Roadway Departure Warning Indicators

Synthesis of Noise Research
Addendum for Years 2013 to 2020

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Acknowledgments

This addendum was prepared by the U.S. Department of Transportation John A. Volpe National Transportation Systems Center, in Cambridge, Massachusetts. It is a synthesis of many researchers' efforts over the last five years and updates the guidance given in the National Park Service "Roadway Departure Warning Indicators: Synthesis of Noise and Bicycle Research" (Volpe, 2013). The authors wish to extend special thanks to the Minnesota Department of Transportation (Katie Fleming, Derek Leuer, and Kenneth Johnson) for their assistance and willingness to share data.

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1. Introduction

Volpe (2013) published "Roadway Departure Warning Indicators: Synthesis of Noise and Bicycle Research" for the National Park Service in June of 2013. Since that time a number of studies have been conducted and reports have been made public that document the wayside sound levels (overall sound level and, in some cases, spectral data) and driver alerting qualities of several types of rumble strips. This document provides an update to the synthesis document, including a summary of literature reviewed and recent findings. Many of these newer studies included published or available wayside noise level measurement data. These data have been, to the extent practicable, standardized and synthesized. They are available as a spreadsheet which accompanies this document (described further in Section 3).

The main objective of this work was to develop a database of rumble strip spectral data by collecting one-third octave band wayside noise levels for a variety of rumble strips. Five recent studies were reviewed and summarized in this report to create the database and provide an updated synthesis. The database contains spectral data for 23 unique rumble strips tested across these studies. In many cases, data were collected for multiple vehicles. A few studies collected data at varying speeds as well as receiver distances. All studies reported data using A-weighted maximum sound level (L_{Amax}), with the exception of one, which utilized unweighted one-second equivalent sound level (L_{eq}). While many studies used the same metric for collecting spectral data, drawing conclusions about differences between rumble strip designs across studies is difficult as there are many uncontrolled variables such as pavement type and temperature in each test that confound comparisons. In the process of reviewing the data from these studies, an updated research synthesis was created, containing a brief overall summary that is followed by summaries and key takeaways from each of the five studies.

1.1 Types of Rumble Strips

Similar to the 2013 report, the four main rumble strip designs studied in the research summarized in this addendum are milled, rolled, formed, and raised. The newer research studied variations on these four types. Milled rumble strips are implemented after the road has been fully paved. They are created by a machine that cuts grooves into the roadside in various designs and dimensions. One variation of the milled rumble strip is the sinusoidal rumble strip design which consists of sinusoidal waves cut into the pavement at varying depths, widths, and spacing. Rolled rumble strips consist of grooves that are pushed into the roadside directly after laying down the asphalt. The asphalt must not yet have set in order to allow the grooves to be pressed into the soft pavement. Formed rumble strips, similar to rolled, are also pressed into the pavement. However, formed rumble strips are only found in Portland cement concrete (PCC), not asphalt. Raised rumble strips can be made of various materials, most commonly rubber buttons or plastic strips, which are adhered to the road surface. [Turochy 2004, Torbic 2009, FHWA 2001 Cited Volpe 2013]



Figure 1. Applications of rumble strips. [Finley 2005, Outcalt 2001-2 Cited Cybulski 2013)

2. Summary of Research: 2013 to 2020

Prior to 2013, few research efforts had focused on measurements of environmental sound levels outside vehicles driving over the rumble strips (wayside sound levels). Authors of the previous synthesis study note that most focused on driver safety and alerting qualities; wayside sound level data were scarce and not standardized. Since that time, a number of studies (summarized below) have included efforts to collect wayside data, providing information that may be useful for evaluating noise levels for the surrounding area.

Consistent with previous literature, recent sources also indicate that sinusoidal (milled) rumble strips are more effective at reducing wayside noise levels than raised pavement or other milled rumble strips. In 2013, it was found that sinusoidal rumble strips appear the be the quietest type of rumble strip available for road applications, noting however, that these applications are not commonplace. FHWA (2017) states that cost of installation is higher – and may be a factor in how often states use the sinusoidal rumble strip. Since 2013, several studies have tested sinusoidal rumble strips and again, found them to be most effective at reducing wayside noise. These recent studies have tested sinusoidal rumble strips of varying depths, wavelengths, and widths to determine an optimal design.

It should be cautioned, however, that sinusoidal rumble strips generally provide less alerting stimulus than other strips via interior sound levels, especially for larger vehicles. In situations where alerting the driver is paramount, a standard milled (other than sinusoidal) or raised pavement rumble strip would generally outperform most sinusoidal rumble strips. This is further supported by the research of several studies below that show that the full impact of driver feedback from the sinusoidal rumble strip is only felt once the tire is fully on the strip. This is not the case for other milled and raised pavement rumble strips. In situations where wayside noise is a significant concern, a sinusoidal rumble strip would generally outperform all other options from an environmental noise perspective, while still producing sufficient interior sound levels to alert the driver. Per NCHRP Report 641, rumble strips should generate a 6 to 15 dBA increase above the ambient, in-vehicle sound level to provide sufficient operator warning. An in-vehicle interior sound level increase of 6 dB is recommended to alert the full range of target drivers, while 3 dBA is considered just perceptible enough to be considered a warning. Increases above 15 dBA have the potential to negatively startle the driver.

Variations of sinusoidal rumble strips were tested in all studies reviewed, other than the Washington DOT 2014 study. The Minnesota 2016 study, “Rumble Strip Noise Evaluation”, tested four variations of sinusoidal rumble strips and found that maintaining a maximum depth of 1/8” was effective in reducing wayside noise. They also noted that, while their designs were able to provide sufficient interior noise levels in passenger cars, they were at the bottom of the range of sufficient operator warning for a pickup truck and below the range for a dump truck. The Caltrans 2018 study, “Optimal Sinusoidal Mumble Strips versus Conventional Ground-in Rumble Strips”, also concluded that the sinusoidal mumble strip they tested was effective at reducing wayside noise while maintaining a sufficient interior noise level. While examining the 1/3 octave band spectrum of the wayside noise they noted a large peak

at 80 Hz for the sinusoidal rumble strip. They suggested that, in a future application, the wavelength of their rumble strip could be increased to 16 inches to reduce the frequency peak. This theoretical principle could be implemented to perhaps tune the rumble strips to any desired frequency at a particular vehicle speed.

Varying situations call for varying rumble strips. In areas with high truck volumes, a sinusoidal rumble strip would reduce exterior sound levels, but may not provide the operator with sufficient warning. On roadways trafficked mostly by passenger cars, a sinusoidal rumble strip would be effective at reducing wayside noise while also providing sufficient operator warning.

2.1 Report Summaries

The sections below provide a brief summary of the five reports reviewed, presented alphabetically by state. See also FHWA Public Roads Magazine (Jan/Feb 2017) for a summary of the Caltrans and Minnesota DOT research.[1]

2.1.1 Caltrans, 2018 Donavan

"Optimal Sinusoidal Mumble Strips versus Conventional Ground-in Rumble Strips" evaluated three types of rumble strips: a sinusoidal 'mumble' strip, a raised pavement marker, and a ground-in rumble strip (See Appendix A, strip A-C for specifications). All were tested with several vehicles including passenger cars, an SUV, and a dump truck. The authors concluded that the mumble strip reduced higher frequency exterior sound and the overall A-weighted exterior sound level as intended, while also providing a sufficient disturbance to provide operator warning. As shown in report Figure 34, the overall A-weighted interior sound level generated by the mumble and ground-in strips were within 4 dB of each other for all test vehicles. The mumble strip produced greater overall A-weighted interior sound levels in the Ford Expedition, Chevy Malibu, and Ford Fusion, while the ground-in rumble strips produced higher overall interior levels in the Honda Civic and the 4-yard dump truck.

As stated in report Section 6.2, the seat track and steering column acceleration on the mumble and ground-in strips exceeded the off-strip levels by at least 9 dB in all cases and the two strips were within 3 dB of each other. It was noted that, when tested for exterior noise, mumble strips reduced the overall A-weighed exterior wayside levels typically generated by conventional warning devices by 6.2 dB for passenger vehicles. While effective at generating lower overall A-weighted wayside levels and quieter mid to high frequency spectral content, "the mumble strip concept does generate narrow band lower frequency noise content that could be of concern to nearby residents." This may be of concern as lower frequencies have larger wavelengths and will propagate further. As demonstrated by the Ford Expedition, the mumble strip external spectral data exhibited a peak at 80 Hz that is up to 20 dBA above the other strips. The authors state that there may be a way to "further optimize the mumble strip design to lower the exterior noise corresponding to the fundamental and harmonics for the strip repetition rate

[1] https://www.fhwa.dot.gov/publications/publicroads/17janfeb/07.cfm

while maintaining adequate interior warning", such as increasing the wavelength to 16 inches, which would correspond to a lower fundamental frequency of 66 Hz at 60 mph. Altering the wavelength of the mumble strip tunes the fundamental frequency of the wayside noise for a particular speed.

2.1.2 Minnesota DOT, 2015 Terhaar & Braslau

"Rumble Strip Noise Evaluation" tested two sinusoidal and one milled rumble strip. The two sinusoidal rumble strips represented the California and Pennsylvania designs, while the milled rumble strip represented the Minnesota design (See Appendix A, strip D-F for specifications). This study tested both interior and exterior wayside sound levels at speeds of 30, 45 and 60 mph. The study showed a direct relationship between exterior noise levels and speed. The data further showed that the amplitude peaks, as a result of the fundamental frequency of the strips, occurred at lower frequencies when the vehicle was driving at slower speeds. The sinusoidal Pennsylvania design was found to have both lower interior and exterior sound levels. While still at a sufficient level, according to NCHRP Report 641, the sinusoidal Pennsylvania design was found to not perform as well as the sinusoidal California and milled Minnesota designs in alerting the driver. As stated on page 32 of the report, "On the (milled) Minnesota strip feedback to the driver occurred immediately upon contact with the rumble strip." This was not the case for the two sinusoidal rumble strips as "the full impact was not realized until the tire was fully on the rumble strip." In situations where immediate driver feedback is desired, a sinusoidal rumble strip may still provide sufficient interior noise levels, but will not provide as much warning as other conventional rumble strips. The conclusion of this study was that, of the three designs tested, the sinusoidal California design had the best exterior to interior sound level ratio as it was most effective at reducing wayside noise while still providing "adequate driver feedback".

2.1.3 Minnesota DOT, 2016 Terhaar, Braslau, & Fleming

"Sinusoidal Rumble Strip Design Optimization Study" tested variations of centerline sinusoidal rumble strips (See Appendix A, strip G-J for specifications). These tests were performed with a passenger car, a pickup truck, and a class 35 tandem dump truck. The study concluded that while all of the designs were comparable of creating sufficient interior noise levels, designs 1 (strip G) and 4 (strip J) produced lower exterior sound levels. The study found that external noise levels correspond to the depth of the rumble strip design. Designs 1 and 4 had a maximum depth of 1/8", while designs 2 and 3 had a maximum depth of ½". These data imply that a deeper rumble strip produces more exterior noise. Per NCHRP Report 641, a deeper rumble strip generally correlates to both louder interior and exterior noise while a shallower rumble strip produces less exterior and interior noise. Terhaar et al. stated that "the interior sound level increases are similar for all four designs but vary by vehicle type. All of the designs created overall interior sound level increases greater than 10 dBA for the passenger car, which is a desirable level for gaining attention of the driver. For the pickup truck, the overall interior sound level increases ranged from 4.5 to 6.8 dBA, while the increases for the dump truck ranged from 0.8 to 2.7 dBA." While sufficient for a passenger car, the interior sound level increases for a dump truck may not be perceptible to the operator. As shown in report Table 7.1, in most test cases design 4 was more

effective than design 1 at reducing exterior sound levels, while design 1 was generally more effective at increasing interior sound levels. Designs 2 and 3 performed very similarly producing louder interior and exterior sound levels than designs 1 and 4.

2.1.4 Washington DOT, 2018 Laughlin & Donahue

"Evaluation of New Rumble Strip Designs to Reduce Roadside Noise and Promote Safety" studied three additional milled cylinder rumble strips and a sinusoidal rumble strip, similar to the designs being used by Minnesota and California. See Appendix A, strips K-N for specifications. All tests were performed with a Ford Escape traveling at 60 mph. The milled cylinder designs maintained a depth of ¼" and a width of 6.9" while varying their length and spacing. As shown in report Table 5, the sinusoidal rumble strip produced an average LA_{max} overall exterior sound level of 82 dBA while the milled cylinder designs ranged from 88 to 93 dBA. This table also shows that milled cylinder design 2 produced the greatest increase in overall interior sound levels while also producing the lowest average exterior sound levels for a milled cylinder rumble strip. As noted on report page 30, all tested rumble strips "shared an 800 Hz dominant frequency and peaks at 80 and 160 Hz with some variations in where the peaks occurred and the relative sound levels of the peaks dependent upon the design." The report considered the sinusoidal and Design 1 rumble strips to be the highest performing of those tested because they produced the lowest overall exterior sound levels, a flatter 1/3 octave band curve with fewer peaks in the lower frequencies, and were within the acceptable range for interior sound levels.

2.1.5 Washington DOT, 2014 Sexton

"Evaluation of Current Centerline Rumble Strip Design(s) to Reduce Roadside Noise and Promote Safety" evaluated the designs of several milled cylinder rumble strips (see Appendix A, strips O-W). Each rumble strip had a different combination of depth, width, length, and spacing, yielding varying interior and exterior sound level increases. All tests were performed with a Ford Escape traveling at 60 mph. As stated on page 37 of the report, an acceptable range for increases in interior sound level is "generally considered to be between 6 to 15 dBA, with a preference for levels nearer the maximum." The rumble strips found on SR 410 were found to increase interior sound levels by 14 dBA and SR 6 by 11 dBA. While these increases are considered to be loud, increases in overall interior sound level on SR 202 were measured in excess of 15 dBA which is considered to have the potential to negatively startle the driver. When tested for overall exterior sound level, SR 410 performed the best, with the lowest exterior sound level, followed by SR 6 and SR 202. The 1/3 octave band spectrum of exterior sound levels showed that the majority of the measured designs, including SR 410, SR 6, and SR 202 shared an 800 Hz dominant frequency. The study concluded that SR 410 and SR 6 should be considered the highest performing of the measured sections because they share the characteristics of having the lowest overall exterior sound level, the flattest 1/3 octave band spectra, the lowest standard deviation among samples, and sufficient overall interior sound level.

3. Accompanying Data

From each of the five reports reviewed, test data were extracted and entered into the accompanying spreadsheet. Among the studies, the test data were collected with diverse vehicles driving at several speeds and measured at varying receiver distances. Where possible, data collected at the same receiver distance, vehicle speed, and/or noise metric were grouped together in a single data table.

The attached spreadsheet has 4 tabs; a Notes tab, a 25' data tab, a 50' data tab, and a 50' data tab organized by speed. All tests were conducted at 60 mph except those found in the 50' data tab organized by speed. One-third octave-band data are generally reported for the frequency range of 31.5 Hz – 16 kHz, with some rumble strip data reported at a more limited frequency range. The Notes tab contains the table found in Appendix A, which provides a reference for rumble strip properties.

The vehicles used to test the rumble strips varied in each study. Caltrans used a Honda Civic, Chevy Malibu, Ford Expedition, Ford Fusion, and a Dump Truck. Minnesota DOT used a Chevy Malibu, Chevy Silverado, and a Volvo tractor trailer in 2015 and a Ford Fusion, Ford F-150, and a Sterling Class 35 tandem in 2016. Washington DOT used a Ford Escape for their 2014 and 2018 studies.

In the 2015 Minnesota DOT report, "Rumble Strip Noise Evaluation", there was a direct relationship between speed and exterior sound levels resulting from the rumble strips. The majority of the rumble strip data collected through all five studies were collected with vehicles driven at 60 mph. Each rumble strip may perform differently at different speeds and with different vehicles so it is important to look for trends when considering the data. For example, Strip D consistently exhibited low frequency peaks at 30, 45, and 60 mph and it is evident that the frequency of the peak is dependent on the vehicle speed. The data also show that sinusoidal rumble strips generally have low frequency peaks (Strips A, D, G, H, I, K), some with higher amplitudes than others, but tend to exhibit a lower amplitude in the mid to high frequency range.

Spectral data from the 2018 study, "Optimal Sinusoidal Mumble Strips versus Conventional Ground-in Rumble Strips", were extracted from graphs within the report using WebPlotDigitizer. In a 2016 study at Central Michigan University, the WebPlotDigitizer was found to be an accurate tool for extracting graphed data.[2]

Like other pavement-related noise, tire size, stiffness and loading will affect the tire/pavement interaction and thus the noise generated. Because the data reviewed utilize only a few vehicles, the mean value for a wider population of vehicles may deviate from the values found utilizing the data in this document and the accompanying spreadsheet. Similarly cautions should be made regarding the dominant vehicle type that may be engaging with roadway rumble strips. This affects not only the considerations related to environmental noise but also the alerting quality to the drivers of the vehicles.

[2] https://journals.sagepub.com/doi/10.1177/0145445516673998

Finally, users should remember that most of these data were collected at 60 mph. there is only a limited amount of data at other speeds, but these data do show speed dependence, which, due to the low sample size, is not clearly defined. Therefore, users of these data should proceed with caution when modeling for conditions not represented by the underlying data (vehicle speed, rumble strip design, or vehicle type).

4. Bibliography

(Caltrans, Donavan 2018) "Optimal Sinusoidal Mumble Strips versus Conventional Ground-in Rumble Strips"

Format: Technical Report

Key Words: Sinusoidal Mumble Strip, Raised Pavement Marker, Ground-in Rumble Strip, Interior and Exterior Noise, Seat Track/Steering Column Acceleration, LA_{max}

Key Findings: The sinusoidal mumble strip was effective at reducing overall A-weighted wayside levels compared to conventional warning devices, but did create a narrow band low frequency peak that could be of concern to nearby listeners.

(Minnesota DOT, Terhaar & Braslau 2015) "Rumble Strip Noise Evaluation"

Format: Research Report

Key Words: Sinusoidal Rumble Strip, Interior and Exterior Noise, Varying Speeds, one second L_{eq}

Key Findings: The California design was most effective in reducing wayside noise while providing sufficient operator warning. The full impact of operator warning provided by sinusoidal rumble strips is not felt until the tire is fully over the rumble strip.

(Minnesota DOT, Terhaar, Braslau, & Fleming 2016) "Sinusoidal Rumble Strip Design Optimization Study"

Format: Research Report

Key Words: Sinusoidal Rumble Strips, Interior and Exterior Noise, one second L_{eq}

Key Findings: Sinusoidal rumble strip designs 1 and 4 produced lower exterior sound levels while still creating interior levels similar to designs 2 and 3. Designs 1 and 4 were more effective at reducing wayside noise as a result of their groove depth (1/8" groove depth is more effective than ½")

(Washington DOT, Laughlin & Donahue 2018) "Evaluation of New Rumble Strip Designs to Reduce Roadside Noise and Promote Safety"

Format: Research Report

Key Words: Sinusoidal Rumble Strips, Milled Cylinder Rumble Strip, Interior and Exterior Noise, LA_{max}

Key Findings: Through testing one sinusoidal and three milled cylinder rumble strips, the sinusoidal strip, SR 155, and milled cylinder strip, Design 1, were found to be the highest performing of the measured strips. This is because they produced the lowest overall exterior sound levels, a flatter 1/3 octave band curve with fewer peaks in the lower frequencies, and were within the acceptable range for interior sound levels.

(Washington DOT, Sexton 2014) "Evaluation of Current Centerline Rumble Strip Design(s) to Reduce Roadside Noise and Promote Safety"

Format: Research Report

Key Words: Milled Cylinder Rumble Strip, Interior and Exterior Noise, L_{Amax}

Key Findings: The study tested a variety of milled cylinder rumble strips with a different combination of depth, width, length, and spacing. The study concluded that SR 410 and SR 6 should be considered the highest performing of the measured sections because they share the characteristics of having the lowest overall exterior sound level, the flattest 1/3 octave band spectra, the lowest standard deviation among samples, and sufficient overall interior sound level.

5. References

Volpe 2013 Jonathan Cybulski, Judith Rochat, and David Read. *Synthesis of Noise and Bicycle Research.* US DOT/Volpe Center. 55 Broadway Cambridge, MA 02142. (2013)

Drevon 2016 Daniel Drevon, Sophie R. Fursa, and Allura L. Malcolm. *Intercoder Reliability and Validity of WebPlotDigitizer in Extracting Graphed Data.* Central Michigan University. Sloan 101 Mount Pleasant, MI 48859. (2016)

FHWA 2017 Lisa Kinner Bedsole, Ken E. Johnson, and Cathy Satterfield. *Did You Hear That?.* Federal Highway Administration Publication No. FHWA-HRT-17-002, Vol 80 No 4. (2017)

NCHRP 2009 Transportation Research Board. *Guidance for the Design and Application of Shoulder and Centerline Rumble Strips.* Report 641. Washington, DC 20001. (2009)

Appendix A

Rumble Strip Identification Table

	Name	Studied By, Year	Strip Type	Specs/Notes	Metric
Strip A	Mumble Strip	Caltrans, 2018	Sinusoidal	14" center to center, 5/16" depth	LAmax
Strip B	Ground-in Rumble Strip	Caltrans, 2018	Ground-In	12" center to center, 3/4" depth, 4" wide	
Strip C	Raised Pavement Marker	Caltrans, 2018	Raised Pavement	12" center to center, 5/16" depth, 5" wide	
Strip D	California Design	MnDOT, 2015	Sinusoidal	14" center to center, 1/32 - 5/8" depth, 8" wide	L_{eq}
Strip E	Pennsylvania Design	MnDOT, 2015	Sinusoidal	24" center to center, 1/8 - 1/2" depth, 8" wide	
Strip F	Minnesota Design	MnDOT, 2015	Milled	12" center to center, 3/8 - 1/2" depth, 16" wide	
Strip G	Design 1	MnDOT, 2016	Sinusoidal	14" center to center, 1/16 - 3/8" depth, 14" wide	
Strip H	Design 2	MnDOT, 2016	Sinusoidal	14" center to center, 1/16 -1/2" depth, two 8 inch wide rumble strips seperated by 4 inches	
Strip I	Design 3	MnDOT, 2016	Sinusoidal	14" center to center, 1/16 - 1/2" depth, 14" wide	
Strip J	Design 4	MnDOT, 2016	Sinusoidal	14" center to center, 1/16 - 3/8" depth, two 8 inch wide rumble strips seperated by 4 inches	
Strip K	SR 155	WashDOT, 2018	Sinusoidal	16" center to center, 1/2" depth, 12" wide	LA_{max}
Strip L	SR 24 - Design 1	WashDOT, 2018	Milled Cylinder	8" length, 1/4" depth, 6.9" width, 18" spacing	

Strip M	SR 24 - Design 2	WashDOT, 2018	Milled Cylinder	12" length, 1/4" depth, 6.9" width, 12" spacing	
Strip N	SR 24 - Design 3	WashDOT, 2018	Milled Cylinder	12" length, 1/4" depth, 6.9" width, 18" spacing	
Strip O	SR 06	WashDOT, 2014	Milled Cylinder	8" length, 1/2" depth, 6.9" width, 12" spacing	
Strip P	SR 12	WashDOT, 2014	Milled Cylinder	12" length, 1/2" depth, 6.9" width, 24" spacing	
Strip Q	SR 14	WashDOT, 2014	Milled Cylinder	10" length, 1/2" depth, 6.9" width, 12" spacing	
Strip R	SR 28	WashDOT, 2014	Milled Cylinder	12" length, 3/8" depth, 6.9" width, 24" spacing	
Strip S	SR 97	WashDOT, 2014	Milled Cylinder	8" length, 3/8" depth, 6" width, 18" spacing	
Strip T	SR 202	WashDOT, 2014	Milled Cylinder	12" length, 1/2" depth, 6" width, 12" spacing	
Strip U	SR 203	WashDOT, 2014	Milled Cylinder	12" length, 1/2" depth, 6" width, 12" spacing	
Strip V	SR 410	WashDOT, 2014	Milled Cylinder	8" length, 3/8" depth, 6" width, 12" spacing	
Strip W	SR 507	WashDOT, 2014	Milled Cylinder	6" length, 3/8" depth, 6" width, 12" spacing	

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