

NCHRP PROJECT 15-68(01)
EFFECTIVE LOW-NOISE RUMBLE STRIPS

APPENDIX A:
Review of Literature and Current Practices

Prepared for
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APPENDIX A

REVIEW OF CURRENT PRACTICES

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INTRODUCTION

This appendix contains the NCHRP Rumble Strip Project literature review and state-of-practice review, completed in 2018 and including 90 national and international references.

LITERATURE REVIEW

Roadway departure warning indicators, also known as rumble strips, are a proven safety countermeasure intended to alert drivers when they leave the roadway across the edge line or center line. Center line rumble strips (CLRSs) are used to reduce head-on, opposite-direction sideswipe crashes and lane departure crashes, and shoulder rumble strips (SRSs) and edge-line rumble strips or stripes (ELRSs) are used to reduce roadway departure crashes. Rumble strips are constructed in/on pavement as longitudinal patterns of variable surface profile, which alert the driver with both an audible noise and tactile vibration.¹

Rumble strips have received a considerable amount of attention in recent years, particularly from a safety and noise point of view. Recent analysis by FHWA has found that around half of the roadway fatal crashes occur from lane departures.² About 44% of these roadway departures (RwD) are attributable to drivers leaving the road in the direction of the shoulder leading to rollovers and tree collisions. About 26% are due to head-on collisions where the vehicle drifts over the centerline of two-lane roads. Beginning in the mid-2000's, RwD fatalities reduced as more agencies began to install edge and center rumble devices. The downward trend has flattened since 2010, however, and RwDs still account for about half of all fatalities. In this same time frame, state agencies have become increasingly aware of noise concerns generated by rumble strips both due to complaints from people living in the vicinity of rumble strips as well as concerns about noise effects on protected species. As a result of these two apparent conflicting needs, reducing RwD crashes and lowering noise, state agencies have recently been conducting research on low noise rumble strips. Results of the various research studies are described in this literature review.

The two primary types of rumble strips are listed below and shown in Figure A-1. **Error! Bookmark not defined.**³ Also shown in the figure are two older types of rumble strips: rolled (grooves pushed into hot asphalt pavements) and formed (similar to rolled, but pressed into portland cement concrete pavement).

¹ Himes, S., H. McGhee, S. Levin, and Y. Zhou, *State of Practice for Shoulder and Center Line Rumble Strip Implementation on Non-Freeway Facilities*, Report No. FHWA-HRT-17-012, Federal Highway Administration, 2017.

² J. Rochat, C. Satterfield, B. Rymer, and P. Donovan, "Highway Rumble Strips: Approaches to Balancing Public Safety and Community Noise", Transportation Research Board Webinar, TRB ADC40 Committee, Transportation-Related Noise and Vibration, Tuesday, March 28, 2017.

³ FHWA online rumble strip guidance: http://safety.fhwa.dot.gov/roadway_dept/pavement/rumble_strips/, 4/11/2019.

- Milled (most common): created by a machine that cuts grooves in asphalt and concrete pavements in various designs and dimensions; traditional are rectangular, cylindrical, or football-shaped, and newer are sinusoidal (discussed more in Section 2.1).
- Raised: most common are rubber buttons or plastic strips adhered to a pavement surface, usually restricted to warmer climates that don't require snow removal.

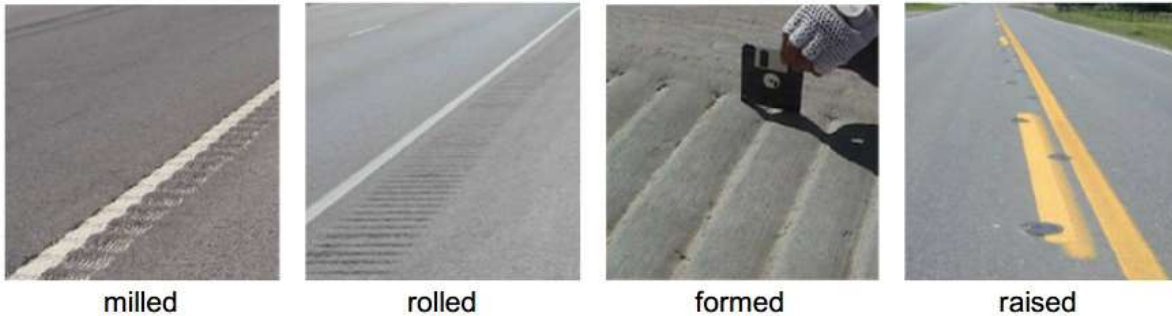


Figure A-1: Basic Types of Rumble Strips^{Error! Bookmark not defined.}^{4,5}

To help understand the parameters involved with rumble strip design, Figure A-2 shows a vehicle in relation to a shoulder rumble strip. Figure A-2 depicts standard design parameters for rumble strips, including: (A) offset, (B) length (perpendicular width), (C) width (parallel), (D) depth, (E) spacing, (F) recovery area, (G) gap, (L) lateral clearance, and (α) departure angle. An additional parameter, (H) height, is commonly used, but not indicated in the figure.

For both traditional and newer types of rumble strips, some parameters can be optimized to minimize noise and maximize bicycle safety. The following design parameters should be considered for a *traditional type of rumble strip* (assumes rectangular) to minimize noise and maximize bicycle safety, understanding that there may be limitations based on what a particular facility can accommodate. Additional information about traditional rumble strips and associated noise studies can be found in the National Park Service synthesis report.²

- Offset (A): include it to minimize accidental strikes; literature suggests 0.3 m (1 ft) outward from the edge of the travel lane and 1.2 m (4 ft) inward from the pavement edge to provide enough lateral clearance (L) for bicycles.
- Length (perpendicular width) (B): short, ≤ 20.3 cm (8 in), although it should be determined if this width allows wide truck tires to engage enough to receive the full effect. For some designs, this is discussed as the perpendicular width (perpendicular to travel lane).

⁴ Torbic, D.J., J.M. Hutton, C.D. Bokenkroger, K.M. Bauer, D.W. Harwood, D.K. Gilmore, J.M. Dunn, J.J. Ronchetto, E.T. Donnell, H.J. Sommer III, P. Garvey, B. Persaud, and C. Lyon, *Guidance for the Design and Application of Shoulder and Centerline Rumble Strips*, NCHRP Report 641, Transportation Research Board, Washington, DC, 2009.

⁵ Turochy, R., "Shoulder Rumble Strips: Evolution, Current Practice, and Research Needs," Transportation Research Board 2004 Annual Meeting, Paper No. 04-3448, 2004.

- Width (parallel) (C): narrow, 20.3 cm (8 in); this width is in the direction parallel to the travel lane.
- Depth (D): shallow, 6 mm (0.25 in), which is the most conservative regarding bicycle safety – up to 10 mm (0.375 in) may be safe according to some studies to minimize noise and bicycle discomfort.
- Spacing (E): large, 0.6 m (2 ft); affects pitch of tonal aspects of associated noise.
- Gap (G): 3.7 m for every 7.3 m (12 ft for every 60 ft), to allow bicycles to cross.

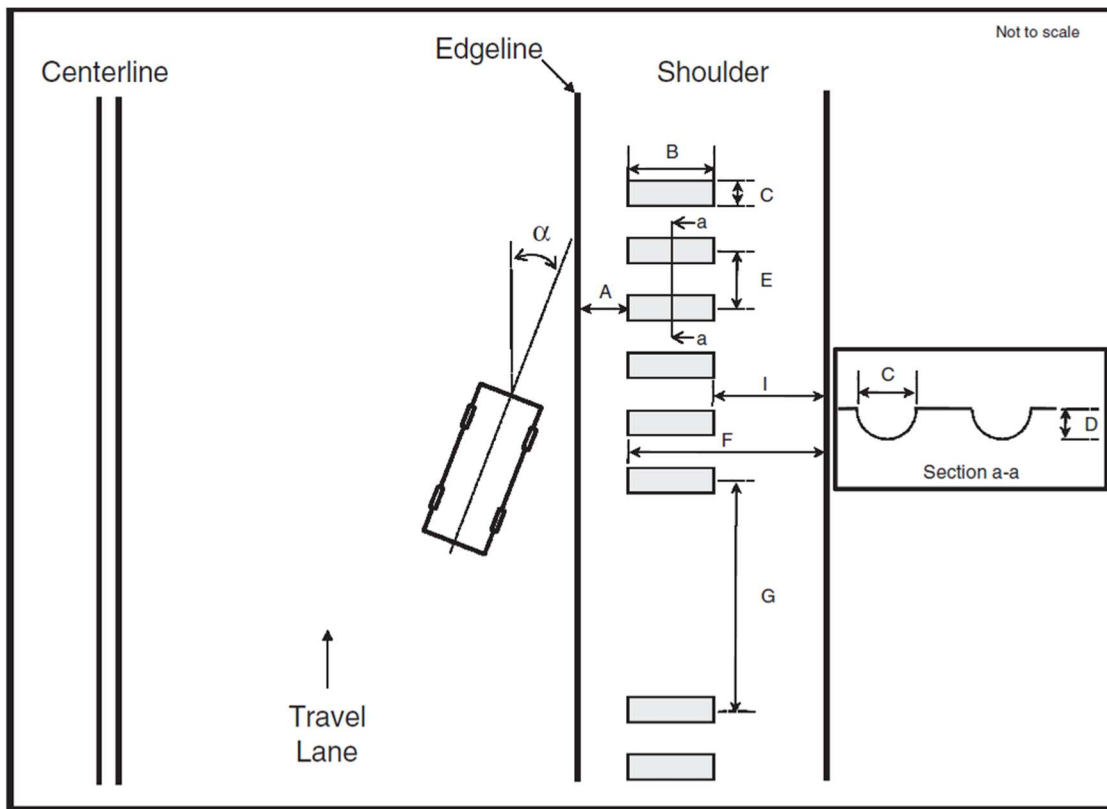


Figure A-2: Standard Design Parameters for Rumble Strips⁶

Design parameters for sinusoidal rumble strips, a low-noise rumble strip design, are discussed in the next section. The recommendations to accommodate bicycles for a traditional design also apply to sinusoidal rumble strips.

⁶ Torbic, D.J., J.M. Hutton, C.D. Bokenkroger, K.M. Bauer, D.W. Harwood, D.K. Gilmore, J.M. Dunn, J.J. Ronchetto, E.T. Donnell, H.J. Sommer III, P. Garvey, B. Persaud, and C. Lyon, *Guidance for the Design and Application of Shoulder and Centerline Rumble Strips*, NCHRP Report 641, Transportation Research Board, Washington, DC, 2009.

The most current FHWA guidance on rumble strips can be found on their related website.⁷ A review of the state of practice can be found in the 2017 FHWA report *State of Practice for Shoulder and Center Line Rumble Strip Implementation on Non-Freeway Facilities*.⁸

The following sections discuss more details on low-noise rumble strips (Section 2.1), bicycle and motorcycle safety (Section 2.2), rumble strip effects on the community and drivers (Section 2.3), and rumble strip noise and vibration data collection (Section 2.4).

SINUSOIDAL LOW-NOISE RUMBLE STRIPS

Summary: Studies in the UK, Denmark, California, Minnesota, Indiana, and Oregon have shown that a rumble strip with a sinusoidal shape can reduce exterior noise levels compared to conventional designs. Generally, sinusoidal rumble strips with wavelengths much greater than 0.35 m (14 in) may not produce sufficient increase in noise and vibration inside the vehicle to alert drivers and sinusoidal rumble strips with wavelengths much less than 0.35 m (14 in) may not provide as much roadside noise benefit. Studies that have included heavy trucks have shown that sinusoidal rumble strips may not alert those vehicles sufficiently, but one study suggests a wider rumble strip may improve the results. Shallower rumble strips produce lower noise levels both inside and outside the vehicle. An optimal depth is not readily apparent; it is expected that testing as part of NCHRP 15-68 will help to define it. The different studies have used different design parameters (wavelength, depth, and perpendicular width), different vehicles, and different measurement set-ups which makes direct comparisons among measurement results difficult.

To-date, the most promising low-noise rumble strip design philosophy has been sinusoidal shapes ground into the pavement surface. Examples of longitudinal profiles for conventional and sinusoidal designs are seen in Figure A-3. In the 2000's, European research indicated that lower pass-by noise levels could be achieved with the sinusoidal design. Research in the U.S. followed, with several States testing sinusoidal rumble strips. Designs for the sinusoidal rumble strips for the various studies described in this section are detailed in Table A-1, along with the conventional rumble strip designs to which they were compared.

⁷ http://safety.fhwa.dot.gov/roadway_dept/pavement/rumble_strips/

⁸ Himes, S., H. McGhee, S. Levin, and Y. Zhou, *State of Practice for Shoulder and Center Line Rumble Strip Implementation on Non-Freeway Facilities*, Report No. FHWA-HRT-17-012, Federal Highway Administration, 2017.

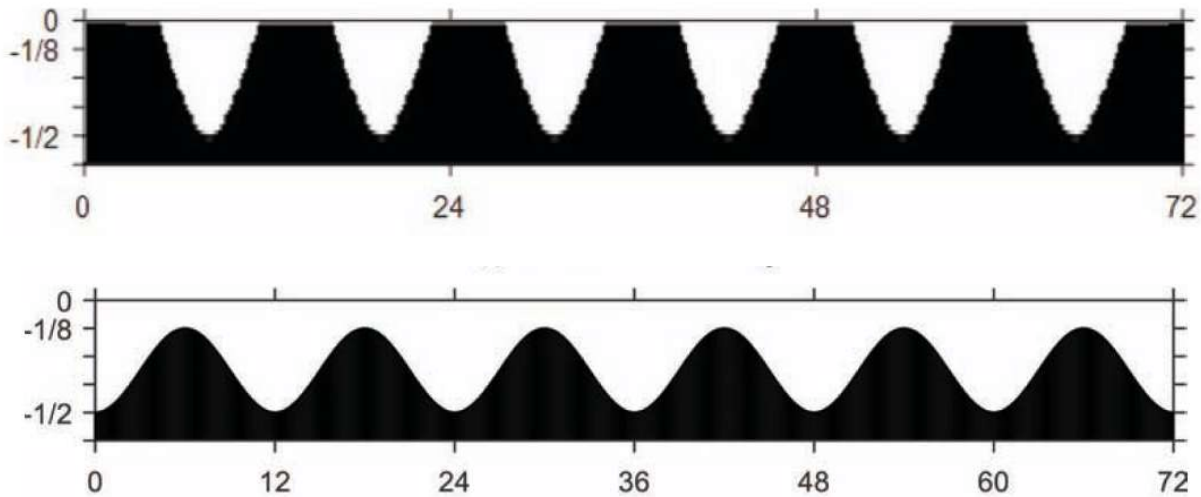


Figure A-3: Longitudinal Cross-sections of Rectangular (top) and Sinusoidal (bottom) Rumble Strips⁹

In the early 2000's, TRL (formerly the UK's Transport Research Laboratory) documented the design and evaluation of a sinusoidal traffic calming surface aimed at lowering pass-by noise levels.^{10, 11} The traffic calming surfaces were wide strips installed in the middle of lanes to alert drivers to lower speeds; the study did not look at rumble strips designed to reduce roadway departures. At the TRL facility, sinusoidal designs with multiple wavelengths were examined, ranging from 0.05 to 4.41 m (1.97 to 174 in). Peak-to-peak amplitudes ranged from 4.14 to 15 mm (0.16 to 0.59 in). The design with a wavelength of 0.35 m (13.8 in) and peak-to-peak amplitude of 6-7 mm (0.24-0.28 in) produced the most desirable effects and was chosen for a public road trial. It was generally found to produce large increases in interior noise and vibration in a range of vehicle types. It also creates little increase in exterior noise levels compared to smooth roadway. Generally, surfaces with wavelengths less than 0.35m (13.8 in) produced appreciable increases in exterior noise, and those with longer wavelengths did not produce enough increase in interior noise and vibration to alert drivers.

In 2007, The Danish Road Institute published results that demonstrated lower pass-by noise levels for sinusoidal rumble strips compared to rectangular rumble strips in the middle of two-

⁹ Mathew, J. K., A.D. Balmos, D. Plattner, T. Wells, J.V. Krogmeier, and D.M. Bullock D.M., *Assessment of alternative sinusoidal rumble strip construction*, Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2018/05, West Lafayette, IN, Purdue University, 2018. <https://doi.org/10.5703/1288284346648>

¹⁰ Watts, G., R. Stait, N. Godfrey, and R. Layfield, "Optimisation of Traffic Calming Surfaces," Proceedings of Inter-Noise 2001, The Hague, The Netherlands, August 2001.

¹¹ Watts, G., R. Stait, N. Godfrey, L. , and R. Layfield, "Development of a novel traffic calming surface 'Rippleprint'," TRL Report TRL545, 2002.

lane rural roads.^{12, 13} The Danish Road Institute Study evaluated sinusoidal rumble strips of two depths [7 mm (0.28 in) and 4 mm (0.16 in) peak-to-peak] and found that the sinusoidal rumble strips resulted in lower community noise levels compared to the rectangular rumble strips for both depths (results similar and preference not stated). The sinusoidal rumble strips had a long wavelength of 0.6 m (23.6 in) and no interior noise data were collected. The rumble strips with sinusoidal shape led to a 0.5 to 1 dB increase in wayside noise level compared to smooth pavement, while cylinder-segment indentations gave an increase of 2-3 dB and rectangular indentations gave an increase of 3-7 dB. Three different passenger cars were used for the measurements.

In 2009, Caltrans sponsored research into developing an optimum sinusoidal design for rumble strips with the intent of reducing exterior noise and maintaining or increasing interior noise and vibration. The recommended sinusoidal design was a wavelength of 0.356 m (14 in) and a peak-to-peak amplitude of 7.94 mm (0.3125 in). The design was based on tire geometry and response and knowledge of vehicle dynamics. The design was installed in northern California and tested in 2012 and 2015.^{14, 15} The design achieved its purposes, demonstrating reduced pass-by levels compared to conventional rumble strips. Wayside sound was reduced by 6.2 dB averaged for three different passenger vehicles and 3.2 dB for a dump truck compared to conventional rumble strips. The design has since been patented by Caltrans. Interior noise and vibration differences between on and off the sinusoidal strips were over 13 dB and within 1 dB of the conventional strips.

Since that time, Minnesota, Indiana, and Oregon State Departments of Transportation have evaluated a variety of sinusoidal designs that also demonstrate improvement over conventional rumble strips.^{16, 17, 18, 19, 20} Table A-1 summarizes the types of rumble strips evaluated in their

¹² Kragh, J., B. Andersen, and S. Thomson, "Low Noise Rumble Strips on Roads – a Pilot Study", Proceedings of Inter-Noise 2007, Istanbul, Turkey, August 2007.

¹³ Kragh, J., B. Andersen, and S. Thomson, *Traffic Noise at Rumble Strips – Internoise paper 2007*, Danish Road Institute Report 156, 2007.

¹⁴ Donavan, P. and B. Rymer., "Design and Evaluation of Quieter Highway Rumble Strips," Proceedings of Inter-Noise 2013, Innsbruck, Austria, September 2013.

¹⁵ Donavan, P., *Design and Acoustic Evaluation of Optimal Sinusoidal Mumble Strips versus Conventional Ground-In Rumble Strips*, California Department of Transportation Report No. CTHWANP-RT-15-365.01.2, 2018.

¹⁶ Terhaar E. and D. Braslau, *Sinusoidal Rumble Strip Noise Evaluation*, No. MN/RC 2015-07, Minnesota Department of Transportation, St. Paul, MN 2015.

¹⁷ Terhaar, E., D. Braslau, and K. Fleming, *Sinusoidal Rumble Strip Design Optimization Study*, Minnesota Department of Transportation Report No. MN/RC 2016-23, 2016.
<http://www.dot.state.mn.us/research/TS/2016/201623.pdf>

¹⁸ Mathew, J. K., A.D. Balmos, D. Plattner, T. Wells, J.V. Krogmeier, and D.M. Bullock D.M., *Assessment of alternative sinusoidal rumble strip construction*, Joint Transportation Research Publication No. FHWA/IN/JTRP-2018/05, West Lafayette, IN, Purdue University, 2018. <https://doi.org/10.5703/1288284346648>

¹⁹ Horne, D., C. Monsere, S. Kothuri, D. Hurwitz, and K. White, "Evaluating the Performance of Sinusoidal Rumble Strips," Transportation Research Board Committee on Transportation-Related Noise and Vibration Summer Meeting, June 2018.

²⁰ Hurwitz, D., D. Horne, H. Jashami, C. Monsere, and S. Kothuri, *Quantifying the performance of low-noise rumble strips*, Joint Oregon Department of Transportation and Federal Highway Administration, Report No. SPR 800, Joint Oregon State University and Portland State University, publication pending 2018.

studies. Each study used a different test set-up for the collection of noise and vibration data, so we cannot make direct comparisons in the pass-by noise benefit for the different rumble strip designs.

The Minnesota study evaluated six different sinusoidal rumble strip designs on a test track, and four different rumble strip designs in the field (only the designs evaluated in the field are included in Table A-1). For the field evaluation, they used a constant wavelength of 0.356 m (14 in) and varied the depth and perpendicular width of the rumble strips, as shown in Table A-1. The study concluded that the exterior noise levels were lower for the shallower rumble strip design; however, the data indicated the interior noise levels may not be sufficiently high in pickups and trucks with the shallower design. A 0.356 m (14 in) wide strip was preferred to the two parallel 0.203 m (8 in) wide strips based on an evaluation of bicycles and motorcycles. In the passenger car, the sinusoidal rumble strip noise increased interior noise levels by at least 12 dB for all designs and increased exterior noise levels by less than 7 dB for all designs compared to smooth pavement.

The Indiana study evaluated sinusoidal rumble strips with three different wavelengths and kept a constant depth and perpendicular width. The results indicate that the longer wavelength designs of 0.457 m (18 in) and 0.610 m (24 in) do not adequately increase in-cabin sound levels to alert the driver, but the 0.305 m (12 in) design adequately increases in-cabin sound levels while minimizing exterior sound levels. The 0.305 m (12 in) sinusoidal rumble strips were found to be 5 to 11 dB quieter than conventional strips at the roadside and were found to produce a sound level increase of 4 to 12 decibels compared to baseline road noise. The measurements were conducted with six different test vehicles ranging from a passenger car to a semi-truck at a speed of 80 kph (50 mph).

The Oregon study evaluated one 0.406 m (16 in) wavelength sinusoidal rumble strip and one conventional rounded (or cylindrical) rumble strip for three vehicle types: passenger car, minivan, and heavy vehicle. The sinusoidal rumble strip was wider (perpendicular to travel direction), but shallower, than the conventional rumble strip. The results showed that for the passenger car and van, the roadside noise was less when striking the sinusoidal design compared to the rounded design. The results also showed that interior noise was less when striking the sinusoidal design for the passenger car and the minivan. The dual-tire heavy vehicle did not generate high exterior or interior noise with the rounded rumble strip. The wider sinusoidal rumble strip generated a sufficient interior alert for the heavy vehicle (6.8 dB) indicating that a wider rumble strip may be an effective design for heavy vehicles. For the passenger car, the increase in roadside noise was 5.4 dB for the rounded strip and 3.1 dB for the sinusoidal design, compared to standard pavement. For the minivan, the increase in roadside noise was 4.6 dB for the rounded strip and -0.2 dB for the sinusoidal strip. For the heavy vehicle, the increase in roadside noise was 2.2 dB for the rounded design and 5.7 dB for the wider sinusoidal design.

As discussed for the Danish Road Institute study, the sinusoidal rumble strips had a long wavelength of 0.6 m (23.6 in) and no interior noise data were collected. The TRL study, Indiana

study, and California study conclude that longer wavelengths (as used in the Danish study) likely generate insufficient interior noise and vibration.

Florida Roadway Design Bulletin 18-03 identifies sinusoidal rumble strips as an appropriate alternative to conventional cylindrical ground-in rumble strips for noise sensitive areas.²¹ The bulletin states that the expected increase in noise levels over typical road noise is approximately 6 decibels for cylindrical ground-in rumble strips and approximately 4 decibels for sinusoidal ground-in rumble strips; however, data from a noise study was not presented to corroborate the results. The Florida Design Manual for sinusoidal rumble strips indicates a wavelength of 0.356 m (14 in) and a depth of 7.94 mm (5/16 in).²²

A Swedish study notes external noise was found to be lower for sinusoidal rumbles strips compared to conventional strips at 90 km/h²³ (56 mph). The effects were studied using cars, and their effects have not been studied for heavy vehicles. The paper did not describe the design parameters (wavelength, depth or length/perpendicular width) of the conventional or sinusoidal rumble strips from the study.

Table A-1: Summary of Design Parameters used in Sinusoidal Rumble Strip Studies

Location	Type of Rumble Strip	Wavelength	Depth	Length/ Perpendicular Width
United Kingdom	Sinusoidal traffic calming surface	0.35 m (13.8 in)	6.62 mm (0.26 in) peak to peak	3 m (118 in)
Denmark	Segment of cylinder	0.6 m (23.6 in), cylinder diameter = 0.15 m (5.9 in)	10 mm (0.39 in)	0.3 m (11.8 in)
	Sinusoidal	0.6 m (23.6 in)	7 mm (0.28 in) peak to peak	NA
	Sinusoidal	0.6 m (23.6 in)	4 mm (0.16 in) peak to peak	NA
	Rectangle	0.33 m (13 in), length of rectangle = 0.1 m (3.9 in)	4 mm (0.16 in)	NA

²¹ Shepard, M., “Audible and vibratory treatments (AVTs),” Roadway Design Bulletin 18-03, Florida Department of Transportation, March 2018.

²² Florida DOT Standard Plans - FY 2019-20. Index 546-010.
<http://www.fdot.gov/design/standardplans/Current/IDX/546-010.pdf>

²³ Vadeby, A. and A. Anund, “Effectiveness and acceptability of milled rumble strips on two-lane roads in Sweden,” Euro. Transp. Res. Rev, 9:29, 2017.

Location	Type of Rumble Strip	Wavelength	Depth	Length/ Perpendicular Width
	Rectangle	0.33 m (13 in), length of rectangle = 0.1 m (3.9 in)	8 mm (0.31 in)	NA
California	Sinusoidal	0.356 m (14 in)	8 mm (5/16 in) peak to peak	0.305 m (12 in)
	Conventional Ground (Cylinder)	0.305 m (12 in), length of cylinder = 0.102 m (4 in)	NA	0.305 m (12 in)
	Pavement Markers (Dots)	0.305 m (12 in)	Raised 25.4 mm (1 in)	0.102 m (4 in) diameter
Minnesota	Sinusoidal	0.356 m (14 in)	1.6 mm (1/16 in) depth at crest, 9.5 mm (3/8 in) depth at trough	0.356 m (14 in)
	Sinusoidal	0.356 m (14 in)	1.6 mm (1/16 in) depth at crest, 12.7 mm (½ in) depth at trough	Two 8 in wide rumble strips separated by 4 in
	Sinusoidal	0.356 m (14 in)	1.6 mm (1/16 in) depth at crest, 12.7 mm (½ in) depth at trough	0.356 m (14 in)
	Sinusoidal	0.356 m (14 in)	1.6 mm (1/16 in) depth at crest, 9.5 mm (3/8 in) depth at trough	Two 0.2 m (8 in) wide rumble strips separated by 0.1 m (4 in)
	Non-sinusoidal	NA	9.5 mm (3/8 in)	0.406 m (16 in)
Indiana	Sinusoidal	0.610 m (24 in)	3.2 mm (1/8 in) depth at crest, 12.7 mm (1/2 in) depth at trough	0.406 m (16 in) centerline, and 0.305 m (12 in) edge

Location	Type of Rumble Strip	Wavelength	Depth	Length/ Perpendicular Width
	Sinusoidal	0.457 m (18 in)	3.2 mm (1/8 in) depth at crest, 12.7 mm (1/2 in) depth at trough	0.406 m (16 in) centerline, and 0.305 m (12 in) edge
	Sinusoidal	0.305 m (12 in)	3.2 mm (1/8 in) depth at crest, 12.7 mm (1/2 in) depth at trough	0.406 m (16 in) centerline, and 0.305 m (12 in) edge
	Standard milled rumble strip	0.357 m (14 in), length of cylinder = 0.152 (6 in), approximate	12.7 mm (1/2 in)	NA
Oregon	Sinusoidal	0.406 m (16 in)	9.6 mm (3/8 in) at depth at trough, 1.6 mm (1/16 in) depth at crest	0.356 m (14 in)
	Rounded (Cylinder)	0.305 m (12 in)	12.7 mm (1/2 in) at trough, 0 mm at crest	0.241 m (9.5 in)
Florida	Sinusoidal	0.356 m (14 in)	7.94 mm (5/16 in)	0.203 m (8 in)
	Rounded (cylinder)	0.305 m (12 in), length of cylinder = 0.140 m (5.5 in)	4.76 mm (3/16 in)	0.203(8 in)

BICYCLE AND MOTORCYCLE SAFETY

Bicyclists and motorcyclists may have difficulty traversing rumble strips, particularly when designed to warn heavy truck drivers.²⁴ Designing an optimal rumble strip for alerting drivers

²⁴ Himes, S., H. McGhee, S. Levin, and Y. Zhou, *State of Practice for Shoulder and Center Line Rumble Strip Implementation on Non-Freeway Facilities*, Report No. FHWA-HRT-17-012, Federal Highway Administration, 2017.

and reducing wayside noise should consider bicyclist and motorcyclist safety. Effects on bicyclists and motorcyclists are described separately in the subsections below.

Bicycle safety

Summary: The main concern for bicyclists is to have designs/placement that allow for safe travel. This includes adequate space between the rumble strip and edge of road, gaps for crossing, and a maximum depth between 6 and 10 mm (0.25 and 0.4 in), based on conclusions from various studies.

While the main consideration for rumble strips is alerting motor vehicle drivers of lane departure, bicyclists can also be affected by the rumble strips, especially by the shoulder rumble strips. The National Park Service provides a review of the effects of rumble strips on bicyclists and design elements to help address issues.²⁵ Several experiments yielded the same result: the longer and deeper the rumble strips become, the more uncomfortable bicyclists will be and the more uncontrollable the ride when maneuvering over them. The reviewed material includes a study for the Kansas DOT²⁶ that states that bicyclists were surveyed and that the main fear they have when dealing with rumble strips is the amount of space on the shoulder not taken up by rumble strips. For riding over the rumble strips, 70% of the 23 participants preferred or somewhat preferred football-shaped rumble strips over rectangular ones. A study published in TRB's TRR²⁷ was conducted to determine if there was any danger associated with rumble strips. The results showed that participants found them to be annoying but not dangerous [the rumble strips evaluated were milled-in 18 cm (7 in) long, 13 mm (1/2 in) deep circular strips and narrower rectangular strips 13 mm (1/2 in) deep]. Another study in TRB's TRR²⁸ was done to determine the necessary gap in rumble strips in order for bicyclists to make a safe exit. The researchers determined that a gap of approximately 3.7 m (12 ft) should be permitted at an interval of every 12 to 18 m (40 to 60 ft) for optimal safety for bicyclists.

The League of American Bicyclists and the Alliance for Biking and Walking suggest these are the key elements of rumble strips in relation to bicycle safety:²⁹ perpendicular width or length (too wide limits space), depth (too deep makes travel dangerous), continuous (no gaps does not allow a safe way for bicyclists to cross), and placement (too far into shoulder leaves less space for travel). The following is recommended by the League and Alliance for

²⁵ Cybulski, J., J. Rochat, and D. Read, *Roadway Departure Warning Indicators: Synthesis of Noise and Bicycle Research*, Natural Resource Technical Report NPS/NSNS/NRTR—2013/780, U.S. Department of Interior, National Park Service, 2013.

²⁶ Gardner, L. W., M.J. Rys, E. Russell, *Comparison of Football Shaped Rumble Strips versus Rectangular Rumble Strips*, Report No. K-TRAN: KSU-00-4P2, Kansas Department of Transportation, 2007.

²⁷ Garder, P., "Rumble strips or not along wide shoulders designated for bicycle traffic?," *Transportation Research Record 1502: Journal of the Transportation Research Board*, 1995.

²⁸ Moeur, R., "Analysis of gap patterns in longitudinal rumble strips to accommodate bicycle travel," *Transportation Research Record 1705: Journal of the Transportation Research Board*, 2000.

²⁹ League of American Bicyclists, "Bicycling and rumble strips," *Advocacy Advance Project – a partnership between the League of American Bicyclists and the Alliance for Biking and Walking*.

bicycle safety (includes AASHTO and FHWA guidance):

- rumble strips should not be installed on popular bicycle routes or anywhere with insufficient shoulder width;
- the minimum clear space needed in a shoulder is 1.2 m (4 ft) from the edge of pavement or 1.5 m (5 ft) if a curb or guardrail is present;
- bicycle-tolerable rumble strips have the following dimensions: width 12.7 cm (5 in), depth 10 mm (0.375 in), and spacing 28.0 or 30.5 cm (11 or 12 in);
- and there must be gaps at regular intervals, at least 3.7 m (12 ft) every 12 or 18 m (40 or 60 ft).

For many state agencies, it is common to provide periodic gaps in shoulder rumble strips of 3 or 3.7 m (10 or 12 ft) in 12 or 18 m (40 or 60 ft) cycles, to allow bicyclists to maneuver from the travel lane to the shoulder without traversing the rumble strips. Also, a presentation prepared for the TRB annual meeting³⁰ states that a groove depth of 10 mm (0.375 in) replaced many agencies' 13 mm (0.5 in) standard depth to help make rumble strips less uncomfortable for bicyclists. FHWA discusses a survey that indicates 13 mm (0.5 in) depth grooves can cause severe control problems for bicyclists.

Studies have also been done in California, Colorado, Pennsylvania, and Great Britain to consider bicyclist comfort and controllability when designing shoulder rumble strips. For the Caltrans sinusoidal rumble strip, the design featured a full depth, peak-to-peak sinusoidal amplitude of 8 mm ($5/16$ in).³¹ This dimension was based on the information generated and reported by the Pennsylvania DOT and by the 2001 Caltrans study and the lack of bicycle gaps in the Caltrans design.³² From the PennDOT study, a range from 6 to 10 mm ($1/4$ to $3/8$ in) was found to be adequate or "bicycle-tolerant," with 6 mm ($1/4$ in) being preferred.³³ The Caltrans study found that rolled-in or ground-in indentations with a depth of 8 mm ($5/16$ in) were optimal for bicycle compatibility. The depth required to produce noticeable interior vehicle noise and vibration to alert drivers was not well documented in the literature;³⁴ however, the Colorado and Pennsylvania studies both showed that the most tolerable sites for bicyclists resulted in the

³⁰ Ahmed, M., M. Sharif, K. Ksaibati, and C. Planche, "Accommodation of bicyclists and nearby residents in rumble strips/stripes policies," Conference Proceedings of the Transportation Research Board Annual Meeting, 2016.

³¹ Donavan, P. and B. Rymer, "Design and Evaluation of Quieter Highway Rumble Strips," Proceedings of Inter-Noise 2013, Innsbruck, Austria, September 2013.

³² Bucko, T. and A. Khorashadi, "Evaluation of Milled-In Rumble Strips, Rolled-In Rumble Strips and Audible Edge Stripe," prepared by Traffic Operations Program, California Department of Transportation, Sacramento, California, May 2001.

³³ Elefteriadou, L., M. El-Gindy, D. Torbic, P. Garvey, A. Homan, Z. Jiang, B. Pecheux, and R. Tallon, *Bicycle-Tolerable Shoulder Rumble Strips*, Final Report Prepared for Commonwealth of Pennsylvania Department of Transportation, prepared by The Pennsylvania Transportation Institute, The Pennsylvania State University, University Park, PA, March 2000.

³⁴ Kragh, J., B. Andersen, and S. Thomson, *Traffic Noise at Rumble Strips – Internoise paper 2007*, Danish Road Institute Report 156, 2007.

lowest interior noise and vibration measurements in motor vehicles.³⁵ The Caltrans study found that a depth of about 8 mm ($\frac{5}{16}$ in) produced interior noise level increases over tire/pavement noise of about 6 dB or more with corresponding increases in vibration levels. From the NCHRP 641 Report, the standard metric for rumble strip design is that interior levels in the passenger compartment be 10 to 15 dB higher than ambient conditions on roadways where bicyclists are not expected, while 6 to 12 dB higher is standard for roadways where bicyclists are expected.³⁶ A small sample size evaluation of rumble strips in the MnDOT study indicated that all sinusoidal designs were preferable over the standard MnDOT non-sinusoidal design, which is very abrupt and jarring to bicycle riders.³⁷

In the U.K., the Transport Research Laboratory reported on bicycle safety for their optimal sinusoidal “rippleprint” rumble strip.³⁸ The peak to trough amplitude of an optimal rumble strip is 6.6 mm (0.3 in) and a wavelength of 0.35 m (13.8 in). Results showed that no handling problems were encountered, and the stopping distances appeared to be similar to the flat track surface. Some of the riders reported that the rumble strip surfaces were uncomfortable. It is recommended that adequate width of smoother surface in the shoulder should be retained.

In addition to a direct effect on bicyclists, rumble strips can also influence driver behavior in a way that can potentially be problematic for bicyclists. The presence of a center line rumble strip may cause vehicles to move away from the center line to avoid contact with the rumble strip, potentially moving these vehicles closer to bicyclists who may be traveling on the outer edge of the lane.³⁹

Motorcycle safety

Summary: In general, motorcyclists can safely traverse rumble strips. There may be some difficulty associated with raised strips or being unaware of centerline rumble strips. A maximum depth of 10 mm (0.375 in) is preferred.

FHWA provides a review of the effect of rumble strips on motorcycles.⁴⁰ The report reviews several studies. One found that both raised pavement markers and rumble strip bars become slick

³⁵ Outcalt, W., “Bicycle-Friendly Rumble Strips,” Report CDOT-DTD-R-2001-4, Colorado Department of Transportation, Denver, Colorado, 2001.

³⁶ Torbic, D.J., J.M. Hutton, C.D. Bokenkroger, K.M. Bauer, D.W. Harwood, D.K. Gilmore, J.M. Dunn, J.J. Ronchetto, E.T. Donnell, H.J. Sommer III, P. Garvey, B. Persaud, and C. Lyon, *Guidance for the Design and Application of Shoulder and Centerline Rumble Strips*, NCHRP Report 641, Transportation Research Board, Washington, DC, 2009.

³⁷ Terhaar, E., D. Braslau, and K. Fleming, *Sinusoidal Rumble Strip Design Optimization Study*, Report No. MN/RC 2016-23, Minnesota Department of Transportation, St. Paul, MN, 2016.

³⁸ Watts, G., R. Stait, N. Godfrey, L. Chinn and R. Layfield, “Development of a novel traffic calming surface ‘Rippleprint’,” TRL Report TRL545, 2002.

³⁹ Datta, T., P. Savolainen, T. Gates, J. Kay, N. Nicita, S. Parajuli, and J. Finkelman, *Evaluation of Non-Freeway Rumble Strips – Phase II*, Report No. RC-1627, Michigan Department of Transportation, Lansing MI, 2015.

⁴⁰ Himes, S., H. McGhee, S. Levin, and Y. Zhou, *State of Practice for Shoulder and Center Line Rumble Strip Implementation on Non-Freeway Facilities*, Report No. FHWA-HRT-17-012, Federal Highway Administration, 2017.

when wet. Another states that center line rumble strips do not pose a hazard to motorcyclists. Also, no steering, braking, or throttle adjustments were found during rumble strip crossing. Another study indicated that half the motorcyclists tested encountered handling problems, but only if unaware of their presence. It is suggested that signs such as “Centerline Rumble Strips Ahead” could warn motorcyclists of upcoming rumble strips.

The MnDOT study³⁷ evaluated motorcyclists, and a survey of these data indicated a preference for rumble strip designs that were 36 cm (14 in) wide (perpendicular to travel direction) with a maximum depth of 10 mm ($\frac{3}{8}$ in).⁶ The study also indicated concern about raised strips and tapered edges, preferring a straight edge.

The same 1995 TRR study that examined bicycle safety also examined motorcycle safety.⁴¹ The study indicates that a Massachusetts State Police test shows that motorcycles had no maneuverability problems traversing rumble strips that were milled-in 18 cm (7 in) long circle segment profile, spaced at 30 cm (12 in), with 41 cm (16 in) perpendicular width (length), and a depth of 13 mm (1/2 in) to 16 mm (5/8 in).

A study in Sweden⁴² involved interviews with motorcyclists who drove over rumble strips with the following dimensions: length or perpendicular width 30 cm (11.8 in), parallel width 15 cm (5.9 in), center-to-center distance 60 cm (23.6 in), and depth 10 mm (0.4 in). The motorcyclists had no objection to the design of the rumble strips or to how they influence driving. The motorcyclists’ impression was that the rumble strips feel less pronounced when one is driving fast, for example, at 90-100 kph (56-62 mph) versus 70 kph (43 mph).

In the U.K., the Transport Research Laboratory reported on motorcycle safety for their optimal sinusoidal “rippleprint” rumble strip.⁴³ The peak-to-peak amplitude of 6.6 mm (0.3 in) and a wavelength of 0.35 m (13.8 in) was tested. Results for motorcycles traveling at 32 to 64 kph (20 to 40 mph) showed that there was some vibration of the handlebars, but no loss of control. It was also reported that braking performance was similar to that with a flat surface. For higher speeds, 80 and 97 kph (50 and 60 mph), there were also no reporting of handling difficulties.

⁴¹ Garder, P., “Rumble strips or not along wide shoulders designated for bicycle traffic?,” Transportation Research Record 1502: Journal of the Transportation Research Board, 1995.

⁴² Vadeby, A. and A. Anund, “Effectiveness and acceptability of milled rumble strips on two-lane roads in Sweden,” Euro. Transp. Res. Rev, 9:29, 2017.

⁴³ Watts, G., R. Stait, N Godfrey, L Chinn and R Layfield, “Development of a novel traffic calming surface ‘Rippleprint’,” TRL Report TRL545, 2002.

RUMBLE STRIP EFFECTS

Rumble strips affect people both inside the vehicle and in areas adjacent to the roadway (in communities). This section describes community effects of noise and vibration, followed by in-vehicle effects.

Community Effects

Noise

Summary: Rumble strips can increase noise by 5-25 dB near the road and cause annoyance and sleep disturbance in communities. The effect is dependent on distance from the road, vehicle type, and speed.

Several transportation agencies have reported that rumble strip noise can annoy people living near a highway and that the number of noise complaints reduce when rumble strips are removed or designed for less-frequent vehicle strikes. Complaints were received from up to 1.6 km (1 mile) away from a roadway with rumble strips.⁴⁴

FHWA reports^{45,46} state that challenges to rumble strip implementation exist in areas where the noise caused by vehicles hitting rumble strips is undesirable to the surrounding environment (e.g., nearby residents, nearby businesses, or in sensitive habitat areas). The sound outside the vehicle may be disruptive to those who live near highways because it is intermittent and differs from other “normalized” sounds in those areas (e.g., highway traffic). Several States have narrowed the focus of public noise complaints to locations where a section of rural highway has suburban characteristics. Noise complaints from the public generally occur in locations where the speed is low, the roadways are rural, and there is a certain degree of development. In some cases, rumble strips are removed when a noise concern is concentrated.

Washington DOT states that in recent years the number of complaints has increased.⁴⁷ The complaints are generally from suburban, semi-rural, and rural residents and focus on sleep disruption. The complaint locations typically have lower nighttime background sound levels than urban areas, which can make rumble strip noise more disruptive due to the greater change in sound level. The reasons stated for rumble strip noise being disruptive are: sporadic, unpredictable occurrence and low, tonal frequencies.

⁴⁴ Cybulski, J., J. Rochat, and D. Read, *Roadway Departure Warning Indicators: Synthesis of Noise and Bicycle Research*, Natural Resource Technical Report NPS/NSNS/NRTR—2013/780, U.S. Department of Interior, National Park Service, 2013.

⁴⁵ *Rumble Strip Implementation Guide: Addressing Noise Issues on Two-Lane Roads*, Federal Highway Administration, 2015.

⁴⁶ Himes, S., H. McGhee, S. Levin, and Y. Zhou, *State of Practice for Shoulder and Center Line Rumble Strip Implementation on Non-Freeway Facilities*, Report No. FHWA-HRT-17-012, Federal Highway Administration, 2017.

⁴⁷ Sexton, T., “Evaluation of Current Centerline Rumble Strip Design(s) to Reduce Roadside Noise and Promote Safety,” WA-RD 835.1, Environmental and Engineering Programs, Washington State Department of Transportation 15700 Dayton Ave N, Seattle, WA, 2014.

A Wyoming Department of Transportation (DOT) research study⁴⁸ reviews noise effects for several States. Their introduction on noise helps to give perspective to the level of noise associated with rumble strips. They state that Minnesota DOT reported that at 15 m (50 ft), the noise level produced by a vehicle driving over a standard rumble strip is comparable to a truck passing by on a standard, non-rumbled surface. They also state that Michigan DOT reported levels associated with a large pick-up truck traveling 113 kph (70 mph) on standard rumble strips are 16.2 dB and 25 dB louder than standard pavement at distances of 29 m and 15 m (95 ft and 50 ft), respectively. Wyoming conducted a survey to investigate the effect on nearby residents and found that those living within 91 m (300 ft) at the first line of houses might notice the noise most, and that the noise level beyond those houses was negligible due to shielding from the first row of houses. For those affected, residents would like to have a quieter design of rumble strips.

A case study presented at TRB involved measurement of rumble strip noise, measurement of community ambient noise, and calculated propagation of the rumble strip noise to a nearby community (using the FHWA Traffic Noise Model).⁴⁹ It was determined that vehicles traversing the rumble strips increased vehicle emission levels by 5 to 10 dB compared to standard pavement and increased the maximum A-weighted noise levels in the community by 5 to 11 dB.

A Transportation Association of Canada synthesis⁵⁰ stated that rumble strips increase noise 10-14 dB for tractor-trailer trucks, 14-17 dB for passenger vehicles, and 5-7 dB for motorcycles, measured at the road edge. Rumble strips terminated approximately 200 m (660 ft) away from residential or urban areas produce tolerable noise impacts on residences, and that at an offset of 500 m (1,600 ft), the noise from rumble strips is negligible.

In the U.K., the Transport Research Laboratory reported exterior noise for their test sinusoidal “rippleprint” rumble strips.⁵¹ It was found that surfaces with smaller wavelengths, < 0.35 m (13.8 in) produced appreciable increase in exterior noise. In a subjective assessment of exterior noise in both outside and inside listening conditions (simulating conditions at residences), results showed that the shorter length sinusoidal surfaces were slightly less annoying than the study’s chosen optimal surface, peak to trough amplitude 6.6 mm (0.3 in) and a wavelength of 0.35 m (13.8 in).

Vibration

Summary: For communities or buildings close to a highway, it’s possible for vibration from road irregularities such as rumble strips to cause disturbances or annoyance. Limits provided in the

⁴⁸ Ahmed, M., M. Sharif, K. Ksaibati, and C. Planche, “Accommodation of bicyclists and nearby residents in rumble strips/stripes policies,” Conference Proceedings of the Transportation Research Board Annual Meeting, 2016.

⁴⁹ Bajdek, C., J. Ross, and L. Chan, “A case study on the effects of rumble strip noise in a community,” Paper No. 03-3817, Proceedings of the 82nd Annual Meeting of the Transportation Research Board, 2003.

⁵⁰ Bahar, G., J. Wales, and L. Longtin-Nobel, *Synthesis of Best Practices for the Implementation of Shoulder and Centerline Rumble Strips*, Project No. 9132, Transportation Association of Canada, August 2001.

⁵¹ Watts, G., R. Stait, N Godfrey, L Chinn and R Layfield, “Development of a novel traffic calming surface ‘Rippleprint’,” TRL Report TRL545, 2002.

Federal Transit Administration (FTA) guidance can be applied to determine potential impacts from vibration.

Regarding the effect or potential effect of vehicle/road induced vibration on communities, several studies discuss vibration levels in terms of vehicle interaction with roadway discontinuities, reviewed in Rochat 2018.⁵² The types of road discontinuities involved with the studies are: embedded train rails, pavement seams, pavement cracks, manhole covers, utility covers, potholes, bumps, and bridge expansion joints. Although not rumble strips, these studies provide insight to potential wayside vibration levels associated with rumble strips. Example measured vibration levels from various projects were provided, where buses traveling over embedded train rails produced vibration similar to the light rail trains passing by, up to ~75 VdB at a distance of 24 m (80 ft) from the tracks.

Another study discusses how vibration generated by road vehicles can have a significant environmental impact on nearby buildings.⁵³ It states that road vibration is primarily a concern for buses and heavy trucks and that groundborne vibration is important up to frequencies of 250 Hz for assessing received vibrations inside structures. The study also states that vibration can travel long distances from its source, and that depending on the ground type, *train* vibration may produce annoyance to people in buildings more than 200 m (656 ft) from the tracks. A different study⁵⁴ describes how a vehicle passage on irregular road pavement surfaces generates the oscillation of the vehicle mass, with a consequent increase of the load applied on the pavements. Heavy goods vehicles and buses are found to produce the most perceptible vibrations, which propagate in the soil, and can impinge on the foundations of nearby structures. The load is a function of several factors, including vehicle mass, speed, suspension type, and road surface irregularities. Through computer analyses, it was found that the road surface is the dominant factor; the generation of vibration fundamentally depends on the longitudinal regularity of the road surface and only to a much lesser extent on the vehicles' increase in speed. The method developed as part of this study can be used to determine the vibration level for the foundation in nearby buildings, potentially to help safeguard the integrity and preservation of historic structures.

The Federal Transit Administration (FTA) provides guidance⁵⁵ for limits due to potentially problematic vibration levels for rail and bus transit projects. Distances out to 46 m (150 ft) are screened for residential land uses. The FTA limits could be applied to vibration generated by highway vehicles. For residences and buildings where people normally sleep, a limit of 72 VdB (maximum, referenced to 1 $\mu\text{in/s}$) is applied for frequent events (> 70 per day), 75 VdB for

⁵² Rochat, J. and T. Evans, "Noise and Vibration from Road Discontinuities," Presentation at Inter-Noise 2015, San Francisco, California, August 2015.

⁵³ Aliyu, D.S., Y.A. Abdu, and D.A. Yusuf, "Transmission of Ground Vibration on Road Side Structures," European Journal of Advances in Engineering and Technology, 3(16): 43-46, 2016.

⁵⁴ Agostinacchio, M., D. Ciampa, and S. Olita, "The vibrations induced by surface irregularities in road pavements – a Matlab approach," Eur. Transp. Res. Rev., 6:267-275, 2014.

⁵⁵ Quagliata, A., M. Ahearn, E. Boeker, C. Roof, L. Meister, H. Singleton, *Transit Noise and Vibration Impact Assessment Manual*, "FTA Report No. 0123, Federal Transit Administration, 2018.

occasional events (30-70 per day), and 80 VdB for infrequent events (< 30 per day). The limits are based on the number of events, since community response to vibration correlates with the frequency of events. Human response to vibration in buildings is very complex, and, in some cases, complaints are associated with measured vibration that is lower than the perception threshold of 65 VdB. Note, however, that the incidence of complaints drops off rapidly below 72 VdB. There are also lower limits associated with buildings where vibration levels would interfere with operations within the building (e.g., hospitals with vibration-sensitive equipment, recording studios, etc.). In addition to groundborne vibration, groundborne noise is evaluated (groundborne vibration can cause generation of noise inside a building, from rumbling to rattling). For residences, the limit is set at 35 dBA for frequent events, 38 dBA for occasional events, and 43 dBA for infrequent events. Lower level limits are applied to special buildings such as concert halls and recording studios. The limits are based on human annoyance and activity interference. Guidance is also provided for structural damage, although this is usually attributed only to blasting and pile-driving during construction, since operational vibration levels are typically well below potential damage limits.

A study involving the Ontario Ministry of Transportation⁵⁶ states that occasionally, transportation agencies receive complaints from residents living near roads about annoying or even structurally damaging traffic-induced vibration. The resolution of these complaints can be very challenging. The sources of vibration caused by a truck driving over road irregularities are: the tire tread (typically in the 1000 Hz range), unsuspended mass of the vehicle (10-15 Hz axle bounce), and suspended mass of the vehicle (typically in the 1-2 Hz range). With groundborne vibration, what is experienced by building occupants depends on distance from the vibration source to the building, soil and other geotechnical characteristics of the ground, building parameters, and on the location of the observer in the building. It is concluded that only in very extreme circumstances could highway traffic-induced groundborne vibration cause structure damage, and that vibration could be perceived in very extreme circumstances. The suggested solution is smooth roads.

Caltrans published a Technical Advisory in 2002⁵⁷ stating that heavy truck vibrations are below the level of perception beyond 45 m (150 ft) from the center of the lane. It is also stated that the peak frequencies are typically in the 10-30 Hz range. Automobile traffic normally generates vibration peaks of one fifth to one tenth of truck vibration. It is pointed out that potholes, pavement joints, differential settlement of pavement, and other irregularities increase the vibration amplitudes. Regarding the effect of vibration on people, it is stated that elderly, retired, or ill people staying mostly at home, people reading in a quiet environment, people involved in vibration sensitive hobbies or activities are but a few examples of people that are potentially

⁵⁶ Hajek, J.J., "Mitigation of Highway-Induced Vibration," Annual Conference of the Transportation Association of Canada, Session on Quiet Pavements: Reducing Noise and Vibration, 2006.

⁵⁷ Hendriks, R., *Transportation Related Earthborne Vibrations*, Technical Advisory TAV-04-01-R0201, California Department of Transportation, 2002. (Note: Can be found in Appendix A in the Caltrans *Transportation and Construction Guidance Manual*, 2013)

annoyed by vibration, and that most routine complaints come from people in these categories. Vibration sensitive manufacturing and laboratory or medical equipment can also be affected.

Alerting Drivers

Summary: For noise, rumble strips causing an increase of 3 to 15 dB above ambient may be required for detection, and tones should help with driver detection and perception of urgency (higher frequency). Frequencies between 1000-2500 Hz and with ≥ 3 harmonics increase warning response time. For vibration, drivers can easily detect steering wheel torque of 1.2 Nm, and at this level, drivers perceive the vibration as alarming. Humans are sensitive to seat vibration from 1-80 Hz and hand-arm vibration from 8-1000 Hz. As an alerting mechanism, seat vibrations of 20-27 m/s² (at 26-30 Hz) are perceivable/appropriate. For steering columns, measured increases in vibration due to standard rumble strips are 1.5 m/s² (vertical), 1.0 m/s² (perpendicular to direction of travel), and 0.5 m/s² (in direction of travel). Vibration warnings may elicit a faster response time than auditory. One study states that a 68 dBA “rumble strip” auditory warning is subjectively equivalent to 11.3 m/s² of seat vibration. For sinusoidal rumble strips, an optimum wavelength is 0.35 m (13.8 in) to have sufficient interior noise and vibration and minimize exterior noise.

NCHRP Report 600C⁵⁸ provides a review of human factors in relation to rumble strips. Rumble strips are intended to provide a tactile/haptic and auditory alert to drivers who stray from a travel lane. When a vehicle’s wheels traverse a rumble strip, they generate both an increase in sound and haptic (physical) vibrations that drivers feel through their seat, foot pedals, floor, and steering wheel. Rumble strips can potentially wake drivers who fall asleep; however, this result typically requires a greater level of sound and vibration. In general, rumble strips must produce sound and vibration levels that are easily detectable, yet not so loud and jarring that they startle drivers. The report provides a table of effects of different shoulder rumble strip (SRS) dimensions on auditory/tactile alerts, shown in Table A-2. The findings in the table were based equally on expert judgement and empirical data. Key implications for effectiveness are that sounds presented for longer durations are generally easier to detect, higher levels relative to background are easier to detect, and higher tones (higher frequency, associated with narrower rumble strip grooves) are perceived as being more urgent. Focusing on more details of auditory warnings in a NHSTA report,⁵⁹ to increase perceived urgency, use: faster auditory signals, regular rhythms, higher fundamental frequencies, and a large pitch range, among other sound characteristics that would not necessarily apply to rumble strips. The ability to perceive urgency is important because it is associated with faster reaction times.

Table A-2: Effects of shoulder rumble strip dimensions on auditory/tactile alerts⁶¹

⁵⁸ Campbell, J., C. Richard, J. Brown, M. Lichty, J. Graham, and M. O’Laughlin, *Human Factors Guidelines for Road Systems*, NCHRP Report 600C, Transportation Research Board, 2010.

⁵⁹ Campbell J., C. Richard, L. Brown, and M. Callum, *Crash Warning System Interfaces: Human Factors Insights and Lessons Learned*, Report No. HS 810 697, National Highway Traffic Safety Administration, Washington, DC, 2007.

EFFECTS OF DIFFERENT SRS DIMENSIONS ON AUDITORY / TACTILE ALERTS

Characteristic	Suitable Values	Direct Effect on Driver	Implications for Effectiveness
Lateral placement / offset	<ul style="list-style-type: none"> • 6+ in. from lane edge (but depends on other factors) 	Drivers encounter the alert sooner, the closer it is to the lane edge.	The sooner the warning occurs, the more space drivers have to recover before reaching the road edge.
Groove Width	<ul style="list-style-type: none"> • 16 in. (12 may be acceptable if the shoulder is narrow) 	Wider SRS will produce sounds/vibrations for a longer duration as the vehicle laterally traverses it.	Sounds presented for longer durations are generally easier to detect.
Groove Depth	<ul style="list-style-type: none"> • 7/16 in. 	Deeper grooves increase sound and vibration alert levels.	Louder sounds and vibrations are easier to detect relative to background noise levels.
Groove Separation	<ul style="list-style-type: none"> • 11-12 in. 	Narrower groove separation slightly increases the frequency.	Drivers generally perceive higher tones as sounding more urgent.
Longitudinal Gaps	<ul style="list-style-type: none"> • None if shoulder not shared with bikes • 12 ft if shoulder shared with bikes 	Gaps of 12 ft or less can reduce the chance that a vehicle will miss the SRS completely.	Effectiveness will be lower than without gaps because alert duration will be shorter over gap sections.

A 1993 NCHRP synthesis⁶⁰ states that driver perception is better for grooved rumble strips than for raised rumble strips, with interior noise measured to be 5 to 15 dBA higher than ambient. The NCHRP human factors report⁶¹ indicates that rumble strips that generate a 3 to 15 dBA increase above the ambient in-vehicle sound level can be detected by awake drivers. Although, the research in NCHRP Report 641⁶² found that there is no conclusive evidence indicating a clear minimum level of stimulus that a shoulder or centerline rumble strip must generate to alert an inattentive, distracted, drowsy, or fatigued driver. For vibrations, laboratory driving simulator studies show that usually drivers easily detect steering wheel or brake pedal vibrations of 1.2-1.5 Nm torque presented over half a second. In contrast to passenger vehicles, cab vibrations in heavy trucks are significant and the size and weight of heavy trucks reduce the vibrations generated by SRS; the vibration component is viewed to have minimal benefit for alerting heavy truck drivers. For the heavy vehicles, the noise generated from rumble strips has a greater effect in alerting drivers than the vibration produced by the same rumble strips (based on traditional designs). It's stated that vibrations of 3.35 m/s² (0.342 G) and 1.47 m/s² (0.150 G) were judged to be minimal and have a low to negligible alerting value; this applies to an average acceleration over several locations/directions on the steering wheel relative to ambient vibration.

⁶⁰ Harwood, D., *Use of Rumble Strips to Enhance Safety*, Synthesis of Highway Practice 191, National Cooperative Highway Research Program, 1993.

⁶¹ Campbell, J., C. Richard, J. Brown, M. Lichty, J. Graham, and M. O'Laughlin, *Human Factors Guidelines for Road Systems*, NCHRP Report 600C, Transportation Research Board, 2010.

⁶² Torbic, D.J., J.M. Hutton, C.D. Bokenkroger, K.M. Bauer, D.W. Harwood, D.K. Gilmore, J.M. Dunn, J.J. Ronchetto, E.T. Donnell, H.J. Sommer III, P. Garvey, B. Persaud, and C. Lyon, *Guidance for the Design and Application of Shoulder and Centerline Rumble Strips*, NCHRP Report 641, Transportation Research Board, Washington, DC, 2009.

In the U.K., the Transport Research Laboratory reported interior noise and vibration for their test sinusoidal “rippleprint” rumble strips.⁶³ It was found that surfaces with larger wavelengths, > 0.35 m (13.8 in), were ineffective in producing sufficient increases in interior noise and vibration to alert drivers. It was determined that the optimal wavelength was 0.35 m (13.8 in) to have sufficient interior alerts while minimizing exterior noise. Subjective ratings of noticeability for drivers indicated that cars and vans that there is little change in ratings with speed. Their optimum design, peak to trough amplitude 6.6 mm (0.3 in) and a wavelength of 0.35 m (13.8 in), was rated in the most noticeable category. For a 5-axle articulated truck there was a lower level of noticeability than the lighter vehicles tested except at the lowest speeds.

A best practices synthesis from Canada⁶⁴ states that a rumble strip depth of 8 mm (0.3 in) is required to create any noticeable effect in the cabins of tractor-trailers. Also, a rumble strip width of 50 cm (20 in) is more effective in the following circumstances:

- when a large portion of the highway traffic is heavy vehicles;
- in known locations where large trucks typically encroach on the roadside;
- where there is a history of run-off-the-road collisions involving trucks; and
- when a benefit/cost analysis shows that the additional cost for a wider shoulder rumble strip is effective.

In the Caltrans study,⁶⁵ differences in interior A-weighted sound levels for on and off the sinusoidal rumble strips mostly ranged from 12 to 19 dB for sinusoidal rumble strips and 10 to 17 dB for conventional rumble strips (see Figure A-4). Even though a measured tone was in the 80 Hz one-third octave band, it was of sufficient strength to influence the overall A-weighted level and produced a sound that would be considered a doubling of loudness. This study emphasizes the need to consider perception of prominent tones.

For vibration feedback, frequency weighting is available in ISO standards.^{66,67} For whole-body vibration, such as that perceived by the vehicle operator through their seat, the sensitive frequencies are from 1 to 80 Hz. For hand-arm vibration, the sensitive frequency range is from 8 to 1000 Hz. These weighting curves can be used to assess the perception of vibration, particularly for sinusoidal rumble strip designs.

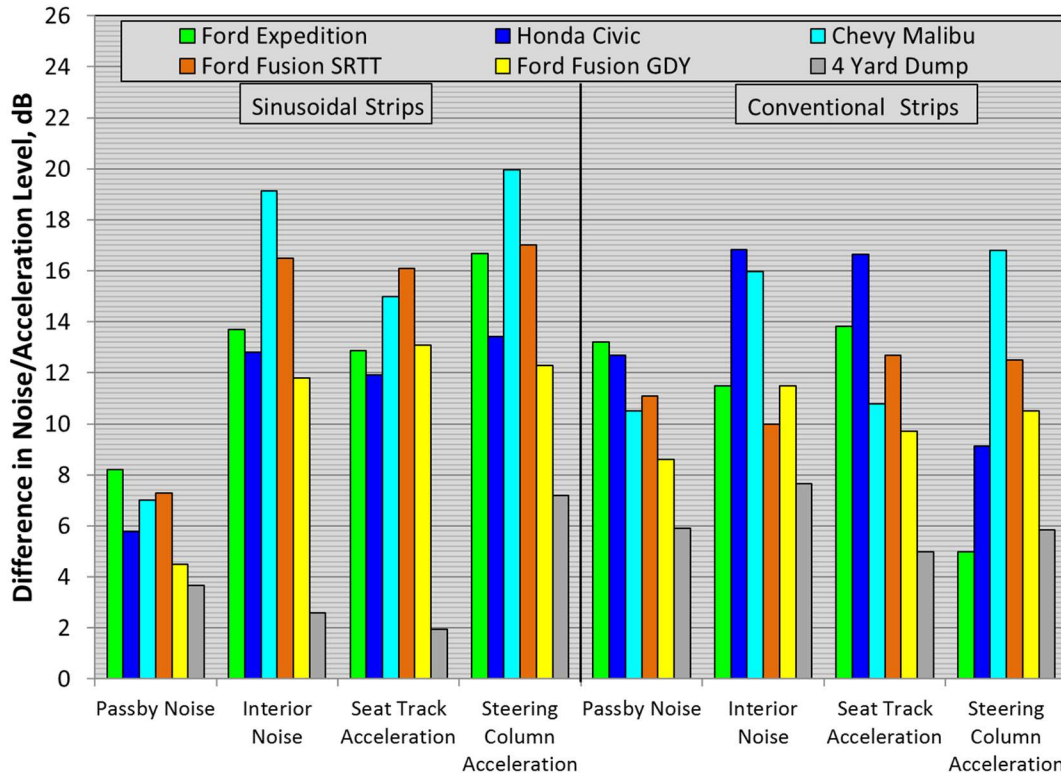
⁶³ Watts, G., R. Stait, N Godrey, L Chinn and R Layfield, “Development of a novel traffic calming surface ‘Rippleprint’,” TRL Report TRL545, 2002.

⁶⁴ Bahar, G., J. Wales, and L. Longtin-Nobel, *Synthesis of Best Practices for the Implementation of Shoulder and Centerline Rumble Strips*, Project No. 9132, Transportation Association of Canada, August 2001.

⁶⁵ Donavan, P. and B. Rymer, “Design and Evaluation of Quieter Highway Rumble Strips,” Proceedings of Inter-Noise 2013, Innsbruck, Austria, September 2013.

⁶⁶ International Organization of Standardization, *Mechanical vibration – Measurement and evaluation of human exposure to hand-transmitted vibration – Part 1: General requirements*, ISO 5349-1:2001, 2001.

⁶⁷ International Organization of Standardization, *Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration – Part 5: Method for evaluation of vibration containing multiple shocks*, ISO 2631-5:2018, 2018.



Figure

A-4: Comparison of different vehicles and tires for on/off rumble strip differences for two rumble strip designs, Caltrans sinusoidal and conventional ground⁶⁸

In the automobile industry, tactile feedback can be used for lane departure warnings, collision warnings, and to increase driver situational awareness. Various studies report results on what type of tactile warning will provide the most meaningful feedback. Some of the material is potentially applicable to vibratory feedback from rumble strips. A study presented in the Journal of Sensory Studies⁶⁹ focuses on vibrotactile stimuli located in the seat, because it is the only part of the car that the driver is reliably in contact with for autonomous vehicles. Testing showed that the signal parameters with the greatest effects for detection are: amplitude, squared amplitude, and pulse duration. Detection rate increased with amplitude and decreased with pulse length and frequency. It's stated that human sensitivity is greatest between 100 and 300 Hz and that vibrations in the back are more clearly distinguished from ambient conditions than vibrations in the seat pan.

A different human factors study focused on information transfer between vehicles and drivers and concentrated on haptic feedback, since there are perceptual overloads visually and auditorily

⁶⁸ Donavan, P. and B. Rymer, "Design and Evaluation of Quieter Highway Rumble Strips," Proceedings of Inter-Noise 2013, Innsbruck, Austria, September 2013.

⁶⁹ Duthoit, V., J-M. Sieffermann, E. Enregle, C. Michon, and D. Blumenthal, "Evaluation and optimization of a vibrotactile signal in an autonomous driving context," Journal of Sensory Studies, 33:e12308, 2018.

when driving.⁷⁰ The study focused on seat vibrations as an alerting mechanism, since the seat touches the largest area of the driver's body. For the seat pan, horizontal vibrations between 2 G (19.6 m/s², 772 in/s²) at 26 Hz and 2.7 G (26.5 m/s², 1042 in/s²) at 30 Hz were determined to be perceivable/appropriate, with greater values determined to be too strong by the participants. For the seat back, vibrations normal to the seat back between 2.7 G (26.5 m/s², 1042 in/s²) at 30 Hz and 3.4 G (33.3 m/s², 1313 in/s²) at 34 Hz were determined to be appropriate.

A study presented at the 2006 annual TRB meeting⁷¹ examined using different rumble strips for the centerline and shoulder so that drivers would be more likely to correctly respond to the signal. Results indicated that driver comprehension was better using different designs. The study examined both audible and haptic data for shoulder and centerline rumble strips and for a standard road. Sound was measured inside the "ears" of an acoustics manikin placed in the passenger seat, and vibration was measured with triaxial accelerometers on the steering column and clutch pedal. Tests were conducted with a vehicle traveling 96 kph (60 mph) on standard rumble strips. Concentrating on the steering column, results showed: 1) measured sound and vibration (all axes) differences are not discernable comparing left- (centerline) and right- (shoulder) side incursions on the same type of rumble strip; and 2) these incursions can be discernable to a driver with a different waveform (from a different type of rumble strip) for the center and shoulder positions. Also, comparing the vibration amplitudes using standard deviation both on and off the rumble strips: 1) in the gravitational direction (perpendicular to the road surface), the vibration amplitude was about 1.5 m/s² larger on a rumble strip; 2) in the lateral direction (perpendicular to direction of travel), the vibration amplitude was about 1 m/s² larger; and 5) in the longitudinal direction (direction of travel), the vibration amplitude was about 0.5 m/s² larger. The differences between on and off rumble strips are described here to help understand the increase in vibration associated with rumble strips that are currently acceptable from a safety perspective (sound levels were not provided).

A NHTSA report⁷² reviews several experiments regarding driver-vehicle interfaces and warning systems. Ones potentially applicable to rumble strips are summarized here. For in-vehicle audible warnings, the report shows that the following criteria are important to drivers hearing sounds as an alarm or sounding highly urgent: peak to total time ratio of ≥ 0.7 (encompasses perception of onset time); perceived tempo ≤ 125 ms, but > 15 ms between sound components; number of harmonics ≥ 3 (contributes to harshness of sound); and base frequency ≥ 1000 Hz and < 2500 Hz. Alarm classification is significantly predictive of response time: the more likely a sound was classified as an alarm, the faster the response time for that alert. For vibration, haptic

⁷⁰ Ji, Y., K. Lee, and W. Hwang, "Haptic perceptions in the vehicle seat," Human Factors and Ergonomics in Manufacturing and Service Industries, Volume 21, Issue 3, 2011.

⁷¹ Dulaski, D. and D. Noyce, *Development and Evaluation of a Unique Centerline Rumble Strip Pattern to Improve Driver Comprehension*, Paper No. 06-2442, Proceedings of the Transportation Research Board Annual Meeting, Traffic Control Services Committee, Washington, DC, 2006.

⁷² Lerner, N. J. Singer, R. Huey, R. Brown, D. Marshall, S. Chrysler, R. Schmitt, C. Baldwin, J. Eisert, B. Lewis, A. Bakker, and D. Chiang, *Driver-Vehicle Interfaces for Advanced Crash Warning Systems: Research on Evaluation Methods and Warning Signals*, Report No. DOT HS 812 208, National Highway Traffic Safety Administration, 2015.

events elicited shorter response times than audio events for a distracted driver. The haptic warnings with the best response were brake pulsing or seat belt tensioning, while seat vibration similar to a rumble strip was not found to rapidly and reliably return driver attention to the road (results based on limited experiments and should not be taken to imply that seat vibration cannot be effective, as it was shown to be in other studies). Steering wheel vibration and seat belt tensioning were found to be effective for decreasing the duration and extent of lane departure.

In a report prepared for the FHWA,⁷³ a study was conducted to better understand basic human factors principles of haptic and auditory interfaces as a collision avoidance technique during run-off-road and head-on collisions and driver perception of the modalities. In this simulator study, participants received alerting cues in three sensory modalities: haptic (seat vibration), auditory (“rumble strip” sound), and combined auditory and haptic sensory warnings. The results of the study showed that haptic modality produced significantly faster reaction times than both the auditory and combination modalities. With a decrease in reaction time, less erratic steering responses, and relatively advantageous perceptions from drivers, haptic warnings have the potential to better assist drivers in returning to the lane more quickly and safely. Participants in the study determined that a 68 dBA “rumble strip” auditory warning was subjectively equivalent to 11.3 m/s² (1.15 G or 444 in/s²) of seat vibration.

The Society of Automotive Engineers (SAE) states that haptic warnings have been found to be effective in alerting drivers quickly. Evidence suggests that drivers can respond faster to haptic (vibrotactile) warnings than visual or auditory warning signals. The most common haptic warnings are vibration (usually seat back, seat pan, or steering wheel) or constant torque (to the steering wheel).⁷⁴

A study from Ford Motor Company⁷⁵ examined human machine interfaces (HMI) for warning drowsy drivers about lane departures. The study evaluated steering wheel vibration and torque (15 Hz, 2 Nm, 1.5 s), rumble strip sound (recordings from a vehicle driving over rumble strips), and a head up display (HUD, row of flashing red LEDs). Figure A-5 shows the steering wheel reaction times for each type of warning. The steering wheel vibration accompanied by torque was found to be the most effective HMI, with faster reaction times and smaller lane excursions. The rumble strip sound tended to decrease reaction time.

⁷³ Stanley, L., *Haptic and Auditory Interfaces as a Collision Avoidance Technique during Roadway Departures and Driver Perception of These Modalities*, Western Transportation Institute, Montana State University, report prepared for the Federal Highway Administration, 2006.

⁷⁴ Society of Automotive Engineers International, “Surface Vehicle Information Report – Lane Departure Warning Systems: Information for the Human Interface,” SAE J2808, January, 2017.

⁷⁵ Kozak, K. J. Pohl, W. Birk, J. Greenberg, B. Artz, M. Blommer, L. Cathey, R. Curry, “Evaluation of lane departure warnings for drowsy drivers,” Proceedings of the Human Factors and Ergonomics Society 50th Annual Meeting, 2006.

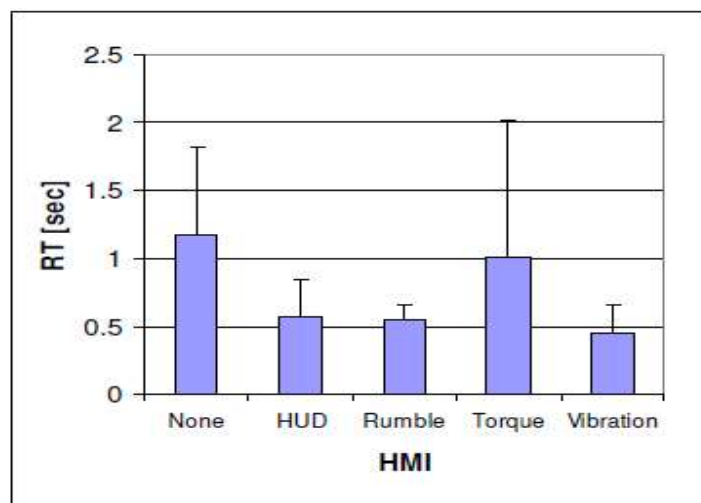


Figure A-5: Average steering wheel reaction time for each warning⁷⁵

There are also many publications that describe driver discomfort in relation to noise and vibration. Those are not described in detail here, since the relationship between discomfort and alerting drivers is unknown. As a brief review, a study in progress by DRI⁷⁶ discusses a transient ride metric that was identified to predict a numerical overall motion and vibration discomfort rating based on acceleration and sound pressure level measurements. The motion and vibration discomfort are rated in relation to these driver/vehicle interfaces: seat/buttock, seat/back, head/torso toss, steering wheel/hands, and floor/feet. SAE J2834⁷⁷ presents a methodology intended to predict human sensitivity to motion and vibration, based on subjective discomfort levels, where vibration is measured at various driver/vehicle interfaces. Also, another SAE publication⁷⁸ describes research where the objective was to identify noise metrics to quantify noise discomfort when a car encounters a discrete transient road input. In addition to suggesting that Fast A-weighted sound pressure level is a practical metric to use for predicting over-the-road transient noise discomfort, the authors suggest that frequency masking, nonlinearities, and other higher order psychoacoustic effects (loudness and sharpness) did not contribute very much to the discomfort experienced by drivers.

Going beyond discomfort, Shabani⁷⁹ discusses human emotional response to automotive steering wheel vibration. Several experiments were conducted with drivers traversing several road surfaces, including rumble strips. A driver emotional semantic scale was developed containing

⁷⁶ Dynamic Research, Inc., DRI-TR-96-2 Vol 1 : *Development of a ride quality metric for passenger cars on rough roads* (in development).

⁷⁷ Society of Automotive Engineers International, "Surface Vehicle Recommended Practice – Ride Index Structure and Development Methodology," SAE J2834, October, 2013.

⁷⁸ Van Auken, M., J.W. Zellner, and D.T. Kunkel, "Correlation of Zwicker's Loudness and Other Noise Metrics with Drivers' Over-the-Road Transient Discomfort," SAE Technical Paper Series, SAE International, International Congress and Exposition, 1998.

⁷⁹ Shabani, A., *Human Emotional Response to Automotive Steering Wheel Vibration: Development of a Driver Emotional Semantic Scale*, Doctoral Thesis, College of Engineering, Design and Physical Sciences, Brunel University London, 2016.

vibrotactile descriptors. Based on six different passenger cars, drivers found rumble strips to have a fairly high arousal rating and to be “powerful,” “alarming,” and “sharp,” with associated vibration acceleration of 1.24 m/s² (49 in/s²). Acceleration was measured on the steering wheel in the 60° (two o’clock) position with respect to the top center, measured in the direction tangential to the steering wheel rotation (this is assumed to be the direction normal to the tangent line).

RUMBLE STRIP NOISE AND VIBRATION DATA COLLECTION

Summary of Previous Data Collection

Summary: Many state and federal agencies have carried out noise and vibration studies of rumble strips. However, the measurement procedures are inconsistent from one study to the next. Table A- summarizes the measurement procedures and general conclusions of the major rumble strip noise and vibration evaluations.

In addition to the recent noise and vibration measurements collected to evaluate low-noise rumble strips in California, Minnesota, Indiana, and Oregon, there have been many other measurement efforts to collect data from conventional rumble strips in the United States. In 2013, the National Park Service (NPS) completed a synthesis of rumble strip noise measurements and in 2017, FHWA completed a literature review on noise and vibration testing methods of rumble strips as part of a state-of-practice review.^{80 81}

The NPS synthesis noted that microphone locations and sound metrics applied are inconsistent from one study to the next. Some studies included acceleration data while others did not. Most studies evaluated continuous driving on rumble strips, but some, including the INDOT study by Mathew in 2018, completed pass-by measurements for intrusions on and off the rumble strips. Another major inconsistency was the vehicle fleet.

Table A-3 presents a summary of noise and vibration measurements that have been carried out at both traditional and sinusoidal rumble strips going back to the year 2000. The information in the table demonstrates the lack of common test and evaluation procedure among studies. The rightmost column of the table is the conclusion from the study.

⁸⁰ Cybulski, J., J. Rochat, and D. Read, *Roadway Departure Warning Indicators: Synthesis of Noise and Bicycle Research*, Natural Resource Technical Report NPS/NSNS/NRTR—2013/780, U.S. Department of Interior, National Park Service, 2013.

⁸¹ Himes, S., H. McGhee, S. Levin, and Y. Zhou, *State of Practice for Shoulder and Center Line Rumble Strip Implementation on Non-Freeway Facilities*, Report No. FHWA-HRT-17-012, Federal Highway Administration, 2017.

Table A-3: Summary of Rumble Strip Noise and Vibration Data Collection

Study / Date	Type of Rumble Strip	Exterior Measurements	Interior Measurements	Vehicles and Speeds	Comments	Conclusions
Donavan 2018 (Caltrans) ⁸²	Sinusoidal and conventional ground shoulder rumble strips	TP98 test procedure, 25 ft from center of lane of travel	SLM at head position of right front seat occupant, accelerometer on steering column and outboard seat track	Chevy Malibu, Honda Civic, Ford Expedition, Ford Fusion, 4-yard dump truck at 60 mph	Two tires on rumble strip for full duration of measurement	Sinusoidal rumble strips provide comparable interior noise levels and lower exterior noise levels
Hurwitz 2018 (Oregon) ⁸³	Sinusoidal and conventional rounded shoulder rumble strips	TP98 test procedure, 25 ft and 50 ft from shoulder rumble strip	SLM in passenger seat at head level, triaxial accelerometer on steering column	Ford Focus hatchback, Dodge Grand Caravan minivan, Volvo VHD dump truck	Tires “strike” rumble strip (about 1 second duration)	Sinusoidal rumble strips provide comparable interior noise levels and lower exterior noise levels
Mathew 2018 (INDOT) ⁸⁴	Three sinusoidal rumble strip configurations	50 ft from closest edge line rumble strip	SLM near drivers’ ear, triaxial accelerometer on driver seat frame	Semi-trailer truck, single axle truck, tandem axle truck, minivan, SUV, and sedan at 50 mph	Rumble strip “incursion” (short duration)	Sinusoidal rumble strips provide comparable interior noise levels and lower exterior noise levels

⁸² Donavan, P., *Design and Acoustic Evaluation of Optimal Sinusoidal Mumble Strips versus Conventional Ground-In Rumble Strips*, California Department of Transportation Report No. CTHWANP-RT-15-365.01.2, 2018.

⁸³ Hurwitz, D., D. Horne, H. Jashami, C. Monsere, and S. Kothuri, *Quantifying the performance of low-noise rumble strips*, Report No. SPR 800, joint Oregon State University and Portland State University, prepared for Oregon Department of Transportation and Federal Highway Administration, 2018.

⁸⁴ Mathew, J. K., A.D. Balmos, D. Plattner, T. Wells, J.V. Krogmeier, and D.M. Bullock D.M., *Assessment of alternative sinusoidal rumble strip construction*, Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2018/05, West Lafayette, IN, Purdue University, 2018.

<https://doi.org/10.5703/1288284346648>

Study / Date	Type of Rumble Strip	Exterior Measurements	Interior Measurements	Vehicles and Speeds	Comments	Conclusions
Terhaar 2016 (MnDOT) ⁸⁵	Four sinusoidal rumble strip configurations	50 ft and 75 ft from centerline rumble strips, 1-second data	SLM at shoulder height in center of car, L10 metric	Sedan, pick-up, and dump truck	Not available	Sinusoidal designs provide adequate driver feedback and minimal exterior noise
Terhaar 2015 (MnDOT) ⁸⁶	Three rumble strip designs: California, Minnesota, and Pennsylvania designs	50 ft and 100 ft from edge of roadway, 1-second data	SLM at shoulder height between front seats, 1-second readings	Sedan, pickup, and semi-trailer at 30 mph, 45 mph, and 60 mph	Not available	The Cal. Strip provided adequate driver feedback while generating less exterior noise than the Minn. Strip; The Penn. Strip did not provide much driver feedback
Sexton 2014 (WSDOT) ⁸⁷	Milled centerline at 9 locations, variable depth and spacing	TP98 test procedure, 25 ft and 50 ft from center of near lane	none	SUV (2010 Ford Escape hybrid) at 60 mph	Two tires on rumble strip for full measurement duration	The results of specific design variables on exterior noise levels were inconclusive.
Datta 2012 (MDOT) ⁸⁸	Milled centerline and shoulder	Microphone at 50 ft from rumble	none	Chrysler Town and Country minivan at 55 mph	Two tires with continuous contact of RS	Depth of RS has greatest impact on noise, sharp increase

⁸⁵ Terhaar, E., D. Braslau, and K. Fleming, *Sinusoidal Rumble Strip Design Optimization Study*, Report No. MN/RC 2016-23, Minnesota Department of Transportation, St. Paul, MN, 2016.

⁸⁶ Terhaar E. and D. Braslau, *Sinusoidal Rumble Strip Noise Evaluation*, No. MN/RC 2015-07, Minnesota Department of Transportation, St. Paul, MN 2015.

⁸⁷ Sexton, T., *Evaluation of Current Centerline Rumble Strip Design(s) to Reduce Roadside Noise and Promote Safety*, Report No. WA-RD 835.1, Washington Department of Transportation, Olympia, WA, 2014.

⁸⁸ Datta, T., T. Gates and P. Savolainen, *Impact of Non-Freeway Rumble Strips – Phase 1*, Report No. RC-1575, Michigan Department of Transportation, Lansing MI, 2012.

Study / Date	Type of Rumble Strip	Exterior Measurements	Interior Measurements	Vehicles and Speeds	Comments	Conclusions
	rumble strips, variable depth	strip, using “Fast” SLM setting				in noise for depths above 0.5 in
Rys 2010 (Kansas) ⁸⁹	Rectangular and football-shaped RS	50 ft, 100 ft, and 150 ft	none	Ford Taurus and Chevrolet Express (15 passenger van) at 40 mph and 60 mph	Two tires with continuous contact of RS	No significant difference in exterior noise between two types of rumble strips
Torbic 2009 (NCHRP Report 641) ⁹⁰	Milled or rolled RS in PA, MN, CO, UT, AZ, and KY	None	Handheld SLM at centerline of vehicle facing forward at ear height, and GPS	Sedan (Chevy Impala) at speeds from 40 to 65 mph	Varied vehicle departure angles	Used data to develop interior noise prediction models for rumble strips
Rys 2008 (Kansas) ⁹¹	Rectangular and football-shaped centerline RS at one site	None	Microphone clipped to driver’s collar, triaxial accelerometer attached to center of steering wheel	Six vehicles: Dump truck, 2 pickup trucks, minivan, sedan, and SUV at 65 mph	Two tires with continuous contact	No difference in interior noise between two types of rumble strips
Kragh 2007	2 sinusoidal RS, 2 rectangular RS, and 1 cylindrical RS	Microphone 7.5 m from road center line	None	3 passenger cars at 80 km/h	Two left tires with continuous contact	Noise levels decrease when using a sinusoidal shape

⁸⁹ Rys, M., D. Karkle, A. Vijayakumar, R. Makarla, E. Russell, *Promoting Centerline Rumble Strips to Increase Rural, Two-Lane Highway Safety*, Report No. K-TRAN: KSU-08-3, Kansas Department of Transportation and University Transportation Center, 2010.

⁹⁰ Torbic, D.J., J.M. Hutton, C.D. Bokenkroger, K.M. Bauer, D.W. Harwood, D.K. Gilmore, J.M. Dunn, J.J. Ronchetto, E.T. Donnell, H.J. Sommer III, P. Garvey, B. Persaud, and C. Lyon, *Guidance for the Design and Application of Shoulder and Centerline Rumble Strips*, NCHRP Report 641, Transportation Research Board, Washington, DC, 2009.

⁹¹ Rys, M., Gardner L., Russel E., “Evaluation of Football Shaped Rumble Strips versus Rectangular Rumble Strips,” *Journal of the Transportation Research Forum*, Vol 47 No. 2, p. 41-54, 2008.

Study / Date	Type of Rumble Strip	Exterior Measurements	Interior Measurements	Vehicles and Speeds	Comments	Conclusions
(Denmark) 92						compared to a rectangular shape
Finley and Miles 2007 (Texas) ⁹³	Milled, rolled, formed, and buttoned RS at 26 sites	None	SLM to right of driver's seat at shoulder level	Sedan, half-ton truck, commercial vehicle	At least on tire in continuous contact with RS	The current standard RS design is the only one shown to provide adequate increase in sound to alert all drivers (milled, 7 in long, 12 in wide, 0.5 in deep, spaced 12 to 24 in)
Russel 2006 (Kansas) ⁹⁴	Milled shoulder rumble strips, 12 test patterns of various lengths	None	Microphone clipped to driver's collar below right ear and accelerometer on steering wheel	7 vehicles: 2 large trucks, full-size pick-up, full-size passenger car, compact passenger car, minivan, and SUV at 60 mph	Two tires with continuous contact	Small difference in noise levels for different test patterns
Bucko 2001	Rolled-in rumble strip and milled rumble strips with 12 in length with	None	SLM and 4 accelerometers on the steering wheel	2 passenger vehicles, 1 pickup, and 3 commercial trucks		Greater effect of alerting drivers for deeper rumble strips

⁹² Kragh J., B. Andersen, and S. Thomson, *Traffic Noise at Rumble Strips – Internoise paper 2007*, Dansish Road Institute Report 156, 2007.

⁹³ Finley, M. and Miles, J. (2007). "Exterior Noise Created by Vehicles Traveling over Rumble Strips," Proceedings of the 86th Annual Meeting of the Transportation Research Board, Washington, DC

⁹⁴ Russell, E. and M. Rys, *Reducing Crossover Accidents on Kansas Highways Using Milled Centerline Rumble Strips*, Report No. K-TRAN: KSU-00-4, Kansas State University, Lawrence, KS, 2006.

Study / Date	Type of Rumble Strip	Exterior Measurements	Interior Measurements	Vehicles and Speeds	Comments	Conclusions
(Caltrans) 95	varying depths, 6 total designs					
Elefteriadiou, 2000 (PennDOT)) ⁹⁶	6 milled rumble strip test patterns	None	SLM next to motorist's head, vertical and pitch-angular acceleration on vehicle floor	Minivan at 45, 55, and 65 mph	3 to 5 degree departure angle	The most "bicycle-friendly" configuration may not provide sufficient in-car noise levels

⁹⁵ Bucko, T. and A. Khorashadi, "Evaluation of Milled-In Rumble Strips, Rolled-In Rumble Strips and Audible Edge Stripe", prepared by Traffic Operations Program, California Department of Transportation, Sacramento, California, May 2001.

⁹⁶ Elefteriadou, L., M. El-Gindy, D. Torbic, P. Garvey, A. Homan, Z. Jiang, B. Pecheux, and R. Tallon, *Bicycle-Tolerable Shoulder Rumble Strips*, Final Report Prepared for Commonwealth of Pennsylvania Department of Transportation, prepared by The Pennsylvania Transportation Institute, The Pennsylvania State University, University Park, PA, March 2000.

Procedures for Exterior Data Collection / Determining community effects

Summary: The most common approach to exterior data collection is to follow the AASHTO Statistical Isolated Pass-by (SIP) procedure TP98-13. The Caltrans study experimented with measurements on the exterior of the vehicle to use as a surrogate for pass-by tests, however, the measurements were not reliable.

Several recent studies have applied the AASHTO Statistical Isolated Pass-by (SIP) procedure TP98-13 measurement technique.⁹⁷ This method was applied in California, Oregon, and Washington studies presented in Table A-3. In the SIP procedure, the noise from individual pass-bys is measured, but the evaluation is statistical and is not dependent on the individual vehicles. The methodology for the SIP procedure is to place a microphone 7.5 m (25 ft) from and 1.5 m (5 ft) above the center of the lane of travel and/or 15 m (50 ft) from and a height of 3.7 m (12 ft) above the center of the lane of travel. During each vehicle pass-by, the maximum A-weighted sound pressure level should be measured using fast time response. The standard includes guidance on acceptable background noise from other traffic and non-traffic sources. The standard recommends, but does not require, measuring one-third octave band frequency spectra. Vehicle speed, air temperature and wind speed should also be measured.

Studies presented in Table A-3 that did not use the SIP procedure typically measured the rumble strip noise 50 feet from the rumble strip using either the “Fast” (0.125 second data) or “Slow” (1-second data) setting on the sound level meter.

Another standard test procedure for roadside highway noise is the Continuous-Flow Traffic Time-Integrated Method (CTIM) defined in TP 99-13.⁹⁸ The CTIM method is not applicable to rumble strip noise because rumble strip incursions are isolated events, not continuous.

The AASHTO T360-6 On Board Sound Intensity (OBSI) procedure is used to evaluate noise level differences for pavements.⁹⁹ NCHRP research has shown that the OBSI procedure is independent of the test vehicle as long as the vehicle meets several criteria that could be found in a large range of vehicles and that differences between pavements could be reliably ranked using a standard reference tire.¹⁰⁰ However, the Donovan 2018 study in California experimented with using the OBSI procedure on rumble strips and was not able to generate useful data. The

⁹⁷ American Association of State Highway and Transportation Officials, “Standard Method of Test for Determining the Influence of Road Surfaces on Vehicle Noise Using the Statistical Isolated Pass-By Method (SIP),” AASHTO TP 98-11, Washington, D.C., May 2012.

⁹⁸ American Association of State Highway and Transportation Officials, “Standard Method of Test for Determining the Influence of Road Surfaces on Traffic Noise Using the Continuous-Flow Traffic Time-Integrated Method (CTIM),” AASTHO TP 99-12, Washington, D.C., 2011.

⁹⁹ American Association of State Highway and Transportation Officials, “Standard Method of Test for Measurement of Tire/Pavement Noise Using the On-Board Sound Intensity (OBSI) Method,” AASTHO T 360-16, Washington, D.C., 2010.

¹⁰⁰ Donovan, P. and D. Lodico, “Measuring Tire-Pavement Noise at the Source”, NCHRP Report 630, Transportation Research Board, Washington, D.C., 2009.

direction of the intensity vector was into the tire rather than propagating outward for the low-frequency noise generated by the sinusoidal rumble strips.¹⁰¹

The Donavan 2018 study also experimented with three other methods of quantifying exterior noise in an attempt to find a surrogate for the pass-by test so that measurements could be made on-board the test vehicle, eliminating the time required to set-up and perform pass-by tests. Sound pressure level measurements were made at two exterior locations: at the OBSI position alongside of the tire and above the rear wheel well. The exterior noise measurement locations were found not to correlate well with pass-by noise. Exterior body panel vibration was also measured. Due to the long wavelengths at the frequencies generated by the sinusoidal rumble strips, efficient sound radiation requires large surfaces such as the exterior body panels. The panels did generally produce a comparable change in vibration levels on and off the strips similar to the pass-by noise levels, but the results were not reliable and were not found to be a suitable surrogate for exterior pass-by noise measurements.

No studies have presented data on roadside vibration or potential community effects from vibration generated by vehicle incursions on rumble strips. Roadside vibration measurements could follow a procedure similar to that presented in the Federal Transit Administration's (FTA) Transit Noise and Vibration Impact Assessment Manual.¹⁰²

Procedures for Interior Vehicle Measurements

Noise

Summary: The Society of Automotive Engineers (SAE) standard for interior vehicle noise measurements is to place the microphone at the operator's head position; however, this is not practical when an operator will be driving the car. Rumble strip noise evaluations have typically placed the microphone at the head position of the passenger's seat or between the seats at ear or shoulder level. More than one microphone position may be required to avoid the null point of any standing waves.

There are no AASHTO standards that apply to interior vehicle noise measurements; however, noise standards have been adopted by Society of Automotive Engineers (SAE) intended for use during vehicle testing. SAE J1477 is a standard for the measurement of interior sound levels of light vehicles and SAE J336 is a standard for measuring sound in a truck cab interior.^{103,104} SAE

¹⁰¹ Donavan, P., *Design and Acoustic Evaluation of Optimal Sinusoidal Mumble Strips versus Conventional Ground-In Rumble Strips*, California Department of Transportation Report No. CTHWANP-RT-15-365.01.2, 2018.

¹⁰² Quagliata, A., M. Ahearn, E. Boeker, C. Roof, L. Meister, H. Singleton, *Transit Noise and Vibration Impact Assessment Manual*, "FTA Report No. 0123, Federal Transit Administration, 2018.

¹⁰³ Society of Automotive Engineers International, "Measurement of Interior Sound Level of Light Vehicles," SAE J1477_200005, 2000.

¹⁰⁴ Society of Automotive Engineers International, "Sound Level for Truck Cab Interior", SAE J336_201109, 2011.

J1477 calls for a microphone placed at the operator's head position. This procedure cannot be applied in active road conditions when an operator is occupying the driver's seat.

Automobile manufacturers typically use their own variations of the SAE procedures with a microphone suspended near the operator's ear or position in the center of an unoccupied front passenger seat. They also typically specify the location of the seat: full back or forward, full up or down.

In the previous rumble strip noise studies listed in Table A-3, the following interior noise measurement locations were used:

- Microphone at head position of right front seat occupant (Donavan 2018, Hurwitz 2018)
- Microphone next to driver's ear (Mathew 2018) or shoulder (Miles and Finley 2007)
- Microphone at centerline of vehicle between front seats at ear height (Torbic 2009) or shoulder height (Terhaar 2016, 2015)
- Microphone clipped to driver's collar (Rys 2008, Russel 2006)

Donavan, in the 2018 Caltrans sinusoidal rumble strip study, hypothesizes that the interior noise level measured in the heavy vehicle cab was likely affected by standing acoustic waves in the interior cavity. The spectral data in the heavy vehicle did not show a peak at the 80 Hz frequency that would correspond to the sinusoidal rumble strip wavelength; a peak at 80 Hz was apparent in other vehicles.¹⁰⁵ The report advises the use of more than one microphone location or to be certain that the microphone position chosen will not be located in a null point of any potential standing waves. The report also notes that because of standing waves and cavity modes of the interior, acoustic measures such as unweighted or C-weighted levels are not a surrogate for vibration measurements.

Van Auken, Zellner, and Kunkell looked at the noise metrics associated with drivers' over-the-road transient discomfort.¹⁰⁶ The interior noise was measured in the vehicle centerline near the driver's right ear. The study considered different metrics including magnitude and sharpness as well as fast and impulse time weightings. The conclusion of the study was that Fast A-weighted sound pressure level is a practical metric for predicting over-the-road transient noise discomfort.

Vibration

Summary: SAE standard J2834 and ISO 2631 advise that human exposure to vibration should be measured at the interface between the human body and the respective vehicle surface, specifically at the seat-buttocks surface, seat-back surface, and the floor-feet surface. Bourne

¹⁰⁵ Donavan, P., Design and Acoustic Evaluation of Optimal Sinusoidal Mumble Strips versus Conventional Ground-In Rumble Strips, California Department of Transportation Report No. CTHWANP-RT-15-365.01.2, 2018.

¹⁰⁶ Van Auken, M., J.W. Zellner, and D.T. Kunkel, "Correlation of Zwicker's Loudness and Other Noise Metrics with Drivers' Over-the-Road Transient Discomfort," SAE Technical Paper Series, SAE International, International Congress and Exposition, 1998.

found that 24 channels of passenger compartment acceleration data at these interfaces are highly inter-correlated.

The SAE standard J2834 was developed to predict human sensitivity to motion and vibration in automobiles.¹⁰⁷ The standard recommends that transducers be located at the interface between the human body and the respective vehicle surface. The standard's recommended locations are:

- Supporting seat/buttocks surface at the location of the “sitting bones.” A commonly used design for accelerometer mount for seat vibration measurements is given in ISO 10326-1
- The seat/back surface
- The floor/feet surface
- For drivers, the steering wheel/hands surface

The standard prescribes that the vibration be measured according to an orthogonal rectilinear coordinate system, shown in Figure A-6. Figure A-6 also labels the recommended measurement locations at the interface between the human body and the vehicle surface.

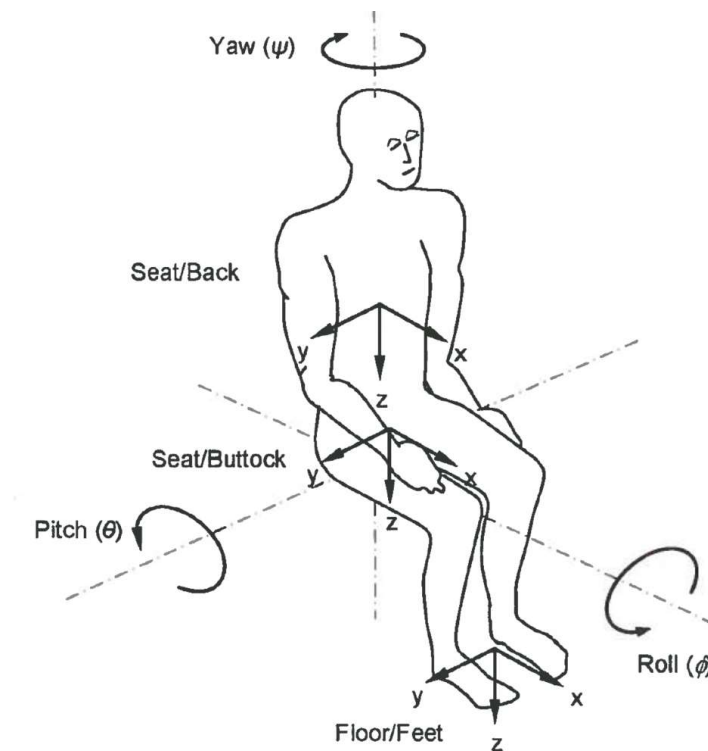


Figure A-6: Orthogonal coordinate system and measurement points for in-vehicle vibration measurements¹⁰⁷

¹⁰⁷ Society of Automotive Engineers International, “Surface Vehicle Recommended Practice – Ride Index Structure and Development Methodology,” SAE J2834, October, 2013.

The standard recommends the measurement duration shall be a minimum of 8 seconds. Where this is not possible due to high speeds or transient events, the standard recommends multiple measurements and an assessment of accuracy based on the observed run-to-run variations. The standard also recommends recording vehicle speed, to ensure consistency in data collection.

The standard lays out a basic processing method using weighted root-mean-square (RMS) acceleration for rough road ride conditions and root-mean-quad (RMS and RMQ) acceleration for transient ride conditions. The standard provides formulas for calculating RMS and RMQ, frequency weightings used for various directions and applications, and a formula to determine whether the ride shall be determined as rough or transient.

ISO standard 2631 addresses human exposure to vibration.¹⁰⁸ The standard provides similar guidance to SAE J2834. It advises the use of the same basicentric coordinate system shown in Figure A-6 and advises that the transducers shall be located so as to indicate the vibration at the interface between the human body and the source of its vibration. The three principal areas for seated persons are the supporting seat surface (seat/buttock), the seat-back, and the floor. ISO standard 5349 addresses hand-transmitted vibration.¹⁰⁹ The ISO standards also provide frequency weightings to assess human exposure to vibration.

Gordon completed a study of vehicle vibration response from a wide variety of rumble strips and other road surface features.¹¹⁰ The goal of the study was to determine whether the captured signals would be sufficient to form the basis of a reliable rumble strip detection system within a short period of time to allow for a safety countermeasure response. The study located sixteen vertically and longitudinally mounted accelerometers on the sprung and unsprung masses at the wheel stations of a sport-utility vehicle. Two laterally oriented accelerometers were mounted on each of the steering linkages. The study concluded that of the 18 signals, only the longitudinal accelerations at the unsprung mass provided a reliable measure of the road surface excitation.

Bourne completed a study focused on ride quality that included both collection of objective vibration data and subjective rating data.¹¹¹ They collected 24 channels of acceleration data including measurements at the key driver/vehicle interfaces: floor/feet, seat/back, and seat/buttock. Both translational and angular acceleration measurements were collected at the seat/buttock and feet/floor locations. The analysis of the data showed that passenger

¹⁰⁸ International Organization of Standardization, Mechanical vibration and shock – Evaluation of human exposure to whole-body vibration – Part 5: Method for evaluation of vibration containing multiple shocks, ISO 2631-5:2018, 2018.

¹⁰⁹ International Organization of Standardization, Mechanical vibration – Measurement and evaluation of human exposure to hand-transmitted vibration – Part 1: General requirements, ISO 5349-1:2001, 2001.

¹¹⁰ Gordon, T.J., Z. Baraket, “Vibration Transmission from Road Surface Features – Vehicle Measurement and Detection, Technical Report for Nissan Technical center North America, Inc., The University of Michigan Transportation Research Institute, Ann Arbor, MI, January 2007.

¹¹¹ Bourne, S.M, J.W. Zellner, and C.C. Matthews, “On the methodology for development of discomfort models for passenger car rough road ride,” C466/035/93, Institute of Mechanical Engineers, 1993.

compartment acceleration data are highly inter-correlated and that vertical acceleration characteristics are dominated by sprung and unsprung mode energies.

Meinhardt notes that it is typical for vehicle manufacturers to measure on the outboard seat track.¹¹² This measurement location could be used to represent the floor/feet interface while avoiding floor panel resonances and modes that would vary from vehicle to vehicle. This measurement location was also used by Donovan in the 2018 Caltrans study and by Mathew in the 2018 INDOT study.

STATE-OF-PRACTICE REVIEW

Roadway departure warning indicators, also known as rumble strips, are a proven safety countermeasure intended to alert drivers when they leave the roadway across the edge line or center line. Center line rumble strips (CLRSs) are used to reduce head-on, opposite direction sideswipe crashes and lane departure crashes, and shoulder rumble strips (SRSs) are used to reduce roadway departure crashes. Edge-line Rumble Strips (ELRS) are a special type of shoulder rumble strip placed directly at the edge of the travel lane with the edge line pavement marking placed through the line of the rumble strip.¹¹³ Rumble strips are constructed in/on pavement as longitudinal patterns of variable surface profile which alert the driver with both audible noise and tactile vibration.¹¹⁴

As rumble strips have gained in popularity as a safety measure, the Federal Highway Administration (FHWA) and National Cooperative Research Program have undertaken efforts to provide guidance on and synthesize State Department of Transportation (DOT) guidance on rumble strips. These resources include details on design parameters, safety considerations, and appropriate locations for installation. Many of the resources also address best practices to accommodate bicyclists. Noise policies and low-noise rumble strip design is covered in some of the existing resources but is often covered less comprehensively. This state-of-practice review gives special consideration to rumble strip noise control policies and low-noise rumble strip design. This state-of-practice review presents information in three sections:

- Section 3.1: Overview of existing FHWA guidance and other syntheses on general state-of-practice on rumble strips, including design parameters and accommodation for bicyclists
- Section 3.2: Noise control policies related to rumble strips
- Section 3.3: Low-noise rumble strip design

¹¹² Meinhardt, G., Z. Sun, and G. Steyer, "An Application of Variation Simulation—Predicting Interior Driveline Vibration Based on Production Variation of Imbalance and Runout," Society of Automotive Engineers Noise and Vibration Conference Proceedings, Paper 2011-01-1543, Grand Rapids, MI., May 2011.

¹¹³ Smadi O. and N. Hawkins, *Practice of Rumble Strips and Rumble Stripes: A Synthesis of Highway Practice*, National Cooperative Highway Research Program Synthesis 490, 2016.

¹¹⁴ Himes, S., H. McGhee, S. Levin, and Y. Zhou, *State of Practice for Shoulder and Center Line Rumble Strip Implementation on Non-Freeway Facilities*, Report No. FHWA-HRT-17-012, Federal Highway Administration, 2017.

To help understand the parameters involved in rumble strip design in this state-of-practice section, Figure A-2 is repeated here as Figure A-7, which shows a vehicle in relation to an SRS. Figure A-7 presents the standard design parameters for rumble strips: (A) offset, (B) length or perpendicular width, (C) parallel width, (D) depth, (E) spacing, (F) recovery area, (G) gap, (I) lateral clearance, and (α) departure angle. An additional parameter, wavelength, is used in sinusoidal rumble strip design. Parameter (B) is commonly referred to as length in standard rumble strip design but is often referred to as perpendicular width in low-noise rumble strip design to avoid confusion with wavelength.

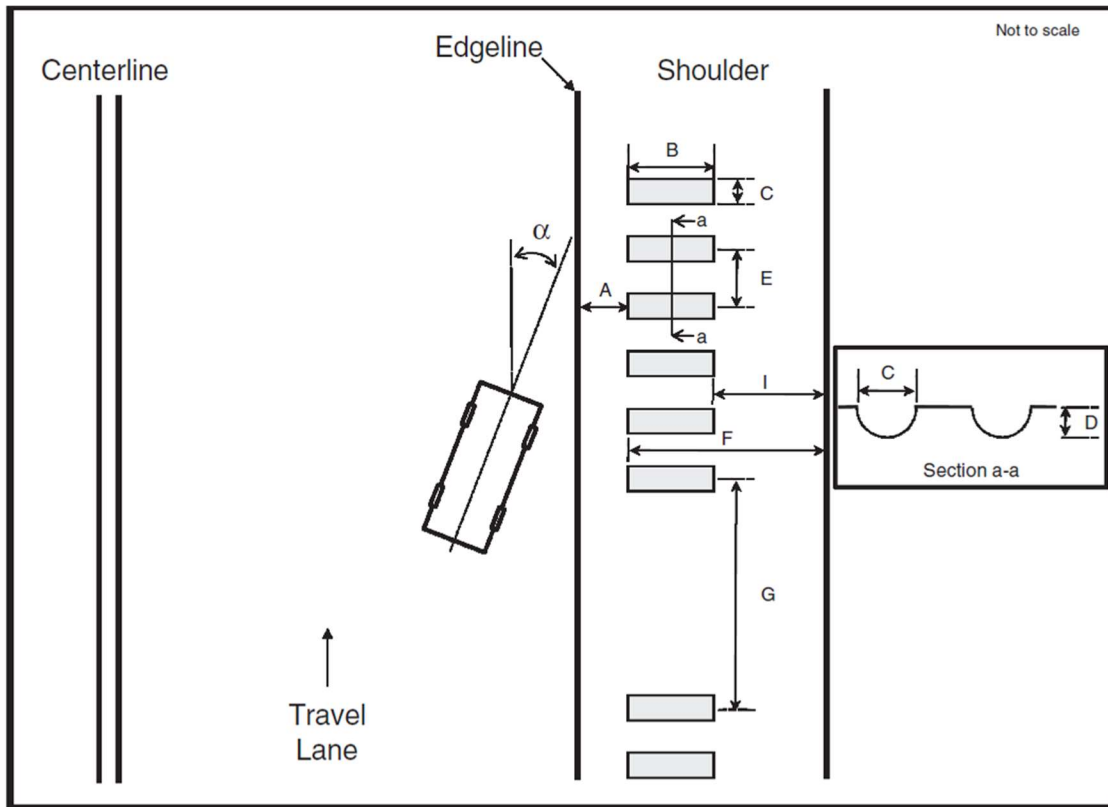


Figure A-7: Standard Design Parameters for Rumble Strips

OVERVIEW OF RUMBLE STRIP STATE-OF-PRACTICE RESOURCES

In 2009, the NCHRP published the report “*Guidance for the Design and Application of Shoulder and Centerline Rumble Strips.*”¹¹⁵ This report provides guidance for the design and application of shoulder and centerline rumble strips as an effective crash reduction measure, while minimizing adverse effects for motorcyclists, bicyclists, and nearby residents. Using the results of previous studies and the research conducted under this project, safety effectiveness estimates were

¹¹⁵ Torbic, D.J., J.M. Hutton, C.D. Bokenkroger, K.M. Bauer, D.W. Harwood, D.K. Gilmore, J.M. Dunn, J.J. Ronchetto, E.T. Donnell, H.J. Sommer III, P. Garvey, B. Persaud, and C. Lyon, *Guidance for the Design and Application of Shoulder and Centerline Rumble Strips*, NCHRP Report 641, Transportation Research Board, Washington, DC, 2009.

developed for shoulder rumble strips on rural freeways and rural two-lane roads and for centerline rumble strips on rural and urban two-lane roads.

Ahmed 2015 (FHWA-WY-15/02) includes a summary of the rumble strip/stripe practice in all 50 States.¹¹⁶ The summary includes the standard design for SRS and CLRS, any considerations in the State’s guidance for other roadway users such as bicycles, and, if available, noise considerations. The survey found that many States had started following the guidelines provided by the NCHRP to install their rumble strips, although some States were still using their own guideline policy. Few States did not have any rumble strips policy.

In 2016, NCHRP published synthesis 490: “Practice of Rumble Strips and Rumble Stripes”.¹¹⁷ The synthesis compiles current practices used by States installing rumble strips and explores variations in practice in terms of design, criteria, and locations for installation, maintenance, perceived benefits, communication of benefits, and what are considered important issues. The synthesis report also includes results from a survey to which 41 State DOTs responded to questions on their rumble strip practices.

In 2017, the FHWA published the report *State of Practice for Shoulder and Center Line Rumble Strip Implementation on Non-Freeway Facilities*.¹¹⁸ The objective of the document was to identify the state of knowledge and practice among State transportation departments for the use and design of CLRSs and SRSs and identify any research gaps. Table 7 of the report summarizes the standard shoulder rumble strip dimensions used in each State, including offset, length, width, depth, spacing and gap.

To supplement the State-of-Practice Report, the FHWA published a Decision Support Guide for the Installation of Shoulder and Center Line Rumble Strips on Non-Freeways.¹¹⁹ The guide informs agencies on center line and shoulder rumble strip installation. It describes methods for identifying appropriate locations for installation, assessing the potential crash reductions and cost-benefit ratio, and developing performance metrics for safety. Additionally, the guide discusses special considerations for rumble strip installations, identifies variability in current practices, and provides a decision-support framework for installing rumble strips.

¹¹⁶ Ahmed, A., M. A. Sharif, and K. Ksaibati, *Developing an Effective Shoulder and Centerline Rumble Strips/Stripes policy to accommodate all Roadway Users*, Wyoming Department of Transportation, Report No. FHWA-WY-15/02, April 2015.

¹¹⁷ Smadi O. and N. Hawkins, *Practice of Rumble Strips and Rumble Stripes: A Synthesis of Highway Practice*, National Cooperative Highway Research Program Synthesis 490, 2016.

¹¹⁸ Himes, S., H. McGhee, S. Levin, and Y. Zhou, *State of Practice for Shoulder and Center Line Rumble Strip Implementation on Non-Freeway Facilities*, Report No. FHWA-HRT-17-012, Federal Highway Administration, 2017.

¹¹⁹ Himes, S., and H. McGhee, *Decision Support Guide for the Installation of Shoulder and Center Line Rumble Strips on Non-Freeways*, Report No. GHWA-SA-16-115, Federal Highway Administration, August 2016.

The FHWA has compiled their guidance on rumble strips on their website.¹²⁰ The website includes links to their decision support guide, technical advisories, and research. It provides information on safety, design and construction, accommodating all users, mitigating noise, and pavement and maintenance.

We have developed a supplementary spreadsheet to this memorandum that includes information on the standard design practices for shoulder rumble strips for each of the States. The spreadsheet includes information on design parameters such as width and length, gapping patterns to accommodate bicyclists, and typical speeds and pavement types. The information on the spreadsheet is sourced from Table 7 of the FHWA state-of-practice report.¹²¹ The range of standard rumble strip design parameters in the spreadsheet will be used to inform the development of low-noise rumble strip design parameters. The spreadsheet is included as Table A-4 and is available as an Excel file for easier review.

¹²⁰ FHWA Office of Safety, “Rumble Strips and Stripes” web page. Available at: https://safety.fhwa.dot.gov/roadway_dept/pavement/rumble_strips/

¹²¹ Himes, S., H. McGhee, S. Levin, and Y. Zhou, *State of Practice for Shoulder and Center Line Rumble Strip Implementation on Non-Freeway Facilities*, Report No. FHWA-HRT-17-012, Federal Highway Administration, 2017.

Table A-4: Summary of State Agency Standard Design Practices

State-of-practice information																	
Columns B-L: Himes, S., H. McGhee, S. Levin, and Y. Zhou, <i>State of Practice for Shoulder and Center Line Rumble Strip Implementation on Non-Freeway Facilities</i> , Report No. FHWA-HRT-17-012, Federal Highway Administration, 2018																	
Columns M-R: See references in NCHRP 15-68 State-of-Practice Review																	
State	Standard Design Guidance for Shoulder Rumble Strips*								Bicycle Accommodation Practices			Noise Abatement Strategies			Sinusoidal Rumble Strip Design*		
	Posted Speed (mi/hr)	Asphalt Condition	Use ELRS?	A - Shoulder Offset (in)	B - Perpendicular Width / Length (in)	C - Parallel Width (in)	D - Depth (in)	D - Spacing (in)	Bike Gap - Run (ft)	F - Bike Gap - Gap (ft)	Shoulder Width (ft)	Design Practices	Implementation near residences	Other design considerations	Wavelength (in)	Depth (in)	Perpendicular Width / Length (in)
Alabama	45	Good	Yes	-	8-12	-	-	-	-	-	2	-	Noise should be considered when determining whether to install RS near residential areas, but the guidance is secondary to safety	Do not install CLRS in passing zones	-	-	-
Alaska	50	Good, > 2 inches	No	4	16	7	1/2	12	68	12	6	-	-	-	-	-	-
Arizona	-	Avoid joint	Yes	10	6-12	7	3/8	12	30	10	5	-	Discontinue RS 2000 ft before a residential area	Do not install CLRS in passing zones near residences	-	-	-
Arkansas	50	Good	Yes	4	6-16	5	3/8	12	48	12	5.25	Reduce RS depth to 3/8 in in areas with residential and commercial development near the roadway	-	Do not install CLRS in passing zones	-	-	-
California	40	-	Yes	6	6-12	5	5/16	14	-	-	5.5	Completed a study on sinusoidal RS design and noise reduction (see Table 4-1)	-	-	14	5/16	12
Colorado	-	-	No	-	12	7	3/8	12	48	12	5	-	-	-	-	-	-
Connecticut	-	-	No	6	16	7	1/2	12	-	-	-	-	Did not use RS from 1999-2014 due to noise complaints	Changed standard design of SRS from 6 in offset of right shoulder to 12 in offset; discontinue CLRS 25 ft before passing zone	-	-	-
Delaware	40	New	Yes	6	6	7	3/8	12	40	12	5	-	Discourages the use of RS in high density residential areas; recommends consulting Engineering Support and Public Relations to determine if noise will be an issue with RS	-	-	-	
Florida	-	-	No	12	16	7	1/2	12	-	-	-	Recommends sinusoidal RS design for noise-sensitive areas	-	-	14	5/16	8
Georgia	55	-	Yes	12	6-16	7	1/2	12	28	12	4	-	-	-	-	-	-
Hawaii	40	-	Yes	2	6-12	5	3/8	12	47	13	4	-	-	-	-	-	-
Idaho	-	Good	Yes	12	6-16	6-7	3/8	12	48	12	2	-	-	-	-	-	-
Illinois	-	-	Yes	-	8-16	7	7/16	12	48	12	-	-	-	-	-	-	-
Indiana	-	-	Yes	-	16	7	1/2	12	50	10	-	Completed a study on sinusoidal RS design and noise reduction in 2018 (see Table 4-1)	-	-	12	1/8 at crest, 1/2 at trough	12
Iowa	50	-	No	6	12	7	1/2	12	48	12	4	-	Discourages the use of RS in areas with relatively high levels of residential development	-	-	-	-
Kansas	-	New, > 1 inch	No	-	12	7	1/2	12	-	-	2	Evaluated the use of "football-shaped" RS, found no improvement compared to standard design	-	-	-	-	-
Kentucky	50	-	Yes	12	8-16	7	3/8	12	50	10	1	-	-	-	-	-	-
Louisiana	50	Avoid joint	Yes	-	6-12	7	1/2	14	40	10	-	-	Only installs RS on roadways with speeds greater than 50 mph, and does not install RS in residential areas	-	-	-	-
Maine	45	< 5 years, > 3 inches	Yes	6	16	7	1/2	12	48	12	4	-	Considerations for high-density residential areas should be weighted in determining installation of RS	If truck off-tracking on inside of curves conflicts with edge line RS placement, then RS shall be omitted in these locations	-	-	-
Maryland	40	Good	Yes	12	6-12	5-7	3/8	12	48	12	5	-	Carefully evaluate the use of RS near residential areas or other sensitive noise receptors; this is a secondary consideration to safety	-	-	-	-
Massachusetts	40	-	No	4	16	6	3/8	12	64	16	8	-	-	-	-	-	-
Michigan	55	-	No	12	12	7	3/8	12	48	12	6	Recommends RS depth between 0.25 to 0.5 in to limit noise	Allows RS omission where the driveway density exceeds 30 driveways per 0.5 mi	Use a 12 in offset for shoulder RS	-	-	-
Minnesota	55	-	Yes	4	8-12	7	3/8	12	48	12	< 4	Adopted a sinusoidal RS design required for concrete pavements and optional for bituminous pavements (see Table 4-1)	Discontinue RS 130 ft before residential areas	-	14	1/16 at crest, 1/2 at trough	variable

STATE-OF-PRACTICE FOR RUMBLE STRIP NOISE CONTROL

Information regarding the state-of-practice of rumble strip policy relating to noise was gathered from an internet search of State rumble strip guidance and from existing syntheses.^{122,123, 124} In general, guidance related to rumble strip noise can be divided into three categories:

1. **Low-noise design options** – Some State DOTs allow for reducing standard rumble strip depth or implementation of a low-noise sinusoidal rumble strip design in areas where roadside noise is a concern. Several States have completed studies showing sinusoidal rumble strips reduce roadside noise compared to conventional strips and recommend their construction in noise sensitive areas. No States have adopted sinusoidal rumble strips as their standard design.
2. **Implementation restrictions near residences** – Some State DOTs specify a specific distance from residences at which rumble strips should be discontinued. Some States do not specify a distance but do allow for an evaluation on whether rumble strips should be omitted near noise sensitive receptors. In general, States discourage the use of rumble strips in areas with relatively high levels of residential development.
3. **Measures to reduce inadvertent rumble strip strikes** - Some States do not place CLRS in passing zones or increase rumble strip gapping in passing zones. Some States do not place ELRS on the inside of horizontal curves where off-tracking is common and there is a greater likelihood of inadvertent strikes. Some States recommend a larger offset for shoulder rumble strips near residences to reduce the likelihood of inadvertent strikes. The drawback of these strategies is that they reduce or eliminate the safety effectiveness of RS.

The FHWA has published a guide on addressing rumble strip noise issues on two-lane roads that includes guidance on the three categories above, as well as outreach and alerting noise considerations for the driver.¹²⁵

Table A-5 shows the noise-specific rumble strip guidance from each State. The row for a State is blank if we did not find any noise-specific guidance.

¹²² Himes, S., H. McGhee, S. Levin, and Y. Zhou, *State of Practice for Shoulder and Center Line Rumble Strip Implementation on Non-Freeway Facilities*, Report No. FHWA-HRT-17-012, Federal Highway Administration, 2017.

¹²³ Ahmed, A., M. A. Sharif, and K. Ksaibati, *Developing an Effective Shoulder and Centerline Rumble Strips/Stripes policy to accommodate all Roadway Users*, Wyoming Department of Transportation, Report No. FHWA-WY-15/02, April 2015.

¹²⁴ CTC & Associates LLC, *Traffic Noise Generated by Rumble Strips*, Caltrans Division of Research and Innovation Preliminary Investigation, March 5, 2012.

¹²⁵ FHWA, *Rumble Strip Noise Implementation Guide: Addressing Noise Issues on Two Lane Roads*, FHWA-SA-15-033, April 2015. Available at: https://safety.fhwa.dot.gov/roadway_dept/pavement/rumble_strips/mitigating-noise.cfm

Table A-5: Summary of State Guidance on Rumble Strip Noise

State	Low-noise design options	Implementation restrictions near residences	Measures to reduce inadvertent rumble strip strikes
Alabama ¹²⁶		Noise should be considered when determining whether to install RS near residential areas, but the guidance is secondary to safety	Do not install CLRS in passing zones
Alaska			
Arizona ¹²⁷		Discontinue RS 2000 ft before a residential area	Do not install CLRS in passing zones near residences
Arkansas ¹²⁸	Reduce RS depth to 3/8 in in areas with residential and commercial development near the roadway		Do not install CLRS in passing zones
California ¹²⁹	Completed a study on sinusoidal RS design and noise reduction (see Table A-)		
Colorado			
Connecticut ^{13, 130}		Did not use RS from 1999-2014 due to noise complaints	Changed standard design of SRS from 6 in offset of right shoulder to 12 in offset; discontinue CLRS 25 ft before passing zone
Delaware ¹³¹		Discourages the use of RS in high density residential areas; recommends consulting Engineering Support and Public Relations to determine if noise will be an issue with RS	
Florida ¹³²	Recommends sinusoidal RS design		

¹²⁶ Himes, S., H. McGhee, S. Levin, and Y. Zhou, *State of Practice for Shoulder and Center Line Rumble Strip Implementation on Non-Freeway Facilities*, Report No. FHWA-HRT-17-012, Federal Highway Administration, 2017.

¹²⁷ Arizona Department of Transportation, *Traffic Engineering Guidelines and Processes, Section 400 – Pavement Markings*, January 2018.

¹²⁸ Vozel, F., *Memorandum: Policy for the Use of Rumble Strips*, Arkansas Highway and Transportation Department, April 2, 2012.

¹²⁹ Donovan, P., *Design and Acoustic Evaluation of Optimal Sinusoidal Mumble Strips versus Conventional Ground-In Rumble Strips*, California Department of Transportation Report No. CTHWANP-RT-15-365.01.2, 2018.

¹³⁰ Ahmed, A., M. A. Sharif, and K. Ksaibati, *Developing an Effective Shoulder and Centerline Rumble Strips/Stripes policy to accommodate all Roadway Users*, Wyoming Department of Transportation, Report No. FHWA-WY-15/02, April 2015.

¹³¹ Delaware Department of Transportation, *Memorandum Number 1-18 Revised: Continuous Centerline and Longitudinal Edgeline Rumble Strips*, Delaware Department of Transportation Division of Transportation Solutions, May 16, 2011.

¹³² Florida DOT Standard Plans - FY 2019-20. Index 546-010.
<http://www.fdot.gov/design/standardplans/Current/IDx/546-010.pdf>

State	Low-noise design options	Implementation restrictions near residences	Measures to reduce inadvertent rumble strip strikes
	or reduced 3/16 in depth of conventional RS for noise-sensitive areas		
Georgia			
Hawaii			
Idaho			
Illinois			
Indiana ¹³³	Completed a study on sinusoidal RS design and noise reduction in 2018 (see Table A-)		
Iowa ¹³⁴		Discourages the use of RS in areas with relatively high levels of residential development	
Kansas ¹³⁵	Evaluated the use of “football-shaped” RS, found no improvement compared to standard design		
Kentucky			
Louisiana ¹³⁶		Only installs RS on roadways with speeds greater than 50 mph, and does not install RS in residential areas	
Maine ¹³⁷		Considerations for high-density residential areas should be weighted in determining installation of RS	If truck off-tracking on inside of curves conflicts with edge line RS placement, then RS shall be omitted in these locations
Maryland ¹³⁸		Carefully evaluate the use of RS near residential areas or other sensitive noise receptors; this is a secondary consideration to safety	
Massachusetts			

¹³³ Mathew, J. K., A.D. Balmos, D. Plattner, T. Wells, J.V. Krogmeier, and D.M. Bullock D.M., *Assessment of alternative sinusoidal rumble strip construction*, Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2018/05, West Lafayette, IN, Purdue University, 2018. <https://doi.org/10.5703/1288284346648>

¹³⁴ Savolainen, P. T., A. Sharma, T. P. Barrette, B. Vafaei, and T.J. Kirsch, *Installation Guidance for Centerline and Edgeline Rumble Strips in Narrow Pavements*, Iowa Highway Research Board Project TR-696, September 2017.

¹³⁵ Rys, M., Gardner L., Russel E., “Evaluation of Football Shaped Rumble Strips versus Rectangular Rumble Strips,” *Journal of the Transportation Research Forum*, Vol 47 No. 2, p. 41-54, 2008.

¹³⁶ Himes, S., H. McGhee, S. Levin, and Y. Zhou, *State of Practice for Shoulder and Center Line Rumble Strip Implementation on Non-Freeway Facilities*, Report No. FHWA-HRT-17-012, Federal Highway Administration, 2017.

¹³⁷ Foley, B., D. Brunell, A. DeGrace, and N. Collins, *Rumble Strip Policy for Non-Interstate Highways*, Maine DOT Engineering Instruction, Sept 8, 2016.

¹³⁸ Maryland State Highway Administration, *Guidelines for Application of Rumble Strips and Rumble Stripes*, Revised August 2017. <https://www.roads.maryland.gov/oots/guidelinesapplrumblestripsstripes.pdf>

State	Low-noise design options	Implementation restrictions near residences	Measures to reduce inadvertent rumble strip strikes
Michigan ^{23, 139}	Recommends RS depth between 0.25 to 0.5 in to limit noise	Allows RS omission where the driveway density exceeds 30 driveways per 0.5 mi	Use a 12 in offset for shoulder RS for non-freeway
Minnesota ^{23, 140}	Adopted a sinusoidal RS design required for concrete pavements and optional for bituminous pavements (see Table A-)	Discontinue RS 130 ft before residential areas	
Mississippi			
Missouri ¹⁴¹		If noise complaints continue beyond a year, complete an evaluation to remove the RS	
Montana ^{28, 142}	Decrease the depth of RS from 5/8 to 3/8 in to reduce noise in residential areas	If a decision is made to eliminate RS in residential areas, they should be terminated 650 ft before nearby residences	Increase the offset from the edge of the travel lane to reduce noise in residential areas
Nebraska ¹⁴³		Rural areas that may become urban can eliminate RS	
Nevada ¹⁴⁴		Discontinue RS 1000 ft before residential areas	Do not install CLRS in passing zones
New Hampshire ¹⁴⁵			
New Jersey			
New Mexico			
New York			
North Carolina			
North Dakota			
Ohio			
Oklahoma			

¹³⁹ Wayne State University Transportation Research Group, *Implementation Guideline for Non-Freeway Centerline Rumble Strips*, Prepared for Michigan Department of Transportation, March 31, 2015.

¹⁴⁰ Daubenberger, N. T., *Technical Memorandum No 17-08-T-02: Rumble Strips and Stripes on Rural Trunk Highways*, Minnesota Department of Transportation, August 21, 2017

¹⁴¹ Himes, S., H. McGhee, S. Levin, and Y. Zhou, *State of Practice for Shoulder and Center Line Rumble Strip Implementation on Non-Freeway Facilities*, Report No. FHWA-HRT-17-012, Federal Highway Administration, 2017.

¹⁴² Kailey, D., *Memorandum: Rumble Strip Guidance*, Montana Department of Transportation, July 8, 2018.

¹⁴³ Nebraska Department of Transportation, *Roadway Design Manual*, Chapter Eight, 2006.

¹⁴⁴ Nevada Department of Transportation, *Road Design Guide*, 2010.

<https://www.nevadadot.com/home/showdocument?id=1535>

¹⁴⁵ Marshall, J. A., *Memorandum: REVISED Guidelines for the Installation of Milled Rumble Strips/Stripes*, New Hampshire Bureau of Highway Design, August 31, 2015

State	Low-noise design options	Implementation restrictions near residences	Measures to reduce inadvertent rumble strip strikes
Oregon ^{146, 147}	Option to install rumble strips designed to minimize noise; completed a study on sinusoidal RS (see Table A-)	RS may be omitted within 600 ft of a residence or a campground; if public outreach is completed the distance may be reduced to 200 ft	Offset SRS up to 4 ft from edge line if the clear shoulder width is sufficient; CLRS may be omitted where frequent passing occurs; RS may be omitted at horizontal curves with frequent vehicle off-tracking and at approaches to intersecting roads and driveways with vehicles frequently turning
Pennsylvania ²⁸			Do not install edge-line RS on inside of horizontal curves
Rhode Island			
South Carolina			
South Dakota ¹⁴⁸	Can use sinusoidal RS design in lieu of standard RS on segments adjacent to residences (see Table A-)	Allows flexibility in gapping RS near residences	
Tennessee			
Texas ¹⁴⁹	Allows for a RS depth of 0.375 in in residential areas		
Utah			
Vermont ¹⁵⁰		Discontinue RS where residences are within 100 ft of the centerline, gap should be the width of the residence and 100 ft on each side of the residence	
Virginia ¹⁵¹	Reduce RS depth to 3/8 in	May omit RS in areas with noise sensitive receptors	Provides for discretion on the installation of CLRS and the lateral placement of SRS to abate noise; can increase CLRS spacing and/or only place within

¹⁴⁶ Oregon Department of Transportation, *Policy for Installing Longitudinal Rumble Strips on STIP Projects on State Highways*, Traffic-Roadway Bulletin TR 17-03(B), September 1, 2017.

¹⁴⁷ Hurwitz, D., D. Horne, H. Jashami, C. Monsere, and S. Kothuri, *Quantifying the performance of low-noise rumble strips*, Joint Oregon Department of Transportation and Federal Highway Administration, Report No. SPR 800, Joint Oregon State University and Portland State University, publication pending 2018.

¹⁴⁸ South Dakota Department of Transportation, *Centerline Rumble Stripe Fact Sheet*, <http://www.sddot.com/transportation/highways/traffic/safety/docs/SDDOTRumbleStripeFactSheet.pdf>.

¹⁴⁹ Himes, S., H. McGhee, S. Levin, and Y. Zhou, *State of Practice for Shoulder and Center Line Rumble Strip Implementation on Non-Freeway Facilities*, Report No. FHWA-HRT-17-012, Federal Highway Administration, 2017.

¹⁵⁰ Devlin, J. A., *Guidelines for Milled Rumble Strips*, Highway and Safety Design Engineering Instructions, Vermont Department of Transportation, May 11, 2017.

¹⁵¹ Keen, S. H. and R. J. Khoury, *Instruction and Informational Memorandum: Rumble Strips and Rumble Stripes*, Virginia Department of Transportation, May 10, 2017.

State	Low-noise design options	Implementation restrictions near residences	Measures to reduce inadvertent rumble strip strikes
			the limits of the passing zone skip lines
Washington ¹⁵²	Low noise rumble strip design may be warranted when installing RS in urban growth areas, and/or within 600 ft of a residence, school, church, or campground		Where low noise RS is not feasible, discontinue RS through frequently used road approaches, passing zones, and in tight curves; do not use edge-line RS on inside of horizontal curves
West Virginia ¹⁵³	Reduce depth of RS to 3/8 in	Non-use of RS recommended in spot locations, so as not to prevent their use along a corridor	Increase offset to SRS where external noise may be a factor
Wisconsin			
Wyoming			

STATE-OF-PRACTICE FOR LOW-NOISE RUMBLE STRIP DESIGN

The following States allow for alternative low-noise rumble strip designs in their guidance or have carried out studies on test sections of low-noise rumble strips: California, Florida, Indiana, Minnesota, Oregon, South Dakota, and Washington. State DOT guidance from Florida, Minnesota, and South Dakota include sinusoidal rumble strips as a low-noise design and recommend specific design parameters. Oregon and Washington refer to low-noise rumble strip designs in their guidance, but do not specify sinusoidal rumble design parameters. California, Indiana, and Oregon have sponsored research and test sections of sinusoidal rumble strips on their roads, but do not call for low-noise rumble strip designs in their guidance. In California, the application of sinusoidal rumble strips is determined at the Caltrans District level and is widely used in some districts.

¹⁵² Washington State Department of Transportation website, accessed December 2018. <http://www.wsdot.wa.gov/Design/Policy/RumbleStrips.htm>

¹⁵³ West Virginia Department of Transportation, *Design Directives*, Division of Highways and Engineering Division, November 2014 (Updated November 2016).

Studies on sinusoidal rumble strips have shown that they reduce roadside noise while generating sufficiently high levels of noise and vibration inside the vehicle to alert drivers.^{154, 155, 156, 157, 158} The roadside noise reduction provided by sinusoidal rumble strips varies with design parameters such as wavelength and depth, and with operating conditions such as vehicle type and speed. Studies have also used different methodologies to measure noise and vibration inside the car and at the roadside, which makes it difficult to compare results and draw conclusions about optimal design parameters. In general, sinusoidal rumble strips have reduced wayside noise compared to conventional strips by about 4 to 12 dB.

FHWA has reported that WSDOT has an ongoing rumble strip research project that has installed several experimental patterns using wider spacing between strips and shallower depth.¹⁵⁹ However, a performance study of these installations is not available. Some States have evaluated ELRS which did reduce external noise but did not provide the same level of internal noise and vibration as conventional strips. Currently, sinusoidal rumble strips are the only low-noise design that have reduced roadside noise levels while providing comparable internal noise and vibration levels as compared to conventional strips.

Table A-6 shows the design parameters of the sinusoidal rumble strips used in different States. The key design parameters for a sinusoidal rumble strip are wavelength, depth into the pavement (or peak-to-peak amplitude), and perpendicular width (or length). Figure A-8 shows the recommended sinusoidal profile for the “mumble” strip design from California.

For California, Indiana, and Oregon, the design parameters in Table A-6 are from the preferred test sections evaluated in studies sponsored by the State DOT and not from State DOT standard drawings. The guidance from Minnesota and South Dakota specifically references the “mumble” strip design from the California study. Florida, although it does not reference the “mumble” strip design in its guidance, uses the same wavelength and depth. However, FDOT does not currently feel that sinusoidal rumble striping is effective.

¹⁵⁴ Watts, G., R. Stait, N. Godfrey, L. Chinn, and R. Layfield, *Development of a novel traffic calming surface ‘Rippleprint’*, TRL Report TRL545, 2002.

¹⁵⁵ Donovan, P., *Design and Acoustic Evaluation of Optimal Sinusoidal Mumble Strips versus Conventional Ground-In Rumble Strips*, California Department of Transportation Report No. CTHWANP-RT-15-365.01.2, 2018.

¹⁵⁶ Terhaar, E., D. Braslau, and K. Fleming, *Sinusoidal Rumble Strip Design Optimization Study*, Minnesota Department of Transportation Report No. MN/RC 2016-23, 2016.

¹⁵⁷ Mathew, J. K., A.D. Balmos, D. Plattner, T. Wells, J.V. Krogmeier, and D.M. Bullock D.M., *Assessment of alternative sinusoidal rumble strip construction*, Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2018/05, West Lafayette, IN, Purdue University, 2018. <https://doi.org/10.5703/1288284346648>

¹⁵⁸ Hurwitz, D., D. Horne, H. Jashami, C. Monsere, and S. Kothuri, *Quantifying the performance of low-noise rumble strips*, Joint Oregon Department of Transportation and Federal Highway Administration, Report No. SPR 800, Joint Oregon State University and Portland State University, publication pending 2018.

¹⁵⁹ FHWA, *Rumble Strip Noise Implementation Guide: Addressing Noise Issues on Two Lane Roads*, FHWA-SA-15-033, April 2015. Available at: https://safety.fhwa.dot.gov/roadway_dept/pavement/rumble_strips/mitigating-noise.cfm

Because the installations of sinusoidal rumble strips are recent and limited in scope, there is no data available on the safety outcomes or crash rate reduction of sinusoidal rumble strips. Similarly, there is not enough information available to definitively determine the sinusoidal rumble strip dimensions that minimize roadside noise while producing sufficient levels of interior noise and vibration to alert drivers. The California “mumble” strip design is most common. However, the mumble strip study concluded that it may be possible to further optimize the mumble strip design to lower exterior noise while maintaining adequate interior warning by decreasing the depth or by slightly increasing the wavelength of the design.¹⁶⁰

Table A-6: Design Parameters of Sinusoidal Rumble Strips used in Different States

Location	Type of Rumble Strip	Wavelength	Depth	Perpendicular Width / Length
California “Mumble Strip” ¹⁶¹	Sinusoidal	0.356 m (14 in)	8 mm (5/16 in) peak to peak	0.305 m (12 in)
Florida	Sinusoidal	0.356 m (14 in)	8 mm (5/16 in)	0.203 m (8 in)
Indiana (design used on test section) ¹⁶²	Sinusoidal	0.305 m (12 in)	3.2 mm (1/8 in) depth at crest, 12.7 mm (1/2 in) depth at trough	0.406 m (16 in) centerline, and 0.305 m (12 in) edge
Minnesota (based on “Mumble Strip”) ¹⁶³	Sinusoidal	0.356 m (14 in)	1.6 mm (1/16 in) depth at crest, 12.7 mm (1/2 in) depth at trough	Variable

¹⁶⁰ Donovan, P., *Design and Acoustic Evaluation of Optimal Sinusoidal Mumble Strips versus Conventional Ground-In Rumble Strips*, California Department of Transportation Report No. CTHWANP-RT-15-365.01.2, 2018.

¹⁶¹ Donovan, P., *Design and Acoustic Evaluation of Optimal Sinusoidal Mumble Strips versus Conventional Ground-In Rumble Strips*, California Department of Transportation Report No. CTHWANP-RT-15-365.01.2, 2018.

¹⁶² Mathew, J. K., A.D. Balmos, D. Plattner, T. Wells, J.V. Krogmeier, and D.M. Bullock D.M., *Assessment of alternative sinusoidal rumble strip construction*, Joint Transportation Research Program Publication No. FHWA/IN/JTRP-2018/05, West Lafayette, IN, Purdue University, 2018. <https://doi.org/10.5703/1288284346648>

¹⁶³ Daubenberger, N. T., *Technical Memorandum No 17-08-T-02: Rumble Strips and Stripes on Rural Trunk Highways*, Minnesota Department of Transportation, August 21, 2017

Oregon (design used on test section) ¹⁶⁴	Sinusoidal	0.406 m (16 in)	9.6 mm (3/8 in) at trough, 1.6 mm (1/16 in) at crest	0.356 m (14 in)
South Dakota (based on “Mumble strip”) ¹⁶⁵	Sinusoidal	0.356 m (14 in)	8 mm (5/16 in) peak to peak	variable
Washington ¹⁶⁶	Sinusoidal	unspecified	unspecified	unspecified

¹⁶⁴ Hurwitz, D., D. Horne, H. Jashami, C. Monsere, and S. Kothuri, *Quantifying the performance of low-noise rumble strips*, Joint Oregon Department of Transportation and Federal Highway Administration, Report No. SPR 800, Joint Oregon State University and Portland State University, publication pending 2018.

¹⁶⁵ South Dakota Department of Transportation, *Centerline Rumble Stripe Fact Sheet*, <http://www.sddot.com/transportation/highways/traffic/safety/docs/SDDOTRumbleStripeFactSheet.pdf>.

¹⁶⁶ Washington State Department of Transportation, Website accessed December 2018. <http://www.wsdot.wa.gov/Design/Policy/RumbleStrips.htm>

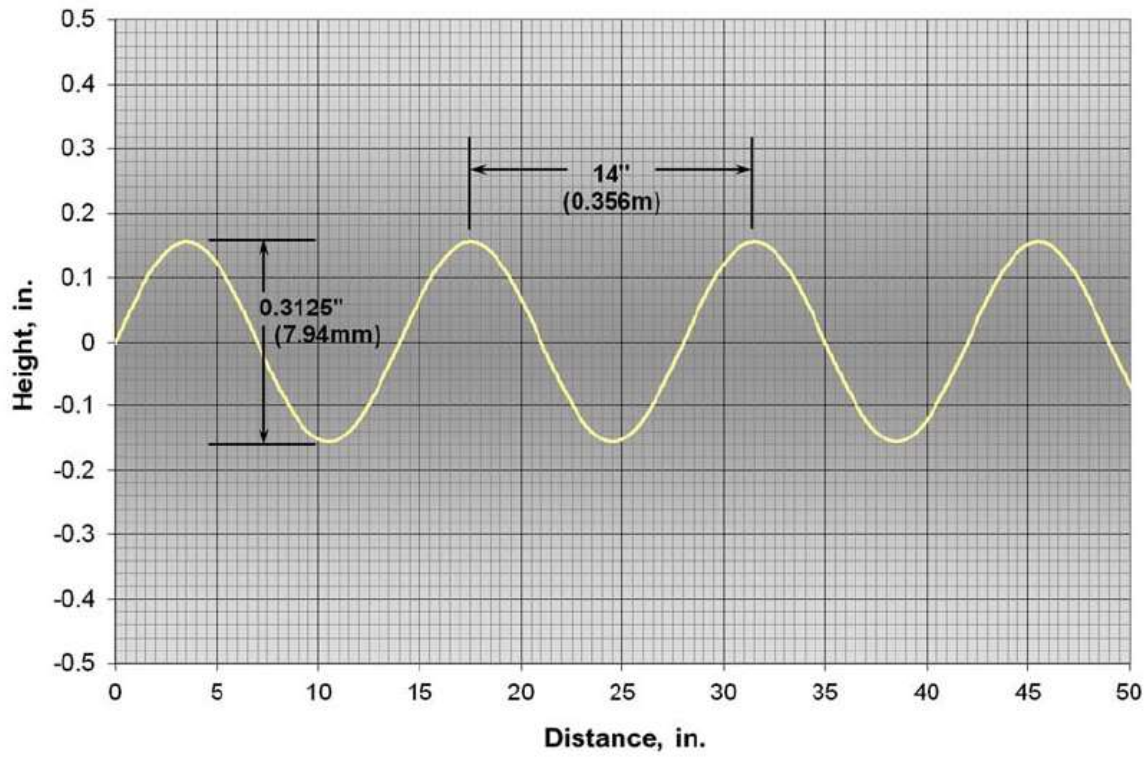


Figure A-8: Recommended sinusoidal profile for rumble strips¹⁶⁷

¹⁶⁷ Donovan, P., *Design and Acoustic Evaluation of Optimal Sinusoidal Mumble Strips versus Conventional Ground-In Rumble Strips*, California Department of Transportation Report No. CTHWANP-RT-15-365.01.2, 2018.