National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

Roadway Departure Warning Indicators

Synthesis of Noise and Bicycle Research

Natural Resource Technical Report NPS/NSNS/NRTR—2013/780

Roadway Departure Warning Indicators

Synthesis of Noise and Bicycle Research

Natural Resource Technical Report NPS/NSNS/NRTR—2013/780

Jonathan D. Cybulski, Judith L. Rochat, and David R. Read

U.S. Department of Transportation
Research and Innovative Technology Administration
Volpe National Transportation Systems Center
Environmental Measurement and Modeling Division
55 Broadway, RVT-41
Cambridge, MA 02142

June 2013

U.S. Department of the Interior
National Park Service
Natural Resource Stewardship and Science
Fort Collins, Colorado

The National Park Service, Natural Resource Stewardship and Science office in Fort Collins, Colorado, publishes a range of reports that address natural resource topics. These reports are of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

The Natural Resource Technical Report Series is used to disseminate results of scientific studies in the physical, biological, and social sciences for both the advancement of science and the achievement of the National Park Service mission. The series provides contributors with a forum for displaying comprehensive data that are often deleted from journals because of page limitations.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner.

This report received formal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data, and whose background and expertise put them on par technically and scientifically with the authors of the information.

This report is available from the Natural Resource Publications Management website (http://www.nature.nps.gov/publications/nrpm/).

Please cite this publication as:

Cybulski, J. D., J. L. Rochart, and D. R. Read. 2013. Roadway departure warning Indicators: Synthesis of noise and bicycle research. Natural Resource Technical Report NPS/NSNS/NRTR—2013/780. National Park Service, Fort Collins, Colorado.

NPS 999/121248, June 2013

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE July 2011	3. REPORT TYPE AND DATES COVERED Final Report

4. TITLE AND SUBTITLE Roadway Departure Warning Indicators: Synthesis of Noise and Bicycle Research	5. FUNDING NUMBERS VX82/JT311 VX82/JT312
6. AUTHOR(S) Jonathan D. Cybulski, Judith L. Rochat, David R. Read	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) U.S. Department of Transportation Research and Innovative Technology Administration John A. Volpe National Transportation Systems Center Environmental Measurement and Modeling Division, RVT-41 Acoustics Facility Cambridge, MA 02142	8. PERFORMING ORGANIZATION REPORT NUMBER DOT-VNTSC-NPS-11-24
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Department of Interior National Park Service (NPS) Natural Resource Program Center Natural Sounds and Night Skies Division Fort Collins, CO 80525	10. SPONSORING/MONITORING AGENCY REPORT NUMBER NPS/NSNS/NRTR—2013/780

11. SUPPLEMENTARY NOTES
NPS program managers: Karen Treviño, Randy Stanley, Vicki McCusker

12a. DISTRIBUTION/AVAILABILITY STATEMENT	12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

The United States National Park Service has voiced concern about roadway departure warning indicators (rumble strips) being installed in locations that affect the natural sound environment inside the park. Rumble strips can effectively alert errant drivers whose vehicles are leaving the travel lane. Some research has been conducted on rumble strips that perform effectively but result in lower noise levels in areas adjacent to a roadway. To date, however, the research is limited and scattered. The purpose of this study was to create a synthesis from collected information in order to have some guidance on how to install rumble strips near or in parks while minimizing disturbances in adjacent noise-sensitive areas. Included in this guidance document is a synthesis of literature on rumble strip noise based on the type of rumble strip, applications of rumble strips, the effects rumble strips have on various road users, including bicyclists, and also recommendations for rumble strip use and application in a park environment.

14. SUBJECT TERMS Highway traffic noise, rumble strips, roadway departure warning indicators, tire-pavement noise	15. NUMBER OF PAGES 50
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

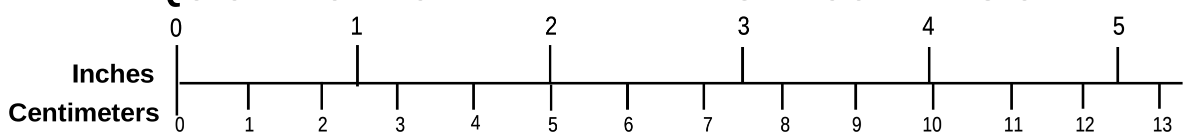
VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures.
Price $2.50 SD Catalog No. C13 10286

Updated 6/17/98

ACKNOWLEDGEMENTS

The authors wish to thank the National Park Service Natural Sounds and Night Skies Division, particularly Karen Treviño, Randy Stanley, and Vicki McCusker, for their vision and support of this work.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1 Background

Roadway departure warning indicators (rumble strips) are longitudinally raised or grooved patterns on a highway system that are an effective countermeasure for preventing roadway departure crashes, alerting the driver by both an audible noise as well as a physical vibration. The two main applications for rumble strips on road systems are Centerline Rumble Strips (CRS), which help prevent lane departure and head-on collisions, and Shoulder Rumble Strips (SRS), which help prevent lane-departure crashes at the side of the road. [FHWA 2001] [FHWA 2010]

It has been proven that rumble strips can be successful in decreasing single vehicle run-off-road crashes (SVROR, when a vehicle drives off the road via the shoulder – also labeled as “ROR” – run-off-road, and “ROTR” – run-off-the-road, by various references in the literature) by 27% on rural roads [Garder 2006], and a reduction ranging from 15-34% of total crashes on various other road systems, [Morena 2002] [Outcalt 2001-1] [Persaud 2003]. This being said, there is still a growing complaint about the anthropogenic noise rumble strips create when a vehicle passes over them.

The majority of literature that deals with rumble strips is focused on their ability to reduce car collisions and ROR crashes. The studies that focus on noise levels usually tend to focus on decibel values inside the car, to determine the level of warning the rumble strips are providing the driver. Data about the noise introduced into the environment by rumble strips are scarce and not standardized, usually being completed just as a smaller element of a large experiment.

1.2 Contents

Section 2 of this guidance document provides a review of rumble strip design and applications. Section 3 compiles the known data for studies on rumble strip noise and the effects of the noise on nearby residents. Section 4 compiles information on the effect of rumble strips on bicyclists. Section 5 provides conclusions and recommendations for the implementation of rumble strips in a park setting, based on available data, identifying best-practice rumble strip design elements for quiet, effective solutions.

1.3 Scope

This document is a synthesis of information available regarding noise generated by rumble strips and bicycle safety with rumble strips; in addition, rumble strip design goals are summarized. For additional information on the research summarized in this document, references are provided. Guidance and recommendations on use of quieter pavements is addressed in a separate, companion document.

2. RUMBLE STRIP APPLICATION

There are four major designs for rumble strip applications on roadways: milled, rolled, formed, and raised, as seen in Figure 1. Milled rumble strips, which are the most popular, are implemented after the road has been fully paved, and are created by a machine that cuts grooves into the roadside in various designs and dimensions. Rolled-in rumble strips are grooves that are pushed into the roadside directly after laying down the asphalt. The asphalt must be fresh because that allows the machine to roll over it and press the grooves into the soft road. Formed rumble strips are similar to rolled in that they are pressed into the pavement, though formed rumble strips are only found in portland cement concrete (PCC), not asphalt. Raised rumble strips can be made of various materials, most commonly rubber buttons or plastic strips, and are adhered to the surface. [Turochy 2004] [Torbic 2009] [FHWA 2001]

milled rolled formed raised

Figure 1. Applications of rumble strips. [Finley 2005, Outcalt 2001-2]

Rumble strips have been shown to be economically viable, when considering the reduction in number of crashes [Khan 1995]. The application of milling the rumble strip into the pavement is currently in wide use in North America, and can accommodate various designs. Rolled rumble strips are limited by the machine that creates them, being a large drum with bars welded around the circumference to press in the strips. Each drum is only capable of creating one set pattern of fixed dimensions; a further limitation is that the application must be done while the pavement is still warm, immediately after laydown. (Note: rolled rumble strip applications are only found in asphalt roads.) Formed rumble strips have limitations similar to those for rolled. Please refer to Figure 2 for photographs of equipment for creating milled and formed rumble strips.

Figure 2. Milling unit [Elefteriadou 2000] and formed-rumble-strip unit [Outcalt 2001-2].

Each type of rumble strip has a characteristic design, though the exact dimensions may vary slightly. Specific examples and parameters will be described further throughout the document.

The purpose for the rumble strip installation is an important part of the application as well, and is typically separated into two categories: Shoulder Rumble Strips (SRS) and Centerline Rumble Strips (CRS). This literature review highlights articles that have focused on the separate designs of rumble strips, as they are used in specific studies.

The application of various rumble strip designs was investigated in a 2001 study by the California Department of Transportation [Bucko 2001]. Among other presented material in the article, the dimensions for several standard rumble strip applications were recorded and summarized in Table 1. Sound level increases shown in the table were measured inside the test vehicle; the increase compares driving over a rumble strip to driving on pavement without a rumble strip. (Note: the sound level metric applied to these measurements was not provided.) It is stated in the study that milled and rolled rumble strips are the most commonly found types, and that raised rumble strips tend to be used only for warmer climate areas since snow-plowing activity would damage them. Specific implementations include the application of basic milled and rolled rumble strips. Also, inverted and profile thermo strips (molded plastic) were laid down on the shoulder imitating a raised rumble strip. A standard design chip seal was used for comparison to the rumble strip designs. The data indicate that the quietest two examples of all the rumble strip designs tested are: a) those produced by shallow-cut milling, and b) those comprised of profile thermo strips. Although profile strips are not commonly used on the roadside, the literature includes such rumble strips implemented in front of crosswalks. It should be noted that vibration levels inside the vehicle were also measured for this study, as shown in Table 1.

Table 1. Standard dimensions for several types of rumble strips commonly used on roadways and increase in interior sound levels. [Table modified from Finley 2005, which was based on Bucko 2001].

ID	Application	Dimensions (inch)				Interior Sound Change (dB)		Vibration Change (g)	
		Width	Length	Height[a]	Spacing	Light[b]	Heavy[b]	Light[b]	Heavy[b]
1	Rolled	2	24	-1.00	8	14	5	0.28	0.34
2	Milled	5	16	-0.25	12	11	2	0.13	0.15
3	Milled	6	16	-0.38	12	17	4	0.41	0.23
4	Milled	7	16	-0.50	12	18	5	0.45	0.25
5	Milled	7.5	16	-0.63	12	20	5	0.57	0.29
6	Chip seal	NA	NA	NA	NA	7	2	0.31	0.12
7	Button	4	4	0.50	12	17	4	0.62	0.18
8	Button, Staggered	4	4	0.50	6	17	5	0.54	0.26
9	Carsonite Bar	4	24	0.50	24	17	4	0.72	0.24
10	Inverted Profile Thermo[c]	1 / 4	4	0.19 / 0.50	1 / 22	9	1	0.24	0.07
11	Profile Thermo	4	4	0.50	22	3	1	0.10	0.10

[a] Height is relative to the distance from the pavement surface to the maximum elevation of the rumble strip and, therefore, will be negative for rolled and milled applications.
[b] Light indicates the light private vehicles, and heavy indicates the heavy commercial vehicles.
[c] If there are two dimensions, the first dimension refers to the inverted portion of the marking, and the second dimension refers to the profile portion of the marking.
NA refers to not applicable, and in the case of the chip seal treatment, the chip seal is a standard design that would be louder than standard hot-mix asphalt (HMA) or concrete.

The Transportation Research Board (TRB) Report 641 from 2009 [Torbic 2009] is an in-depth synthesis that summarizes much of the rumble strip data available to date. The aim of the synthesis is to provide guidance for the design and application of shoulder and centerline rumble strips to enhance safety, while minimizing the adverse effects on roadway users. The report introduces types of roadways that are typically found installed with rumble strips, freeways and two-lane urban roads, and identifies a research gap for studies of rumble strip benefits for other types of roadways, such as back country roads or single-lane roads.

The report also addresses the purposes, types, and dimensions of rumble strips. The four major purposes of rumble strips identified are:

1. Shoulder rumble strips, which are placed on either shoulder of the road and help to reduce single-vehicle run-off-road (SVROR) crashes.
2. Centerline rumble strips, which are constructed near or on the centerline of the road or lane, and are primarily installed to reduce head on collisions and opposite-direction sideswipe crashes.
3. Transverse rumble strips, which usually take up the width of the lane they are in, and warn the driver of upcoming stops, curves, intersection or hazards.
4. Midlane rumble strips – a theoretical idea only, since none have yet to be installed (may be incompatible with motorcycle use and have other adverse effects, including additional lane maintenance costs and noise) – which would be placed in the middle of the lane and may be able to decrease cross over and SVROR crashes.

The types of rumble strips identified in the report consist of the four categories previously introduced: milled, rolled, raised and formed. Finally, the report examines the designs and measurements that are commonly used for rumble strip designs.

Figure 3 depicts standard design parameters for rumble strips, including: (A) offset, (B) length, (C) width, (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 Figure 3.

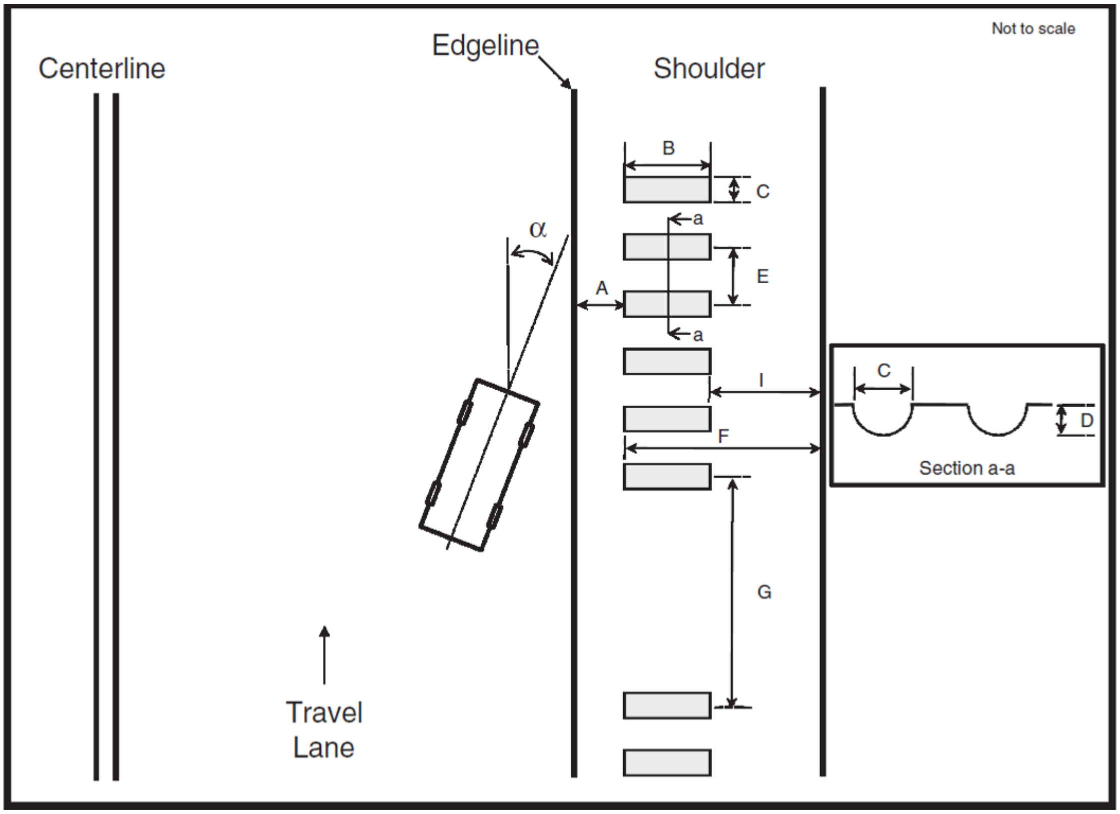


Figure 3. Design parameters associated with rumble strips. [Torbic 2009]

3. RUMBLE STRIP NOISE AND IMPACTS OF NOISE

3.1 Rumble Strip Noise

Several studies have been conducted on rumble strips since their creation in the 1950's. Few have focused on their anthropogenic noise levels on the surrounding environment, but some information is available. This section focuses on pertinent data since 1984. The main challenge found when examining the majority of these studies is that the distance that the microphones were placed from the road for measurements is not consistent from one study to the next. This may be due to the fact that recording the external noise is usually a secondary objective for the researchers, so a standardized distance has never been determined for these types of experiments. Therefore, unless stated in the summary given, the distance from the road at which these sound levels were recorded is unknown. Also, several studies included only interior noise levels. In addition, several studies did not provide information or provided only partial information regarding the sound metric applied to the sound level measurements; where available, information about frequency weighting, time integrating characteristics, etc. are provided. Note: vibration levels are not emphasized in this report, but some data are discussed here; for more information regarding human response to vibration, please refer to the ISO standard 2631-1.

Higgins and Barbel conducted a study in 1984 in Illinois focusing on the vibration levels and sound levels inside the vehicle as well as the noise produced by rumble strips outside the vehicle. This study specifically investigated rolled-in and cut shoulder rumble strips (SRS). Outside the vehicle, microphones were placed at various distances from the road, ranging from 50 ft (15.2 m) from the center of the rumble strip out to the vicinity of nearby homes, and tests were conducted with various vehicle types traveling at medium to high speeds. It was stated in the research that the study was limited, but enough information was obtained to determine that these types of rumble strips produce low frequency noise (in the region below 400 Hz) that can increase the equivalent sound level (L_{Aeq}) by 6 to 7 dB over sound levels produced by traffic on normal pavement; the noise at residences did not significantly vary with rumble strip designs. It was mentioned that the groove spacing has an effect on driver perception; smaller center-to-center distances (spacing), 5.9 inches (15 cm) as compared to 12.6 inches (32 cm), appeared to be more effective on vehicles traveling at higher speeds. It was also stated that the average A-weighted fast time response maximum sound level (L_{AFmax}) was 90 dBA at 50 ft (15.2 m). Additional information related to vibration: it was stated that frequencies of most concern to passenger comfort are 2 to 5 Hz and that most vehicle suspension systems are designed to resonate at frequencies of 5 to 20 Hz; in a test of driver perception, limited vibration data collected on the steering column of a truck showed a significant displacement amplitude due to the rumble strip for one site (rolled-in rumble strip) in the 1 to 20 Hz range (also had generally higher interior and exterior noise levels than other sites), and not at another site (cut rumble strip). [Higgins 1984]

In evaluation of milled, rolled-in, and raised rumble strips [Bucko 2001], Bucko reported on several different tests that focused on collecting vehicle interior vibration and sound data from several different rumble strip types, using several different vehicle models. For milled and rolled-in rumble strips:

- The study concluded that the quietest rumble strip was a variation of milled strips (Section 2), which yielded an average increase in the interior sound level by 10.2 to 11.8 dB for light vehicles (for 62.1 and 49.7 mph (100 and 80 km/h), respectively), and 1.9 dB for commercial sized vehicles at 49.7 mph (80 km/h)..
- The next quietest rumble strip design was a rolled style (Section 1) for light vehicles, where the other designs were fairly equivalent in terms of sound level for commercial vehicles.

For raised rumble strips:

- The study concluded that the quietest rumble strip was a raised thermoplastic stripe (Section 11), which yielded an average increase in the interior sound level by 3.6 to 3.1 dB for light vehicles (for 62.1 and 49.7 mph (100 and 80 km/h), respectively), and 0.6 dB for commercial sized vehicles at 49.7 mph (80 km/h).
- The next quietest rumble strip design was a raised and inverted thermoplastic stripe (Section 10).

Average sound level results of the study can be seen in Table 1 (located in Section 2 of this document). (Note: the sound level metric applied to these measurements was not provided.) Another significant finding from this experiment was that the deeper the cuts were in the milled rumble strips, the more interior noise the vehicle would create in a pass over them (see Table 1). In this study, there was generally a linear increase of sound levels which correlated to the linear increase of depth. Additional notes: 1) steering wheel vibration levels followed the same trend as the noise levels; and 2) test drivers subjectively concluded that the noise produced from the rumble strips had a greater affect in alerting the drivers than the vibration produced by the same rumble strip.

A study done by Chen in 2003 [Chen 2003] was prompted by a report that 41% of fatalities in Virginia resulted from run-off-the-road (ROTR) crashes. Chen conjectured that continuous shoulder rumble strips (CSRS) could be implemented to help lower that percentage. CSRS with a break in them were not tested in this study. This study was completed to determine what could lower the number of ROTR crashes, but in addition, the sound and vibration levels of the rumble strips tested were recorded so a comparison could be made at the end of the experiment to see which design was most effective. The results show that the mean increases from the recorded reference levels (vehicle not driving over rumble strip) outside the vehicle traveling at 65 mph (105 km/h) were 2.5 dB, 7.0 dB, and 10.9 dB for rolled, formed, and milled patterns of rumble strips, respectively. (Note: the sound level metric applied to these measurements was not provided.) The study concludes that for its purposes, the milled design of rumble strip was optimal giving the highest roughness and sound level rating, making it the most audible inside and outside the vehicle as well as giving the most vibration of all rumble strips tested. (Note: it was mentioned that a 4-dB increase above the reference noise level was found to be the minimum noticed by the traveling public.) This report was a continuation of an article Chen had written in 1994, which was used to create a mathematical model for determining the most effective rumble strip design in audible and tactical terms. [Chen 1994]

Gardner conducted a study on the noise generated by football-shaped (oval) rumble strips [Gardner 2007] compared to rectangular shaped designs, both milled, which are typical on roads (please refer to Figure 4 for photographs of rectangular and football-shaped milled rumble strips). The study was conducted to test the relative effectiveness and safety of the football-shaped designs as compared to the rectangular shaped designs. Although this study did not measure the noise from an environmental standpoint, data were collected from inside the vehicle, and several types of vehicles were used, driven at highway speeds. The results showed that each type of rumble strip produced a recognizable amount of noise when crossed over, and that football-shaped rumble strips produced at least as much noise as rectangular designs; an example of the results is shown in Table 2, where there was a noticeable difference in the designs for three of the cases, with the football shape being louder. (Note: the sound level metric applied to these measurements is unknown – it was stated as an average A-weighted sound level measured with dosimeter.) The base level shown in the table represents the sound level recorded inside the vehicle while driving on the smooth pavement. The increase in sound level came when the vehicles tires ran over the rumble strips. Though the study focused on the noise created inside the vehicle, Gardner stated that the complaints about the environmental noise created did not outweigh the role the rumble strips played in the safety of the drivers. (Note: it was mentioned that a 9 to 10 dB increase in interior vehicle sound level, due to a rumble strip, was necessary for a driver to be alerted.)

Figure 4. Rectangular and football-shaped milled rumble strips (photos from Gardner 2007).

Table 2. Example differences in interior noise levels for each type of rumble strip and the base levels (dBA). [Gardner 2007]

Vehicle Type	Rectangular Rumble Strips vs. Base	Football Rumble Strips vs. Base	Football Rumble Strips vs. Rectangular Rumble Strips
1996 International 4900 DT 466 Dump truck	23.1	31.4	8.3
1999 Chevrolet 2500 Diesel Pickup truck	7.7	7.7	0.0
1996 Ford Taurus LX	9.3	13.7	4.4
2000 Ford Ranger XLT 2WD Pickup Truck	7.8	8.5	0.7
2002 Dodge Caravan	12.3	16.2	3.9
2005 Lexus RX 300 SUV	16.2	15.9	-0.3

In a study by the Kansas Department of Transportation [Russell 2006], noise level testing was conducted inside vehicles where the sound level metric applied to the measurements was stated as the average for all vehicles of the high decibel reading, using a dosimeter. The data proved to be inconsistent, but basic trends showed that longer lengths of rumble strips, about 12 inches (30.5 cm) and greater, generated louder noise than smaller, about 8 inches (20.3 cm) or lower.; it was thought that this was due to vehicle tires not remaining in full contact with shorter rumble strip patterns, i.e., the shorter the grooves, the lower the probability of the vehicles' tires making full contact with the grooves. Lengths from 5 to 16 inches (12.7 to 40.6 cm) were examined.

A study completed by Finley in 2005 examined various forms of traffic control devices, and how effectively they alert a driver of a hazard. Noise created by a car and a heavy truck as they passed over different rumble strips was measured in this study. The measurements were taken 50 feet (15.2 meters) from the outside edge of the rumble strip application, and measured at speeds of 55 and 70 mph (89 and 113 km/h) for the car and 55 mph for the heavy truck. Results showed that rolled rumble strips created the largest average increase in exterior sound of 9 to 12 dB over the reference condition (which was described in this study as the average noise created by the vehicle that did not include driving over the rumble strip, with no other traffic noise) closely followed by raised transverse rumble strips, 8 to 10 dB above reference. Button, profile, and milled applications yielded similar changes in the exterior sound, 3 to 7 dB above reference. Milled rumble strip applications of 12 inches (30.5 cm) or wider resulted in an 8 to 14 dB increase in the exterior sound, but those 8 inches (20.3 cm) or less in width only increased the exterior sound by 4 dB or less, giving it a lower average increase than the rolled rumble strips. With respect to spacing and the milled rumble strip applications, sound levels decreased as spacing increased (spacings of 12, and 24, and 36 inches (30.5, 61, and 91.4 cm) were examined). (Note: the sound level metric applied to these measurements was described as being the "peak value" – based on the instrumentation used, this is likely a maximum sound level, although the time response and frequency weighting are unknown.) [Finley 2005]

In 1995 an experiment was conducted by the Maine Department of Transportation [Garder 1995-1] and presented in a final report by Garder of the University of Maine Orono. This study focused on the significant increase in accidents due to fatigued drivers, and how Continuous

Shoulder Rumble Strips (CSRS) could be effective in alerting the drivers of a hazard. Part of this study was to measure the external noise generated by the milled-in CSRS in response to complaints received by other state DOTs who had found the noise to be problematic for the public in the area. Results showed that from 65.6 feet (20 meters) away, a passenger car driving on the milled-in CSRS increased the peak noise level by about 11 dB over the level for a car pass-by that did not hit the rumble strips, a pickup truck increased the level by about 10 dB, and a full size truck increased the peak noise level by about 9 dB. These results were measured at speeds ranging from 55 to 65 mph (89 to 105 km/h). (Note: the sound level metric applied to these measurements was described as the "peak level.")

A study conducted by the Transport Research Laboratory in the UK measured exterior noise created by several different vehicles (small car, mid-sized car, van, and heavy truck) traveling from 15 to 40 mph (24 to 64 km/h) over various rumble strip designs. Preliminary testing of sinusoidal rumble strips showed that a wavelength of 14.2 inches (0.36 m) generally provided the highest levels of interior noise and vibration without generating significant increases in exterior noise at a distance of 25 ft (7.5 m); smaller wavelengths produced appreciable increases in exterior noise, and longer wavelengths were ineffective in producing sufficient increases in interior noise and vibration to alert drivers. An optimal excitation frequency was identified as 37 Hz (calculated using frequency = speed/wavelength and assuming an average speed of 30 mph (48 km/h) and wavelength of 14.2 inches (0.36 m)). Further testing compared wavelength sinusoidal designs (13.8 inches or 0.35 m) with varying peak-to-peak amplitudes (depth) with one 0.28 inch (7 mm) deep pattern milled in a herring bone pattern, and one 0.59 inch (15 mm) raised rectangular pattern. At distances of 25 ft (7.5 m) and 98 ft (30 m), the results for the cars and van showed that there was no significant increase over the reference condition, measured when the vehicles drove by without running over the rumble strips, for two sinusoidal patterns with peak-to-peak amplitudes of 0.26 and 0.16 inches (6.6 and 4.1 mm), but for the two non-sinusoidal patterns, there were significant increases in noise, especially at higher speeds. The heavy truck showed exterior sound level increases over reference for the 0.26 inch peak-to-peak amplitude sinusoidal surface and the raised rectangular pattern, but not for the others. (Note: the sound level metric applied to these measurements was the A-weighted maximum sound level, L_{AFmax}.) [Watts 2001]

The Danish Road Administration has taken great interest in the study of various types of rumble strips and the effects they have at increasing sound levels both inside and outside of the vehicle. In a recent study completed in 2007, Jorgen Kragh ran an experiment of five different types of shoulder rumble strips [Kragh 2007]. Design 1, 0.39 inch (10 mm) deep segments of a circle per 23.6 inches (0.6 m), was created to represent the dimensions of a rumble strip the Swedish road authorities had decided to install on the roads at the time of the study. Designs 2 and 3, a 0.28 inch (7 mm) peak-to-peak depth sinusoidal shape of 23.6 inches (0.6 m) wavelength, and a 0.16 inch (4 mm) peak-to-peak depth sinusoidal shape of 23.6 inches (0.6 m) wavelength, were created to represent sinusoidal shaped rumble strips that mimic ones used in a former British experiment that worked to determine the best frequency created by rumble strips to alert drivers [Watts 2001]. The wavelength for the Kragh study was larger than the one for the Watts study, based on the targeted vehicle speed for Kragh of 50 mph (80 km/h) and the excitation frequency of 37 Hz. Finally, designs 4 and 5, a 0.32 inch (8 mm) deep rectangular shape (spacing 13 inches (0.33 m)), and a 0.16 inch (4 mm) deep rectangular shape (spacing 13 inches (0.33 m)), were created to represent the dimensions of rumble strips that the Danish road authorities had implemented on roadsides in the past. Please refer to Figure 5 for design drawings. Kragh used three different passenger vehicles for each set of rumble strips: a 1995 Volkswagen Golf, a 2006 Skoda Octavia, and a 2003 Toyota Combivan. Exterior sound level measurements were conducted at a distance of 25 ft (7.5 m) from the road center line with the vehicles traveling at a speed of approximately 50 mph (80 km/h). For comparison, reference sound levels were measured on aged stone mastic asphalt (SMA) pavement, without the vehicles touching a rumble strip. The results show that the sinusoidal strips led to a 0.5 to 1 dB increase over the recorded reference external noise level while the “circle segment” strip gave an increase of 2 to 3 dB. The “rectangular” strips gave slightly different results depending on the depth of the rumble strip; at 4 mm depth, the increase in noise ranged from 4 to 6 dB, whereas at 8 mm depth the range of increase was from 5 to 8 dB. (Note: the sound level metric applied to these measurements was the A-weighted fast response maximum sound level, L_{AFmax}.) It was stated in the report that the warning effect on the drivers was not tested as part of the study, but drivers involved in a pilot study, presumably for the same rumble strip designs, agreed that the noise/vibration in their vehicle when driving on the tested rumble strips would give sufficient warning.

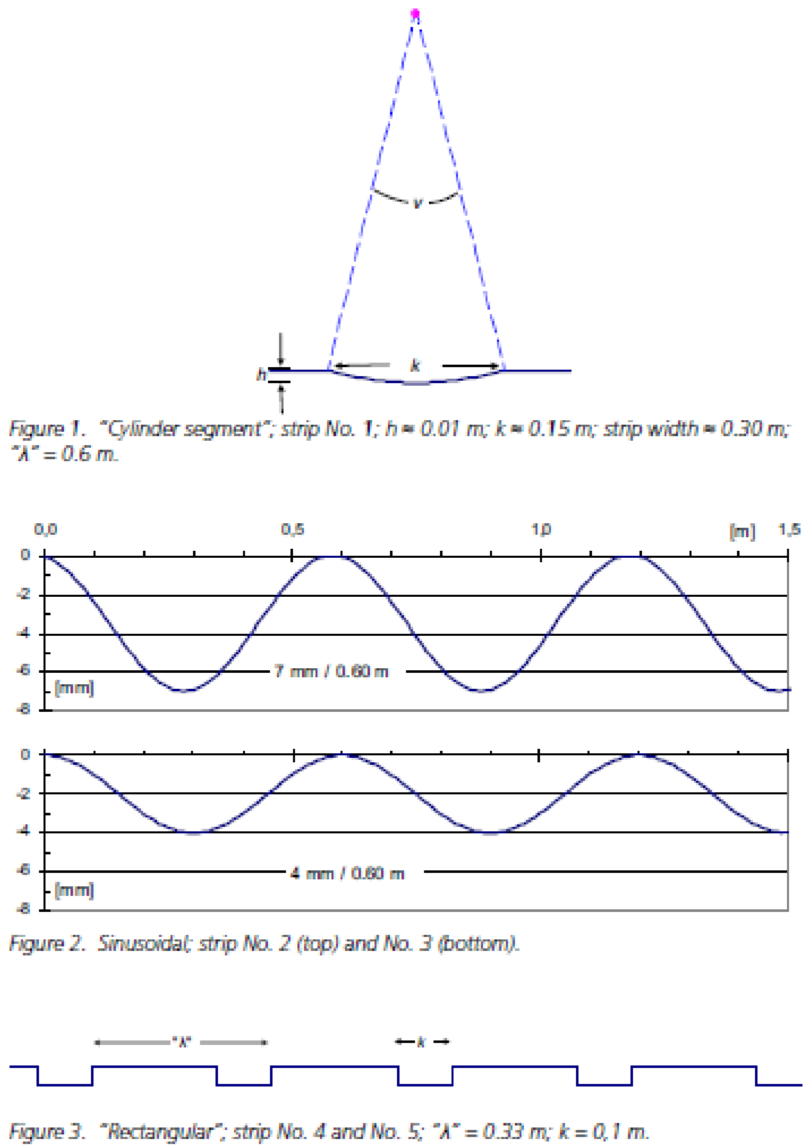


Figure 5. Drawn representations of rumble strip designs from Kragh study [Kragh 2007].

Sinusoidal rumble strip designs are also being investigated by the California Department of Transportation (Caltrans). Recommendations for an initial design [Donavan 2009], in part based on the previous two studies described [Watts 2001] [Kragh 2007], included a 5/16 (0.3125)-inch (7.9-mm) peak-to-peak sinusoid, which is stated to be sufficiently shallow for bicycle tolerance and also deep enough to increase interior noise levels by 6 dB or more, with corresponding vibration levels. The wavelength of the sinusoid was designed considering vehicle speed, tire footprints, and exterior sound radiation from tires; the wave length of 14 inches (0.36 m) was recommended for the speed range of 40-60 mph (64-97 km/h), with mention that 14 inches may be optimal regardless of speed.

Outcalt conducted an experiment on rumble strips for the Colorado Department of Transportation [Outcalt 2001-2] to determine the most bicycle-friendly design for a shoulder rumble strip application. Part of the experiment had bicyclists riding over 10 different rumble strip designs (shown in Figure 6), while a second experiment took place that had four test vehicles (station wagon, pick-up truck, minivan, heavy truck) run over the strips at highway speeds to obtain interior sound and vibration data. Results from this experiment show that on average, the increased noise inside the vehicle, created by traveling over a rumble strip, ranged from 0 to 18 dBA over the recorded reference noise. (This reference noise was recorded for each test vehicle by driving on smooth road without traveling over a rumble strip.) Table 3 shows the results of the experiment. It is seen here that rumble strips 1, 1A, 2A, 3, and 10 proved to be the quietest tested (note that these designs were the best for bicyclists – see Section 4). Designs 1, 1A, 2A, and 3 were milled-in rumble strips with 5 to 10 inches (12.7 to 25.4 cm) spacing (louder designs generally were continuous groves (zero spacing) or smaller than 5-inch (12.7 cm) spacing), and design 10 was the rolled-in rumble strip variation. The Outcalt 2001-2 report also mentioned that a 6-dB change from standard pavement to rumble strips is generally accepted as a clearly noticeable change (signaling an errant driver); of the five quietest designs, the average change over all vehicle types was 6 dB, except for designs 1 and 3, where it was only 4 and 5 dB, respectively. (Note: the sound level metric applied to these measurements was not provided, although the results were A-weighted.)

Type	Description
1:	Asphalt, 2" wide by 1/2" deep groove, 10" flat, Continuous
1A:	Asphalt, 2" wide by 1/2" deep groove, 10" flat, Interrupted Pattern
2:	Asphalt, 2" wide by 1/2" deep groove, S" flat, Continuous
2A:	Asphalt, 2" wide by 1/2" deep groove, 5" flat, Interrupted Pattern
3:	Asphalt, 2" wide by 3/8" deep groove, 5" flat, Interrupted Pattern
4:	Asphalt, 2" wide by 1/2" deep groove, 3" flat, Continuous
4A:	Asphalt, 2" wide by 1/2" deep groove, 3" flat, Interrupted Pattern
5:	Asphalt, 3/4" deep standard groove, Continuous
6:	Asphalt, 1/2" deep standard groove, Continuous
7:	Asphalt, 3/8" deep standard groove, Continuous
8:	Asphalt, 1/4" deep standard groove, Continuous
9:	Asphalt, 1/8" deep standard groove, Continuous
10:	Concrete, 1-3/8" wide groove, 1-5/8" flat, Continuous

Figure 6. Design descriptions and example photos of continuous and interrupted patterns of rumble strips from Outcalt Study. [Outcalt 2001-2]

Table 3. Results from study on bicycle friendly rumble strips. (Specific dimensions shown in Figure 6). Increase in interior sound level (dBA) above reference (smooth road). [Outcalt 2001-2]

Vehicle type	Speed (mph)	Rumble Strips												
		1	1A	2	2A	3	4	4A	5	6	7	8	9	10
Station Wagon	55	9	6	11	8	7	10	9	12	13	12	12	9	10
Van	55	7	6	10	8	8	10	8	13	15	13	13	13	11
Pick-up	55	4	3	6	5	4	7	6	18	17	14	14	13	12
Dump Truck	55	1	0	1	1	0	1	3	10	11	10	8	6	0
Station Wagon	65	6	4	11	8	7	8	7	15	12	9	10	10	6
Van	65	9	8	12	11	9	12	10	13	13	13	12	11	0
Pick-up	65	7	6	8	7	5	10	9	14	15	16	14	12	9
Dump Truck	65	1	0	2	1	0	2	1	4	5	7	5	3	0

In a case study done by Bajdek, exterior sound created by vehicles traversing over milled-in rumble strips was recorded as well as the sound environments of the surrounding neighborhoods. The data were then used in the Federal Highway Administration Traffic Noise Model® (TNM®) [Menge 1998][Anderson 1998] to see what effect rumble strip noise would have on surrounding inhabitants. The algorithms used in the model allowed the authors to be able to project the rumble strip noise levels that would be created at four different neighborhood locations. The results show that vehicles traversing over rumble strips were found to be 7 to 10 dB louder than the emission levels for vehicles on standard pavement. [Bajdek 2002] (Note: the sound level metric applied to these measurements was the A-weighted maximum sound level, L_{Amax}, in 1/3 octave bands.) The rumble strip noise data were recorded by microphones placed 5 feet (1.5 meters) from the edge of the roadway shoulder. Measurements were then taken at four separate neighborhood locations to determine the average ambient sound levels when the road noise tends to be the quietest and intrusions from rumble strips would be the most noticeable. These two data sets were then used in TNM algorithms to project the noise created by rumble strips in the community. Results from the study are shown in Table 4. The table shows that at the four community sites, rumble strips increased the maximum A-weighted noise levels for vehicle pass-bys by 5 to 11 dB.

Table 4. Maximum A-weighted noise levels in the community due to vehicles traveling 55 mph on rumble strips and on standard pavement [dBA]. [Bajdek 2002]

Site	Distance to Nearest Existing rumble Strips in feet (meters)	Automobile		Medium Truck		Heavy Truck	
		Rumble Strips	Standard Pavement	Rumble Strips	Standard Pavement	Rumble Strips	Standard Pavement
1	673 (205)	56	46	64	53	63	54
2	591 (180)	56	46	64	54	63	56
3	545 (170)	54	45	64	54	62	57
4	1080 (330)	47	37	57	46	53	48

A recent study was completed by the Kansas Department of Transportation that specifically measured various types of center line rumble strips and their involvement in the creation of exterior noise when ridden on by various motorized vehicles [Rys 2010]. The study focused on the exterior noise created by two different types of CLRS: football-shaped (oval) rumble strips, and rectangular rumble strips. The two test vehicles driven over the rumble strips were a 2006 Ford Taurus and a 2008 Chevrolet Express 15-passenger van, driven at speeds of 45 and 60 mph (72 and 97 km/h). The study was conducted by running both vehicles over smooth pavement in the area of the rumble strips first, then running the vehicles over the CLRS second. This allowed for the noise created by running over the CLRS to be compared to an average reference (for smooth pavement) for the target area. Sound level data were collected at distances of 50, 100, and 150 ft (15.2, 30.5, and 45.7 m) from the "center line of the highways" … based on the description and a corresponding illustration, it is unclear what is meant by "center line of the highways." The study showed that for an average over the 10 sites that were tested, the noise increased approximately 7.7 dBA (from 61.2 to 68.9 dBA) from when the vehicles drove over smooth pavement compared to the CLRS; there was no significant difference between the football and rectangular shapes. (Note: the sound level metric applied to these measurements was the A-weighted fast time response maximum sound level, L_{AFmax}.) With this data, four regression models were created which were used to predict CLRS noise levels at various distances from the road. Based on these models, it was recommended that any CLRS implementation design should take into consideration nearby residences, and should include a set back for construction of new buildings of at least 200 ft (61 m) from the highway centerline, in order to minimize adverse effects due to exterior rumble strip noise.

3.2 Impact of Noise on the Public

Rumble strips can be implemented on almost any type of road or highway. Since the purpose of conventional rumble strips is to create significant vibration and auditory warnings to alert an errant driver, it is obvious that external noise would be created as well when a vehicle passes over the strip. Though this may be necessary for the rumble strips to be effective in warning a driver, the noise can be heard elsewhere and has been reported by several transportation agencies to annoy people that are living close by. [Harwood 1993]

Although rumble strip noise only occurs intermittently when a vehicle veers from the travel lane, several reports have mentioned noise-related complaints from area residents. In a report given by the Connecticut Department of transportation (CTDOT) [Annino 2003], after the implementation of shoulder rumble strips, the agency began to receive a heavy inflow of residential complaints about the exterior noise. In response to the complaints, the CTDOT re-implemented the rumble strips to be 6 to 12 inches (15 to 30.5 cm) farther away from the travel lane (into the shoulder) than they were previously. This was done in hope that vehicles would drive over the strips only when they were truly in need of a warning, and not when they were simply drifting slightly out of the lane. After this design change, the noise complaints from the residents significantly declined. Other reports have shown that 17% of the states that had implemented rumble strips in the past year had received significant complaints about exterior noise from nearby residents [Turochy 2004]. Although the report did not specify what each state did to deal with the problem, it was said that one state completely removed all rumble strips since the complaints were so frequent. For CRS, Bahar reported [Bahar 2005] that residents complained about being able to hear the noise of rumble strips from over 1 mile (1.61 km) away. His suggestion – based on research and the literature – was to stop the implementation of rumble strips within 656 feet (200 m) of the nearest residential area, to help reduce the external noise. As previously mentioned, a Kansas DOT report [Rys 2010] suggested that residences should be at least 200 ft (61 m) from a rumble strip in order to avoid adverse effects. Another study completed by Garder [Garder 1995-1] surveyed 32 residents that lived within the vicinity of a highway that was having new rumble strips implemented. Of everyone surveyed, 25 reported that the noise created by the rumble strips was audible, but only 4 said that it was loud enough to cause them annoyance.

Although no testing has been done to evaluate the annoyance experienced by visitors to national parks due to rumble strip noise, it can be assumed that the noise generated there would be similar if not the same as to what residents have reported hearing. In a park setting, however, visitors may be more sensitive to the noise since ambient sound levels are generally lower than next to highways, and 72% of park visitors say that one of the most important reasons for preserving National Parks is to provide opportunities to experience natural quiet and the sounds of nature [NPS 2010].

4. RUMBLE STRIP EFFECTS ON BICYCLISTS

4.1 Effects of Rumble Strip Design

Bicyclists have voiced their concerns about having to ride over rumble strips on many occasions, and feel that it should be mandatory that states implementing rumble strips should have safety measures for bikes. The bicyclists' concerns also apply to park environments. This synthesis compiles the available literature that address the effects of rumble strips on bicyclists.

Gardner, in his assessment of football-shaped (oval) rumble strips for the Kansas Department of Transportation [Gardner 2007], surveyed bicyclists to see whether or not they preferred football-shaped rumble strips to the typical rectangular shaped design. Gardner stated that the main fear bicyclists have when dealing with rumble strips on the road is the amount of space on the shoulder not taken up by the rumble strips, and the depth of the rumble strip if they do have to ride on them. The results of the survey showed that 70% of the 23 participants preferred or somewhat-preferred the football-shaped rumble strips over the rectangular shaped ones.

Garder [Garder 1995-2] assessed the legitimacy of complaints from bicyclists about rumble strips being a hazard. Taking 20 students from the university as subjects, Garder had them ride over two different milled rumble strip configurations to determine if there was any danger. When queried in a survey after the tests, the results showed that the students had no problems riding over the rumble strips, and at most they found them only annoying, not dangerous.

Moeur ran a brief test to determine whether or not there should be periodic gaps in SRS in order to allow for bicyclists to pass through the warning devices without having to run over them. The test had bicyclists travelling at a slight downgrade so that they were able to get up to speeds averaging in the mid 20 mph range (around 40 km/h). To determine how much space was needed for a bicyclist to make a safe exit without striking the rumble strips, markings were set up for the riders to aim to cross from the shoulder to the road, and measurements were taken to establish the optimal length. It was determined that a gap of approximately 12 feet (3.7 m) should be permitted in the rumble strips at an interval of every 39 to 59 feet (12 to 18 m) in the roadway, to allow optimal safety for bicyclists. No research was done on the effect this would have on drivers of motorized vehicles. [Moeur 1981]

Elefteriadou and the Pennsylvania Department of Transportation (Penn DOT) ran an experiment in 2000 with the goal of developing several rumble strip configurations that would both alert inattentive/drowsy motorists by supplying a sufficient audible warning yet could be safely and comfortably traversed by bicyclists by minimizing vibratory effects [Elefteriadou 2000]. The experimental methodology consisted of test subjects riding over six different rumble strip patterns at various speeds, followed by a survey showing what their perception of comfort was during the test. Being that this part of the experiment was subjective, Elefteriadou developed a methodology for quantifying whole-body vibrations based on the International Standard (ISO) 2631, in which vertical and pitch angular accelerations were combined into one measure to assess the effect of comfort and controllability on the bicyclist. Comparing these two methods showed that there was a significant linear relationship between whole-body vibration and comfort; when vibration increased, comfort decreased. With this data, two of the six rumble strip patterns were determined to be best for bicyclist comfort as well as still being able to warn inattentive drivers of the shoulder line. Determined-best rumble strip designs are shown in Table 5.

Table 5. Recommended “bicycle-tolerable” rumble strip configurations. [Elefteriadou 2000]

Test Pattern	Grooves Width inches (mm)	Flat Portion between Cuts inches (mm)	Depth inches (mm)	Facility Type
3	5” (127 mm)	7” (178 mm)	0.375 “ (10mm)	High Operating Speeds
5	5” (127 mm)	6” (152 mm)	0.375” (10mm)	Low Operating Speeds

A Study was completed a year later by Torbic, which included similar testing to the 2000 study on bicycle friendly rumble strips by Elefteriadou. Torbic evaluated an increased number of rumble strip designs, and all were run through a computer simulation before field testing. The designs that scored the best on the simulation were brought to the field, and the results in the field were the same as Elefteriadou’s experiment in 2000. [Torbic 2001]

An experiment done for the Colorado Department of Transportation by Outcalt had 29 bicyclists, with both mountain and road bikes, ride over 10 different rumble strip designs (described/shown in Figure 6, located in Section 3 of this document) to see which were the most comfortable and controllable. The tests were done at speeds of 5, 10, 15, and 20 mph (8, 16, 24, and 32 km/h). Riders were asked to ride both directly on the rumble strip pattern, and to weave in and out of the strip as if they were entering or exiting the road. After bicyclists had completed a test, they filled out a survey ranking the comfort and controllability of the rumble strips on a scale from 1 (best) to 5 (worst). The results showed that design 10 proved the best rated for riders, and design 5 was the worst. A second test involved driving cars over the same rumble strip designs, in order to determine the interior noise and vibration level of each strip. The results show that the best rumble strips for bicyclist comfort and controllability were the "worst" (lowest sound levels) at warning drivers by way of noise and vibration. [Outcalt 2001-2]

4.2 Overview of Effects on Bicyclists

There has been a fair amount of research completed on the effect that rumble strips have on bicyclists, though the subjects researched have only been of comfort and controllability. Several experiments have yielded the same results: the longer and deeper the rumble strips become, the more uncomfortable bicyclists will be and the more uncontrollable the ride when maneuvering over them. [Garder 1995-1] [Garder 1995-2] [Elefteriadou 2000] [Torbic 2001] [Moeur 1981] Although the data resulting from these studies are useful, other problems have arisen that need further investigation.

Research shows that complaints have arisen from bicyclists about not having enough space on the shoulder to ride. Although many of the rumble strip designs have them taking up no more than half of the shoulder space, the remaining area left for bikes to ride on is usually littered with debris from the road, or in poor condition. This lack of maneuverable space could result in bikers choosing to ride in the travel lane with motorized vehicles, putting both rider and driver in danger. In order to allow safe travel for bicyclists, there should be at least 4 ft (1.2 m) of space, more if guard rails exist, between the rumble strip and the edge of the pavement, and the area should be kept clean. [Advocacy 2010]

Recommendations given by bicyclists have been collected in various surveys. Some recommendations have been that the length of the rumble strips on the shoulder be decreased, allowing for more room for the bikes to pass. Also, the depth of each rumble strip indentation could be decreased as well to not collect debris which could move into the bike lane. Further suggestions ask for regular gaps in the strip in case the biker has to exit the lane for some reason, and does not feel safe riding over the strips themselves. Finally, it has been suggested to not implement rumble strips at all if they are to be in a heavily biked area [Advocacy 2010].

A brief article shows that certain states have written policies for the implementation of rumble strips with regards to bicyclists, but further research is needed in this area [Advocacy 2010].

5. GUIDANCE AND RECOMMENDATIONS

Although research investigating low-noise rumble strip implementation is scarce, some of the information from these experimental studies was useful in forming the recommendations stated in this section. Additionally, data acquired from research in other areas pertaining to rumble strips, such as determination of audible-alert effectiveness and specific current rumble strip applications, proved useful. Further research is needed to achieve a better understanding of crucial parameters for specification and optimization of “low exterior noise” rumble strip design.

5.1 Overview

The applications for rumble strip implementation in National Parks should ultimately be decided by the intended use of the strip, but basic guidelines can be set.

Raised rumble strips feature easy construction and removal, but have limited practicality in extreme climates. In areas with snow or harsh conditions where plowing or other road maintenance may need to be done, raised plastic rumble strips could become damaged or hinder the process necessary to keep roads safe. In these situations, negative-textured rumble strips may be preferred. Note that research has shown that some raised rumble strips can be fairly quiet when compared to other designs [Bucko 2001][Finley 2005], and raised rumble strips such as raised thermoplastic stripes [Bucko 2001] should be considered in favorable climates.

Negative texture rumble strips include the milled, rolled, or formed designs. The remainder of the discussion and recommendations focuses on the milled application, since it is most widely used in the U.S. [Chen 1994] [Turochy 2004] [Torbic 2009] and allows for flexibility in design and dimensions (note: literature shows mixed results as to which of the three applications – milled, rolled, or formed – is the quietest). The specific dimensions of milled rumble strips that should be implemented can be extracted from known research. From the literature search completed, it has been shown that there were three basic styles of milled rumble strips: rectangular, sinusoidal, and football-shaped (oval). Based on the available research, the sinusoidal rumble strips appear to be the quietest type available for road application, followed by rectangular, then football-shaped (Watts 2001 and Kragh 2007 showed sinusoidal was quieter than rectangular, and Gardner 2007 showed that rectangular was quieter than football-shaped). It should be noted that sinusoidal milled applications are not common.

An important consideration for trying to develop specifications for dimensions of a low noise rumble strip is the need for effective interior noise and vibration to act as a successful driver alert. It was stated in various areas of the research that 4 to 10 dB (value dependent on reference) increase in sound level over the standard pavement must be present inside the vehicle for an effective warning [Chen 2003][Gardner 2007][Outcalt 2001-2]. Some studies have shown that there is a relationship between interior and exterior vehicle sound levels; in these cases, higher interior sound levels, which may be needed to effectively warn drivers for conventional rumble strips, are associated with higher exterior sound levels. As a potential alternative, vehicle movement and feedback to a driver from rumble strip applications such as a sinusoidal design may provide an effective warning without substantially increasing interior or exterior noise levels; this needs to be further investigated. (A sinusoidal shape in theory produces a single frequency of oscillation, providing feedback to a driver without higher frequency content from more complex shapes.) Whatever is chosen, a careful balance of alerting the driver but not annoying the nearby residents has to be considered in the design.

Finally, due to the continuous concern bicyclists have with rumble strips, the design parameters and dimensions should reflect those which have been proven to be acceptable to bicyclists.

5.2 Quieter Rumble Strip Design Elements

Regardless of the chosen application for the rumble strips (not all parameters apply to raised rumble strips, recommended for use in favorable weather conditions in Section 5.1), to minimize the noise, current research shows that the design should include shallow depth, narrow width, large spacing, non-zero offset, and be non-continuous (gap > 0). Please refer to Section 2 for parameter descriptions.

Taking all of the research and dimensions data available, the parameters of a quieter rumble strip that could be implemented can be suggested. Design parameters for two basic designs will be listed: rectangular milled rumble strip and sinusoidal rumble strip. The rectangular milled rumble strip design parameters are described in case it is necessary for documented research to show that the implemented rumble strip design creates a minimum of 4 to 10 dB level change inside the vehicle (referenced minimum sound level increase for effectiveness). The sinusoidal rumble strip design parameters are described to provide guidance for the quietest possible rumble strip, where the design is likely to provide adequate vehicle movement and feedback created by the sinusoidal pattern to alert drivers without generating additional noise.

The parameters listed below have been consolidated from multiple research studies and are suggestions for best-practice designs. Note: specific designs should be evaluated in terms of safety and the potential impact on pavement performance (e.g., degradation due to water being trapped, rumble strip techniques that may initiate cracks or introduce microstructural damage, etc.).

Suggested parameters to minimize noise and maximize bicyclist safety for traditional **rectangular milled rumble strips** (summarized in a table below the bulleted items, Table 6):

- Length: A relationship has been identified between the length of rumble strip grooves and the sound level generated by vehicle interaction with them. In a 2006 study, it was found that larger length rumble strip grooves, about 12 inches (30.5 cm) and longer, generate more noise than smaller grooves, about 8 inches (20.3 cm) or shorter. [Russell 2006].
- Depth: Recommendation for a quiet application is 0.25 inches (0.6 cm) [Bucko 2001]. Research shows a correlation between the depth of rumble strips and the amount of noise created, showing that the deeper the design, the more noise generated [Finley 2005] [Bucko 2001].
- Spacing and width: The research done by Finley shows that the quietest rumble strip designs are created when they are spaced a minimum of 24 inches (60 cm) from center to center, with a width (in direction of travel of roadway) of 8 inches (20.3 cm) [Finley 2005].
- Offset and gap: An offset of 12 inches (30.5 cm) is recommended to minimize accidental incursion by vehicles [Annino 2003]. In order to allow safe travel for bicyclists, there should be at least 4 ft (1.2 m) of space, more if guard rails exist, between the rumble strip and the edge of the pavement, and the area should be kept clean [Advocacy 2010]. A gap of 12 feet (3.7 m) of regular pavement for every 60 feet (18.3 m) of rumble strip is recommended to allow for the exiting and entering of bicyclists [Bucko 2001].

Table 6. Suggested parameters to minimize noise and maximize bicyclist safety for traditional rectangular milled rumble strips.

Length (in)	Depth (in)	Spacing (in)	Width (in)	Offset		Gap (ft)
				outward from edge lane (in)	inward from edge of pavement (ft)	
≤ 8	0.25	24	8	12	4	12-ft regular pavement for every 60 ft

Suggested parameters to minimize noise and maximize bicyclist safety for **sinusoidal rumble strips** (summarized in a table below the bulleted items, Table 7):

- Wavelength and depth: Based on designs tested, an ideal wavelength was determined as 13.8 – 14.2 inches (0.35 – 0.36 m) for vehicles traveling an average of 30 mph (48 km/h); shorter wavelengths appreciably increase exterior noise, and longer wavelengths do not provide sufficient feedback to alert drivers [Watts 2001]. From these experiments, it was determined that the best warning effect is obtained by applying a waveform generating an excitation frequency of 37 Hz (based on frequency = speed/wavelength). So the ideal wavelength is dependent on vehicle speed and should be calculated using wavelength = road speed / 37. Other investigations into ideal wavelengths suggest that 14 inches (0.36 m) is ideal for vehicle speeds of 40-60 mph (64-97 km/h) and may be optimal regardless of speed [Donavan 2009]; research results are needed to validate the suggestion. Peak-to-peak depths of approximately 0.28 and 0.16 inches (4 mm and 7 mm) have been investigated, both providing low-noise outcomes [Kragh 2007][Watts 2001]. It is stated that these sinusoidal designs are sufficient to alert drivers.
- Length: Although not specifically studied for sinusoidal designs, longer length rumble strips, about 12 inches (30.5 cm) and longer, generate more noise than smaller, about 8 inches (20.3 cm) or shorter [Russell 2006]. It should be investigated, however, as to whether or not an 8-inch (20.3-cm) length adequately vibrates a vehicle for the sinusoidal design; effectiveness results may be dependent on the tire width in relation to the rumble strip length.
- Offset and gap: An offset of 12 inches (30.5 cm) is recommended to minimize accidental incursion by vehicles [Annino 2003]. In order to allow safe travel for bicyclists, there

should be at least 4 ft (1.2 m) of space, more if guard rails exist, between the rumble strip and the edge of the pavement, and the area should be kept clean [Advocacy 2010]. A gap of 12 feet (3.7 m) of regular pavement for every 60 feet (18.3 m) of rumble strip is recommended to allow for the exiting and entering of bicyclists [Bucko 2001].

Table 7. Suggested parameters to minimize noise and maximize bicyclist safety for sinusoidal rumble strips.

Wavelength (in)	Peak-to-peak depth (in)	Length (in)	Offset		Gap (ft)
			outward from edge lane (in)	inward from edge of pavement (ft)	
Road speed/37*	0.16, 0.28**	≤ 8	12	4	12-ft regular pavement for every 60 ft

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

**Both providing low-noise outcomes.

Other considerations when applying rumble strips:

- If residences or other sensitive receivers (e.g., people in campgrounds or popular visitor areas in a park setting) are close to the road, unacceptable sound levels due to the rumble strips could occur, and the necessity of implementation of rumble strips should be reconsidered. Distances mentioned for potential adverse effects due to traditional rumble strip noise are 200 ft (61 m) [Rys 2010] and 656 ft (200 m) [Bahar 2005]. It should be investigated as to whether or not noise from sinusoidal rumble strips is found to be unacceptable.
- When comparing noise generated by rumble strips to a standard pavement (pavement without rumble strips), it is important to consider that there is broad variation in sound levels associated with standard pavements. A recent NPS guidance document on quieter pavements [Volpe 2011] shows a range of 12 dB for typical tire-pavement noise levels for various pavement types. Therefore, if a specified vehicle interior noise increase due to rumble strips is required to alert drivers, it may or may not be achieved depending on

the pavement type of the road. For louder pavement types, the sound generated by rumble strips may be imperceptible. On the other hand, as quieter pavements are implemented in parks, the relative loudness of rumble strips may grow, increasing annoyance and unacceptability for park visitors. Therefore, when rumble strips are required for safety, the selection of quieter, effective rumble strip technologies may have increasing importance for parks.

REFERENCES

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

Anderson 1998 Anderson, Grant S., Cynthia S.Y. Lee, Gregg G. Fleming, and Christopher W. Menge, *FHWA Traffic Noise Model, Version 1.0: User's Guide*, Report No.s FHWA-PD-96-009 and DOT-VNTSC-FHWA-98-1, U.S. Department of Transportation, John A. Volpe National Transportation Systems Center, Massachusetts (1998, TNM v2.5 Addendum 2004).

Annino 2003 Annino, J. M. *Rumble Strips in Connecticut: A Before/After Analysis of Safety Benefits*. Connecticut Department of Transportation. (2003).

Bajdek 2002 Bajdek, Christopher J. and Jason C. Ross. *Rumble Strips: Effective Safety Measure or Just a Nuisance?* Harris Miller Miller & Hanson Inc. (2002).

Bucko 2001 Bucko, Troy. *Evaluation of Milled-In Rumble Strips, Rolled-In Rumble Strips and Audible Edge Strips.* California Department of Transportation. (2001).

Chen 1994 Chen, Chung. P.E. *A Study of Effectiveness of Various Shoulder Rumble Strips on Highway Safety*. Virginia department of Transportation. (1994).

Chen 2003 Chen, Chung. Emmanuel Darko, Tanqueray Richardson. *Optimal Continuous Shoulder Rumble Strips and the Effects on Highway Safety and the Economy*. ITE Journal. (2003).

Cybulski 2010 Cybulski, Jonathan and Jordan Aro. *Optimal Quieter Rumble Strip Design.* Us DOT/Volpe Center. 500 Broadway Street. Cambridge, Ma, 02142. (2010).

Donavan 2009 Donavan, Paul. "Recommendation for Initial Sinusoidal Rumble Strip Design." Technical Memorandum to Dennis McBride and Bruce Rymer at California Department of Transportation. August 4 (2009).

Elefteriadou 2000Elefteriadou , L., M. El-Gindy, D. Torbic, P. Garvey,, A. Homan, Z. Jiang, B. Pecheux, and R. Tallon. *Bicycle-Tolerable Shoulder Rumble Strips.* The Pennsylvania Transportation Institute. (2000).

FHWA 2001 US DOT/Federal Highway Administration. *Technical Advisory: Roadway Shoulder Rumble Strips.* T 5040.35. (2001).

FHWA 2010 Federal Highway Administration (FHWA). "Rumble Strips and Stripes" website. http://safety.fhwa.dot.gov/roadway_dept/pavement/rumble_strips/. Visited 2010.

Finley 2005 Finley Melisa d, Jeffrey d. Miles, and Paul j. Carlson *An assessment of various rumble strip designs and pavement marking applications for crosswalks and work zones*. Form DOT F 1700.7 (8-72). (2005).

Garder 1995-1 Garder, Per. John Alexander. *Continued research Continuous Rumble Strips*. Technical report 94-4. (1995).

Garder 1995-2 Garder, Per. *Rumble strips or not along wide shoulders designated for bicycle traffic?* In transportation research record No. 1502. TRB, national research council, Washington D.C.(1995).

Garder 2006 Garder, Per. Michael Davies. *Safety Effect of Continuous Shoulder Rumble Strips on Rural Interstates in Maine*. Transportation Research Record: Journal of the Transportation Research Board, No. 1953. (2006).

Gardner 2007 Gardner, Lucas W., Margaret J. Rys, Ph.D., Eugene Russell, Ph.D. *Comparison of Football Shaped Rumble Strips versus Rectangular Rumble Strips*. Report No. K-TRAN: KSU-00-4P2. (2007).

Geni 2005 Geni Bahar, P.Eng. *Synthesis of Practices for the Implementation of Centerline Rumble Strips.* Transportation Association of Canada. (2005).

Harwood 1993 Harwood, Douglas W. NCHRP *Synthesis of Highway Practice 191: Use of Rumble Strips to Enhance Safety*. © Transportation Research Board.(1993).

Higgins 1984 Higgins, John S. and William Barbel. *Rumble Strip Noise*. Transportation Research Record 983. (1984).

ISO 2631-1 International Organization for Standardization, *Mechanical vibration and shock – evaluation of human exposure to whole-body vibration*, International Standard ISO 2631-1, Geneva, Switzerland. (1997).

Khan 1995 Khan, A M, BACCHUS, A. *Economic Feasibility and Related Issues of Highway Shoulder Rumble Strips.* Transportation Research Record No. 1498. (1995).

Kragh 2007 Kragh, Jorgen. Bent Andersen. *Traffic noise at rumble strips*. Danish Road Institute Report 156. (2007).

Menge 1998 Menge, Christopher W., Christopher F. Rossano, Grant S. Anderson, and Christopher J. Bajdek, *FHWA Traffic Noise Model, Version 1.0: Technical Manual*, Report No.s FHWA-PD-96-010 and DOT-VNTSC-FHWA-98-02, U.S. Department of Transportation, John A. Volpe National Transportation Systems Center, Massachusetts (1998, 2004 update sheets available from FHWA).

Miles 2007 Miles, Jeffrey d. and Melisa d. Finley. *Factors that influence the effectiveness of rumble strip design*. Transportation Research Record 2030. (2007).

Moeur 1981 Moeur, Richard C. *Analysis of Gap Patterns in Longitudinal Rumble Strips to Accommodate Bicycle Travel.* Transportation Research Record: Journal of the Transportation Research Board. (1981).

Morena 2002 Morena, David A. *The Nature and Severity of Drift-Off Road Crashes on Michigan Freeways, and the Effectiveness of Various Shoulder Rumble Strip Designs*. TRB 2003 Annual Meeting CD-ROM. (2002).

NPS 2010 National Parks Service. Natural Sounds Program. Visited 2010. http://www.nature.nps.gov/naturalsounds/

Outcalt 2001-1 Outcalt, William. *Centerline Rumble Strips*. Colorado Department of Transportation, Report No. CDOT-DTD-R-2001-8. (2001).

Outcalt 2001-2 Outcalt, William. *Bicycle-friendly rumble strips*. Colorado Department of Transportation, Report No., CDOT-DTD-R-2001-4. (2001).

Persaud 2003 Persaud, Bhagwant N. Richard A. Retting Craig Lyon. *Crash Reduction Following Installation of Centerline Rumble Strips on Rural Two-Lane Roads*. Ryerson University, Toronto, Canada. (2003).

Russell 2006 Russell, Eugene R. and Margaret . 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).

Rys 2010	Rys, Dr. Margaret, Ph.D., Daniel E. Karkle, Arun Vijayakumar, Rohit, Makarla, Eugene Russell, Professor Emeritus. *Promoting Centerline Rumble Strips to Increase Rural, Two-Lane Highway Safety*. Kansas Department of Transportation, Report No. K-TRAN: KSU-08-3. (2010).
Torbic 2001	Torbic, Darren, Lily Elefteriadou, and Moustafa El-Gindy. *Development of Rumble Strip Configurations That Are More Bicycle Friendly*. Transportation Research Record: Journal of the Transportation Research Board. (2001).
Torbic 2009	Torbic, Dr. Darren J., Ms. Jessica M. Hutton, Ms. Courtney D. Bokenkroger, Ms. Karin M. Bauer, Mr. Douglas W. Harwood, Mr. David K. Gilmore, Ms. Joanna M. Dunn, and Mr. John J. Ronchetto *NCHRP REPORT 641: Guidance for the Design and Application of Shoulder and Centerline Rumble Strips.* ©Transportation Research Board. (2009).
Turochy 2004	Turochy, Rod E. *Shoulder Rumble Strips: Evolution, Current Practice, and Research Needs*. TRB Paper No. 04-3448. (2004).
Volpe 2011	Sohaney, Richard, et al., *Quieter Pavements Guidance Document*, Report No. DOT-VNTSC-NPS-11-16, prepared for the U.S. Department of Transportation / Volpe National Transportation Systems Center for the U.S. Department of Interior / National Park Service / Natural Sounds and Night Skies Program (Fort Collins, Colorado). (2011).
Watts 2001	Watts, G.R. et al. *Optimization of Traffic Calming Surfaces*. Transport Research Laboratory. (2001).

NPS 999/121248, June 2013

National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science
1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525

www.nature.nps.gov

EXPERIENCE YOUR AMERICA ™