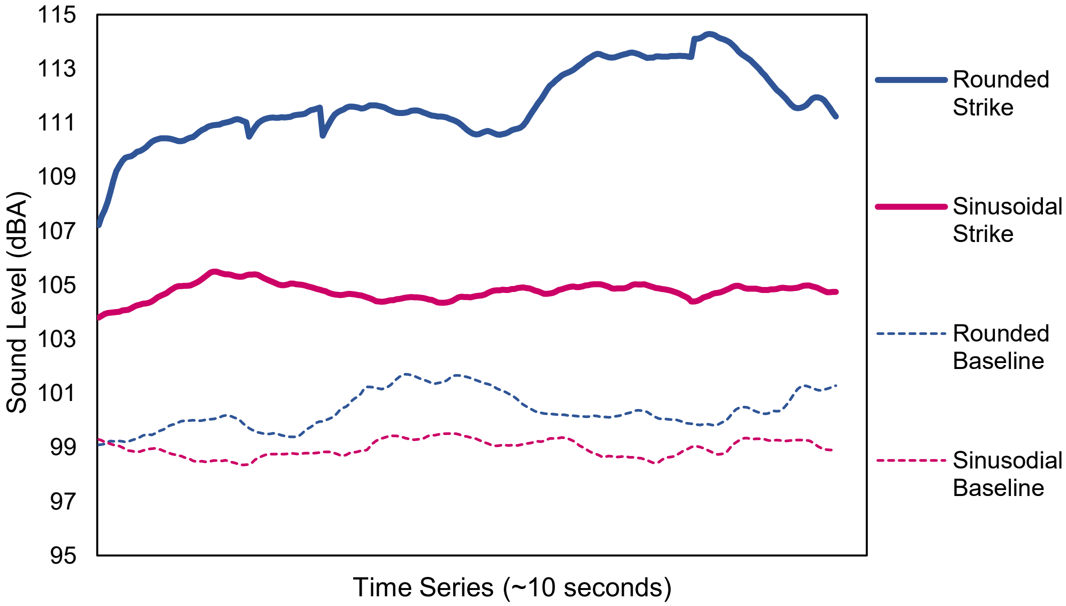


Figure C.2:Passenger car RS interior comparison

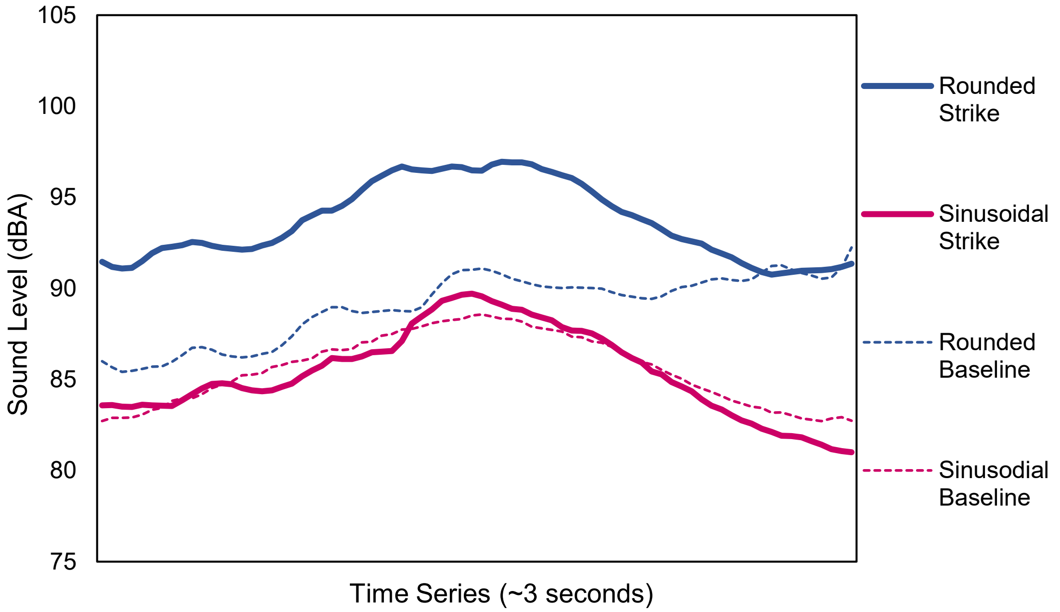


Figure C.3: Van RS exterior comparison

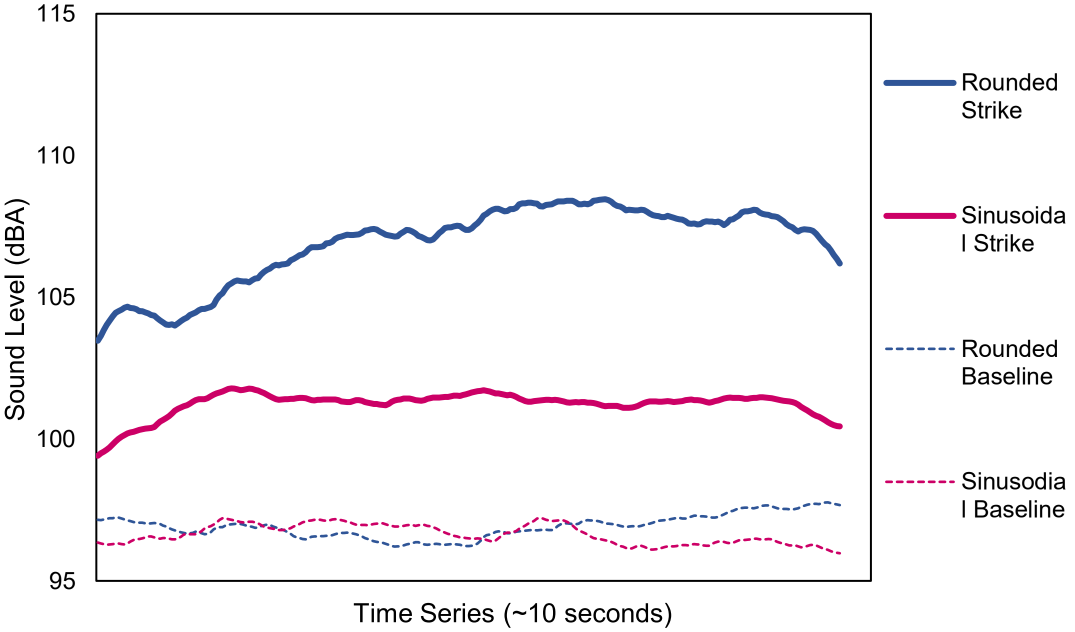


Figure C.4: Van RS interior comparison

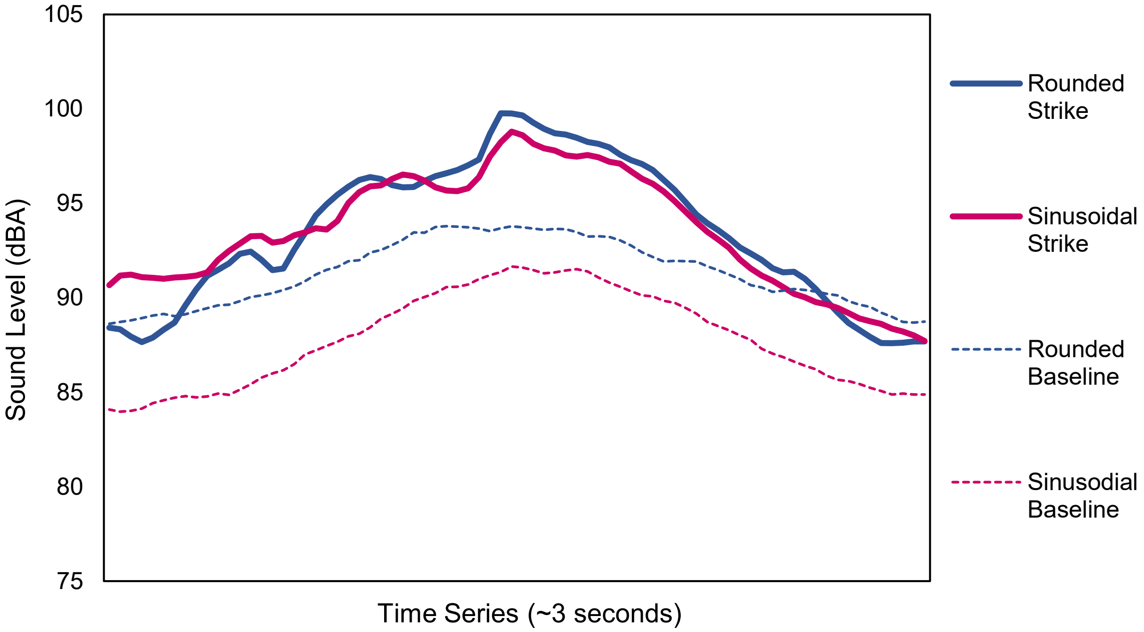


Figure C.5: Heavy vehicle RS exterior comparison

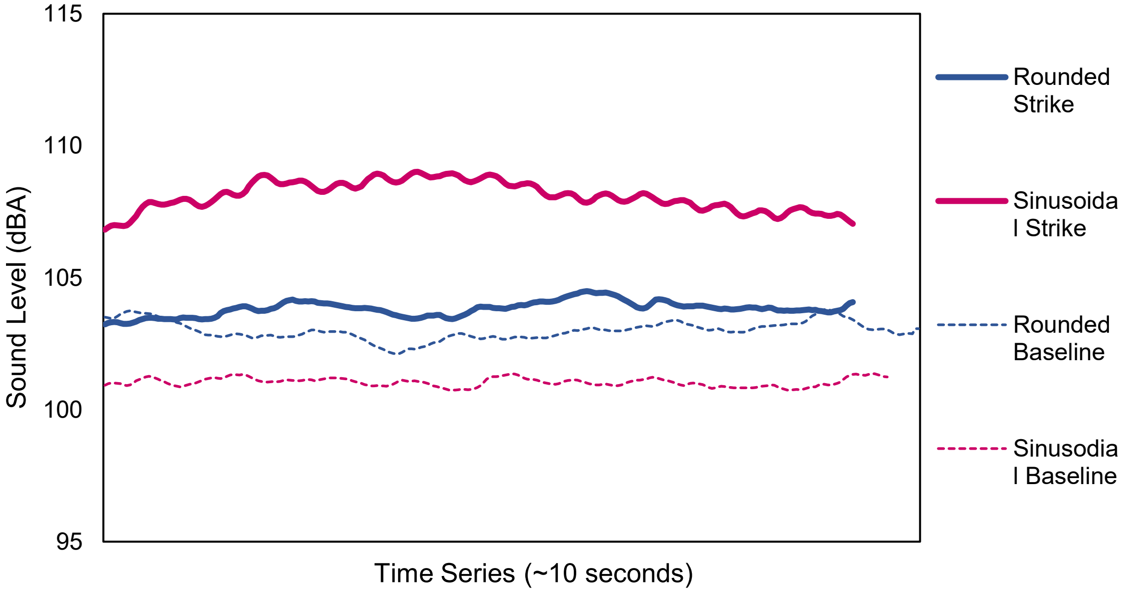


Figure C.6: Heavy vehicle RS interior comparison

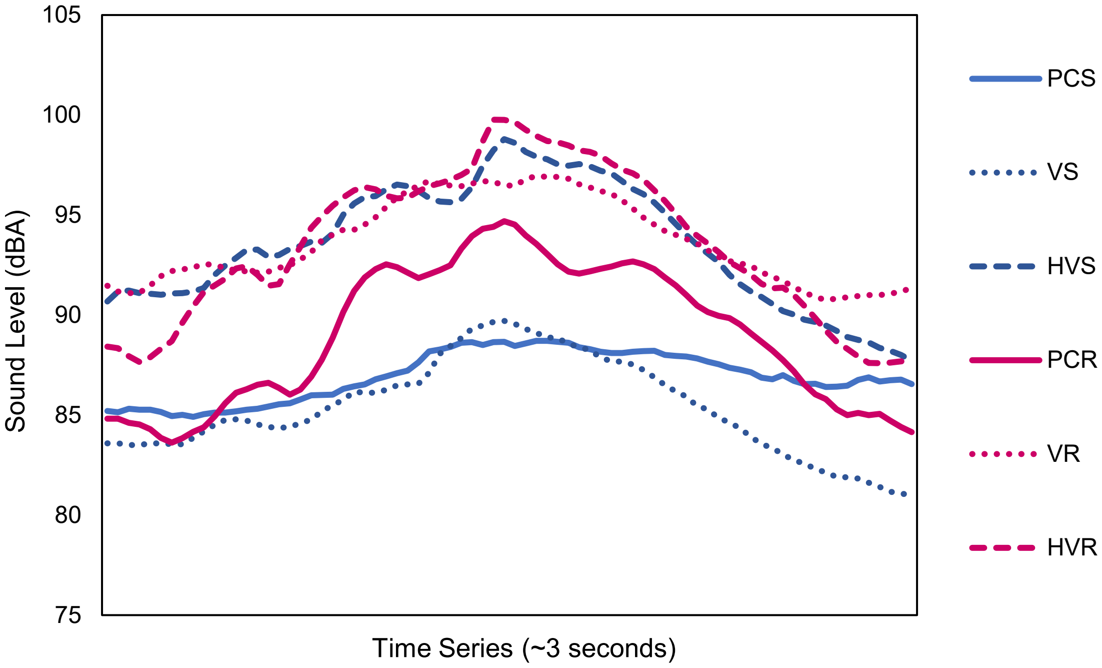


Figure C.7: By vehicle and RS type for exterior sound level measurements

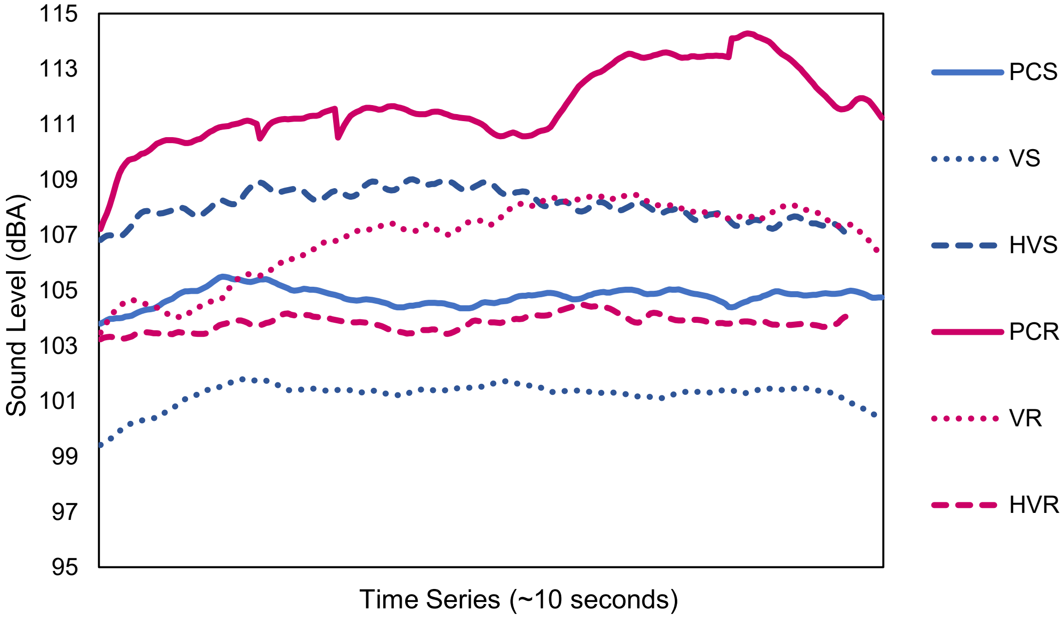


Figure C.8: By vehicle and RS type for interior sound level measurements

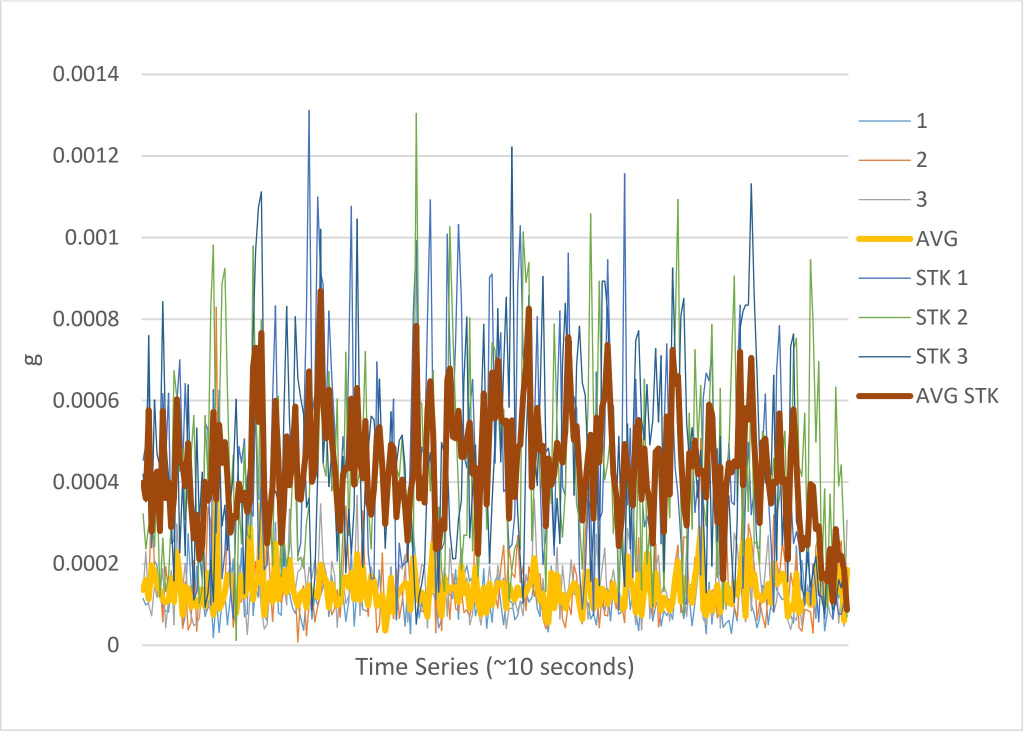


Figure C.9: Van rounded RS vibration resultant measurement

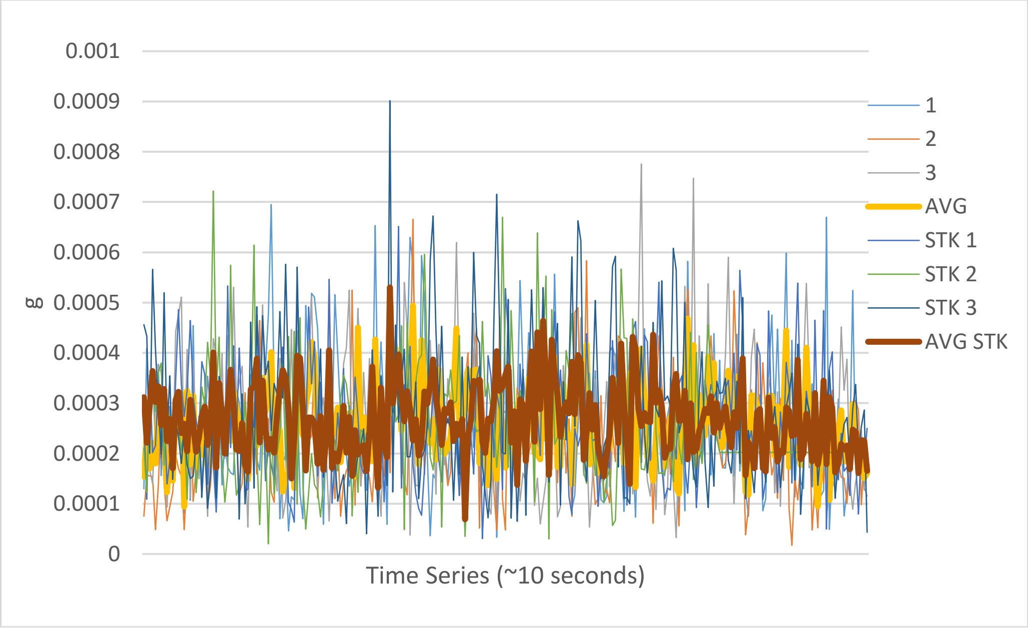


Figure C.10: Van sinusoidal RS vibration resultant measurement

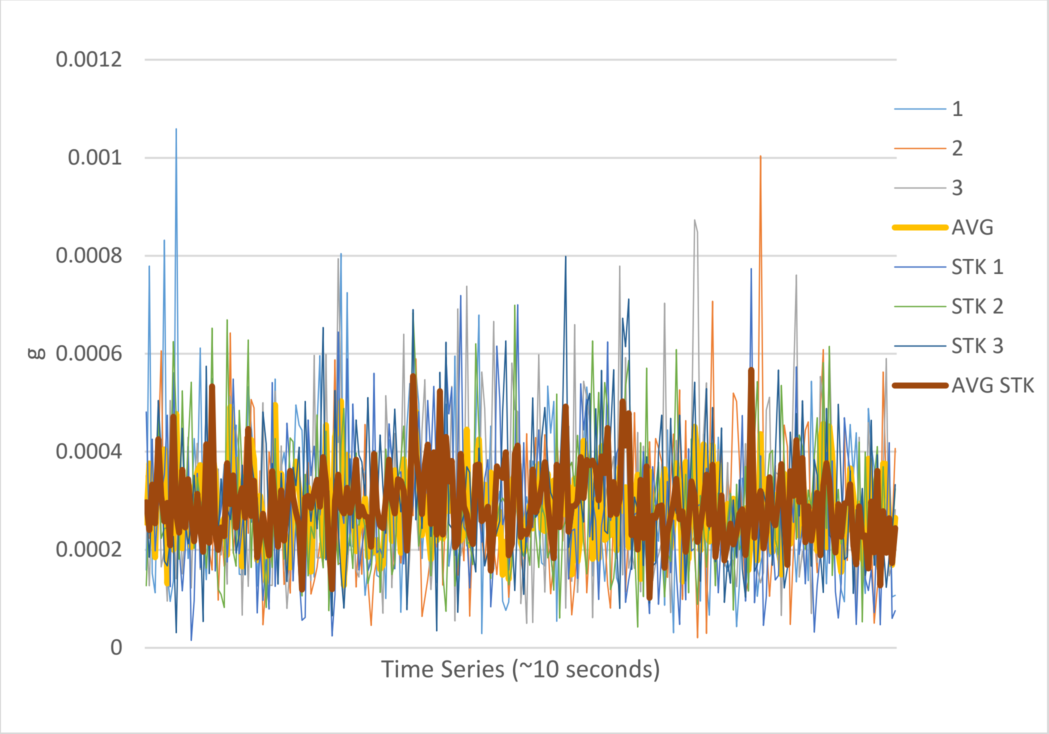


Figure C.11: Passenger car sinusoidal RS vibration resultant measurement

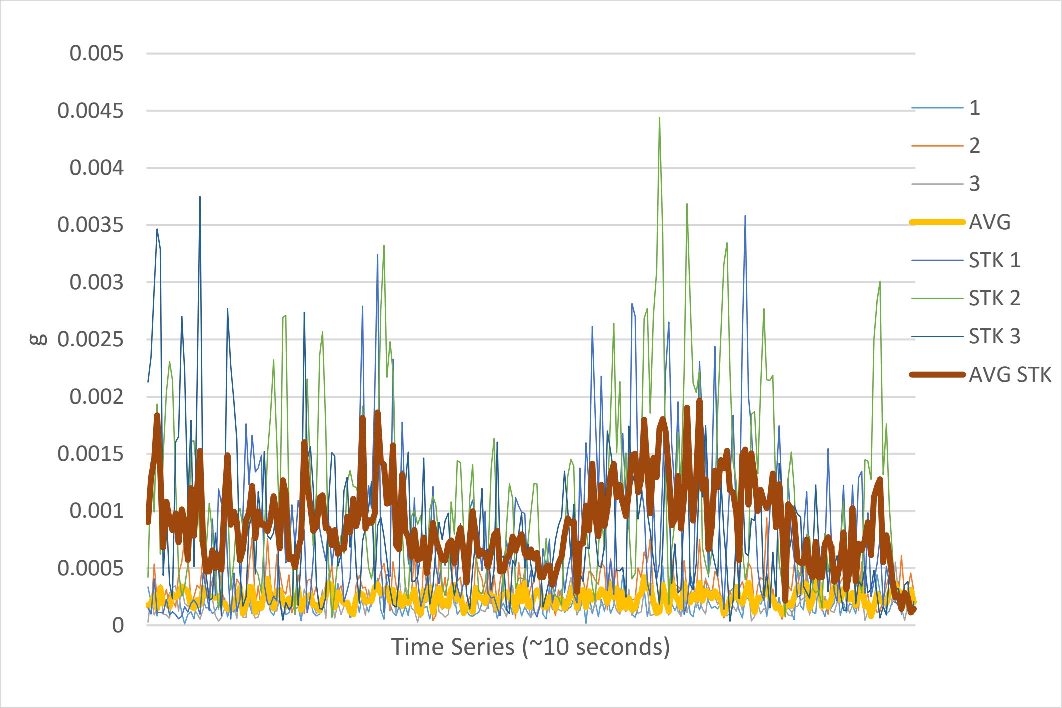


Figure C.12: Passenger car rounded RS vibration resultant measurement

APPENDIX D

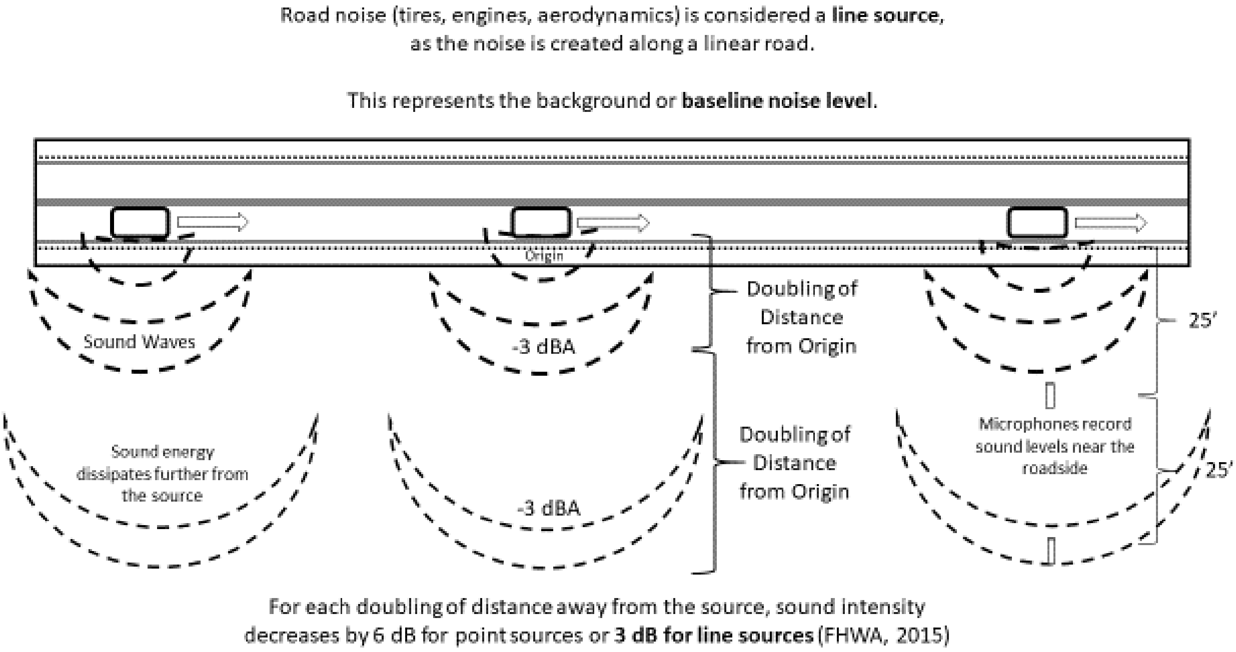


Figure D.1: Line source sound decay with doubling of distance relationship

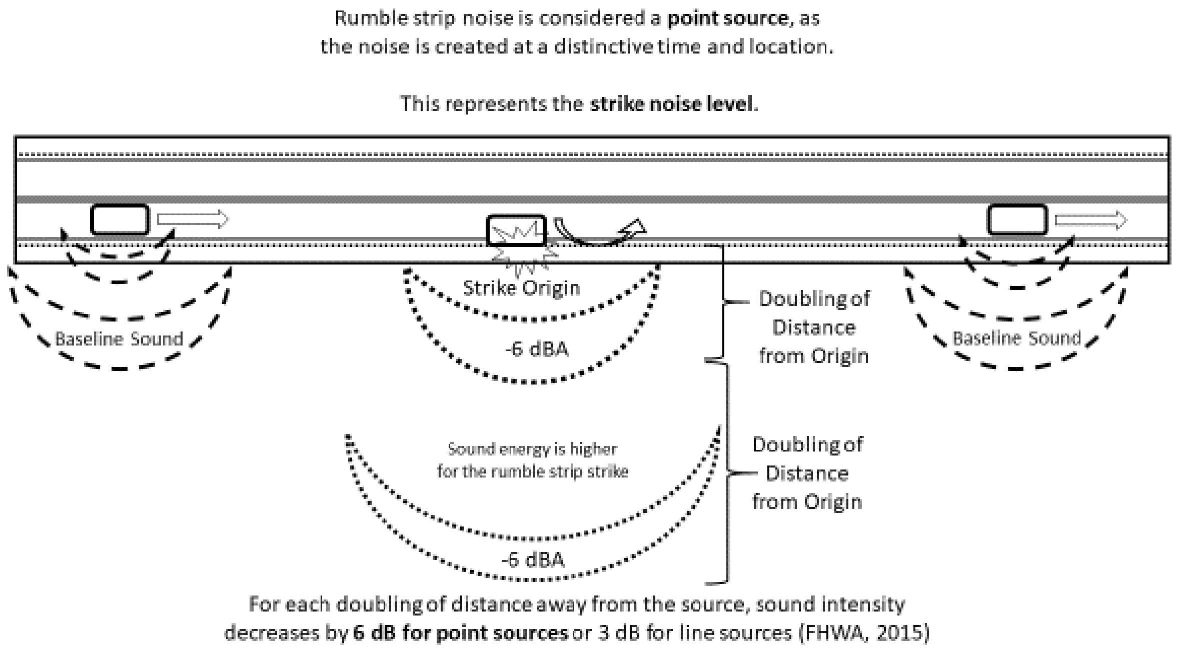
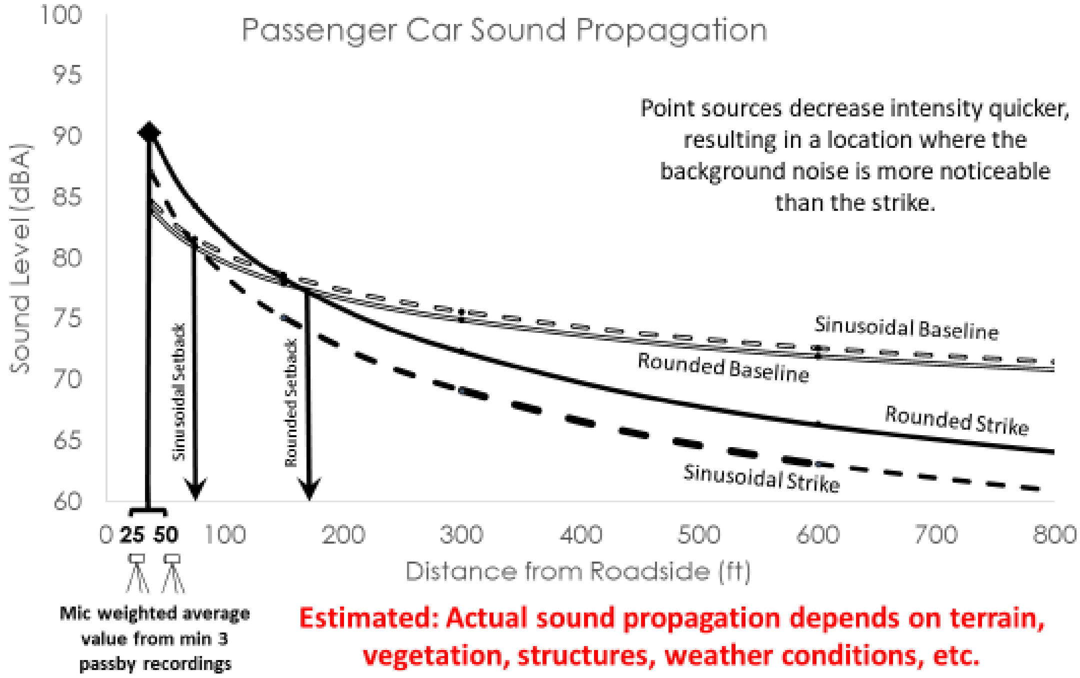


Figure D.2: Point source sound decay with doubling of distance relationship

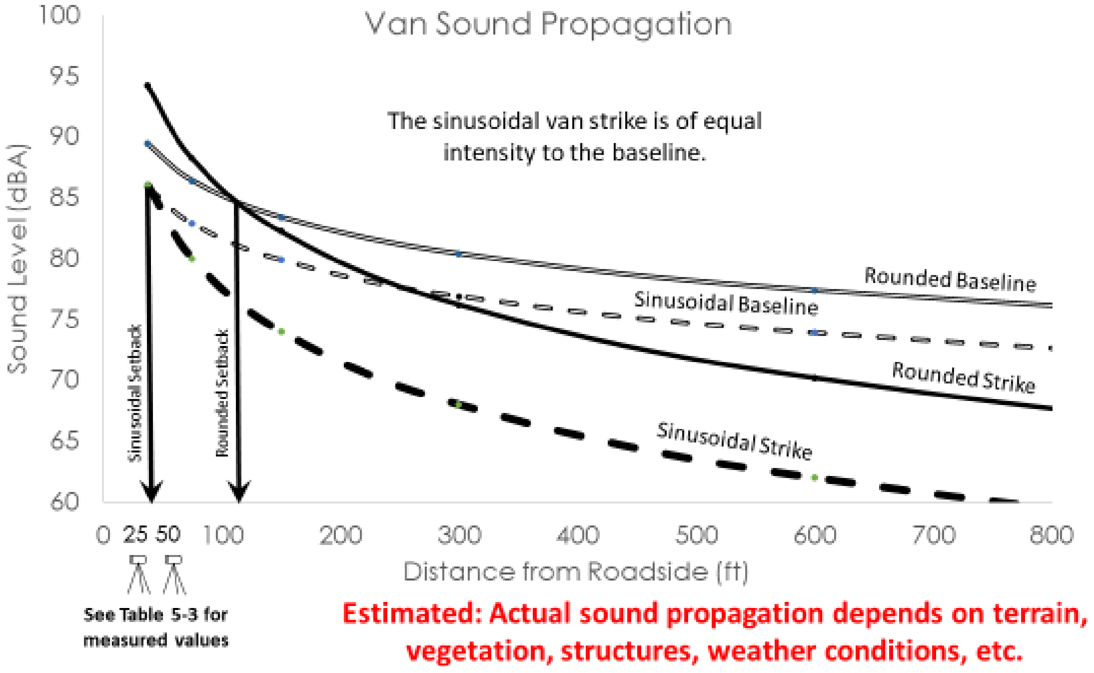


Point sources decrease intensity quicker, resulting in a location where the background noise is more noticeable than the strike.

Mic weighted average value from min 3 passby recordings

Estimated: Actual sound propagation depends on terrain, vegetation, structures, weather conditions, etc.

Figure D.3: Passenger car RS noise decay with respect to distance from roadway

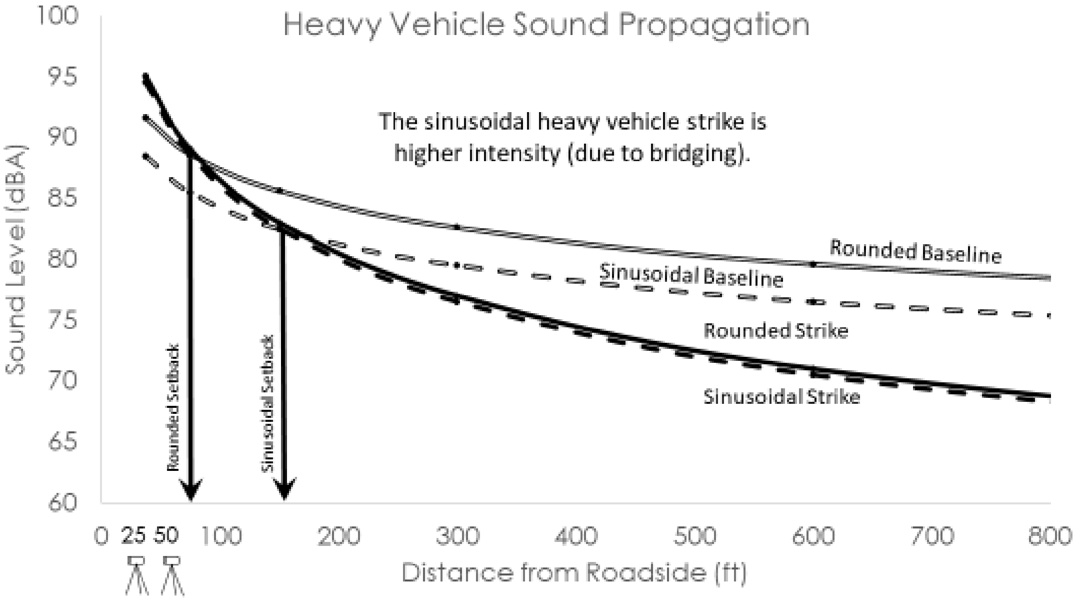


The sinusoidal van strike is of equal intensity to the baseline.

See Table 5-3 for measured values

Estimated: Actual sound propagation depends on terrain, vegetation, structures, weather conditions, etc.

Figure D.4: Van RS noise decay with respect to distance from roadway



Estimated: Actual sound propagation depends on terrain, vegetation, structures, weather conditions, etc.

Figure D.5: Heavy vehicle RS noise decay with respect to distance from roadway

APPENDIX E

MAINT

STATE OF OREGON

DEPARTMENT OF TRANSPORTATION

PLANS FOR PROPOSED PROJECT

PAVEMENT MARKINGS

RUMBLE STRIP INSTALLATIONS
SINUSOIDAL RUMBLE STRIP INSTALLATIONS (SCP)

VARIOUS HIGHWAYS

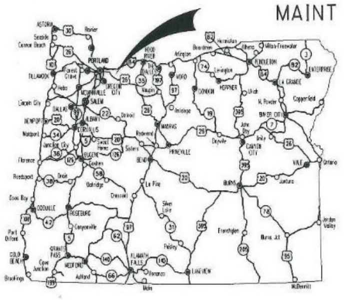
CLACKAMAS, MULTNOMAH, & WASHINGTON
SEPTEMBER 2016

INDEX OF SHEETS

SHEET NO.	DESCRIPTION
1	Title Sheet
1A	Index of Sheets, Standard Drawings
2, 2A Thru 2A-5	Details

Standard Drg. Nos.

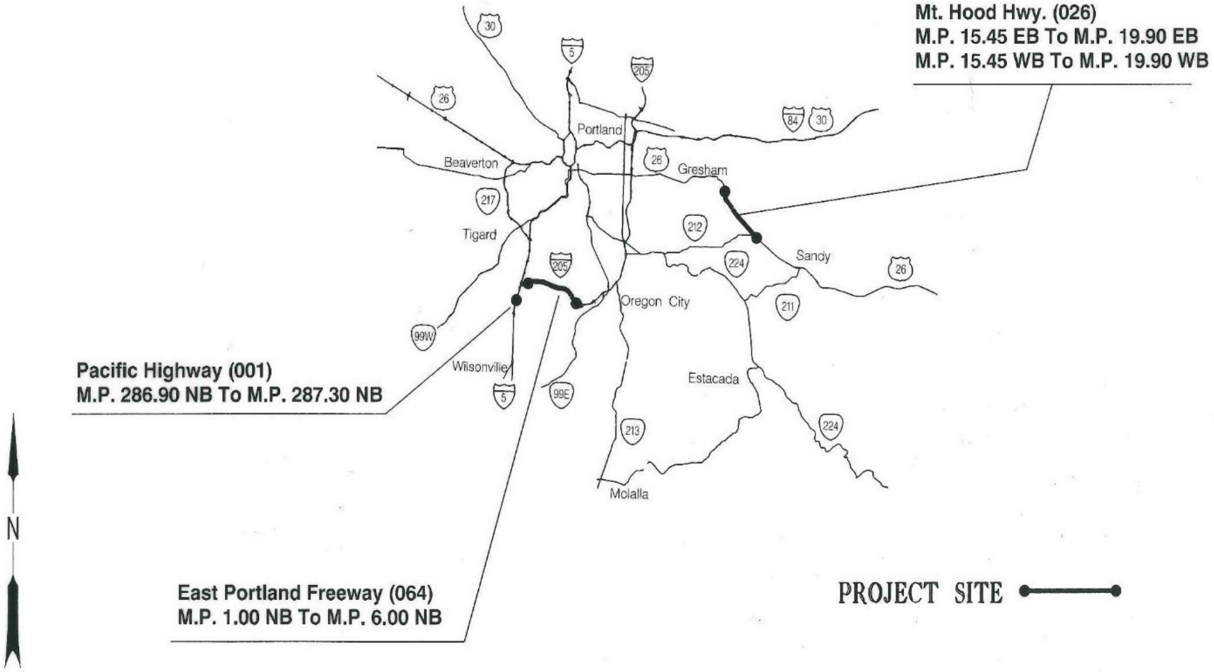
TM200	- Sign Installation Detail
TM502	- Pavement Marking
TM670	- Wood Post Sign Supports
TM671	- 3 Second Gust Wind Speed
TM676	- Sign Attachments
TM800	- Tables, Abrupt Edge And PCMS Details
TM820	- Temporary Barricades
TM821	- Temporary Sign Supports
TM850	- 2-Lane, 2-Way Roadways
TM851, TM852	- Non-Freeway Multi-Lane Sections
TM860, TM861, TM862	- Freeway Sections



ATTENTION:

Oregon Law Requires You To Follow Rules Adopted By The Oregon Utility Notification Center. Those Rules Are Set Forth In OAR 952-001-0010 Through OAR 952-001-0090. You May Obtain Copies Of The Rules By Calling The Center. (Note: The Telephone Number For The Oregon Utility Center Is (503) 232-1987.)

LET'S ALL
WORK TOGETHER
TO MAKE THIS
JOB SAFE



Mt. Hood Hwy. (026)
M.P. 15.45 EB To M.P. 19.90 EB
M.P. 15.45 WB To M.P. 19.90 WB

Pacific Highway (001)
M.P. 286.90 NB To M.P. 287.30 NB

East Portland Freeway (064)
M.P. 1.00 NB To M.P. 6.00 NB

OREGON TRANSPORTATION COMMISSION

Tommy Boney	CHAIR
David Lohman	COMMISSIONER
Susan Morgan	COMMISSIONER
Alando Simpson	COMMISSIONER
Sean O'Hollaren	COMMISSIONER
Matthew L. Garrett	DIRECTOR OF TRANSPORTATION

These plans were developed using ODOT design standards. Exceptions to these standards, if any, have been submitted and approved by the ODOT Chief Engineer or their delegated authority.

Approving Authority: Tamira Clark
Tamira J. Clark
Technical Center Manager, Region 1

RUMBLE STRIP INSTALLATIONS
SINUSOIDAL RUMBLE STRIP INSTALLATIONS (SCP)
VARIOUS HIGHWAYS
CLACKAMAS, MULTNOMAH, & WASHINGTON

FEDERAL HIGHWAY ADMINISTRATION	PROJECT NUMBER	SHEET NO.
OREGON DIVISION	STATE	1

Standard Drawings located on the web at:
http://www.oregon.gov/ODOT/HWY/ENGSERVICES/Pages/standard_drawings_home.aspx

PE002283 000

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MAINT

RUMBLE STRIP AND
SINUSOIDAL RUMBLE STRIP INSTALLATION SCHEDULE

ROUTE	HIGHWAY NAME	PROJECT LIMITS FROM (*)	PROJECT LIMITS TO (*)	Left Shoulder (Continuous pattern) SRS	Left Shoulder (Continuous pattern) S-SRS	Right Shoulder (Gap pattern) SRS	Right Shoulder (Gap pattern) S-SRS	Construction Notes
I-5 (freeway)	(001) Pacific Highway Northbound lanes	MP 286.90	MP 287.00	X		X		12" Shoulder rumble strips (Install per Sheet 2A)
		MP 287.00	MP 287.10		X		X	12" Sinusoidal rumble strips (Install per Sheet 2A-2 & 2A-3)
		MP 287.10	MP 287.20	X		X		16" Shoulder rumble strips (Install per Sheet 2A)
		MP287.20	MP 287.30		X		X	16" Sinusoidal rumble strips (Install per Sheet 2A-2 & 2A-3)
	(001) Pacific Highway Southbound lanes	NO WORK						
I-205 (freeway)	(064) East Portland Freeway Northbound lanes	MP 1.00	MP 6.00		X		X	16" Sinusoidal rumble strips (Install per Sheet 2A-2 & 2A-3)
	(064) East Portland Freeway Southbound lanes	NO WORK						
US26	(026) Mt. Hood Highway Eastbound lanes	MP 15.45 (SE Hillyard Rd)	MP 19.90		X		X	12" Sinusoidal rumble strips (Install per Sheet 2A-2, 2A-3, & 2A-5). Omit rumble strips at intersections where Hwy is NOT divided: 1) 600 ft west to 600 ft east of SE 267th Ave 2) 550 ft west to 550 ft east of SE Stone Rd 3) 500 ft west to 500 ft east of SE Haley Rd.
	(026) Mt. Hood Highway Westbound lanes	MP 15.45 (SE Hillyard Rd)	MP 19.90		X		X	12" Sinusoidal rumble strips (Install per Sheet 2A-2, 2A-3, & 2A-5). Omit rumble strips at intersections where Hwy is NOT divided: 1) 600 ft west to 600 ft east of SE 267th Ave 2) 550 ft west to 550 ft east of SE Stone Rd 3) 500 ft west to 500 ft east of SE Haley Rd.

See Sheet 2A-4 for detail layout

(*) exact limits to be field verified or as directed by Engineer
SRS - Shoulder Rumble Strips (regular)
S-SRS - Sinusoidal Shoulder Rumble Strips
MP - Mile Point

14,419
OREGON
May 30, 1989
DENNIS J. MITCHELL
RENEWAL DATE: 12-31-2016

OREGON DEPARTMENT OF TRANSPORTATION

REGION 1 - TRAFFIC ENGINEERING UNIT

RUMBLE STRIP INSTALLATIONS
SINUSOIDAL RUMBLE STRIP INSTALLATIONS (SCP)
VARIOUS HIGHWAYS
CLACKAMAS, MULTNOMAH, & WASHINGTON

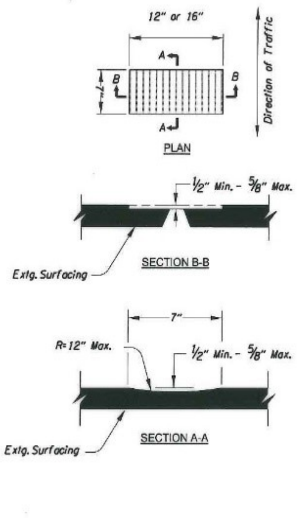
Designed By - Chhommony Mao
Reviewed By - Merle E Hill
Drafted By - Chhommony Mao

DETAILS

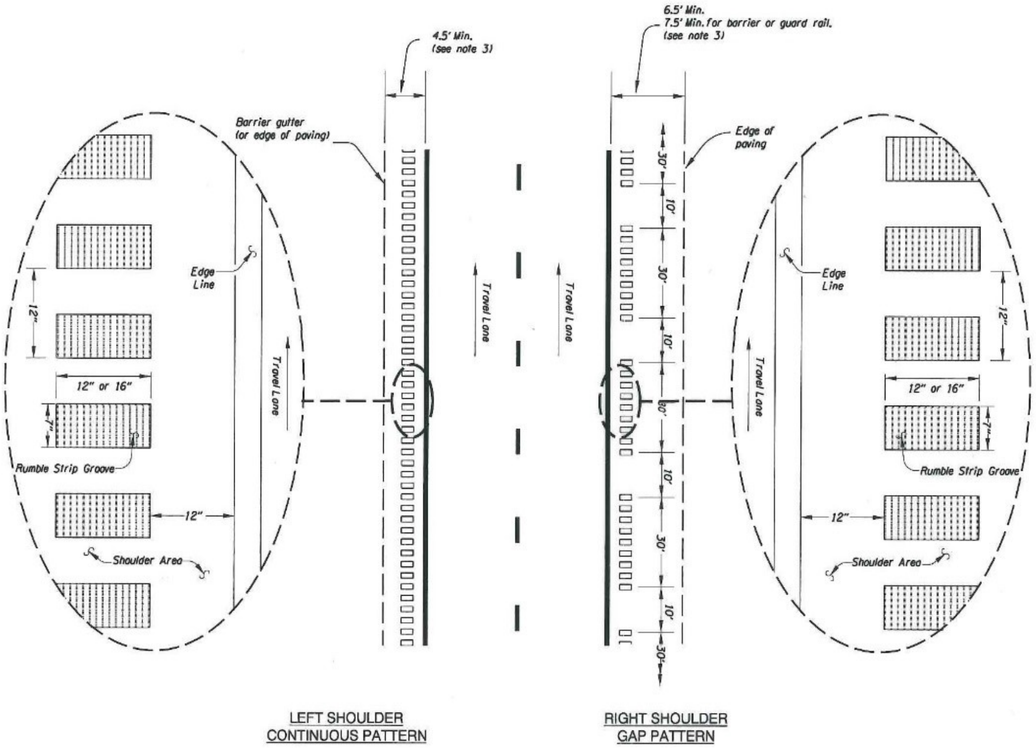
SHEET NO. 2

MAINT

MILLED RUMBLE STRIPS FOR SHOULDER APPLICATION



RUMBLE STRIP GROOVE



LEFT SHOULDER
CONTINUOUS PATTERN

RIGHT SHOULDER
GAP PATTERN

RUMBLE STRIP
TYPICAL SHOULDER INSTALLATION

GENERAL NOTES:

1. Install rumble strips on left shoulders (continous pattern) and right shoulders (gap pattern) as shown.

2. Omit rumble strips:
- *on bridge decks and end panels*
- *on Portland cement concrete surfaces*
- *at interchange ramps as shown*
- *other locations as directed by Engineer.*

3. Do not install rumble strip when the width of existing shoulder:
Left shoulder: is less than 4.5'.
Right shoulder: is less than 6.5' (or 7.5' at barrier or guard rail areas).

4. Retain and protect existing stripe lines.

5. Drawings are not-to-scale.

LEGEND

▭ ▭ ▭ ▭ *Gap Pattern*
▭▭▭▭▭▭▭▭ *Continuous Pattern*

REGISTERED PROFESSIONAL ENGINEER
14,419
OREGON
May 30, 1989
DENNIS J. MITCHELL

RENEWAL DATE: 12-31-2016

OREGON DEPARTMENT OF TRANSPORTATION

REGION 1 - TRAFFIC ENGINEERING UNIT

RUMBLE STRIP INSTALLATIONS
SINUSOIDAL RUMBLE STRIP INSTALLATIONS (SCP)
VARIOUS HIGHWAYS
CLACKAMAS, MULTNOMAH, & WASHINGTON

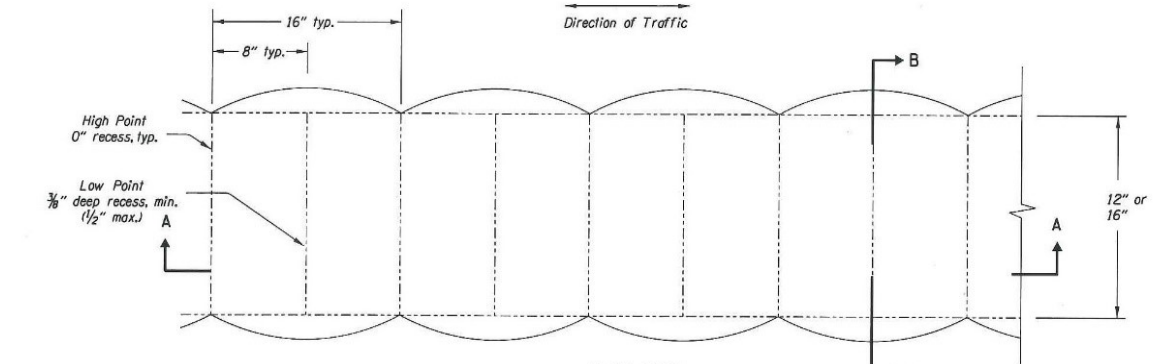
Designed By - Chhommony Moo
Reviewed By - Merle E Hill
Drafted By - Chhommony Moo

DETAILS

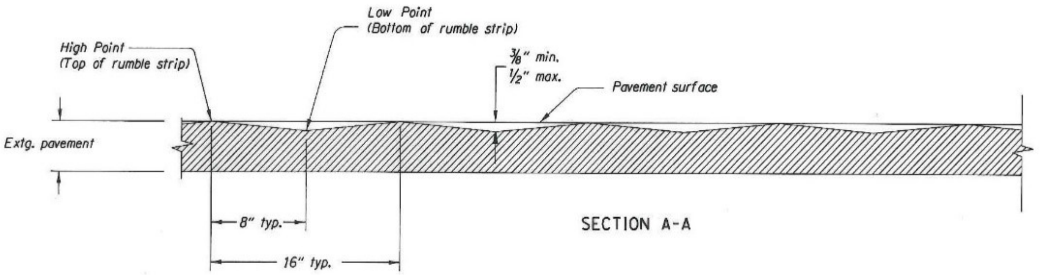
SHEET NO. 2A

MAINT

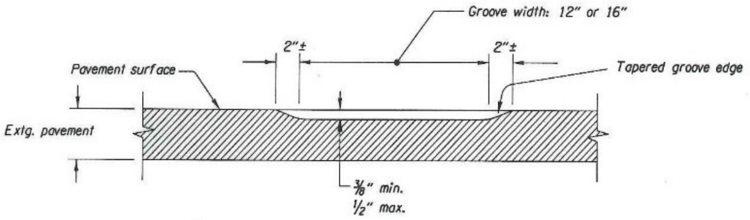
MILLED SINUSOIDAL RUMBLE STRIPS FOR SHOULDER APPLICATION



PLAN VIEW



SECTION A-A



SECTION B-B

GENERAL NOTES:

1. Sinusoidal rumble strip tapers down from roadway surface to ⅜" below surface over a 8" distance repeating continuously.
2. Omit rumble strips:
   - on bridge decks
   - on Portland cement concrete surfaces
   - at intersections with public roads as shown
   - at two-way left turn lanes
   - other locations as directed.
3. Install gap pattern sinusoidal rumble strips per pattern shown on Sheet 2A-3 (10' gap for every 30'± rumble strips).

14,419
DENNIS J. MITCHELL
MAY 30, 1989
RENEWAL DATE: 12-31-2016

OREGON DEPARTMENT OF TRANSPORTATION

REGION 1 - TRAFFIC ENGINEERING UNIT

RUMBLE STRIP INSTALLATIONS
SINUSOIDAL RUMBLE STRIP INSTALLATIONS (SCP)
VARIOUS HIGHWAYS
CLACKAMAS, MULTNOMAH, & WASHINGTON

Designed By - Chhommony Mao
Reviewed By - Merle E Hill
Drafted By - Chhommony Mao

DETAILS

SHEET NO. 2A-2

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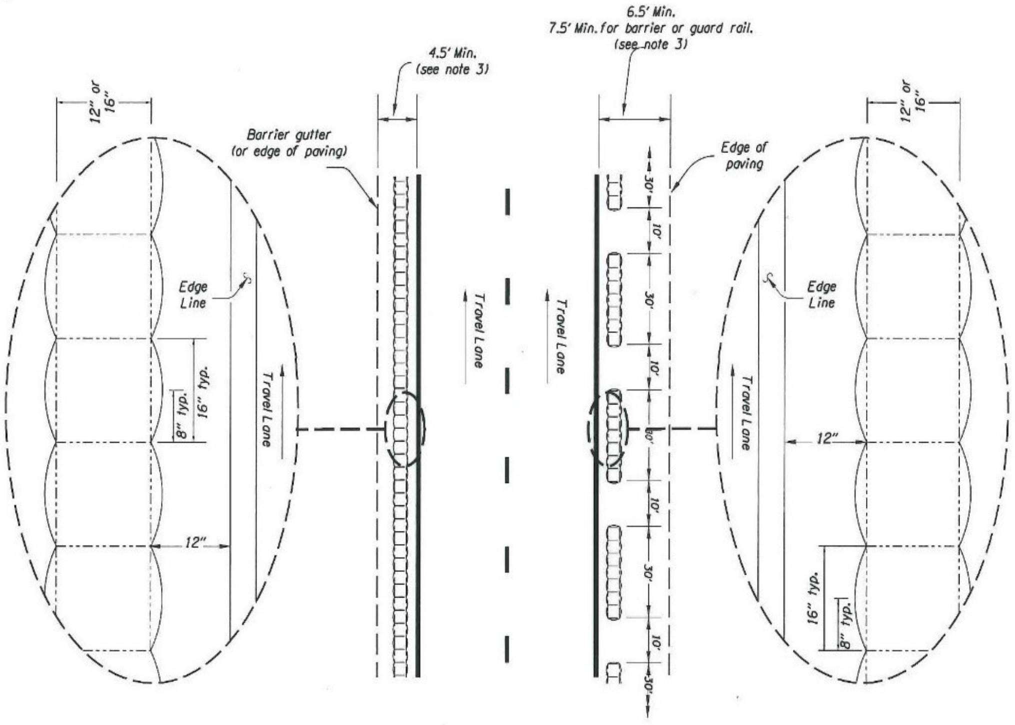
MILLED SINUSOIDAL RUMBLE STRIPS FOR SHOULDER APPLICATION



LEFT SHOULDER
CONTINUOUS PATTERN

RIGHT SHOULDER
GAP PATTERN

SINUSOIDAL RUMBLE STRIP
TYPICAL SHOULDER INSTALLATION

GENERAL NOTES:

1. *Install rumble strips on left shoulders (continous pattern) and right shoulders (gap pattern) as shown.*
2. *Omit rumble strips:*
   - *on bridge decks and end panels*
   - *on Portland cement concrete surfaces*
   - *at interchange ramps as shown*
   - *other locations as directed by Engineer.*
3. *Do not install rumble strip when the width of existing shoulder:*
   Left shoulder: is less than 4.5′.
   Right shoulder: is less than 6.5′ (or 7.5′ at barrier or guard rail areas).
4. *Retain and protect existing stripe lines.*
5. *Drawings are not-to-scale.*

LEGEND

▬ ▬ ▬ ▬ *Gap Pattern*
▬▬▬▬▬▬ *Continuous Pattern*

14,419
DENNIS J. MITCHELL
May 30, 1989

RENEWAL DATE: 12-31-2016

OREGON DEPARTMENT OF TRANSPORTATION

REGION 1 - TRAFFIC ENGINEERING UNIT

RUMBLE STRIP INSTALLATIONS
SINUSOIDAL RUMBLE STRIP INSTALLATIONS (SCP)
VARIOUS HIGHWAYS
CLACKAMAS, MULTNOMAH, & WASHINGTON

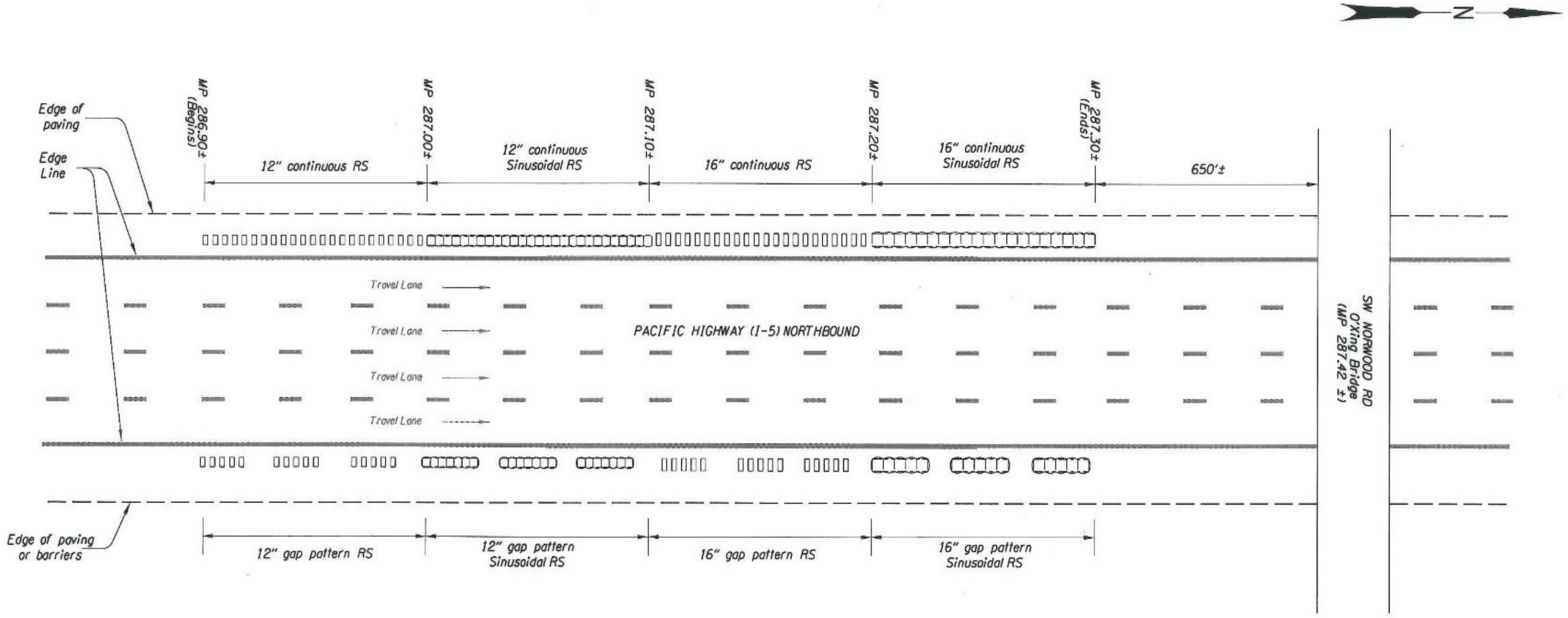
Designed By - Chhommony Mao
Reviewed By - Merle E Hill
Drafted By - Chhommony Mao

DETAILS

SHEET NO. 2A-3

MAINT

CONTINUOUS AND GAP PATTERN RUMBLE STRIPS AND SINUSOIDAL RUMBLE STRIPS INSTALLATION AT PACIFIC HIGHWAY (I-5 NORTHBOUND) SITE



GENERAL NOTES:

1. *Install rumble strips on left shoulders (continous pattern) and right shoulders (gap pattern) as shown.*
2. *For detail not shown, see Sheet 2A, 2A-2, and 2A-3.*
3. *Retain and protect existing stripe lines.*
4. *Drawings are not-to-scale.*

LEGEND

▭▭ ▭▭ ▭▭ ▭▭ *Gap Pattern*

▭▭▭▭▭▭▭▭▭▭ *Continuous Pattern*

REGISTERED PROFESSIONAL ENGINEER
14,419
OREGON
May 30, 1989
DENNIS J. MITCHELL

RENEWAL DATE: 12-31-2016

OREGON DEPARTMENT OF TRANSPORTATION

REGION 1 - TRAFFIC ENGINEERING UNIT

RUMBLE STRIP INSTALLATIONS
SINUSOIDAL RUMBLE STRIP INSTALLATIONS (SCP)
VARIOUS HIGHWAYS
CLACKAMAS, MULTNOMAH, & WASHINGTON

Designed By - Chhommony Mao
Reviewed By - Merle E Hill
Drafted By - Chhommony Mao

DETAILS

SHEET NO.
2A-4

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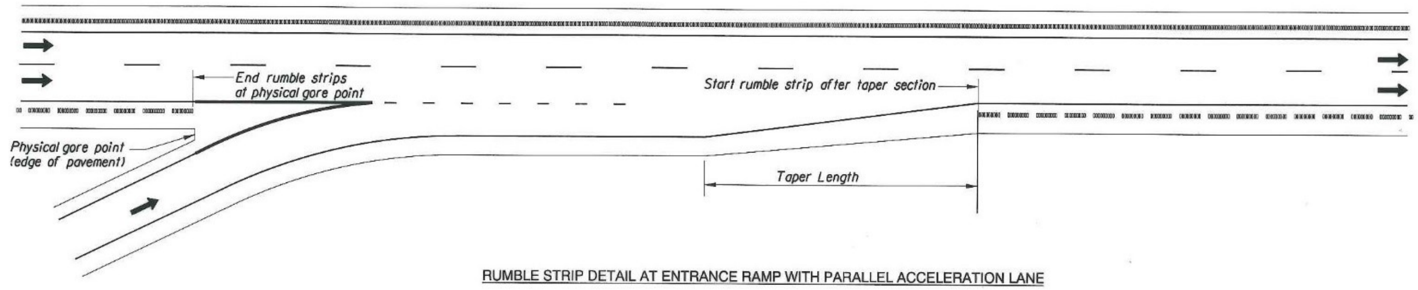
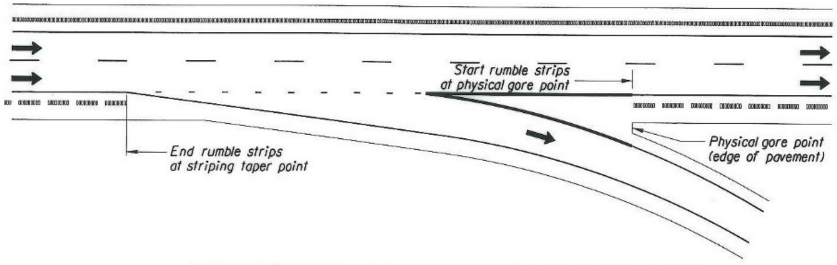
MAINT

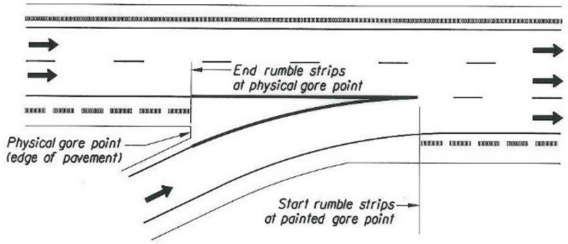
FREEWAY SHOULDER RUMBLE STRIPS (I-205)
DIVIDED HIGHWAY SHOULDER RUMBLE STRIPS (US26)



RUMBLE STRIP DETAIL AT ENTRANCE RAMP WITH PARALLEL ACCELERATION LANE



RUMBLE STRIP DETAIL AT EXIT RAMP WITH TAPERED DECELERATION LANE



RUMBLE STRIP DETAIL AT ENTRANCE RAMP WITH ADDED LANE

GENERAL NOTES:

1. *Install rumble strips on left shoulders (continous pattern) and right shoulders (gap pattern) as shown.*
2. *Omit rumble strips:*
   - *on bridge decks and end panels*
   - *on Portland cement concrete surfaces*
   - *at interchange ramps as shown*
   - *other locations as directed by Engineer.*
3. *Do not install rumble strip when the width of existing shoulder:*
   Left shoulder: is less than 4.5'.
   Right shoulder: is less than 6.5' (or 7.5' at barrier or guard rail areas).
4. *Retain and protect existing stripe lines.*
5. *Drawings are not-to-scale.*

LEGEND

▬ ▬ ▬ ▬ *Gap Pattern*
▬▬▬▬▬▬ *Continuous Pattern*

14,419
OREGON
May 30, 1989
DENNIS J. MITCHELL

RENEWAL DATE: 12-31-2016

OREGON DEPARTMENT OF TRANSPORTATION

REGION 1 - TRAFFIC ENGINEERING UNIT

RUMBLE STRIP INSTALLATIONS
SINUSOIDAL RUMBLE STRIP INSTALLATIONS (SCP)
VARIOUS HIGHWAYS
CLACKAMAS, MULTNOMAH, & WASHINGTON

Designed By - Chhommony Mao
Reviewed By - Merle E Hill
Drafted By - Chhommony Mao

DETAILS

SHEET NO.
2A-5

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