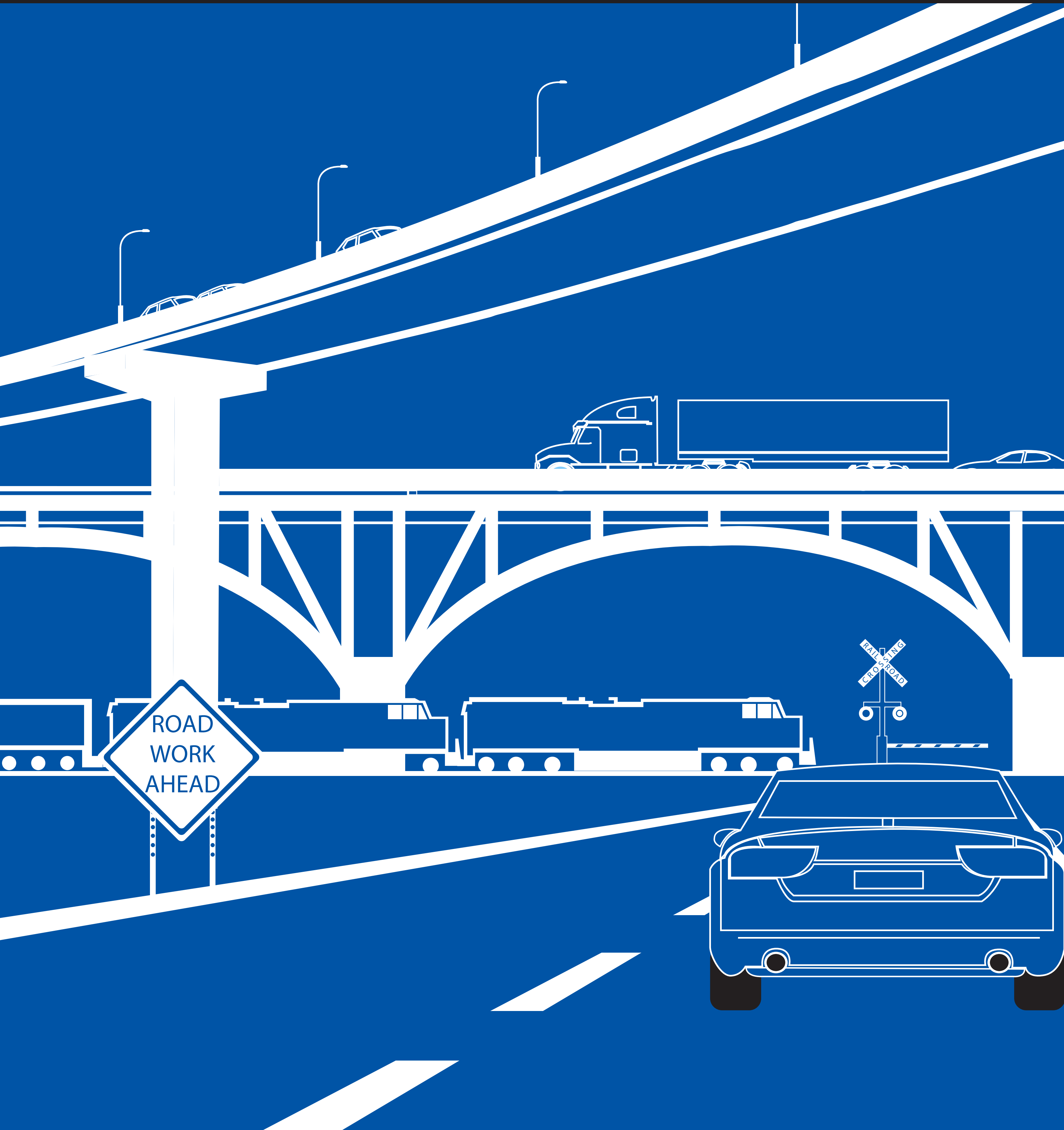
Excellence In Motion

Evaluation of Alternative Rumble Strip Designs

Report Number: KTC-20-28/SPR20-595-1F

DOI: https://doi.org/10.13023/ktc.rr.2020.28



Kentucky Transportation Center
College of Engineering, University of Kentucky, Lexington, Kentucky

in cooperation with
Kentucky Transportation Cabinet
Commonwealth of Kentucky

The Kentucky Transportation Center is committed to a policy of providing equal opportunities for al persons in recruitment, appointment, promotion, payment, training, and other employment and education practices without regard for economic, or social status and will not discriminate on the basis of race, color, ethnic origin, national origin, creed, religion, political belief, sex, sexual orientation, marital status or age.

Kentucky Transportation Center
College of Engineering, University of Kentucky, Lexington, Kentucky

in cooperation with
Kentucky Transportation Cabinet
Commonwealth of Kentucky

KENTUCKY
Transporation Center

Kentucky Transportation Center • University of Kentucky
176 Raymond Building • Lexington, KY 40506 • 859.257.6898 • www.ktc.uky.edu

University of Kentucky

Research Report
KTC-20-28/SPR20-595-1F

Evaluation of Alternative Rumble Strip Designs

William Staats, M.S., P.E.
Research Engineer

Ken Agent, M.S., P.E.
Research Engineer

and

Brian Howell, M.S., P.E.
Research Engineer

Kentucky Transportation Center
College of Engineering
University of Kentucky
Lexington, Kentucky

In Cooperation With
Kentucky Transportation Cabinet
Commonwealth of Kentucky

June 2020

1. Report No. KTC-20-28/SPR20-595-1F	**2. Government Accession No.**	**3. Recipient's Catalog No**
4. Title and Subtitle Evaluation of Alternative Rumble Strip Designs		**5. Report Date** June 2020
		6. Performing Organization Code
7. Author(s): William Staats, Ken Agent, Brian Howell		**8. Performing Organization Report No.** KTC-20-28/SPR20-595-1F
9. Performing Organization Name and Address Kentucky Transportation Center College of Engineering University of Kentucky Lexington, KY 40506-0281		**10. Work Unit No. (TRAIS)**
		11. Contract or Grant No. SPR 20-595
12. Sponsoring Agency Name and Address Kentucky Transportation Cabinet State Office Building Frankfort, KY 40622		**13. Type of Report and Period Covered**
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

Since Kentucky's initial rumble strip designs were adopted, there has been additional research and experimentation in other states with alternative designs as a response to complaints from the public about noise pollution caused by rumble strips. The new research indicates that other rumble strip designs might provide increased interior noise/vibration with decreased exterior noise. Application of these alternative designs in Kentucky could result in improved rumble performance, reduced damage to new pavement, decreased noise pollution, installation on roadways with lower speed limits, and allow reinstallation of rumbles on thin overlays/microsurfacing.

The research team reviewed national and state guidelines for conventional and alternative rumble strip designs and compiled a synthesis of current rumble strip practices. A series of site visits to rumble strip installations across the state revealed many findings about Kentucky's current rumble strip practices.

This research provides recommendations for conventional, sinusoidal, and shallow rumble strips as well as for rumble strip maintenance, rumble strips on thin overlays, and the use of edgeline and centerline rumble strips.

17. Key Words rumble strips, sinusoidal rumble, shallow rumble, alternative rumble, road markings		**18. Distribution Statement** Unlimited	
19. Security Classification (report) Unclassified	**20. Security Classification (this page)** Unclassified	**21. No. of Pages** 50	**19. Security Classification (report)**

Table of Contents

List of Figures

List of Tables

Executive Summary

The Kentucky Transportation Cabinet's (KYTC) current centerline rumble strip design was selected over 15 years ago when there was limited experience with rumble strip implementation in the state. At the time, Kentucky's centerline rumble strip design was based on designs from other states. Since Kentucky's initial rumble strip designs were adopted, there has been additional research and experimentation in other states with alternative designs as a response from complaints from the public about noise pollution caused by rumble strips. The new research indicates that other rumble strip designs might provide increased interior noise/vibration with decreased exterior noise. Application of these alternative designs in Kentucky could result in improved rumble performance, reduced damage to new pavement, decreased noise pollution, installation on roadways with lower speed limits, and allow reinstallation of rumbles on thin overlays/microsurfacing.

The research team reviewed national and state guidelines for conventional and alternative rumble strip designs and compiled a synthesis of current rumble strip practices. NCHRP 641 and FHWA's Rumble Strip Implementation Guide both recommend that rumble strips should ideally provide 6 dBA of noise to alert drivers of lane departure, with 3 dBA being the minimum sound threshold for driver detection and 15 dBA being the maximum recommended noise level for rumble strips. Although rumble strips are a proven safety countermeasure that reduce lane departure crashes, the public often complains about the noise pollution associated with these devices. To combat this issue, many states — including Minnesota, Indiana, Washington, California, Oregon, and Florida — have explored alternative rumble strip designs that provide sufficient warning to drivers while limiting excess exterior noise. The most widely tested and accepted alternative rumble strip design has been sinusoidal rumble strips. Another alternative rumble strip design is a conventional cylindrical rumble strip with a shallower milled depth. Washington, Pennsylvania, Maryland and Florida have successfully tested shallow, conventional rumble strips and have confirmed that they meet the NCHRP and FHWA guidelines for interior noise production while limiting exterior noise pollution.

A series of site visits to rumble strip installations across the state revealed many findings about Kentucky's current rumble strip practices. Most notably, installation techniques vary widely across the different highway districts, particularly regarding edgeline and shoulder rumble strip installation. The research team also noted deteriorating longitudinal striping on edgeline rumble stripes with rough milled rumbles. In several cases, rumble strips were moved from the shoulder to the edgeline to allow for earlier lane departure warning, a move that the research team believes to be beneficial to highway safety on all roadway types.

Based on the positive test results and adoption of sinusoidal and shallow rumble strips by multiple states, this research study recommends that KYTC install and evaluate these alternative rumble strip designs on an experimental basis to determine if they are suitable for inclusion in their Standard Specifications and Standard Drawings. This study also provides further recommendations regarding conventional rumble strips, rumble strip maintenance, rumble strips on thin overlays, and the use of edgeline and centerline rumble strips.

Chapter 1 Background and Objectives

Kentucky's current centerline rumble strip design was selected over 15 years ago when there was limited experience with rumble strip implementation in the state. At the time, Kentucky's centerline rumble strip design was based on designs from other states. Kentucky's edgeline and shoulder rumble strip designs were also developed in a similar manner. Initially, Kentucky's rumble strips were installed by rolling the rumble strip on the hot asphalt during the paving process. This resulted in varying depths, with some of the rolled rumble strips being very shallow and ineffective. The current construction procedure involves milling cylindrical rumble strips into the pavement.

Since Kentucky's initial rumble strip designs were adopted by the state, there has been additional research and experimentation in other states with alternative designs, such as shallower cut rumble strips and sinusoidal/mumble strips. New research into alternative designs indicates that other types of rumble strips might provide increased interior noise/vibration with decreased exterior noise, which addresses complaints from the public about noise pollution caused by rumble strips. Application of these alternative designs in Kentucky could result in improved rumble performance, reduced damage to new pavement, decreased noise pollution, installation on roadways with lower speed limits, and allow reinstallation of rumbles on thin overlays/microsurfacing. The objectives of this study include the following:

1. Synthesize research on new rumble strip technology
2. Summarize KYTC's rumble strip practices
3. Recommend improvements/additions to KYTC's procedures and designs

Chapter 2 Literature Review

The KTC research team collected documents from state and national publications to synthesize the current research on alternative rumble strip designs.

2.1 NCHRP

Many state DOT agencies use rumble strips to safely alert errant drivers, but that same noise may produce undesired and excessive noise to nearby residents and neighborhoods. Various studies have shown that rumble strips increase safety by safely alerting errant drivers whenever they depart the roadway due to fatigue or distracted driving. The rumble strips activate by producing audible noise levels within the vehicle's interior and prompt the driver to correct their travel path. However, as rumble strips have been increasingly employed across the country, they have also received some criticism from nearby residents and businesses due to their excessive roadside noise. Some DOT agencies have consequently began investigating approaches to optimize the desired outcomes (e.g., interior noise) while minimizing the undesired side effects (e.g., exterior noise). Researchers at Iowa State University recently evaluated DOT agency practices on rumble strips and examined how state officials are balancing safety needs with noise considerations. In their research, Smadi et al. conducted a survey of various DOT agencies and released their findings in *NCHRP Synthesis 490: Practice of Rumble Strips and Rumble Stripes*.

The NCHRP survey asked state officials how they used noise considerations in conjunction with design specifications for rumble strip installations. The survey had a robust response, with the large majority of DOT agencies participating. The survey had two major findings, including 39 DOTs responding that they do not having noise specifications for rumble strips and 27 DOTs responding that they are actively in the process of addressing noise concerns. Some DOT agencies have adopted changes to their policies and installation practices to mitigate noise concerns. Some examples include "installing strips away from urban areas, eliminating roads with speeds less than 45 mph, and being sensitive to community needs."[1]

A few DOT agencies have investigated their rumble strip installation practices for noise concerns and modified their practices to accommodate those concerns. California's agency, CALTRANS, evaluated other DOT agency programs on noise issues in 2012. They found that sinusoidal rumble strips improved upon conventional installations by maintaining necessary noise levels within the vehicle's interior while reducing excessive noise levels outside of the vehicle. In 2014, Minnesota drew upon California's original study to compare its rumble strip designs to California's. Their researchers also found that California's sinusoidal design was superior to its conventional design for the same reasons: a minimum required level of interior noise coupled with reduced exterior noise. Similarly, Montana has modified its rumble strip designs to address noise concerns. For rumble strips installed near residential areas, the agency reduced its standard 5/8-inch depth to 3/8-inch to reduce exterior noise. In other cases, Montana may place the rumble strip further away from the edge of the travel lane to reduce the frequency of vehicles striking the strip (22). Ohio has adopted the placement approach as its primary noise reduction method. Rather than modify its design, the Ohio DOT simply places rumble strips further from the edge of the traveled lane in residential areas. The modified rumble strip offsets cannot exceed 2 feet.[2]

In another NCHRP study (report 641), Torbic et al. examined designs and best practices for state DOT agencies across the U.S. to determine the optimal designs for safety while minimizing unwanted roadside noise. DOT agency officials often receive complaints in residential areas experiencing excessive roadside noise due to rumble strips. To counteract, many officials have taken steps to change their rumble strip designs and/or installation practices to minimize noise levels. This study focused on existing rumble strip installation practices across the nation and used statistical modeling to assess their corresponding safety benefits and noise levels. Based on these models, the researchers proposed design and installation best practices that could maximize safety benefits while still reducing unwanted roadside noise levels.

The study's authors began their research by distributing a survey to all 50 U.S. state DOT agencies and 12 Canadian provincial transportation agencies. They received a total of 27 responses from U.S. agencies and 4 responses from Canadian agencies. The survey demonstrated that agencies place their rumble strips at different locations from the roadway's edgeline. Most agencies install rumble strips at an offset anywhere from 0 to 30 inches from edgeline. Rumble strips placed closer to the edgeline provide earlier warnings on roadway departures than those placed at a greater offset. However, those near-edgeline rumble strips also experience more frequent vehicle crossovers which may not constitute true emergencies. This, in turn, increases the occurrence of unwanted noise in the area.

The placement of rumble strips relative to the edgeline was found to often produce different effects under different scenarios. The study focused on the safety benefits of single-vehicle run-off road (SVROR) fatality and injury (FI) crashes for roadways for roadways with and without rumble strips. SVROR crashes were examined due to the consistency of the safety analysis results between different roadway types. Using this crash analysis, Torbic et al. published the following conclusions:

> "On rural freeways, rumble strips placed closer to the edgeline (i.e., edgeline rumble strips) are more effective in reducing SVROR FI crashes than rumble strips placed further from the edgeline (i.e., non-edgeline rumble strips).
> On rural two-lane roads, there is no difference in the safety effect of rumble strips placed closer to the edgeline (i.e., edgeline rumble strips) as compared to rumble strips placed further from the edgeline (i.e., non-edgeline rumble strips).
> On rural freeways, shoulder rumble strips resulted in an estimated reduction of SVROR crashes involving heavy vehicles of approximately 40 percent."[3]

Upon validating the safety benefits from rumble strips, the researchers next examined past research conducted on optimal noise levels. Fatigued or distracted drivers at high-risk for roadway departures must receive an auditory stimulus at a required level for rumble strips to be effective. Prior studies have shown rumble strips generating a noise at least 3-6 dBA above normal interior sound levels are most effective. Other studies have shown noise levels should range anywhere from 3-10 dBA, or even up to 15 dBA, to be most effective.

Next, the study examined the types of rumble strip installations used by surveyed participants, including an examination of rumble strip dimensions to determine if they met the minimum threshold to alert fatigued or distracted drivers. The NCHRP study used clearly defined dimensions when comparing agency practices, as illustrated in Figure 1. The authors listed the dimensions used in this study as:

> "Offset (A): Lateral distance from the edge of the travel way to the inside edge of the rumble strip.
> Length (B): Dimension of the rumble strip measured lateral to the travel way. This dimension is sometimes referred to as the transverse width.
> Width (C): Dimension of the rumble strip measured parallel to the travel lane.
> Depth (D): Dimension is the vertical distance measured from the top of the pavement surface to the bottom of a rumble strip pattern. This distance refers to the maximum depth of the cut or groove.
> Spacing (E): Distance measured between rumble strips patterns. Typically this dimension is measured from the center of one rumble strip to the center of the adjacent rumble strip, or it could be measured from the beginning of one rumble strip to the beginning of the adjacent rumble strip. Typical terms used to describe this dimension are on-center spacing, spacing on-center, center-to-center spacing, or simply "spacing".[4]

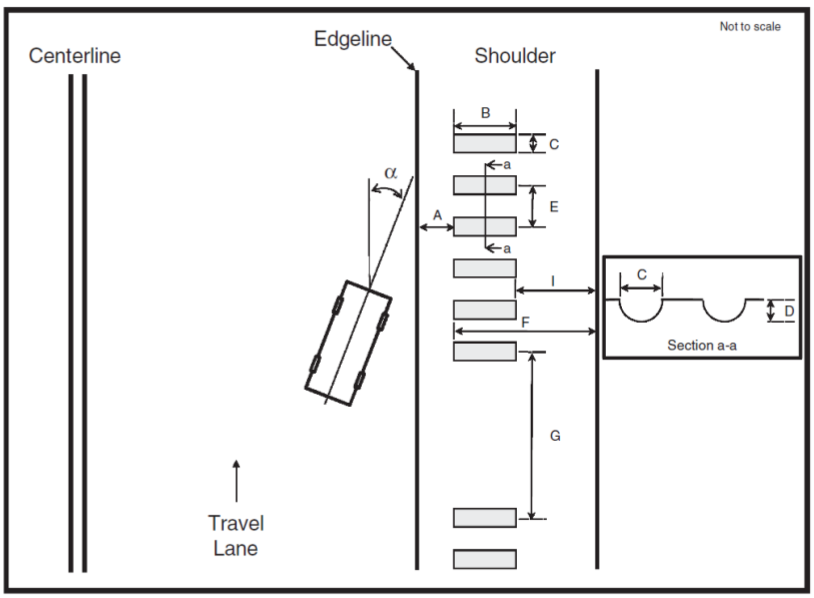


Figure 2.1 Design Parameters Associated With Shoulder Rumble Strips

The NCHRP survey revealed that the most common milled rumble strips installed in the U.S. have the dimensions listed in Table 1 below.

Table 2.1 Most Common Milled Rumble Strip Dimensions in U.S.

Dimensions	**Shoulder**	**Centerline**
Length	16 inches	12 or 16 inches
Width	7 inches	7 inches
Depth	0.5 – 0.625 inches	0.5 inches
Spacing	12 inches	12 inches

These common shoulder rumble strip dimensions generated a sufficient level of noise differentiation (between 3-15 dBA) to alert inattentive drivers and are therefore, sufficient to meet safety goals (137-138). The centerline rumble strip dimensions also generated sufficient noise levels although in their case, those levels should be between 6-12 dBA for desired noise differentiation. In these two cases, both shoulder and centerline dimensions generated noise levels on the higher end of the spectrum to alert the driver. However, it remains unknown if they reduced roadside noise to desirable levels.

Therefore, the study researchers also developed regression models to simulate which dimensional factors most influenced roadside noise levels. They found four dimensions that most influenced noise levels and were statistically significant: length, width, depth, and spacing (134). Increasing a rumble strip's length, width, or depth all corresponded to an increase in the noise level difference between the vehicle interior and its exterior. Conversely, increasing the rumble strip spacing decreased the noise level difference (126-127). Therefore, DOT agencies should consider optimizing these dimensions to meet necessary internal noise levels for distracted drivers while minimizing undesired roadside noise.

The placement of rumble strips also influences outcomes. Using their safety analysis, the study's authors concluded that "rural freeways rumble strips placed closer to the edgeline are more effective in reducing SVROR FI crashes compared to rumble strips placed farther from the edgeline". DOT officials should therefore place rural freeway rumble strips near to the edgeline. In the case of rural two-lane roads, there was no statistical difference demonstrated between rumble strip offset and subsequent impacts related to safety.[5]

2.2 FHWA

In 2015, the Federal Highway Administration (FHWA) released guidance on addressing noise concerns associated with rumble strips. Since their inception, rumble strips have provided safety benefits through noise-induced driver alerts. However, these same alerts increase noise to the surrounding environment and have sometimes been viewed as disruptive by nearby residents. This FHWA guide provides information on assessing and addressing these noise concerns, along with citing several state departments of transportation (DOTs) efforts in this area.

Sound-level meters measure the noise produced by rumble strips. The meters determine the maximum noise generated through the unit of decibels (dB), a measurement of intensity. Noise disruptions are primarily derived from two factors: volume and frequency. Low-volume frequencies tend to travel farther but the human ear can only perceive frequencies between 20 Hz and 20,000 Hz. For point sources, sound levels typically decrease by 6 dB for each doubling of the distance between the noise source and recipient. For example, a person standing 6 feet from a source would hear the noise at 74 dB, while the person standing 12 feet away would only hear it at 68 dB. To account for noises not perceived by the human ear, the noise meter measures sounds through the A-weighted decibel scale, otherwise known as dBA.

State DOTs have examined and instituted several different policies for rumble strip installation. Policies can range from omission to modification of the rumble strips. In the former case, three states have excluded rumble strip installation when the following criteria have been met:

- Michigan DOT – Any rumble strip installation on roadways with a driveway density greater than 30 entrances per 0.5 miles.
- Missouri DOT – Centerline or edgeline rumble strips on roadways with speeds limits less than 50 mph.
- Pennsylvania DOT – Edgeline rumble strips for moderate/sharp curves near residential pockets (recommendation only).

All three states essentially reduce rumble strip installation when located near high-population residential areas. In other cases, states have modified the rumble strip installation to mitigate noise concerns. These modified rumble strip installation cases include:

- Washington State DOT – Selective installation of rumble strips with a shallower design (3/8 inch). They are also examining different design patterns with variable spacing options and design depths for optimal noise patterns.
- Pennsylvania DOT – Selective installation of rumble strips with a shallower design (3/8 inch) for passing zones.
- California DOT and Minnesota DOT – Examination in progress of the use of sinusoidal rumble strips to decrease exterior noise levels from conventional rumble strips.

In all instances, rumble strips should generate enough interior vehicle noise to alert the driver and allow time for the driver to make corrections. FHWA touted a recent report from NCHRP 641 pointing to recommended noise levels for the vehicle interiors. This report stated that rumble strips should provide at least 3 dBA at a minimum (but not exceed 15 dBA) and reach a desired level of 6 dBA. Each vehicle's characteristics (e.g., type, size, age) will ultimately influence the internal noise generated.[6]

In addition to the rumble strip noise guidance, FHWA has also provided guidance for pavement issues related to rumble strips. In terms of maintaining the structural integrity of rumble strips, FHWA mentioned that in the past, states have attempted to use fog seals to serve as a moisture barrier in rumble strips, preventing deterioration from oxidations and moisture. However, there is a lack of documented findings showing fog sealing provides any measureable benefit for rumble strips, therefore most states have discontinued the use of fog seals in conjunction with rumble strips. Moreover, South Carolina DOT reports that fog sealing is incompatible with thermoplastic striping materials.

Surface preparation prior to a new pavement overlay on roadways with an existing rumble strip varies from state to state. Some states choose to overlay the rumble strip with no preparation, while others mill out the existing rumble and either inlay or overlay new pavement in its place. Some states mill the entire roadway prior to a new overlay, which in effect removes the rumble strip entirely. After the overlay, some states choose to remill new rumbles immediately, while others wait for scheduled intervals to do statewide rumble strip milling. FHWA does not recommend milling rumble strips after a chip seal as this may cause delamination of the seal around the rumble strips. Conventional rumble strips maintain enough of their original volume after a chip seal to remain an effective safety countermeasure. According to FHWA, microsurfacing fills in existing rumble strip voids, however rumble strips can be remilled in the same location without significant delamination.[7]

2.3 State Departments of Transportation

Minnesota

In 2016, the Minnesota Department of Transportation sponsored a research study on their rumble strip program, specifically to address noise concerns. This study was enacted in response to Minnesota residents' objections to excessive noise produced by conventional rumble strips. The Minnesota DOT worked in conjunction with outside researchers to evaluate conventional rumble strips versus sinusoidal rumble strips. Sinusoidal rumble strips are designed to minimize external noise to the roadside environment while maintaining—or even increasing—internal noise to the vehicle's occupants. The goal for this noise accentuation reduces unwanted residential noise while still providing alert notifications to drivers as they cross a rumble strip.

Initially, researchers installed and examined seven types of rumble strip designs, including six sinusoidal and one non-sinusoidal (conventional). They installed these designs at a controlled pavement test track.

The research study initially evaluated the rumble strip designs through motorcycle driver surveys. They used this approach because motorcycles do not have an interior cab to measure noise levels. Fifty-two motorcycle drivers took pre-participation and post-participation surveys that collected information pertaining to three factors: comfort, control, and function. Comfort measured the ability of the driver to comfortably navigate across the rumble strips. Control indicated the driver did not lose traction during the crossing event. The last measure, function, gathered the driver's input on the effectiveness of the rumble strip alert (i.e., enough vibration/noise). They survey revealed two designs with high-level favorability (e.g., TS2, TS5), two with mid-level favorability (e.g., TS1, TS6), and two with low-level favorability (e.g., TS3, TS7).

After survey completion and several trial runs, the seven designs were scaled down to four designs for field testing purposes. These designs possessed the following characteristics shown in Table 2:

Table 2.2 Minnesota Rumble Strip Test Designs

Design 1	**Design 2**
• Sinusoidal with straight edge	• Sinusoidal with straight edge
• 14-inch center-to-center wavelength	• 14-inch center-to-center wavelength
• 14 inches wide	• Two 8-inch-wide rumble strips separated by 4 inches
• 1/16–3/8 inch depth	• 1/16–1/2 inch depth
Design 3	**Design 4**
• Sinusoidal with straight edge	• Sinusoidal with straight edge
• 14-inch center-to-center wavelength	• 14-inch center-to-center wavelength
• 14 inches wide	• Two 8-inch-wide rumble strips separated by 4 inches
• 1/16–1/2 inch depth	• 1/16–3/8 inch depth

Sinusoidal rumble strips differ from conventional, cylindrical rumble strips in their design. They use continuously running longitudinal indentations in the pavement surface instead of alternating between brief indentations and an unmarked surface. They also employ a vertical profile that continuously changes gradient from incline to decline for an uninterrupted noise effect. The figures below show planar views of a sinusoidal test strip design (e.g., Design 1) and a conventional rumble strip design.

Figure 2.2 Minnesota DOT, Design 1 Sinusoidal Rumble Strips

Figure 2.3 Minnesota DOT, Conventional Rumble Strips

The oscillating gradient characteristics for the sinusoidal design are illustrated in the profile illustration below.

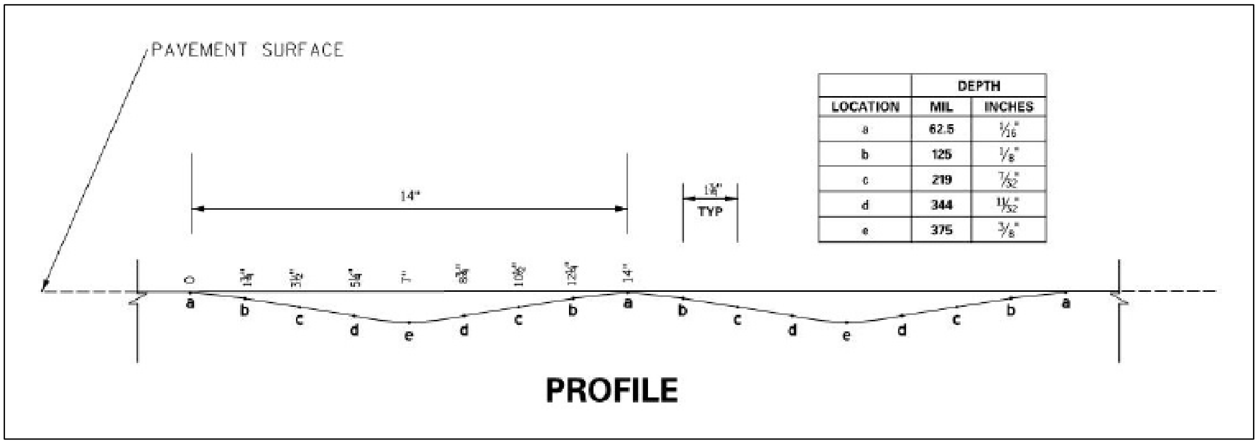


Figure 2.4 Minnesota DOT, Design 1 Profile Specification

In the final phase, the research team installed the four designs on TH 18—a two-lane rural roadway—in east central Minnesota. Each rumble strip type spanned one-mile increments. The team placed noise meters at 50 feet and 75 feet distances from the roadway centerline to capture external noise, while simultaneously placing a noise meter within each vehicle. They evaluated three vehicle types for noise: a passenger car (Ford Fusion), small truck (Ford F-150), and dump truck (Sterling Class 35). The noise meters collected sounds through A-weighted decibels (dBA). Overall, the study revealed performance discrepancies across the different rumble strips. Some rumble strips performed differently between different vehicle types. For instance, trucks experienced increased external noise for some designs, while motorcyclists perceived differences in performance across rumble strip types. Overall, the research authors recommended rumble strip design 3 as the best overall performer. The complete results from their field tests are shown in Figure 5 below.[8]

	Increase (dBA) over No-Strip		
Rumble Strip	Exterior at 50 ft.	Exterior at 75 ft.	Interior
Car			
Strip 1	4.5	3.3	14.9
Strip 2	6.4	8.6	15.2
Strip 3	5.9	5.2	14.7
Strip 4	2.3	2.4	12.5
Minnesota Design[1]	18.5	na	16.7
Pickup			
Strip 1	3.0	2.2	5.7
Strip 2	5.8	6.8	5.9
Strip 3	5.8	6.1	6.8
Strip 4	2.9	2.1	4.5
Minnesota Design[1]	13.7	na	8.4
Truck			
Strip 1	-0.4	-1.1	0.8
Strip 2	3.0	2.8	2.7
Strip 3	2.5	2.3	1.4
Strip 4	1.8	0.1	1.2

Figure 2.5 Minnesota DOT, Increase (dBA) Over No-Strip for Rumble Strip Designs

As a result of sinusoidal rumble strip study, Minnesota Department of Transportation Director Nancy Daubenberger released a technical memorandum allowing for a sinusoidal rumble strip design to be used on rural highways with speed limits 55 mph or greater. Based on the reduction in exterior noise and the increased rideability for both bicyclists and motorcyclists, MNDOT was willing to adopt the new design. The sinusoidal design calls for a 14-inch wavelength, 1/16-inch minimum depth and 1/2-inch maximum depth of rumble with 8-12 inch width for a shoulder or edgeline rumble strip. Minnesota's traditional centerline rumble strip is a 14-inch-wide rumble crossing the centerline pavement joint. However, due to concerns from engineers in the state about rumble strips causing deterioration on centerline joints, the technical memo calls for centerline sinusoidal rumble strips to be split into two 6-inch rumble strips both 2 inches away from the centerline joint. Also, due to concerns about wet nighttime visibility, all sinusoidal rumble strips must be striped with wet-reflective media.[9]

Indiana

In 2018, researchers at the Indiana Department of Transportation (INDOT) and Purdue University conducted a study to assess the use of alternative sinusoidal rumble strip designs on Indiana's roadway network. Researchers evaluated sinusoidal rumble strips with 12, 18, and 24-inch wavelengths, comparing the exterior and interior noise produced from these rumbles to Indiana's conventional rumble strip design. Figure 6 compares the four rumble strip designs.

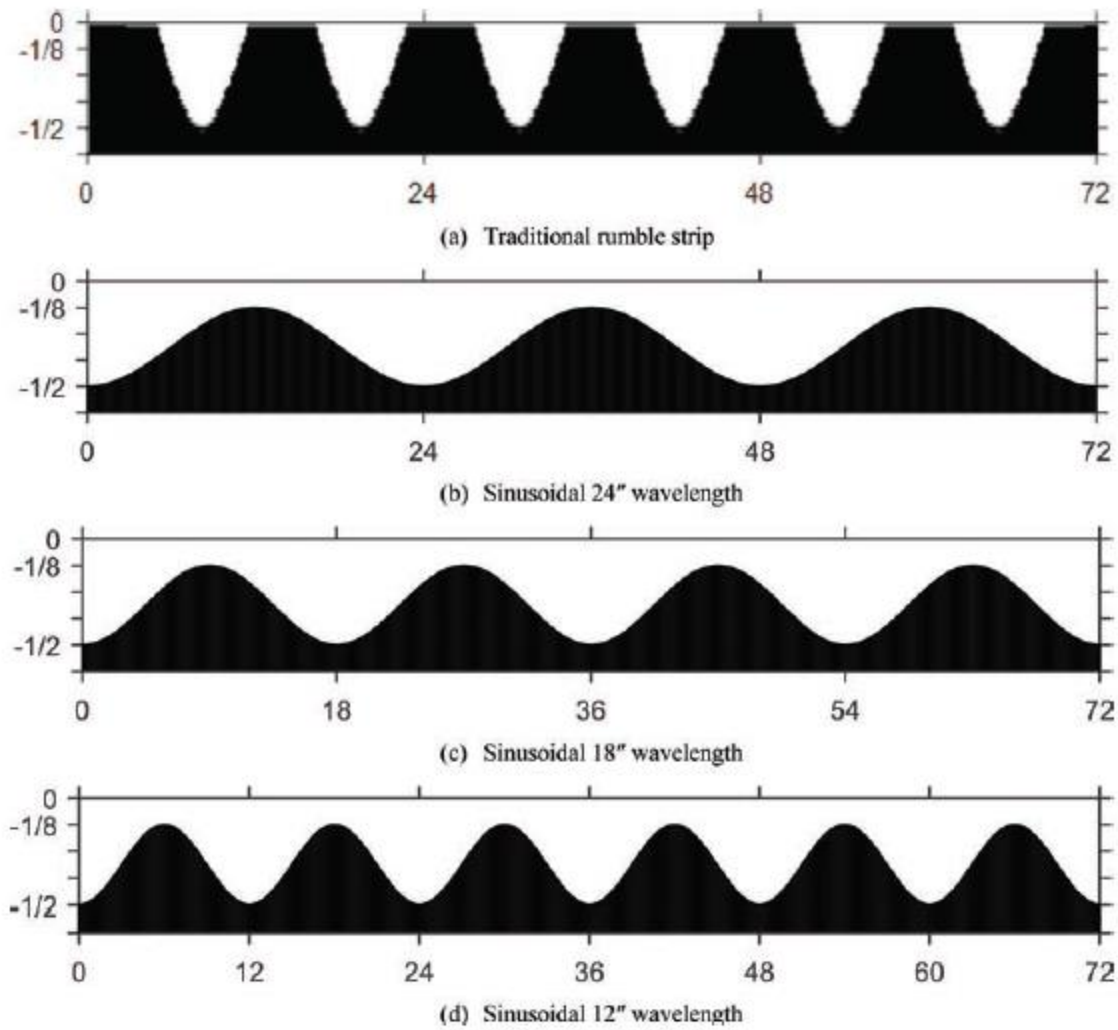


Figure 2.6 Indiana's Conventional and Sinusoidal Rumble Strip Designs for Testing

The conventional rumble strips begin at the surface of the pavement and are milled to a depth of ½ inch. The three sinusoidal designs are all recessed into the pavement to a depth of 1/8 inch down to ½ inch at the bottom of the rumble.

The researchers used six vehicles ranging from a typical passenger car to a semi-truck to traverse the four rumble strip designs at a fixed speed of 50mph. Exterior sound levels were measured 50 feet from the edgeline and interior sound levels were measured in the cabin. Results of the field testing showed the three sinusoidal rumble strip designs produced 5-11dBA less exterior noise and up to 9dBA higher interior noise when compared to the conventional rumble strip. Retroreflectivity testing was also performed on the sinusoidal designs, all of which produced greater than the minimum threshold required by INDOT specifications. As a result, the research team recommended adopting the 12-inch wavelength sinusoidal rumble strip design because it reliably produced the recommended sound levels outlined in NCHRP 641 for all vehicle types.[10]

On February 8, 2019, the INDOT release a memo outlining the adoption of the 12-inch sinusoidal rumble strip design into their design specifications, allowing for the use of this design on all projects let after March 1, 2019. Researchers at KTC have been in contact with the authors of the original Indiana study to request information about locations of newly installed sinusoidal rumble strips throughout Indiana to visit as a part of this research effort.[11]

Washington

In May of 2018, researchers at the Washington State Department of Transportation (WSDOT) published the findings of their evaluation of new rumble strip designs used to reduce roadside noise and promote safety. Due to an increasing number of noise complaints from residents near Washington's major roadways with rumble strips, WSDOT conducted a research study to consider additional rumble strip designs. At the time of the study, WSDOT's standard design plan allowed for milled cylinder rumble strips with depths varying from 0.5-0.675 inches, a length of 12 inches, spacing of 12 inches, and width of 6.5-7.5 inches. The alternative designs considered by WSDOT included a sinusoidal patterned rumble strip and three milled cylinder rumble strips like their current designs, but shallower at a depth of 0.25 inches. The four alternative designs are shown in Table 3.

Table 2.3 Washington Sinusoidal Rumble Strip Test Designs

Design Type	Depth (in.)	Width (in.)	Length (in.)	Spacing (in.)
Sinusoidal	0.50	12.00	16.00	-
1	0.25	6.9	8.00	18.00
2	0.25	6.9	12.00	18.00
3	0.25	6.9	12.00	12.00

A midsized SUV traveling at 60mph was used as a test vehicle for all four designs. Exterior sound levels were captured at 25 feet and 50 feet from the center of the traveled lane. Interior sound levels were measured at the ear level in the passenger seat of the SUV. Of the selected designs, the sinusoidal rumble had the lowest exterior sound levels, followed by Designs 1 and 2. All four designs created sufficient interior noise according to the guidelines from NCHRP 641, with Design type 2 being the loudest. The researchers considered the sinusoidal and Design 1 to be the best performing designs due to their lowest overall sound levels. It should be noted that this study did not compare these four alternative designs to the performance of WSDOT's standard rumble strip design.[12]

California

In 2008, researchers from Caltrans published a study comparing the steering column vibration, exterior noise, and interior noise created from driving over sinusoidal rumbles, raised pavement markers, and conventional milled rumble strips. This research was a result of increasing complaints from citizens living near roadways with elevated roadside noise levels from rumble strips. The research group used computer-based models to design a sinusoidal rumble strip that would produce optimal interior noise and vibration while keeping exterior noise to a minimum when driven over by a standard vehicle. The models suggested a sinusoidal design with 14-inch spacing and a 5/16 inch depth.

Sinusoidal rumble strips matching the design recommended by the computer model were constructed to use as a field test. This rumble strip design was compared to the standard Caltrans rumble strip design, which is a 4-inch-wide and 8-inch-long cylindrical milled rumble strip with a 12 inch spacing. A third roadside warning device was also tested; round raised pavement markers with a 4-inch diameter and 1-inch maximum height, spaced at 12 inches. Five vehicles traveling at 60 mph were used as test vehicles to measure interior noise, exterior noise, and steering column vibration, ranging from a Honda Civic to a 4-yard dump truck.

Results of the study showed that the sinusoidal rumble strips reduced lower frequency exterior noises by 6 dBA on average across the passenger type vehicles, and by 3 dBA for the heavy dump truck when compared to the conventional rumble strip. For passenger vehicles, interior noise generated by the sinusoidal rumble strip was comparable to the interior noise generated by the conventional rumble strip (13 vs. 14 dBA). However, with the dump truck, the sinusoidal rumble strip only produced 2.6 dBA interior noise compared to 7.6 dBA on the conventional rumble strip. The round raised pavement markers produce similar noise levels to the conventional rumble strips. The research team recommended the sinusoidal rumble strip design to reduce exterior noise while maintaining interior noise and vibration levels sufficient to alert a driver to roadway departure. The study also suggested it may be possible to reduce exterior noise further with the sinusoidal rumble strip by reducing the depth of the sinusoidal wave to ¼ inches and increasing the spacing to 16 inches. However, field testing would need to occur to confirm this suggestion.[13]

Pennsylvania

In 2014, researchers at the Pennsylvania Transportation Institute at the Pennsylvania State University published a synthesis of best practices from other states and transportation agencies regarding the use of rumble strips on thin pavement overlays. The synthesis focuses on the use of 3/8 inch and ½ inch rumble strips on thin overlays constructed with hot-mix asphalt, seal coats, and microsurfacing. At the time of the study, Pennsylvania Department of Transportation provided no guidance on the installation of rumble strips in conjunction with thin pavement overlays. Through their literature review, the researchers found little documentation regarding the use of rumble strips on thin pavement overlays. There was no common guidance followed by state and federal transportation agencies, with most agencies developing their own thin overlay rumble strip guidelines based on previous field experience. Based on the variable guidance used by other states, the researchers developed a set of guidelines for using rumble strips on the three targeted thin overlay surface types based on the roadway's characteristics before the construction of the thin overlay. Tables 4, 5, 6, and 7 summarize the recommendations of the research.[14]

Table 2.4 Pennsylvania Thin Overlay Recommendations for Highways with Edgeline or Shoulder Rumble Strips Only

Thin Overlay Type	Overlay Depth	Existing Rumble Strip Treatment Process				
		Mill	Mill Dimensions		Inlay Materials	Re-milled Rumble Strip Depth
Hot-mix Asphalt	7/8- to 1-inch	Yes*	SRS	20-inches wide > ½-inch deep	Tack coat on milled surface and apply dense-graded hot-mix asphalt that is level with existing pavement surface	3/8-inch
	> 1-inch		ERS	12-inches wide > ½-inch deep		3/8- or 1/2-inch
Seal Coat	1st seal coat	No, if material does not fill rumble strip groove	Maintain ≥ 3/8-inch existing groove depth**			
	2nd seal coat	Yes*	SRS	20-inches wide > ½-inch deep	Tack coat on milled surface	3/8-inch
			ERS	12-inches wide > ½-inch deep	Dense-graded hot-mix asphalt that is level with surface of 1st seal coat	3/8- or 1/2-inch
Microsurfacing	Varies	No, if material will not fill rumble strip groove	Maintain ≥ 3/8-inch existing groove depth**			
		No, if material will fill existing rumble strip groove	Fill existing grooves with scratch layer and then tack coat surface			3/8- or ½-inch
		Yes*	SRS	20-inches wide > ½-inch deep	Tack coat on milled surface	3/8- or ½-inch
			ERS	12-inches wide > ½-inch deep	Dense-graded hot-mix asphalt that is level with surface existing pavement surface	3/8- or ½-inch

*If the entire roadway surface (travel lanes and shoulders) will be overlaid because of poor pavement conditions, the entire roadway surface should be milled at least as deep as the depth shown in the "Mill Dimensions" column.

** Groove depth of existing rumble strip pattern should be checked along 100-foot test section within the limit of the seal coat or microsurfacing overlay project. If a rumble strip groove depth ≥ 3/8-inch is maintained, no milling is recommended. If the average groove depth, measured in at least 5 locations within the test section, is less than 3/8-inch, the existing rumble strip pattern should be milled and inlayed in accordance with the hot-mix asphalt guidelines presented here.

Table 2.5 Pennsylvania Thin Overlay Recommendations for Undivided Highways with Centerline Rumble Strips Only

Thin Overlay Type	Overlay Depth	Existing Rumble Strip Treatment Process			
		Mill	**Mill Dimensions**	**Inlay Materials**	**Re-milled Rumble Strip Depth**
Hot-mix Asphalt	7/8- to 1-inch	Yes*	20-inches wide > ½-inch deep	Tack coat on milled surface	3/8-inch
	> 1-inch			Dense-graded hot-mix asphalt	3/8- or 1/2-inch
Seal Coat	1st seal coat	No, if material does not fill rumble strip groove	Maintain ≥ 3/8-inch existing groove depth**		
	2nd seal coat	Yes*	20-inches wide > ½-inch deep	Tack coat on milled surface	3/8- or 1/2-inch
				Dense-graded hot-mix asphalt that is level with surface of 1st seal coat	
Microsurfacing	Varies	No, if material will not fill rumble strip groove	Maintain ≥ 3/8-inch existing groove depth**		
		No, if material will fill existing rumble strip groove	Fill existing grooves with scratch layer and then tack coat surface		3/8- or ½-inch
		Yes*	20-inches wide > ½-inch deep	Tack coat on milled surface	3/8- or ½-inch
				Dense-graded hot-mix asphalt that is level with surface of 1st seal coat	3/8- or ½-inch

*If the entire roadway surface (travel lanes only or travel lanes and shoulders) will be overlaid because of poor pavement conditions, the affected roadway surface should be milled at least as deep as the depth shown in the "Mill Dimensions" column.

** Groove depth of existing rumble strip pattern should be checked along 100-foot test section within the limit of the seal coat or microsurfacing overlay project. If a rumble strip groove depth ≥ 3/8-inch is maintained, no milling is recommended. If the average groove depth, measured in at least 5 locations within the test section, is less than 3/8-inch, the existing rumble strip pattern should be milled and inlayed in accordance with the hot-mix asphalt guidelines presented here.

Table 2.6 Pennsylvania Thin Overlay Recommendations for Undivided Highways with Centerline Rumble and Edgeline or Shoulder Rumble Strips

Thin Overlay Type	Overlay Depth	Existing Rumble Strip Treatment Process			
		Mill	**Mill Dimensions**	**Post-milling Materials**	**Re-milled Rumble Strip Depth**
Hot-mix Asphalt	7/8- to 1-inch	Yes	Full roadway (travel lanes and shoulders)	Tack coat on milled surface	3/8-inch
	> 1-inch				3/8- or 1/2-inch
Seal Coat	1st seal coat	No, if material will not fill rumble strip groove	Maintain ≥ 3/8-inch existing groove depth*		
	2nd seal coat	Yes	Full roadway (travel lanes and shoulders)	Tack coat on milled surface	3/8- or 1/2-inch
Microsurfacing	Varies	No, if material will not fill rumble strip groove	Maintain ≥ 3/8-inch existing groove depth**		
		No, if material will fill existing rumble strip groove	Fill existing grooves with scratch layer and then tack coat surface		3/8- or ½-inch
		Yes*	Full roadway (travel lanes and shoulders)	Tack coat on milled surface	3/8- or ½-inch

* Groove depth of existing rumble strip pattern should be checked along 100-foot test section within the limit of the seal coat or microsurfacing overlay project. If a rumble strip groove depth ≥ 3/8-inch is maintained, no milling is recommended. If the average groove depth, measured in at least 5 locations within the test section, is less than 3/8-inch, the existing rumble strip pattern should be milled in accordance with the seal coat or microsurfacing rumble strip treatment process.

Table 2.7 Pennsylvania Recommendations for New Rumble Strips on Thin Pavement Overlays

Thin Overlay Type	Overlay Depth	Pre-Rumble Strip Milling Surface Preparation	Milled Rumble Strip Depth
Hot-mix Asphalt	1 to 1.25-inches	Crack seal	3/8-inch
	≥ 1.25-inches	Crack seal	3/8- or ½-inch
Seal Coat	1 Seal Coat	Do not apply milled rumble strip on single seal coat	N/A
	2 Seal Coats	None	3/8- or ½-inch
Microsurfacing	7/8- to 1-inch	None	3/8-inch
	> 1-inch	None	3/8- to ½-inch

Although Pennsylvania's recommendations for thin rumble strips on pavement overlays in the above tables have not been proven in the field and are only an amalgamation of suggestions from other states and federal agencies, their guidance is the most complete and well researched in the nation.

Oregon

Researchers at the Oregon State University published a 2019 report assessing the feasibility of sinusoidal rumble strips in place of conventional milled rumble strips on Oregon roadways in conjunction with the Oregon Department of Transportation. The researchers used a passenger car, van, and dual tire heavy vehicle traveling at 55 mph to compare the exterior noise, interior noise, and interior vibration created by the two rumble strip designs. The sinusoidal rumble strip was 14 inches wide with a wavelength of 16 inches, peak depth of 1/16 inch and maximum depth of 3/8 inch. The milled rumble strip was 9.5 inches wide, 8 inches long, 7/16 inch deep and spaced at 12 inches.

Results of the study showed that the conventional rumble strip produced and increase in exterior noise of approximately 5 dBA for the passenger car and van, however the sinusoidal rumble strip produced only an additional 3 dBA of exterior noise for the car and no measurable difference in exterior noise for the van. The conventional rumble strips produced interior noise levels between 10 and 12 dBA for both the van and passenger car, while the sinusoidal rumble strips produced interior noise levels ranging from 4.6 - 5.8 dBA. NCHRP recommends 6 - 12 dBA on interior noise as a sufficient warning for drivers, meaning the sinusoidal design fell short of this recommendation. However, the FHWA rumble strip state of practice document suggests as little as 3 dBA of interior noise would serve as a sufficient warning to drivers.

The dual tire heavy vehicle failed to produce significant interior or exterior noise on the conventional rumble strip due to the narrower width (9.5 inches). However, the wider (14 inches) sinusoidal rumble strip produced 5.7 dBA of exterior noise and 6.8 dBA of interior noise on average during testing with the heavy vehicle.

A separate component of this study involved a survey sent to contractors to investigate the process of installation of sinusoidal rumble strips compared to conventional milled rumble strips. This survey showed that sinusoidal rumble strips take roughly three times longer to install than conventional rumble strips due to the continuous cutting required. Contractors specified that it is much easier to install sinusoidal rumble strips on asphalt pavement, although it is still possible to use a sinusoidal rumble strip on concrete pavement. Some contractors recommended the addition of tapered edges to sinusoidal rumble strips as it can reduce water ponding and improve cyclist and motorcyclist mobility. Finally, the contractors recommended sinusoidal rumble strips with widths greater than 8 inches to ensure effectiveness with various tire widths.[15]

Florida

In March of 2018, the Florida Department of Transportation's (FDOT) State Roadway Engineer released a memo detailing revisions to Florida's audible and vibratory treatments on arterial and collector roads in Florida's Design Specs, Plans Preparation Manual, and Design Manual. (Memo) In 2019, FDOT presented their changes to the audible and vibratory roadway features they use on arterial and collector roads at the Getting to Zero Together National Safety Engineer Peer Exchange hosted by FHWA and AASHTO. FDOT considered the use of profiled thermoplastic rumbles, ground-in cylindrical rumbles (full depth and shallow), and ground-in sinusoidal rumbles. FDOT allows for 3/16 inches cylindrical rumbles on arterials and collectors instead of their standard ½ inch used on other roadways in an attempt to reduce the ambient noise in nearby residential areas. These shallower conventional rumbles produce 6 dBA additional exterior noise. FDOT's profiled thermoplastic striping produces roughly 2 dBA additional exterior noise.[16]

Florida's sinusoidal rumble strip design, which has a 14 inch wavelength, 8 inch width, 5/16 inch maximum depth, and is flush with the pavement surface at its peak, produces 4 dBA additional exterior noise.[17] It should be noted that FDOT's sinusoidal rumble strip design differs from most states in that the peak of the sinusoidal waves is flush with the pavement surface. The sinusoidal rumble design for most states involves the peak of the waves to be recessed below the pavement surface by 1/16 inches so that the entire stripe painted on the rumble is sheltered below the pavement surface. This sheltering protects the pavement from potential damage from snow plowing or other similar activity. Florida rarely has a need for snow plowing; hence their design does not fully recess the sinusoidal wave below the pavement's surface.[18]

Maryland

Maryland's rumble strip guideline documents do not currently recommend the use of sinusoidal rumble stripes, but they do include provisions for narrower and shallower rumble strips. Maryland's rumble strip specifications require a 7 inches long and 1/2-5/8 inches deep milled cylindrical rumble for all interstates, expressways, and roadways with speed limits over 40 mph. However, if bicyclists are permitted on a given roadway, designers must consider the use of narrower (5 inches long) and shallower rumble (3/8 inch deep) strip.[19] According to Maryland's guidelines, their shallow and narrow rumble strip design still provides sufficient auditory and vibratory warning to drivers.[20]

Chapter 3 KYTC Current Practices

KYTC provides two guidance documents along with seven standard drawings to govern the use of rumble strips on Kentucky's roads. KYTC's *Standards and Specifications for Road and Bridge Construction* detail the construction procedures contractors shall use to install rumble strips on asphalt (Sections 403.03.08, 403.04.03, and 403.04.07) and concrete (Sections 501.03.13, 501.04.01, 501.04.03, and 501.04.04), as well as the measurement procedures to determine the amount of rumble strip installed for billing purposes.[21]

KYTC also publishes a *Traffic Operations Guidance Manual* which indicates that the Traffic Operations branch at KYTC's Central Office maintains the standard drawings for rumble strips and other traffic-related items. This manual also sets the precedent that the installation of rumble strips on roadways that do not have a speed limit greater than 45 mph or lane width of at least 11 ft. must be approved by the director of the Traffic Operations branch. Since roadways with speeds lower than 45 mph are often in close proximity to residential areas, the exclusion of rumble strips on those roadways was intended to reduce the impact of the exterior noise created by vehicle interaction with rumble strips.

According to the Traffic Operations Manual, "normal practice would be to include centerline, edgeline, and/or shoulder rumble strips on projects involving long sections of qualifying roadway. The nature of certain projects (such as guardrail installation, bridge replacement, etc.) would not require installation of rumble strips with the project. Likewise, rumble strips would not be installed when only short, sporadic sections of a roadway meet the qualifying criteria. If a majority of a roadway does not meet the qualifying criteria, rumble strips may be eliminated from consideration. For projects involving small sections of qualifying roadway (such as the approaches to bridges on bridge replacement projects), rumble strips should be included in the project if the remainder of a roadway already has rumble strips installed." The manual directs readers to KYTC's seven design standards for rumble strips, where the design is chosen based on a roadway's geometry.[22]

The standard rumble strip designs and geometric requirements distinguish between rumble strips on two-lane road and rumble strips on multilane roads. Kentucky uses three types of rumble strips: centerline, edgeline, and shoulder rumble strips. Centerline rumble strips (CLRS) are placed in conjunction with the centerline stripe on undivided roads. Edgeline rumble strips (ELRS) are milled and the edgeline stripe is placed over top of the rumble strip. Shoulder rumble strips (SRS) are rumble strips milled to the right of the edgeline on the right shoulder and the left of the edgeline on the left shoulder. The following sections of the report summarize the rumble strip design requirements for the two roadway types, which were recently updated in 2020. [23]

3.1 Two-Lane Roads

Edgeline Rumbles

Table 8 below prescribes the use of edgeline and centerline rumble strips for two-lane roads based on total pavement width, lane width, and shoulder width.

Table 3.1 KYTC Guidelines for Edgeline and Centerline Rumble Strips on Two-Lane Roads

PAVEMENT WIDTH (W) ②	TYPES OF RUMBLE STRIPS TO INSTALL ⑦	LANE WIDTH (Y) ③	SHOULDER WIDTH (Z) ④	LENGTH OF EDGELINE RUMBLE (X) ⑥
22'	INSTALL ONLY EDGELINE RUMBLE STRIPS	10'	1'	8"
23'		10'	1.5'	8"
24'		10.5'	1.5'	8"
25'	INSTALL BOTH EDGELINE AND CENTERLINE RUMBLE STRIPS	11'	1.5'	8"
26'		11'	2'	8"
27'		11.5'	2'	8"
28'		12'	2'	8"
29'		12'	2.5'	8"
30'		12'	3'	8"
31'		12'	3.5'	8"
32'		12'	4'	8"
33'		12'	4.5'	8"
>33'	REFER TO TPR-125			

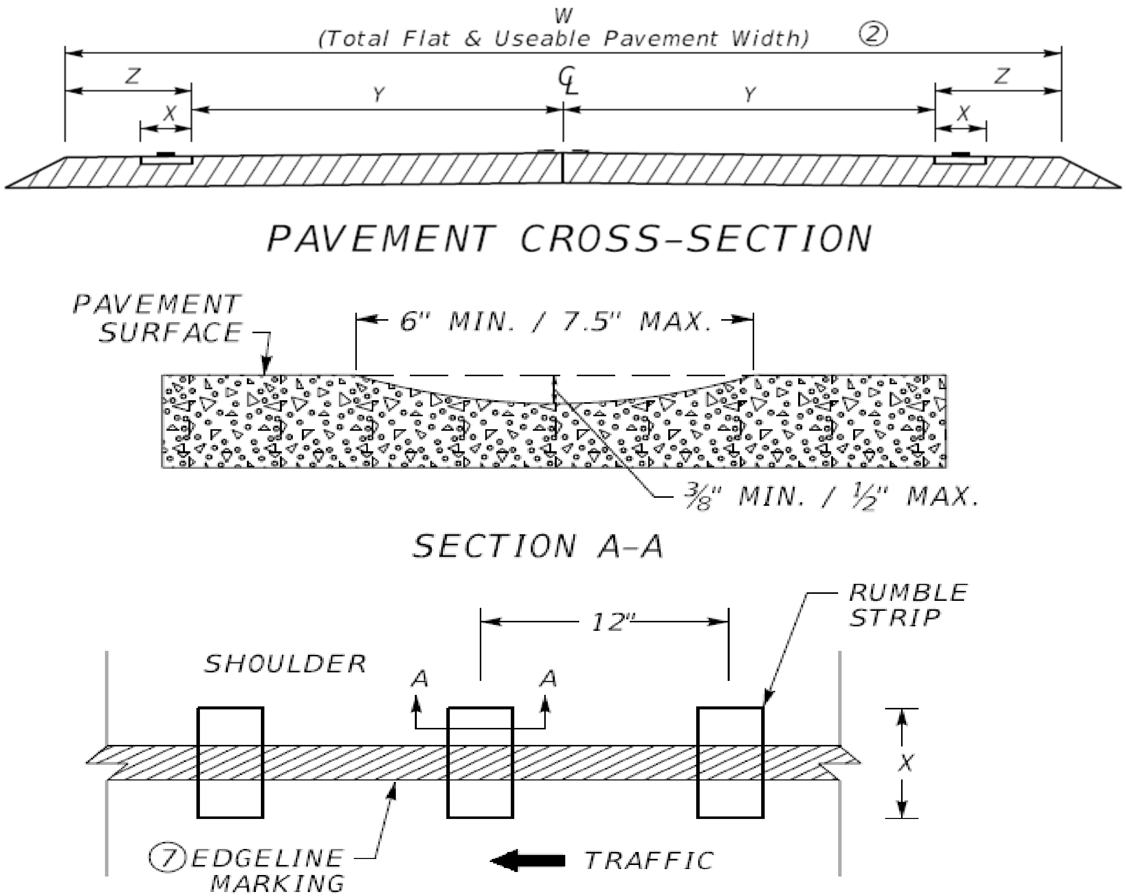


Figure 3.1 KYTC Diagrams for Rumble Strips on Two-Lane Roads

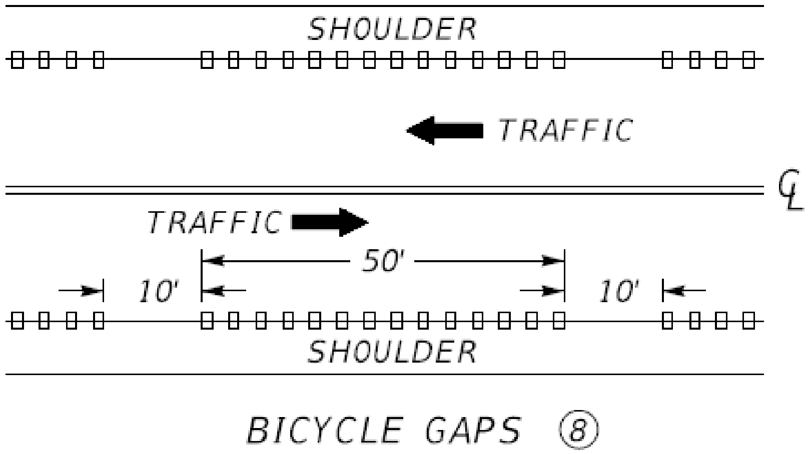


Figure 3.2 KYTC Diagrams for Bicycle Gaps Needed for Edgeline Rumble Strips on Two-Lane Roads

Two-lane roads should have edgeline rumbles if the total pavement width is 22-33 feet. Centerline rumbles are included if pavement width is >=25 feet and lane/shoulder width requirements are met. All edgeline rumble strips with 3 feet or more shoulder must include bicycle gaps as detailed in Figure 8. On two-lane roadways with pavement widths greater than 20 feet, but less than 22 feet, edgeline rumbles may be installed. The division of traffic operations at KYTC's central office may be consulted in determining if an edgeline rumble strip is appropriate in these instances. Rumble width can be modified at the engineer's discretion. No rumbles are allowed if the speed limit is 45 mph or less.

Previously, rumble strips were allowed to be installed on two-lane roads with widths as low as 20 feet, however this caused issues for large agricultural vehicles that frequently operated on narrow roads with edgeline rumble strips. Therefore, the design was updated in 2020 to set a minimum road width of 22 feet for rumble strips on two-lane roads.

Shoulder Rumbles

Table 9 below prescribes the use of shoulder and centerline rumble strips for two-lane roads based on total pavement width, lane width, and shoulder width.

Table 3.2 KYTC Guidelines for Shoulder and Centerline Rumble Strips on Two-Lane Roads

PAVEMENT WIDTH (W) ②	TYPES OF RUMBLE STRIPS TO INSTALL	LANE WIDTH (Y) ③	SHOULDER WIDTH (Z) ④	SHOULDER RUMBLE LENGTH (X) ⑥	SHOULDER RUMBLE OFFSET ⑥
<34'	REFER TO TPR-120				
34'	INSTALL BOTH SHOULDER AND CENTERLINE RUMBLE STRIPS	12'	5'	8"	6"
35'		12'	5.5'	8"	6"
36'		12'	6'	8"	6"
37'		12'	6.5'	12"	12"
38'		12'	7'	12"	12"
39'		12'	7.5'	12"	12"
>=40'		12'	>=8'	16"	12"

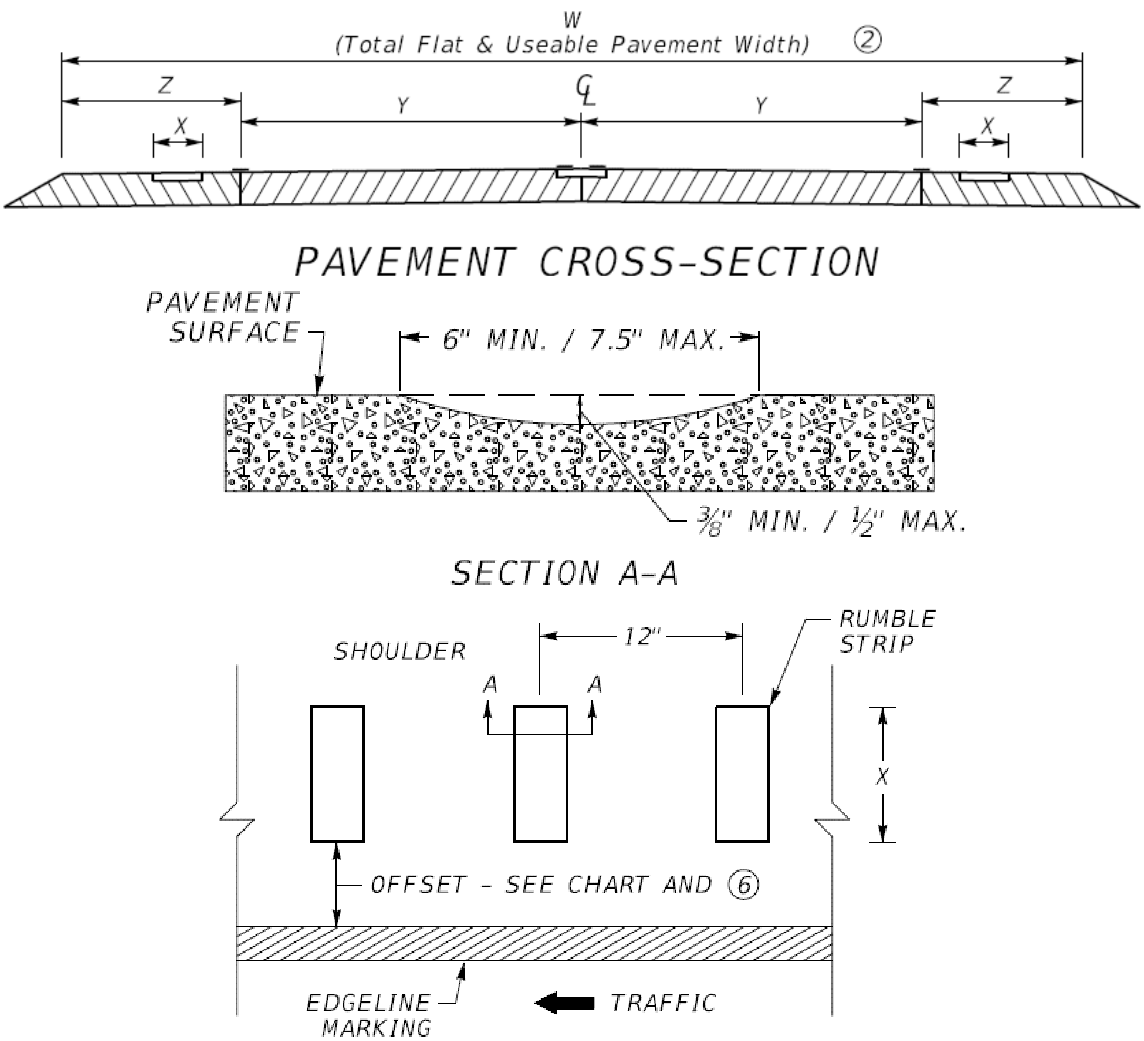


Figure 3.3 KYTC Diagrams for Shoulder and Centerline Rumble Strips on Two-Lane Roads

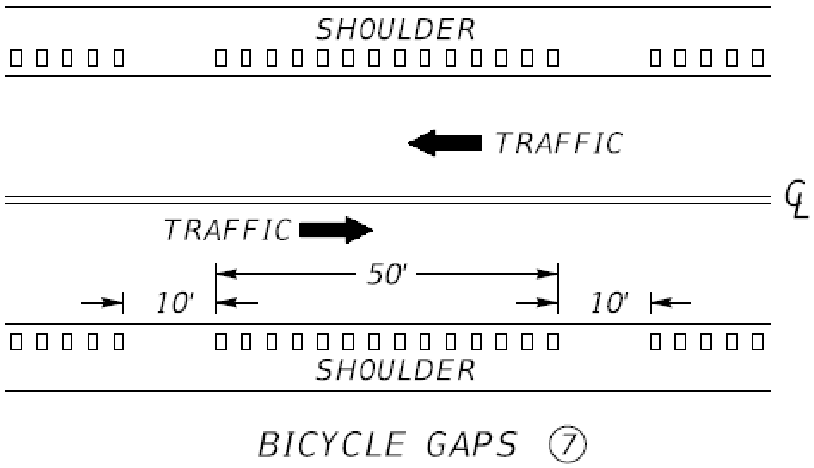


Figure 3.4 KYTC Diagrams for Bicycle Gaps Needed for Shoulder Rumble Strips on Two-Lane Roads

Shoulder rumbles on two-lane roads are only used if the total pavement width is greater than or equal to 34 feet. Centerline rumbles are added if lane/shoulder width requirements are met. Bicycle gaps must be included for all shoulder rumble strips as detailed in Figure 9. Rumble width and offset can be modified at the engineer's discretion. No shoulder rumbles are allowed if the speed limit is 45 mph or less.

3.2 Multilane roads (Divided)

Table 10 prescribes the use of edgeline or shoulder rumble strips for multi-lane divided roadways based on shoulder width.

Table 3.3 KYTC Guidelines for Edgeline and Shoulder Rumble Strips on Multilane Divided Roads

SHOULDER WIDTH (Z) ②	RUMBLE TYPE ①	RUMBLE LENGTH (X) ③	OFFSET ③
>=1'	ELRS	8"	N/A
2'	ELRS or SRS	8"	ELRS-N/A SRS-6"
3'	ELRS or SRS ⑥	8"	ELRS-N/A SRS-6"
4'	ELRS or SRS ⑥	8"	ELRS-N/A SRS-6"
5'	SRS ⑥	8"	6"
6'	SRS ⑥	8"	6"
7'	SRS ⑥	12"	12"
>=8'	SRS ⑥	16"	12"

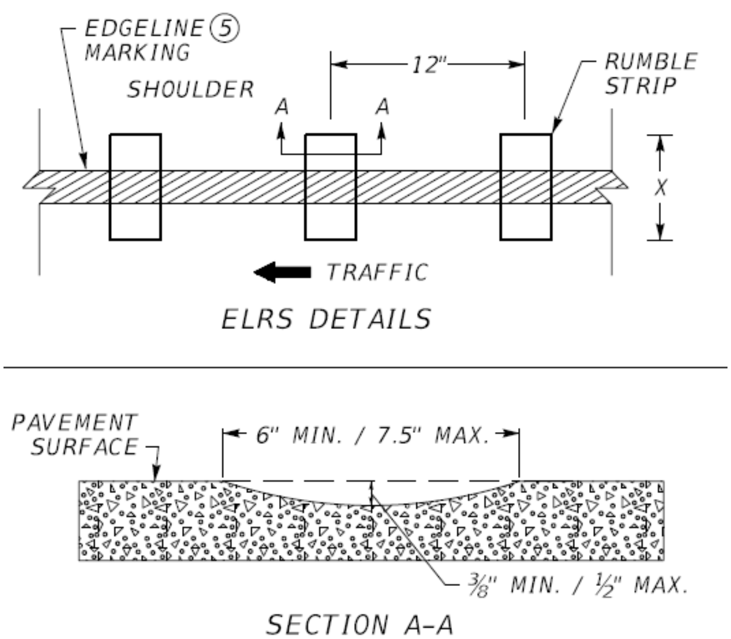


Figure 3.5 KYTC Diagrams for Edgeline Strips on Multilane Divided Roads

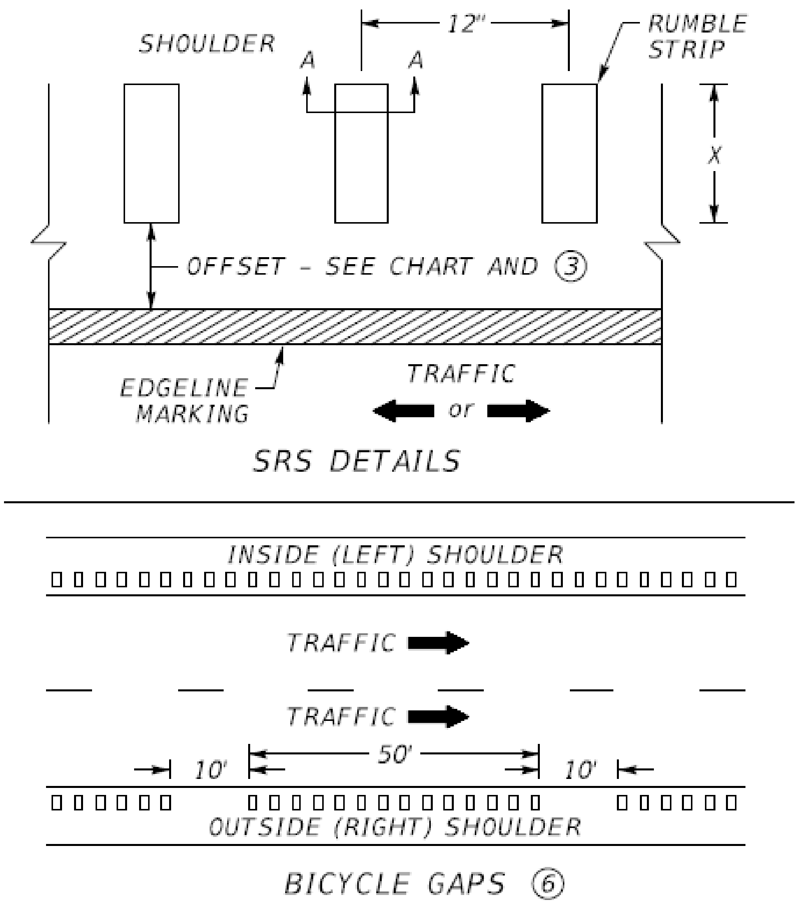


Figure 3.6 KYTC Diagrams for Shoulder Rumble Strips on Multilane Divided Roads

Multilane roads with shoulders 4 feet or less can be designed with edgeline or shoulder rumbles. For shoulders 5 feet or greater, only shoulder rumbles are used. When shoulder rumble strips are used and the shoulder is 3 feet or greater, bicycle gaps must be included as detailed in Figure 12. Rumble width and offset can be modified at the engineer's discretion. No edgeline or shoulder rumbles are allowed if the speed limit is 45 mph or less or the shoulder is less than 1 foot.[24]

3.3 Longitudinal Joint Adhesive

There have been discussions about whether longitudinal joint adhesive are beneficial to maintaining the structural integrity of a centerline rumble strip when applied to the centerline joint during construction. Indiana often uses joint adhesive in locations where they install centerline rumble strips, but the Indiana Department of Transportation has not published any studies confirming the benefit of this practice. A new longitudinal joint adhesive has recently been developed named J-Band, which is applied to the roadway surface at the joint location prior to laying pavement. Once the two strips of pavement are laid adjacent to each other, J-Band migrates upward and fills voids in the joint for a stronger joint bond.[25] Currently, KYTC does not prescribe any guidance on when to use longitudinal joint adhesive, but KYTC has published a Special Note for longitudinal pavement joint adhesive describing the material requirements, installation procedure, and testing methods applicable for the installation.[26]

Chapter 4 Surveys

4.1 KYTC District Survey

The research team contacted a representative from each of Kentucky's 12 highway districts that are in charge of rumble strip-related activity in their district. Each representative was asked about the following items:

- Types of rumble strips used in the district
- Which contractors install rumble strips for the district
- Year district began milling rumble strips
- Rumble Strip durability issues common in the district
- Complaints from public due to rumble strips
- Opinion on safety performance of rumble strips
- Any preference between edgeline and shoulder rumble strips
- Use of rumble strips on thin overlays
- Use of longitudinal pavement joint adhesive
- Opinion of potential changes with rumble strip design

Most district personnel reported no major durability issues with centerline pavement joints when rumble strips were installed. Centerline rumble strip deterioration was mainly reported only once pavements had aged significantly. When questioned about the use of longitudinal pavement joint adhesive on centerline pavement joints with rumble strips to improve durability, many districts had limited experience with that potential solution. The districts that had used longitudinal joint adhesive reported little to no improvement in centerline rumble strip durability. Districts often experienced issues retrofitting rumble strips on old pavements and they also had limited experience with the placement of rumble strips on thin pavement overlays (where rumble strips previously existed before the overlay). All the districts' representatives agreed that rumble strips have had a positive effect on safety performance and reduction in run-off-road crashes in their districts. Most districts reported very limited complaints about rumble strips from the public and from cyclists, who may have difficulty traversing rumble strips.

As far as changes to KYTC's current rumble strip practices, several highway districts believed the rumble strip depths currently used in Kentucky should be decreased, both to reduce exterior noise and to improve durability of the pavement. There is a desire among the highway districts for smoother milled rumbles to aide in the adhesion and durability of longitudinal striping. District personnel have varying opinions of moving shoulder rumble strips to the edgeline to allow for earlier lane departure warnings. Some district representatives argued that the warning of lane departure is the primary benefit of rumble strips, so the earlier the warning can be provided, the better the rumble strip. However, some district representatives still favored the shoulder rumble strip because they think edgeline rumble strips could produce an increase in exterior noise pollution. The shoulder rumble strip is viewed as a way to reduce accidental rumble strip traversing and to serve as a warning only to drivers significantly outside of their travel lane. Overall, the district representatives were receptive to changes to Kentucky's rumble strip design and practices.

4.2 Kentucky Highway Contractor Survey

The KTC research team held a discussion with local highway contractors regarding the use of alternative rumble strip designs in the state. When questioned about the use of sinusoidal rumble strips, the contractors believed these rumble strips would be beneficial to the state because they provide a recessed pavement groove to protect higher cost wet-reflective pavement markings. The contractors were familiar with the equipment necessary to install sinusoidal rumble strips. The sinusoidal equipment mills pavement much slower than conventional cylindrical rumble strip milling equipment; it requires continuous milling of pavement at varying depth rather than a repetitive, intermittent milling at a prescribed depth. Due to the nature of the sinusoidal equipment, contractors stated that sinusoidal rumble strips are more feasible to install on straight roads (such as interstates) than the curvy, narrow, lower volume roads that are common in Kentucky. Also, the sinusoidal milling equipment is wide such that if a shoulder or edgeline sinusoidal rumble strip is to be milled, the roadway must have at least a 4-foot shoulder to accommodate the equipment.

The research team also approached local contractors with the MNDOT method of installing dual rumble stripes 2 inches from either side of a centerline joint to increase pavement and rumble strip lifespan. This method would be in place of using centerline joint adhesives to protect the centerline joint. The contractors believe that milling a rumble strip within 2 inches of a pavement joint is too narrow of a tolerance to prevent the equipment from crossing the centerline joint during installation. Therefore, they do not believe this would be a feasible solution to centerline joint damage from rumble strips in Kentucky.

When questioning contractors about other rumble strip related issued they have faced in the state, one company mentioned how common it is in Kentucky and other states in the county for the pavement on either side of a centerline joint to not be level. The contractor reported that often pavement on one side of a centerline joint is higher than the opposing side creating a height difference between the adjacent pavement strips. Typically this is due to an excess of pavement near one side of the centerline joint where pavers add too much pavement in an attempt to make the joint flush. This height difference can also be caused by a lack of compaction at the joint to level the pavement on both sides of the joint. The height difference makes it difficult for the rumble strip equipment to mill an even rumble strip across the centerline joint. This also tends to lead to future durability issues with the centerline rumble strip.

4.3 State Installation Costs Survey

KTC researchers reached out to multiple state DOTs who have implemented sinusoidal rumble strips in their jurisdictions. The research team inquired about the average costs states were experiencing to install sinusoidal rumble strips. More specialized equipment is required and is of limited availability compared to conventional rumble strip installation equipment. Data was also gathered on the prices states are paying to install conventionally milled cylindrical rumble strips. Table 11 shows the prices per foot of sinusoidal and conventional rumble strip installation in each of the states that responded.

Table 4.1 Sinusoidal and Conventional Rumble Strip Installation Cost by State Per Foot

State	Sinusoidal	Conventional	Increase
South Dakota	$0.25	$0.14	$0.11
Michigan	$0.33	$0.30	$0.03
Indiana	$0.49	$0.33	$0.16
Maine	$0.46	$0.25	$0.21
New Hampshire	$0.60	$0.42	$0.18
Oregon	$0.31	$0.28	$0.03
Colorado	$0.55	$0.25	$0.30
Wisconsin	$0.48	$0.21	$0.27
Average	$0.43	$0.26	$0.16

Chapter 5 Case Studies

5.1 Kentucky Standard Rumble Installations

The recent resurfacing of KY 9 in Carter County serves as an example of a rumble strip installation. There are dual 6-inch thermoplastic stripes and a 6-inch gap between the centerline centerlines. This results in 18 inches between the outside edges of the double centerline. The centerline rumble strips have a width of 16 inches. Recessed pavement markers are installed between the centerlines. There is also a shoulder rumble strip where the edgeline strip is separated from the shoulder rumble strip by a foot.

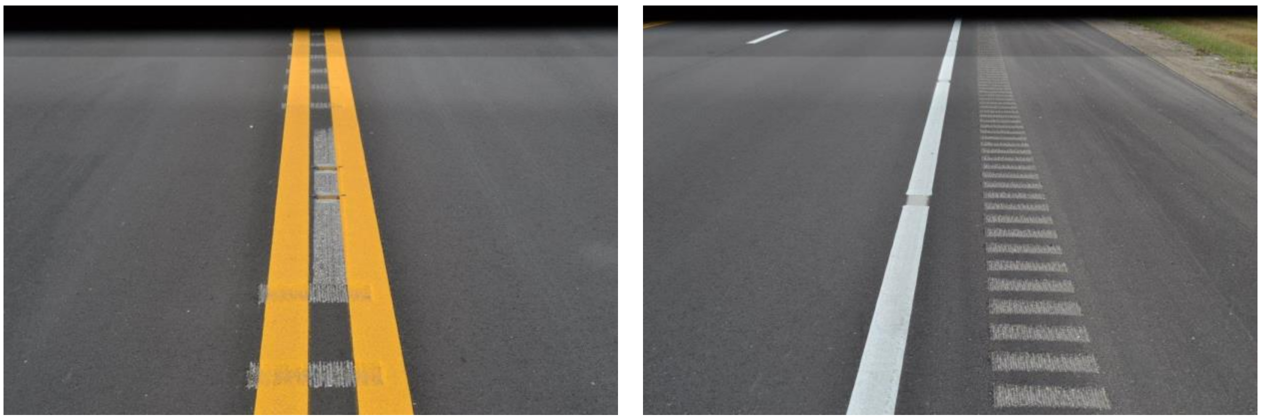


Figure 5.1 KY-9 Centerline and Shoulder Rumbles

The following images show an example of shoulder rumble strip with a gap for bicycles (typically 50 feet of rumble strip with a 10-foot gap).

Figure 5.2 Kentucky Shoulder Rumble with Bicycle Gaps

The following images show an example of shoulder rumble strips with no bike gaps.

Figure 5.3 Kentucky Shoulder Rumble Without Bicycle Gap

The following photos show a thermoplastic rumble stripe (with the 6-inch thermoplastic stripe placed in an 8 inch wide rumble strip). These rumble strips and thermoplastic stripes do not show any durability issues.

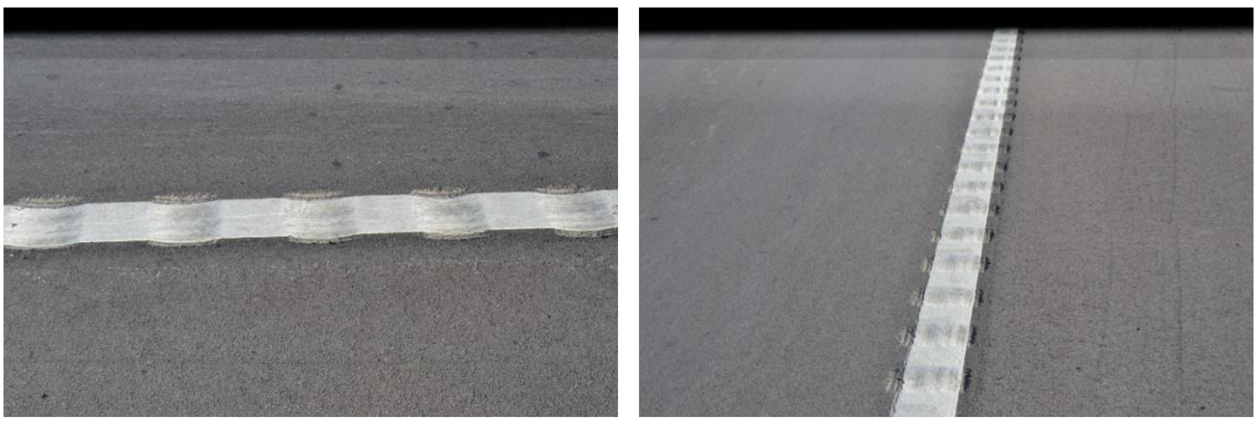


Figure 5.4 Thermoplastic Edgeline Rumble Strip With No Durability Issues

5.2 I-75

The following photos show thermoplastic striping placed in groove on skip lines and edgelines, with recessed markers and shoulder rumble strips on I-75.

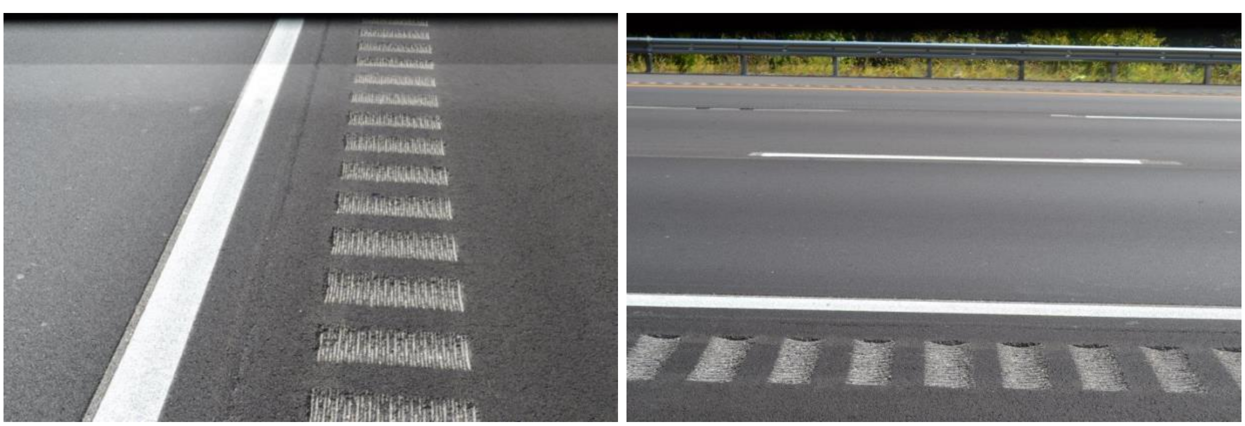


Figure 5.5 I-75 Recessed Thermoplastic Striping and Shoulder Rumble Strip

The following photos are an example of moving a shoulder rumble strip to an edgeline rumble strip using thermoplastic pavement markings. This rumble strip is 16 inches wide with 12-inch center spacing and a 6-inch stripe on the left edge of the rumble (rather than the typical interstate location where the rumble strip is placed about 1 foot from the edgeline).

The issue in question with this location is where the rumble strip should be installed on the 10-foot shoulder. Typically, a 16-inch rumble on a 1-foot center is placed with the near edge 1 foot from the edgeline. There has been debate on whether the rumble strip should be placed on the shoulder (with the edgeline not placed over the rumble strip) or if the rumble strip should be installed as an edgeline rumble strip. The advantage of installing the rumble strip at a location where the edgeline is placed over the rumble is that it provides more wet-nighttime delineation and earlier warning to vehicles straying from their lane. The potential issue is that a durability problem could occur with increased contact from vehicles. A potential solution for durability issues would be to install the rumble strip with a higher RPM cutting device to create a better surface for the striping to adhere. Experienced KTC researchers believe the edgeline should always be placed over the rumble strip (resulting in a "rumble stripe") on two lane roads. This is because raised pavement markers or recessed markers will not be installed on this type of road. In the past the state has placed rumble strips on the narrow 4-foot shoulder rather than at a location where the edgeline would be placed over the rumble strip. KYTC should consider altering construction practices such that the shoulder and centerline joint is shifted several inches so edgeline and centerline rumbles can be installed adjacent to pavement joints rather than across pavement joints. According to KYTC construction personnel, this type of pavement joint shift is feasible if it is only by a few inches. Any joint shift larger than a few inches would result in a severe shift in the roadway’s crown and may affect drainage and superelevation. Shifting pavement joints for 8-inch rumbles would be most appropriate because a 4-inch shift would provide enough space to mill edgeline and centerline rumbles adjacent to the joints, rather than centered on the joints.

Figure 5.6 I-75 Edgeline Rumble Strip

The following photos were taken on I-75 at a location where the shoulder was resurfaced for a short distance. The construction for this shoulder patch is interesting because originally the rumble strip was a shoulder rumble strip, but the rumble on the patched shoulder segment was milled as an edgeline rumble strip.

Figure 5.7 I-75 Shoulder Patch and Shifted Rumble Strip

5.3 Natcher Parkway

The following photos show the shoulder and rumble strip on the Natcher Parkway in Warren County after it was sealed. The sealing produces a good contrast between the pavement and the striping.

Figure 5.8 Natcher Parkway Shoulder Rumble Strip After Pavement Sealing

5.4 Mountain Parkway

This section of the Mountain Parkway shows the use of centerline rumble strips and recessed markers as a centerline. The width of the centerline rumble strips is 16 inches and they are installed on 2-foot centers. Recessed markers were also installed on the two-lane road.

Figure 5.9 Mountain Parkway Centerline Rumble Strip and Recessed Markers

The following photos, also on the Mountain Parkway, show an example of a centerline rumble failure along the centerline pavement joint. The pavement age was over 10 years.

Figure 5.10 Mountain Parkway Centerline Rumble Strip Failure at Pavement Joint

5.5 KY-4 Shoulder to Edgeline Rumble

Recently the shoulder rumble strip on New Circle Road (KY 4) in Lexington was moved to edgeline to create an edgeline rumble stripe. The new rumble width is 8 inches on a 12-inch center with a 6-inch wide thermoplastic stripe.

Figure 5.11 New Circle Thermoplastic Edgeline Rumble Strip

Several months after the installation of the edgeline rumble with a thermoplastic stripe on New Circle Road, the thermoplastic stripe began to show signs of wear. The following photos show the durability issues. Contractors in the state who install rumble strips have stated they would prefer to have equipment that would cut with a higher RPM, resulting in a smoother cut. The ridges in a rough cut provide a durability issue.

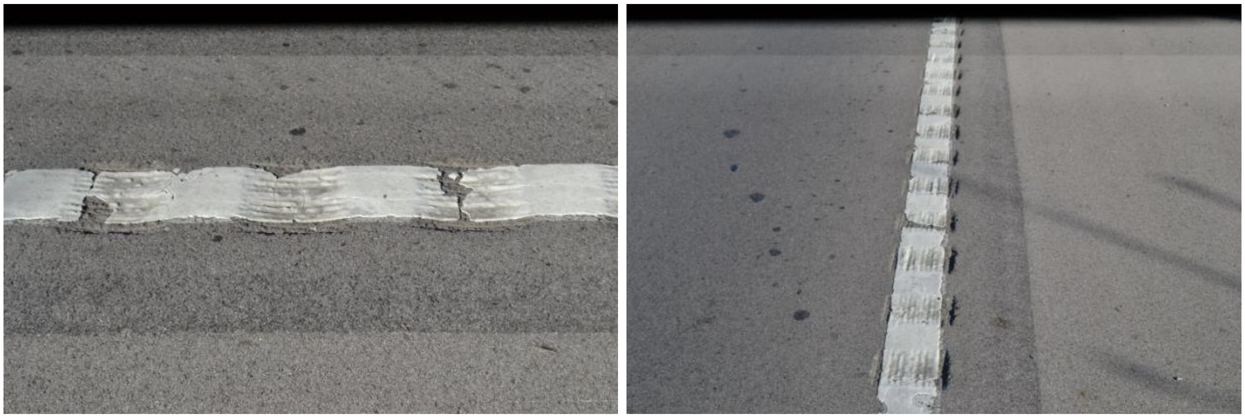


Figure 5.12 New Circle Thermoplastic Edgeline Rumble Strip Deterioration

5.6 US-60

US 60 in Fayette/Clark Counties have a section of pavement where the centerline and edgeline rumble strips were recently paved over and not remilled as part of a microsurfacing project. The new delineation is 6-inch spray thermoplastic markings. The width between the outside of the two centerline markings is 18 inches. The old rumble strips are still visible under the new pavement and drivers still feel and hear the rumble strips when a vehicle drifts onto either the centerline or edgeline. The depth of the old rumble strip varied but the remaining depth would still allow a driver to know they were out of their lane. So far, there have been no durability issues with the new pavement where it was placed over the rumble strips. This example provides evidence that remilling rumble strips on a microsurfacing project may not be necessary and that shallow rumble strips can still serve as an effective means to alert drivers of lane departures.

Figure 5.13 US-60 Thin Overlay on Existing Edgeline Rumble Strip

5.7 US-27

The following images of US 27 in Pendleton County show what can occur when pavement with rumble strips becomes very old.

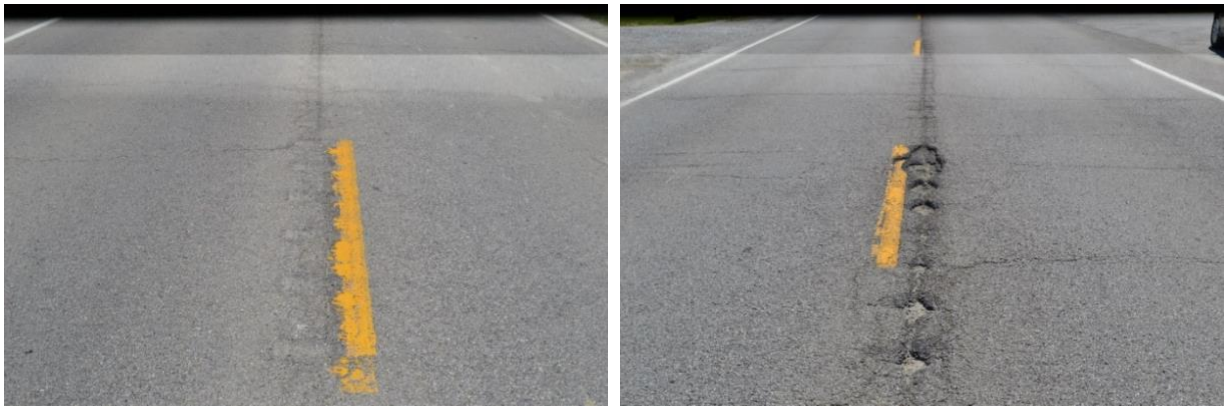


Figure 5.14 US-27 Centerline Rumble Strip Failure Due to Pavement Age

The following is a typical centerline on US 27 in Pendleton County with 12-inch rumble on 2-foot center. The issue of the rough cut from milling equipment is shown. The edgeline rumble is placed on the narrow shoulder (8 inches wide on 12-inch center) rather than at location where the edgeline could be placed over the rumble strip (with no raised pavement markers to provide wet, nighttime delineation).

Figure 5.15 US-27 Rough Cut Centerline and Shoulder Rumble Strips

The following photos show a separate location (on a thin overlay) on US-27 in Pendleton County where a 12-inch rumble was installed in the centerline where the width between the edges is 18 inches (six-inch stripes with 6 inches between the stripes). Note that the shoulder rumble strip (8 inch wide at 1 foot center) is placed on a relatively narrow shoulder rather than having the stripe placed over the rumble strip.

Figure 5.16 US-27 Centerline and Shoulder Rumble Strip of Different Widths

In this installation, the durability of the rumble strip on the thin overlay appeared good with only a few issues noted. Second, the width of the rumble strip did not have to match the width of the centerline to achieve an effective alert to motorists, which is inconsistent with the previous example on US-27. Third, the rumble strip was placed on the shoulder rather than at a location where the edgeline could be installed over the rumble strip, which would serve as an earlier warning to drivers of lane departure and as a means to protect portions of the striping.

5.8 US-62

This case study shows a thin overlay on US 62 in Hopkins County. At this location, the 8-inch wide rumble strip was installed so that the edgeline could be placed over the rumble strip, rather than on the narrow paved shoulder. This provides an example of how edgeline rumble strips should be installed on roadways with narrow shoulders. There is no centerline rumble strip and the width between the edgelines is 21 feet.

Figure 5.17 US-62 Edgeline Rumble Strip on a Narrow Shoulder

5.9 Bluegrass Parkway

The following photos show several rumble strip locations on the Bluegrass Parkway, illustrating the different ways rumble strips are installed by various districts. In Hardin County in District 4, the rumble was placed in the narrow repaved portion of the shoulder. This compares to I-75 in District 7 where the rumble was installed at a location where the edgeline was placed over the milled rumble strip. There is debate in the state concerning whether the shoulder rumble strip should be placed at about 1 foot off the edgeline or if the edgeline should be moved to where the rumble is normally placed.

Figure 5.18 Bluegrass Parkway Shoulder Rumble Strip

In the past on two lane roads, the milled rumble strip would be placed on a narrow shoulder (such as 30 inches) rather than at a location where the edgeline would be placed over the rumble strip. KTC researchers believe the rumble strip should be installed such that the edgeline is placed over the rumble strip, which is especially important on two lane roads where the Cabinet will no longer be placing raised pavement markers.

5.10 KY-80

These photos are from KY 80 in Laurel County where pavement grooves have been sealed. There has been debate concerning whether a sealer should be placed in the groove for recessed markers or for rumble strips and this serves as a positive example for the use of sealers.

Figure 5.19 KY-80 Sealed Recessed Marker Pavement Grooves

5.11 KY-245

The following photos show a comparison between new and old rumble strips where a section of the roadway was repaved in Nelson County.

Figure 5.20 KY-245 New vs. Old Shoulder Rumble Strips

5.1AA Highway

These photos are on the AA highway in Bracken County. The old rumble strip with durability issues is 24 inches wide on 2-foot centers. The new rumble strip is 16 inches wide on 2-foot centers.

The stripes are 6 inches with 4 inches between so the distance between the edges of the stripes is 16 inches (which match the width of the rumble).

Figure 5.21 AA Highway Centerline Rumble Strip Durability Issues

On many two-lane roads in Kentucky, the stripes have a width of 4 inches with 4 inches between, with a total width of 12 inches between the outside of the stripes. The question here is whether the centerline rumble strip should be 12 inches or 16 inches to match the width of the centerline (which depends on whether the width of the centerline strip is 4 inches or 6 inches). With a recent policy change, more and more roads be restriped with 6-inch lines. Many of the roads left with 4-inch lines will likely be too narrow for center rumbles. Another question that has come up with the recent policy change to 6-inch durable lines on wider roadways is whether the double yellow pattern gap should be changed to 4 inches so the entire line fits in rumble, and if the centerline rumble should be narrowed, allowing for better lane keeping.

5.13 RT-63 in Tennessee

This is a location on a two-lane road in Tennessee (RT 63) with a wide shoulder. The rumble strip was moved from the shoulder to the edgeline.

Figure 5.22 RT-63 Shoulder Rumble Strip Moved to Edgeline

5.14 SR-50 Indiana Sinusoidal Rumble

The following is an example of sinusoidal rumble strips on SR 50 at Lawrenceburg, Indiana. They were installed on the centerline of the four lane, undivided roadway. The width is 16 inches which consists of the two, 4-inch yellow lines with 8 inches between the stripes. The wavelength is 24 inches. The markings are thermoplastic. The centerlines are recessed into the sinusoidal rumble so they would not be damaged by snowplows. The lane lines and edgelines are also recessed into milled groves in the pavement (but there were no edgeline/shoulder rumbles). There were steel-casting snowplowable markers installed in the centerline and lane lines. Driving over the sinusoidal rumble strips resulted in a warning very similar to the centerline rumble strips currently used in Kentucky.

Figure 5.23 SR-50 Indiana Sinusoidal Centerline Rumble Strip

Chapter 6 Summary And Conclusions

A review of FHWA and NCHRP guidance and documentation relative to rumble strips shows that rumble strips are an effective countermeasure to reduce road departure crashes. Rumble strips work by interacting with a vehicle's tires when a vehicle begins to stray from its lane, causing vibration in the cab of the vehicle and a noise detectable by the driver, both of which serve as an alert that the driver is leaving their travel lane. NCHRP 641 and FHWA's Rumble Strip Implementation Guide both recommend that rumble strips should ideally provide 6 dBA of noise to alert drivers of lane departure, with 3 dBA being the minimum sound threshold for driver detection and 15 dBA being the maximum recommended noise level for rumble strips.

Although rumble strips are a proven safety countermeasure to reduce lane departure crashes, the public often complains about the noise pollution associated with these devices. To combat this, many states, including Minnesota, Indiana, Washington, California, Oregon, and Florida, have explored alternative rumble strip designs to find a rumble strips that can provide sufficient warning to drivers while limiting excess exterior noise pollution. The most widely tested and accepted alternative rumble strip design has been sinusoidal rumble strips. This rumble strip is a continuous wave pattern milled into the pavement, instead of the intermittent cylindrical milled rumbles found with a conventional design. The sinusoidal rumble strip provides sufficient interior noise and vibration for drivers, but limits exterior noise production because of the smoother wave pattern. Another benefit of the sinusoidal rumble strip is the added protection of pavement striping when placed in conjunction with the sinusoidal rumble. Sinusoidal rumbles are milled entirely below the pavement's surface, which provides protection to striping and wet-reflective media placed on the rumble. Sinusoidal rumble strips require specialized equipment which is not readily available in all parts of the country at this time. Therefore, the cost to install is higher than conventional rumble strips. A survey of states currently installing sinusoidal rumble strips shows an average installation cost of $0.43 per foot compared to an average cost of $0.27 per foot for conventional rumbles. Table 12 below summarizes accepted sinusoidal rumble strip designs by state.

Table 6.1 Summary of Sinusoidal Rumble Strip Designs by State

State	Wavelength (inches)	Maximum Depth (inches)	Minimum Depth (inches)	Width (inches)
Minnesota	14	1/2	1/16	8-12
Indiana	12	1/2	1/8	>=8
Washington	16	1/2	not specified	12
California	14	5/16	not specified	8
Oregon	16	3/8	1/16	14
Florida	14	5/16	0	8

Another alternative rumble strip design commonly used across the country that provides sufficient warning to drivers, but limits exterior noise is a conventional cylindrical rumble strip with a shallower milled depth. States including Washington, Pennsylvania, Maryland and Florida have successfully tested shallow, conventional rumble strips to confirm that they meet the NCHRP and FHWA guidelines for noise production while limiting exterior noise pollution.

FHWA guidance indicates that fog sealing is not effective at protecting rumble strips from deterioration and that fog sealing is incompatible with thermoplastic striping. However, FHWA does support the use of chip sealing over conventional rumble strips without remilling the rumble afterwards. Rumble strips will maintain enough volume after a chip seal to remain an effective safety countermeasure. According to FHWA, most states have varying surface preparation techniques to overlay pavement on roads with existing rumble strips, however most end up remilling rumble strips after the overlay is completed. Pennsylvania has developed a comprehensive guide for installing rumble strips on thin pavement overlays.

A series of site visits to rumble strip installations across the state revealed many findings about Kentucky's current rumble strip practices. Most notably, installation techniques vary widely across the different highway districts, particularly regarding edgeline and shoulder rumble strip installation. On roadways with similar widths and traffic characteristics, some districts will use a shoulder rumble while others use an edgeline rumble. The site visits also identified several areas with failing centerline rumble strips. The research team also noted deteriorating longitudinal striping on edgeline rumble stripes with rough milled rumbles. Micro-overlays have been placed over existing rumble strips with no durability problems. The old rumble strip still provides an audible rumble, but is not as effective. In several cases, rumble strips were moved from the shoulder to the edgeline to allow for earlier lane departure warning, a move that the research team believes to be beneficial to highway safety on all roadway types. A benefit of placing the pavement markings over the rumble strip is the creation of a "rumble stripe" that will provide more wet nighttime delineation. Water will drain down the slope of the rumble strip, exposing the reflective beads in the pavement marking on the slope, allowing retroreflectivity from those beads. According to a study by the FHWA, edgeline rumble strips on freeways and interstates show higher reductions in single vehicle run-off-road fatal and injury crashes than shoulder rumble strips. There was no statistical difference in crash totals between edgeline and shoulder rumble strips on two-lane roads. However, edgeline rumble strips will provide an earlier warning to drivers than a shoulder rumble strip.

Chapter 7 Recommendations

Conventional Rumble Strips

- KYTC should work with contractors to explore the possibility of requiring a higher RPM cutting device to provide a smoother cut for the rumble strip. This will improve durability of the rumble and the striping.
- When milling of rumble strips across a joint cannot be avoided, ensure pavement on each side of the joint is flush to avoid uneven rumble strips and future durability issues.

Sinusoidal Rumble Strips

- The literature review of states and inspection of an Indiana installation warrant the experimental use of sinusoidal rumble strips. Sinusoidal rumble strips would reduce exterior noise pollution, protect centerline and edgeline markings, and would allow the use of wet-reflective beads without damage from snowplows. This protection increases the lifecycle of roadway markings and reduces future costs.
- There are conflicting optimal sinusoidal rumble strip designs among the various states as far as maximum and minimum wave height and overall wavelength. However, most studies agree that optimal sinusoidal rumble strip designs should be a minimum of 8 inches in width to properly interact with a vehicle's tire. To start, the research team recommends testing a 14-inch wavelength sinusoidal rumble with a minimum depth of 1/8 inch and maximum depth of 7/16 inch as this is the most common wavelength from other states and the 1/8inch minimum depth provides enough protection for pavement striping. A 16-inch wavelength should be considered next if the 14-inch wavelength is not satisfactory.
- Based on information from local contractors, sinusoidal rumble strips should only be installed on wider/straighter roads (such as interstates) due to current equipment constraints. Current sinusoidal rumble strip equipment does not work well on curves or on narrow roadways. Sinusoidal rumble strip milling equipment also requires around 4 feet of shoulder if a sinusoidal rumble strip is to be milled on the edgeline or shoulder. Sinusoidal rumble strips would not be installed on narrower/curvier roads until equipment is commercially available that accommodates the installation of sinusoidal rumble strips on such routes.
- KYTC should consider selecting pilot projects with high cyclist traffic to evaluate the impacts of sinusoidal rumble strips on cyclists.

Shallow Rumble Strips

- Since there have been comments from the public that the depth of KYTC's standard rumble strip is too deep, the research team recommends a pilot study to examine the impact of a shallower rumble strips. If a shallower conventional rumble strip is found to be adequate to alert drivers, the shallower depth could replace KYTC's current rumble strip depth specification for all conventional rumble strips.
- Maryland, Washington, and Pennsylvania have found success with a 3/8 inch rumble strip depth and Florida has approved a 3/16 inch rumble strip depth. These depths should be considered for pilot testing in Kentucky.
- KYTC should consider selecting pilot projects with high cyclist traffic to evaluate the impacts of shallow rumble strips on cyclists.

Rumble Strip Maintenance

- Sealing the rumble strip may increase the lifespan of the pavement and rumble strip. District personnel have limited positive experience with using joint sealers to increase pavement longevity. This debate warrants an exploration of the use of joint adhesive to increase centerline rumble strip longevity. KYTC may also consider the use of the J-Band joint sealer as an innovative joint sealing product.
- Pavement longevity can be increased by milling smoother rumbles using higher RPMs. Sinusoidal rumble strips are installed with high RPM equipment, providing a smoother and longer-lasting rumble by default. Shallow rumble strips may also benefit from reduced wear upon impact and may experience longer lifespans.

Thin Overlays

- Chip sealing can be performed on conventional rumble strips without the need to remill rumble strips.
- Rumble strips can be installed on thin overlays with limited durability problems. KYTC can consider following the guidance from Pennsylvania regarding rumble strips on thin overlays.

Centerline, Edgeline, and Shoulder Rumble Strips

- On two lane roadways, a rumble strip (typically 8 inches wide) should be installed at a location where the edgeline stripe is placed over the center of the rumble strip. Edgeline rumble strips wider than 8 inches should have the edgeline stripe placed over the left portion of the rumble strip. This should be achieved by moving the rumble strip to be in line with the edgeline to avoid changing lane widths.
- On multi-lane roadways, rumble strips should be installed where the edgeline is placed over the rumble strip with the edgeline placed either in the center of an 8-inch wide rumble strip or the side nearest traffic when wider rumble strips (12-inch or 16-inch) are utilized. This should be achieved by moving the rumble strip to be in line with the edgeline to avoid changing lane widths.
- Transitioning from shoulder to edgeline rumble strips would require the edgeline rumble strip to be placed in line with current edgeline pavement joints. Shifting longitudinal pavement joints several inches (for both centerline and edgeline joints) would eliminate interaction between the centerline and edgeline rumble strips and increase pavement longevity. This shift would provide a lifecycle benefit for pavement markers as well. The research team recommends shifting longitudinal pavement joints for 8-inch wide centerline and edgeline rumble strips only. Shifting pavement joints to accommodate wider rumble strips could cause a severe shift in roadway crown.
- On two-lane roadways with adequate width and undivided multi-lane roads, a centerline rumble strip width of 16 inches will allow 6-inch wide pavement markings with a 4-inch gap when there is a double centerline. For single line centerline markings, the 6 inch stripe can be placed in the middle of the rumble strip. For roadways with 4-inch markings, the rumble strip, if used, should be 12 inches wide.
- 16-inch wide rumble strips should not be installed anywhere other than the centerline on two-lane roads. A 16-inch rumble strip is wider than necessary in all other applications and

does not provide significantly greater lane departure warning than 8-inch or 12-inch wide rumble strips.

References

[1] NCHRP, "NCHRP Synthesis 490: Practice of Rumble Strips and Rumble Stripes." National Cooperative Highway Research Program, Project 20-05, Topic 46-13, 2016, p. 19.
[2] NCHRP, "NCHRP Synthesis 490: Practice of Rumble Strips and Rumble Stripes." *National Cooperative Highway Research Program*, Project 20-05, Topic 46-13, 2016.
[3] NCHRP, "NCHRP Report 641: Guidance for the Design and Application of Shoulder and Centerline Rumble Strips." National Cooperative Highway Research Program, MTU TTAP ID#2233, 2009, p. 91.
[4] NCHRP, "NCHRP Report 641: Guidance for the Design and Application of Shoulder and Centerline Rumble Strips." National Cooperative Highway Research Program, MTU TTAP ID#2233, 2009, p. 14.
[5] NCHRP, "NCHRP Report 641: Guidance for the Design and Application of Shoulder and Centerline Rumble Strips." *National Cooperative Highway Research Program*, MTU TTAP ID#2233, 2009.
[6] FHWA, "Rumble Strip Implementation Guide: Addressing Noise Issues on Two-Lane Roads." FHWA-SA-15-033, April 2015.
[7] FHWA, "Rumble Strip Implementation Guide: Addressing Pavement Issues on Two-Lane Roads." FHWA-SA-15-034, April 2015.
[8] Terhaar, E.; Braslau, D.; and Fleming, K., "Sinusoidal Rumble Strip Design Optimization Study." *Minnesota Department of Transportation*, MN/RC 2016-23, June 2016.
[9] Daubenberger, Nancy, "Rumble Strips and Stripes on Rural Trunk Highways." *Minnesota Department of Transportation*, Technical Memorandum No. 17-08-T-02, August 2017.
[10] Mathew, J.K.; Balmos, A.D.; Plattner, D.; Wells, T.; Krogmeier, J.K.; and Bullok, D.M., "Assessment of Alternative Sinusoidal Rumble Strip Construction." *Indiana Department of Transportation and Purdue University*, FHWA/IN/JTRP-2018/05, March 2018.
[11] Boruff, David, "Design Memorandum No. 9-01." *Indiana Department of Transportation*, February 2019.
[12] Laughlin, J. and Donahue, J., "Evaluation of New Rumble Strip Designs to Reduce Roadside Noise and Promote Safety." *Washington State Department of Transportation*, WA-RD 881.1, May, 2018.
[13] Donavan, Paul, "Design and Acoustic Evaluation of Optimal Sinusoidal Mumble Strips vs. Conventional Ground-In rumble Strips." *California Department of Transportation*, CTHWANP-RT-18-365.01.2, April 2018.
[14] Donnell, E.T.; Solaimanian, M.; Stoffels, S.M.; and Kulis, P.N., "Rumble Strips Installation on Tin Pavement Overlays." *Pennsylvania Transportation Institute*, LTI-2015-04, September 2014.
[15] Hurwitz, D.S.; Ross, D.; Jashami, H.; Monsere, C.M.; and Kothuri, S., "Quantifying the Performance of Low-Noise Rumble Strips." *Oregon State University and Portland State University*, FHWA-OR-RD-19-07, January 2019.
[16] Santos, Joseph, "Florida Department of Transportation: Audible and Vibratory Treatments on Arterials and Collectors." *Florida Department of Transportation*, Getting to Zero Together: A National Safety Engineer Peer Exchange, July 2019.
[17] FDOT, "Ground-In Rumble Strips." *Florida Department of Transportation*, Standard Plans 546-10, April 2018.
[18] Shepard, Mark, "Audible and Vibratory Treatments (AVTs)." *Florida Department of Transportation*, Roadway Design Bulletin 18-03, March 2018.

19 MDOT, “Shoulder Rumble Strip and Rumble Stripe Details.” *Maryland Department of Transportation State Highway Administration*, Standards for Highways and Incidental Structures MD 670.05, May 2017.
20 MDOT, “Guidelines for Application of Rumble Strips and Rumble Stripes.” *Maryland Department of Transportation State Highway Administration*, August 2014.
21 KYTC, “Standard Specifications for Road and Bridge Construction.” *Kentucky Transportation Cabinet*, June 2019.
22 KYTC, “Traffic Operations Guidance Manual.” *Kentucky Transportation Cabinet*, June 2005.
23 KYTC, “Standard Drawings.” *Kentucky Transportation Cabinet*, Sepias 002-008, February 2020.
24 KYTC, “Active Design Sepias.” *Kentucky Transportation Cabinet*, Sepias 002-008, November 2016.
25 Asphalt Materials, Inc. “J-Band” *Asphalt Materials, Inc.*, 2019. https://thejointsolution.com/product/
26 KYTC, “Special Note for Longitudinal Pavement Joint Adhesive.” *Kentucky Transportation Cabinet*, June 2019.