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16. Abstract

This report documents the first year activities of a 30-month project in which the evaluation of various rumble strip applications will be tested. The focus has been on in-lane and centerline rumble strips. The pertinent literature was reviewed. State agencies with significant experience with centerline and in-lane rumble strips were contacted, and their policies were reviewed. The researchers then developed initial application guidelines for these types of rumble strips. The application guidelines were then modified based on the project advisory committee comments.

The in-lane rumble strips are currently being evaluated at stop-controlled intersections and horizontal curve locations throughout the state. The researchers plan to be completed with this part of the research by the end of 2003. There are currently no centerline rumble strips installed on TxDOT highways. However, there are currently two districts planning to install centerline rumble strips as part of this research project. Two highway sections in the Brownwood District should have centerline rumble strips by the end of 2003. There has also been promising discussion to identify sites and have centerline rumble strips installed in various locations in the Austin District.

The second year activities of this project will focus on the completion of the in-lane rumble strip analysis. Guidelines for application of in-lane rumble strips will be developed based on the results. Also to be emphasized in the second year will be the installation and study of centerline rumble strips. It is expected that several sites will be installed within the second year, and surrogate safety measures will be studied in order to develop guidelines for the application of centerline rumble strips. Another focus of the second year of this project will be an ad-hoc safety study of profiled pavement markings.

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EFFECTIVENESS OF RUMBLE STRIPS ON TEXAS HIGHWAYS: FIRST YEAR REPORT

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DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Federal Highway Administration (FHWA) or the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation. The engineer in charge was Paul J. Carlson, P.E., (TX # 85402).

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CHAPTER 1
INTRODUCTION

Research findings have clearly shown that continuous rumble strips along the shoulder of highways have significant benefits in terms of reducing run-off-the-road crashes. More recently, studies are beginning to show that continuous rumble strips installed along the centerline of highways have the potential to impact safety in a positive manner. Less understood, but potentially just as beneficial, are in-lane or transverse rumble strips, which are normally installed on approaches to rural, high-speed intersections, unexpected horizontal curves, or other locations where crashes occur more frequently than expected.

This project includes an investigation of these three different types of rumble strips on Texas highways. The primary focus of the project is on transverse rumble strips and centerline rumble strips. Also included in the research scope but with less emphasis is the evaluation of edgeline rumble strips on two-lane highways and edgeline and centerline rumble strips that may potentially increase the wet-nighttime retroreflectivity performance.

This report documents the first-year activities related to in-lane or transverse rumble strips and centerline rumble strips. Researchers conducted a literature review to determine the state-of-the-art with respect to these rumble strips. States identified as having experience with these rumble strips were contacted and surveyed. A database of specifications, applications, and usage was developed to aid in the development of draft guidelines for edgeline, centerline, and in-lane rumble strips for testing. A theoretical safety analysis was also conducted to determine the relative impacts of edgeline and centerline rumble strips. Testing of in-lane rumble strips has started but is only just beginning, and the results are not yet available. A statewide search is currently underway to determine study sites for centerline rumble strips. Tentative sites have been selected in the Brownwood, Austin, and Bryan Districts.

CHAPTER 2
STATE-OF-THE-ART RUMBLE STRIPS

TYPES OF RUMBLE STRIPS

There are four common types of rumble strips: milled, rolled, formed, and raised. The four types of rumble strips differ in the manner in which they are installed, shape and size, and the amount of noise and vibration provided. Milled rumble strips are prevalent because of the ease of implementation on new or existing asphalt or Portland cement concrete pavements and shoulders. Milled rumble strips are generally installed with a longitudinal width of 7 inches (180 mm) and a transverse width of 16 inches (400 mm). Tires that pass over milled rumble strips drop roughly 0.5 inch (13 mm) (*1*, *2*). Rolled rumble strips are generally rounded or V-shaped grooves that have been pressed into hot asphalt pavements when a newly constructed or reconstructed surface coarse is compacted. The grooves are generally 1.3 inches (32 mm) deep and 1.6 inches (40 mm) wide. The rolled rumble strips are generally constructed using a roller with steel pipes welded to drums (*1*, *2*). Formed rumble strips resemble the rolled rumble strips. The dimensions are the same, 1.3 inches (32 mm) deep and 1.6 (40 mm) wide. Formed rumble strips are either rounded or V-shaped grooves that are pressed into hot asphalt pavements and shoulders during compaction of the constructed or reconstructed surface coarse. The strips are formed by a roller with steel pipes welded to drums, which leave depressions in the hot pavement as they pass over (*1*, *2*). Raised rumble strips are 2 to 12 inches (50 to 305 mm) wide rounded or rectangular markers that adhere to new or existing pavements. These types of rumble strips are restricted to use in warmer climates where snow removal is of minimal concern (*1*).

Shoulder Rumble Strips

The first shoulder rumble strips (SRS) appeared on New Jersey's Garden State Parkway in 1955 when 25 miles (40 km) of singing shoulders were installed in Middlesex and Monmouth Counties (*3*). The singing shoulder was a strip of corrugated concrete that produced a sound when driven upon. From the 1960s on, various states have utilized SRS in a variety of forms. Due to the growing record of documented studies on safety effectiveness of SRS, an increase in installation on many high-volume roads has occurred in the past 10 years. The popularity of SRS has recently led to their installation on many two-lane rural roadways.

Continuous shoulder rumble strips (CSRS) operate as a countermeasure to a class of crashes related to driver inattention. Driver inattention comes in many forms, including distraction, daydreaming/competing thoughts, fatigue/drowsiness, and alcohol/drug impairment. CSRS are continuous bands of raised material or indentations formed or grooved in the shoulders to alert drivers starting to drift off the road. They alert drivers by transmitting sound and vibration through a vehicle. The warnings provided by CSRS give notice to drivers to take corrective action before they run off the roadway.

The concept of CSRS has been studied and is well documented. An FHWA report took investigated crash rates from different states before and after the installation of CSRS (*3*). The findings show a reduction in single-vehicle run-off-the-road crashes ranging, on average, from 7 to 18 percent.

The FHWA web site on rumble strip effectiveness reports experiences from several states (*4*). For instance, a 1985 before-and-after study from California indicated a 49 percent reduction in run-off-the-road crashes after shoulder rumble strips were installed along sections of Interstates 15 and 40 in San Bernardino County. Recent follow-up evaluation for freeway segments where shoulder rumble strips have been in-place for 3 or more years indicated an average reduction of 33 percent statewide.

Another example, this time from Pennsylvania, reports on the installation of CSRS to help decrease the number of accidents caused by drowsy drivers on the Pennsylvania Turnpike. Various lengths and depths of grooves were tested to select a design with enough sound and vibration to be perceptible in a truck cab and yet not too severe for cars or motorcycles. After installation of CSRS, drift-off-the-road accidents per month decreased by 70 percent.

Rolled versus Milled Rumble Strips versus Raised Rumble Strips

FHWA has a comprehensive summary of roadway shoulder rumble strips in its Technical Advisory T 5040.35 (*5*). The advisory contains a description of each basic type of rumble strip, which is detailed below.

There are four basic rumble strip designs or types: milled-in, rolled-in, formed, and raised:

- Milled-in: This design is made by cutting (or grinding) the pavement surface with carbide teeth affixed to a 24 inches (600 mm) diameter rotating drum. The indentations formed are approximately 0.5 inches (13 mm) deep, 7 inches (180 mm) wide parallel to the travel lane, and 16 inches (400 mm) long perpendicular to the travel lane. The indentations are approximately 12 inches (300 mm) on center and offset from the edge of the travel lane a distance of 4 inches (100 mm) to 12 inches (300 mm). Some research has been completed recently on the effectiveness of narrower and shallower cuts. Such variations from the original dimensions are discussed in detail a bit later.

- Rolled-in: The rolled-in design is generally installed by using a steel wheel roller to which half sections of metal pipe or solid steel bars are welded. The compaction operation presses the shape of the pipe or bar into the hot asphalt shoulder surface. The resultant shape is generally 1 inch (25 mm) deep, 2 inches (50 mm) to 2.5 inches (64 mm) wide parallel to the travel lane, and 18 inches (450 mm) to 35 inches (900 mm) long perpendicular to the travel lane. The indentations are usually set 8 inches (200 mm) on center and offset from the travel lane edge from 6 inches (150 mm) to 12 inches (300 mm).

- Formed: The formed rumble strip is added to a fresh concrete shoulder with a corrugated form, which is pressed onto the surface just after the concrete placement and finishing operations. The resultant indentations are approximately 1 inch (25 mm) deep, 2 inches (50 mm) to 2.5 inches (64 mm) wide parallel to the travel lane, and 16 inches (400 mm) to 35 inches (900 mm) long perpendicular to the travel lane. The indentations may be in continuous pattern, but are generally in groups of five to seven depressions spaced approximately 50 feet (15 m) apart and offset from the travel lane at about 12 inches (300 mm).

- Raised: Raised rumble strip designs can be made from a wide variety of products and installed using several methods. The elements may consist of raised pavement markers, a marking tape affixed to the pavement surface, an extruded pavement marking material with raised portions throughout its length, or an asphalt material placed as raised bars on the shoulder surface. The height of the raised element may vary from 0.25 inches (6 mm) to 0.5 inches (13 mm). Spacing and width across the shoulder vary widely.

Field tests conducted by Virginia Department of Transportation for pavement roughness and sound levels on various typical rumble strips found that the milled type was 12.6 times and 3.35 times greater in the pavement roughness index and sound levels, respectively, than the rolled type (*6*).

Other types of rumble strips that can be used are raised rumble strips, especially in areas with little concern about snowfall and the subsequent snow plows. In such states, profiled pavement markings can be used instead of rumble strips. In fact, Texas already includes profiled or inverted markings as an option. A picture of a profile marking with ceramic buttons installed in Texas is shown in Figure 1.

Figure 1. Profiled Marking on State Highway 6.

Other raised rumble strip materials that the researchers currently are aware of include Swarco's rumbler and seal-coat treatments. Other potential materials will be identified in the work plan.

State of the Practice from State DOTs

A total of eight states were found to have material on rumble strip design available online, either in design or traffic manuals or typical plan sheets. Those states have a variety of dimensions, spacings, and offsets for shoulder rumble strip design, but the general consensus is that strips should be between 6 and 12 inches (150 and 300 mm) wide and offset from the edgeline by 4 to 12 inches (100 to 300 mm). Following are excerpts from two states' online manuals.

The California Traffic Manual (*7*) has the following guidance for the design of shoulder rumble strips:

> "Shoulder rumble strips are 0.75 inches (19 mm) or less in height if raised, 1 inch (25 mm) in depth for rolled-in indentations and 0.333 ± 0.0625 inches (8.5 ± 1.5 mm) for ground-in indentations that extend along the highway shoulder. The maximum width of shoulder rumble strips is 12 inches (300 mm) for both rolled-in and ground-in indentations.
>
> Where bicycles are permitted, shoulder rumble strips should not be used unless approximately 5 feet (1.5 m) of clear shoulder width for bicycle use is available between the rumble strips and the outer edge of the shoulder. If shoulder width is less than 5 feet (1.5 m) and rumble strips are required, then only raised and inverted profile thermoplastic strip shall be used. Ground-in rumble strip treatments that are greater than 0.333 ± 0.0625 inches (8.5 ± 1.5 mm) in depth shall not be installed on shoulders where bicyclists are allowed."

Table 1 is used by California district traffic engineers to determine the appropriate rumble strip treatment for various shoulder types.

Table 1. California Rumble Strip Installation Guide.

Rumble Strip Treatment	Rumble Strip Depth (in/mm)	Shoulder Type[1]	Bicycles Permitted	Min. Shoulder Width (ft/m)
Rolled-In Rumble Strip Treatment Standard Plan A40	1 (25)	ACC Only	Yes	5 (1.5)
			No	4 (1.2)
Ground-In Rumble Strip Treatment Standard Plan A40	0.3125 (8)	ACC and PCC	Yes	5 (1.5)
			No	4 (1.2)
Raised and Inverted Profile Thermoplastic	N/A	ACC and PCC	Yes	No minimum
			No	No minimum
NOTE: Adapted from Table 6-1, California Traffic Manual, and values in parenthesis are in metric units.				

1 Asphalt Cement Concrete (ACC), and Portland Cement Concrete (PCC)

Arizona's Traffic Engineering Manual (*8*) contains the following instructions for designers:

> "Continuous longitudinal ground-in rumble strips may be applied to the mainline roadway on projects per the recommendations and requirements of this document." Table 2 should be used as a guideline in determining the groove width of the rumble strips to be installed.

Table 2. Arizona Guidelines for Determining Groove Width of Installed Rumble Strips.

Type of Roadway	Right Shoulder Width	Groove Width (both shoulders)
Undivided	less than 4 ft (1.2 m)	6 in (152 mm)
Undivided	greater than or equal to 4 ft (1.2 m)	8 in (203 mm)
Divided	less than 6 ft (1.8 m)	8 in (203 mm)
Divided	greater than or equal to 6 ft (1.8 m)	12 in (305 mm)

"For divided roadways, the groove width for the left shoulder of the roadway should be the same as the width applied to the right shoulder, where possible. On undivided two lane highways with shoulders four feet and greater in width, longitudinal rumble strips should be applied. The use of longitudinal rumble strips on shoulders less than four feet may be considered on a case by case basis when supported by a written traffic evaluation. On divided highways, longitudinal rumble strips should be applied on the right (outside) shoulders with a width of four feet or more and on left (median) shoulders which have a width of two feet or more. The use of longitudinal rumble strips on divided highways with narrower shoulders than those noted may be considered on a case by case basis when supported by a written traffic evaluation.

The use of longitudinal rumble strips on all roadway shoulders less than six feet wide with sections of guardrail and/or barrier shall be evaluated. The effective clear width of the shoulder in these areas if a continuous longitudinal rumble strip is installed shall be determined. The effective clear shoulder width is defined as the distance between the outside edge of the proposed rumble strip and the front face of the guardrail or barrier.

The effective clear shoulder width is important for the following reasons:

(a) Constructability - To allow for installation equipment, i.e. grinding, a minimum effective clear shoulder width of two feet is needed from the outside edge of the rumble strip groove to the front face of the barrier or guardrail. If the barrier is on a sharp curve, additional width may be needed. This constructability issue applies to all shoulders and all types of highways.

(b) Bicycle Traffic - If appreciable bicycle traffic exists or is anticipated, then a minimum effective clear shoulder width of 3 feet 5 inches (1 m) should be provided from the outside edge of the rumble strip groove to the front face of the barrier or guardrail. If this clear area can not be maintained, then a change of configuration and/or deletion of the rumble strip should be considered."

RUMBLE STRIP DESIGNS

On an abandoned stretch of turnpike, Pennsylvania Turnpike engineers tested only narrow and recessed rumble strip patterns with varying lengths and depths and selected an effective design with enough sound and vibration to be perceptible in a truck cab and yet not too severe for cars or motorcycles (*9*).

All tested patterns used an indentation spacing of 1-foot (0.3-m) along the direction of travel so vehicle tires could not miss them at typical departure paths. This length between grooves was selected based on vehicles drifting off at a shallow 3-degree departure angle, striking a succession of indentations to produce a tone with enough duration to awaken a drowsy driver. All test patterns were 16 inches (406 mm) wide, (transverse to the direction of travel) so that wide truck tires would drop in enough indentations along any likely departure path. By trying several depths, researchers found that 0.50 inches (13 mm) was deep enough for tire drop to produce an alerting sound, provided that the opening (length in the direction of travel) was large enough for various sized tires. Two-inch (51-mm) grooves were not heard over a 79 decibel noise level in truck cabs. Openings 4 inches (102 mm) long with 8 inches (203 mm) between produced sound audible in both cars and trucks with 86 decibels in a truck cab at 65 mph (105 km/hour).

Almost all 350 miles (563 km) of CSRS on the Pennsylvania Turnpike now have 7 x 16 inches (178 x 406 mm) indentations, one groove per foot (0.3-meter), and milled 0.50 inches (13 mm) deep starting 4 inches (102 mm) outside the roadway edgeline along the shoulder. At highway speeds, a high enough acoustic pitch of 95 cycles per second at 65 mph (105 km/hour) and tactile vibration is produced by vehicle tire drop to alert even truck drivers quite effectively. Turnpike maintenance vehicles can use the rest of the shoulder for routine work and can plow down to bare pavement without "shoes" on the snowplows. CSRS's shallow shape and proximity to passing traffic keeps them cleaned out. When milled-in, they have not been wearing or smoothing out after use because material was physically removed in the milling process. Rolled-in or impressed patterns show some smoothing out since material was pushed out of shape for installation, and flexible asphalt pavement can recover shape under traffic (*10*).

Lateral Placement

Recent surveys have shown that an inconsistency exists in determining a standard offset for CSRS placement. The two main theories are to place the CSRS close to the edgeline or close to the edge of the shoulder. Most states are following the practice of installing the CSRS near the edgeline, but some states place CSRS near the edge of the shoulder.

CSRS placed near the edgeline allow the remainder of the shoulder to be utilized by other users, such as bicyclists or pedestrians. This small offset provides a warning to errant drivers as soon as they leave the travel lane and generates the largest amount of recovery area for the errant driver. Furthermore, it also places a warning device between errant motor vehicles and bicyclists. However, this offset forces the bicyclist to decide whether to travel in the travel lane (if legal) or on the right side of the shoulder, which may contain debris.

CSRS placed close to the edge of the shoulder allow bicyclists to travel freely between the travel lane and the shoulder. Additionally, it also allows for the sweeping action of the motor vehicles to clear a larger section of the bikeable shoulder. The drawback of this large offset is that it reduces the amount of recovery area available for an errant vehicle and lessens the CSRS's potential safety benefit.

Pennsylvania has a variable offset for CSRS placement, even though it does not modify the traverse width of their CSRS from 16 to 17 inches (406 to 432 mm). While their recommended offset is 18 ± 0.5 inches (457 ± 13 mm) from the pavement/shoulder joint, for free (non-limited) access highways the designer has the flexibility to adjust the offset from 4 to 18 ± 0.5 inches (102 to 457 ± 13 mm). When the offset is designed to be more than 18.5 inches (470 mm), the designer is directed to attach revised details to show selected offset dimensions accordingly.

Maintenance

One of the concerns related to CSRS is the impact on pavement durability. However, according to FHWA**,** there appears to be little early deterioration of milled shoulder rumble strips on either cement concrete or asphalt pavements from either source. Rumble strips have little effect on the rate of deterioration of new pavements. Older pavement shoulders tend to degrade more quickly, but tests in several states show that these rumble strips continue to perform their original function—making noise and creating vehicle vibration. There are also no apparent problems with installation or faster deterioration of rumble strips on open-graded pavements.

Figure 2 shows recent pictures of CSRS with rather severe pavement degradation. The researchers hypothesize that the pavement would have failed regardless of the installation of the CSRS.

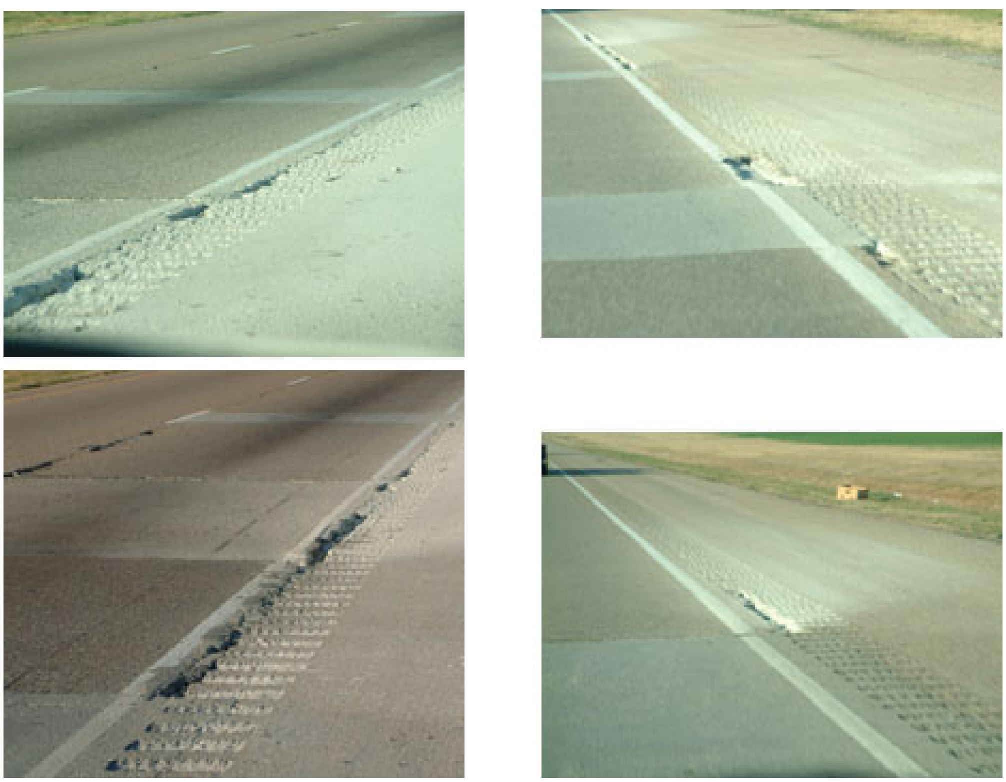

Figure 2. CSRS on NB I-35.

Weather also appears to play no significant role in the durability of shoulder rumble strips. Field tests refute concerns about the effects of the freeze-thaw cycle as water collects in the grooves. These tests show that vibration and the action of wheels passing over the rumble strips in fact knock debris, ice, and water out of the grooves. Ironically, snowplow drivers have come to depend on shoulder rumble strips to help them find the edge of the travel lane during heavy snow and other low visibility situations. In mountainous areas, shoulder rumble strips are handy because they provide tread for vehicles traveling up long slopes.

Of course, weather does play havoc with raised rumble strips. Snowplow blades passing over the rumble strips tend to scrape them off the road surface, which is why this type of rumble strip is usually restricted to use in areas that do not contend with snow removal (like most of Texas).

Bicycle Concerns

One of the biggest concerns regarding shoulder rumble strips has been bicyclists. In 2000, 28 bicyclists (5 basic, 17 skilled, and 6 experienced) evaluated CSRS by riding over various skipped CSRS sections to determine acceptable skip patterns. Researchers determined that 12-feet (3.7-meter) skips in ground-in CSRS pattern would acceptably permit bicyclists to cross at high speeds (speeds were assumed to be between 23 to 28 mph (37 to 45 km/hour)). Either 40- or 60-foot (12.2- or 18.3-meter) cycles for the skip pattern were determined acceptable.

The objective of a similar study by Elefteriadou et al. was to develop new CSRS configurations that decrease the level of vibration experienced by bicyclists while providing an adequate amount of stimulus to alert inattentive or drowsy drivers. Six configurations were tested by 25 intermediate and advanced bicyclists. The researchers recommended the adoption of two new "bicycle-tolerable" rumble patterns, one for non-freeway facilities operating near 55 mph (89 km/hour) and the other for those operating at 45 mph (72 km/hour).

The work performed by Elefteriadou et al. has highlighted the possibility of using multiple CSRS designs in one state. The possibility exists to examine vehicular traffic to determine if a deeper CSRS, which has been shown to be effective with large vehicles, is required on a road that does not carry many large vehicles. A shallower rumble strip may provide adequate stimulus to the inattentive driver of a pickup truck and be gentler to bicyclists.

In 2001, the California Department of Transportation (Caltrans) performed a study of various CSRS designs, as well as five prototypes of incised or pressed rumble strip configurations. This study was based on the work done by Elefteriadou et al. Six test vehicles, ranging from a compact automobile to large commercial vehicles, were used to collect auditory and vibration data while traversing the CSRS. Two test drivers were asked to subjectively rate characteristics of the various test patterns, based on the driver's perspective. Finally, 55 bicyclists of various skill levels and ages volunteered to evaluate the CSRS designs. The recommendation of the study was to replace the existing rolled CSRS design with a milled CSRS design that is 1-foot (0.3-meter) in transverse width and 0.3125 ± 0.0625 inch (8 mm ± 2 mm) in depth on shoulders that are at least 5-foot (1.5-meter) wide. For shoulders less than this width, the installation of raised/inverted profile thermoplastic was recommended.

Another study in 2001 compared various styles of CSRS in Colorado. The study's recommendations were based upon the input of 29 bicyclists as well as vibration and auditory data collected in four different types of vehicles. While data were collected on milled and rolled asphalt CSRS and milled concrete CSRS, no recommendations were made concerning concrete CSRS. Of the 10 styles tested, those that provided the most noticeable vibration and auditory stimuli to the vehicle were rated worst by bicyclists. The milled CSRS with a depth of 0.375 ±

0.125 inches (10 mm ± 3 mm) on 12 inches (305 mm) centers in a skip pattern of 48 feet (14.6 m) of CSRS followed by a 12-foot (3.7-meter) of gap was recommended.

Motorcycles

Caltrans has performed a motorcycle CSRS evaluation of various CSRS designs. In its study, participants rode over a series of various CSRS at either 55 or 65 mph (89 or 105 km/hour) or another speed they were comfortable with and then asked to rate their comfort and control for each of the CSRS traversed. It has also been reported that Kansas and Massachusetts have tested motorcycles traversing rumble strips. While the composition of the Kansas test group was unknown, the Massachusetts test group was comprised of the police motorcycle squad. Both test groups reported noticing the rumble strips; however, they did not feel out of control.

Centerline Rumble Strips

Centerline rumble strips (CRSs) have not been as comprehensively tested as shoulder rumble strips. In fact, there are only a few documented reports concerning the effectiveness of centerline rumble strips, although it should be noted that many states have indicated that they are experimenting with them or are about to start. In September 2002, the University of Massachusetts, in Amherst completed the final report of a survey of current state practices with regard to CRSs. This report further supports that most states are using similar dimensions in their CRS design and that the primary reason for installation is to reduce crash frequency and, thereby improve safety.
Table 3 contains the general findings with regard to use of CRSs in the United States (*11*).

Table 3. Current State Practices with Regard to CRSs.

Likelihood of CRS Installation (2002 Survey Responses)	Number of States
Already installed[1]	20
Definitely will install	1
Considering installing	15
Probably will install	4
May test	1
Will not install	7
Have not considered	2

1 Sine the completion of the survey in 2002, Idaho, Nebraska, and Texas have installed CRSs. Now there are at least 23 states with CRSs installed.

CRS are a countermeasure for cross-over crashes. Before a countermeasure is ever installed in a location, an assessment of how cost-effective the countermeasure will be is conducted. Recently, the National Cooperative Highway Research Program (NCHRP) published a final draft guide, *Guidance for Implementation of the AASHTO Strategic Highway Safety Plan: A Guide for Addressing Head-On Collisions*, that summarized CRS versus other countermeasures for opposite direction crashes (*12*). Table 4 summarizes these countermeasures.

Table 4. Countermeasure Relative Cost Comparison.

Implementation Timeframe	Strategy	Relative Cost to Implement and Operate			
		Low	Moderate	Moderate to High	High
Short (<1 year)	CRS for two-lane roads	☑			
	PTS[1] for centerlines	☑			
	TWLTL[1] for two and four-lane roads		☑		
Medium (1-2 years)	Adjust lane and shoulder widths on two-lane roads to allow narrow "buffer median"	☑			
	Median barriers for narrow-width medians on multi-lane roads		☑		
	Alternating passing lanes or four-lane roadway sections at key locations [2]			☑	
Long (>2 years)	Redesign with wider cross-sections on two-lane roads[2]			☑	

1 Profiled thermoplastic strips (PTS), and Two-way, left-turn lane
2 This strategy will become high cost if additional right-of-way is required.

One of the first installations of centerline rumble strips that was systematically evaluated was installed in Delaware in 1994 (*13*). The main reason for installation was head-on crashes along a rural section of two-lane, undivided roadway. A video of the installation along a permitted passing zone can be downloaded at http://www.deldot.net/static/projects/rumblestrip/index.html. In summary, a 3-year before-and-after study showed a decrease in head-on crashes by 95 percent and a complete reduction in fatalities. The Federal Highway Administration awarded Delaware with a 2001 National Highway Safety Award for the centerline rumble strip project. A picture of their centerline rumble strips is shown in Figure 3.

Figure 3. Delaware Centerline Rumble Strips.

It should be noted that Delaware installed rumble strips in passing zones. This practice is not uniform throughout the other states in the U.S., and in particular, the states that do not install them in passing zones are concerned that motorists will think passing is prohibited. Delaware has not recorded any problems with regard to this concern.

The State of Colorado has also conducted an evaluation of centerline rumble strips (*14*). They installed their centerline rumble strips in 1996 along a 17-mile (27-kilometer) section of winding two-lane, undivided mountain highway. The CRSs were only installed in no-passing zones. Traffic records from similar 44-month periods before and after the installation of the rumble strips showed the following: Head-on crashes decreased from 18 to 14 (22 percent reduction), and sideswipe from the opposite direction decreased from 24 to 18 (25 percent reduction).

Colorado also received several positive comments from the public. Also reported was that there was no noticeable effect on the pavement due to moisture and only a slight decrease in the apparent wear on the paint stripe. Figure 4 shows a picture of their application.

Figure 4. Colorado Centerline Rumble Strips.

In the fall of 1999, researchers at Kansas conducted a national survey concerning the use of centerline rumble strips (*15*). At that time only eight states replied using centerline rumble strips, although it is noteworthy that many others were considering their use. The researchers then installed 12 varieties of centerline rumble strips and measured the vehicle interior noise and steering wheel vibrations. They concluded that two patterns provided the best results. One pattern was a continuous pattern 12 inches (305 mm) on-center and 12 inches (305 mm) long, and the other was an alternating pattern 12 and 24 inches (305 and 610 mm) on-center and 12 inches (305 mm) long. Kansas is reportedly conducting additional centerline rumble strip evaluations in the summer of 2003. These evaluations include stopping motorists and asking them questions concerning their opinions and perceptions about the centerline rumble strips.

Kentucky is also recording their experiences with an experimental stretch of centerline rumble strips. So far, only seven months of after-crash data are available for comparisons, and the results are disappointing. During an equivalent seven-month before period, the same stretch of the Daniel Boone Parkway experienced four crashes caused by crossing the centerline (note: those crashes caused by snow or ice were not included). During an equivalent seven-month after period, there were also four crashes related to crossing the centerline. Figure 5 shows pictures of their application. Public comments so far have been less than expected but mostly positive.

Figure 5. Kentucky's Centerline Rumble Strips.

A more recently completed national survey concerning the use of the centerline rumble strips was just completed by the University of Massachusetts (UMass). The responses are currently being tabulated and will be provided to the research team once completed. Additional information describing the UMass effort will be described in the work plan.

Pennsylvania has been a leader among the states to study rumble strips as cost-effective countermeasures. The Pennsylvania Department of Transportation's (PennDOT) more recent studies focus on lateral vehicle placement with respect to CRS on two-lane, undivided highways (*16*). The research revealed that motorists offset themselves further laterally from the centerline after the installation of CRS. Another study, "Surrogate Measures for Accident Experience at Rural Isolated Horizontal Curves," has shown that safety increases as motorists travel closer to the center of their specific lane of travel (*17*). The increased lateral offset of the vehicles in the PennDOT study put motorists closer to the center of their respective lane of travel, thus improving safety. PennDOT found that the variance of the lateral offset was decreased.

The use of CRS as countermeasures for opposite direction crashes is not limited to the U.S. In particular, Canada has recently published a report on the subject, *Best Practices for the Implementation of Shoulder and Centreline Rumble Strips* (*18*). While many provinces have already formulated policies with regard to SRS, CRS have only been installed in Alberta, Canada. The Transportation Association of Canada (TAC) generated this report to provide a guideline to other agencies as they study CRS and create their own unique local policies for the use and installation of CRS.

TAC has looked at the various aspects of implementing CRS such as type, design, application, maintenance, benefit-to-cost (B/C), and perceived problems (e.g., noise). Canada's implementation policies for CRS appear to agree with U.S. policies. For instance, Canada will not use RPM in areas prone to snow cover. This is a common practice in northern states in the U.S. While the dimensions prescribed in Canada are very similar to current state policies in the U.S., the depth of their milled rumble strips is consistently less than in the U.S. TAC recommends the use of milled rumble strips to the depth of 0.3125 inches (8 mm) versus the 0.375 to 0.5 inches (10 to 13 mm). One of the major noteworthy differences is that TAC specifically states that they believe CRS should only be placed in no-passing zones on two-lane, undivided highways (TAC report). The TAC summary of the suggested guidelines for Canada provinces is listed below:

- CRS should be installed in the following locations:
  - Two-lane and four-lane, undivided roadways in no-passing zones.
  - Horizontal curves with a small radius and/or with a history of crashes.
  - Climbing or passing lanes with no-passing zones.
- CRS should not be installed in the following locations:
  - Within 660 feet (201.2 m) of a residential or urban area.
  - Bridge decks.
  - Passing zones on two-lane roadways.
  - Across the intersection of the roadway with another road or commercial entrance.
- The use of CRS in passing zones should be reinvestigated once additional studies have been conducted.
- Continuous CRS may be installed on undivided highways that have a history of head-on and/or sideswipe collisions and where the B/C ratio is cost effective.
- A B/C analysis should be conducted prior to the installation of CRS on roadways with low Annual Average daily traffic (AADT) volumes.
- CRS have been installed on roadways with lane widths as narrow as 11 feet (3.4 m).
- Pavement markings should be reinstalled in both directions to ensure adequate coverage over the milled surface.

Transverse Rumble Strips

Transverse rumble strips are warning devices intended to alert drivers to the possible need to take some precautionary action. Rumble strips provide motorists with an audible and tactile warning that their vehicle is approaching a point of critical importance to safety. Figure 6 shows common examples of these types of rumble strips.

A transverse rumble strip is a raised or grooved pattern placed on the surface of the traveling roadway. Rumble strips provide motorists with an audible and tactile warning that their vehicle is approaching a decision point of critical importance to safety. An audible warning is provided to drivers by the noise generated by the vehicle tires passing over the rumble strip. The tactile warning is attained via the vibration that is induced by the rumble strips when the vehicle tires travel over the strip. The six basic reasons to use rumble strips are to (*19*):

- warn drivers of the need to stop;
- warn drivers of the need to slow down;
- warn drivers of the need to change lanes;
- warn drivers of a change in roadway alignment;
- warn drivers that they are leaving the traveled way; and
- warn drivers of other potentially unexpected conditions.

Figure 6. Transverse Rumble Strips.

Applications of Transverse Rumble Strips

A1969 article notes that Texas was the apparent leader in the use of rumble strips and began using them in 1956. At that time, Texas used a ceramic bar or strip anchored to the roadway with an epoxy resin. Maryland was noted as being the second most active state for rumble strips with 238 installations. Maryland used strips consisting of slag or stone laid on a bed of bitumen. Nebraska was reported to have 20 sets of bonded aggregates cemented to the road surface with epoxy, and Illinois had 10 similar installations. North Carolina had one experimental installation with strips made from sand. Both Colorado and Indiana were performing tests. As early as 1947, New Jersey experimented with “singing lanes” to warn drivers that they were encroaching on an adjacent lane. The 1969 article also notes that tests conducted by the New Jersey DOT provided the following conclusions:

- A strip-to-critical-area distance of 800 feet (243.8 m) at the test location with a 55 mph (89 km/hour) maximum speed limit was just about right.
- A reduction in accidents was seen on the approach where rumble strips were installed.
- The following recommendations were also made:
  - Serious consideration should be given to the question: “Does the motorist require advance notice of the oncoming rumble strip? And if so, how should it be given?” This seems nonsensical in a way because the rumble strip in itself is to warn, alert, and wake up the motorist. However, quite a few drivers, given no advance notice of the experience and apparently not acquainted with such an experience, pull off to the side and examine their car for mechanical trouble. This type of reaction slows traffic and is hazardous to the motorist.

- Consideration should be given to whether a series of strip patterns, rather than only one, would better suit the purpose.
- When the decision to use rumble strips is reached, consideration should be given to whether they should be installed on more than one of the roads that form the dangerous intersection.
- Consideration should be given to the possible necessity of developing ways and means for preventing the local motorist, familiar with the installation, from deliberately driving around it. This is dangerous to the motorist and may encourage other non-local motorists to follow the local driver in this behavior.
- Every consideration should be given to establishing the proper distance between the warning device and the critical area. If the distance is too great, acceleration, rather than deceleration, can be effected by the determined aggressive motorist; if too short, the alert motorist, who however, is exceeding the speed limit, is in trouble. *(20)*

Harwood et al. (*19*) performed a survey of state and local highway agencies and toll road authorities to determine the usage of transverse rumble strips. The survey was a mail questionnaire sent to the 50 state highway agencies, 98 selected local agencies, and 50 selected toll road authorities. Of the 163 entities surveyed, 123 responses were garnered for an overall response rate of 76 percent. Table 5 presents the results of the survey.

Table 5. Transportation Entity Usage of Transverse Rumble Strips.

Response	State Highway Agencies	Local Agencies	Toll Road Authorities	Total
Yes	41 (91.1)	7 (46.7)	9 (69.2)	57
No	4 (8.9)	8 (53.3)	4 (30.8)	16
Total	45	15	13	73
Note: The numbers in parentheses are column percentages.				

As part of the survey, the transportation entities were asked as to where transverse rumble strips were utilized. Transverse rumble strips were found to be used at approaches to the following: intersections, toll plazas, horizontal curves, lane drops, and work zones. Table 6 shows the percentage of transportation agencies surveyed that use transverse rumble strips at the aforementioned areas.

Table 6. Transverse Rumble Strip Usage Locations.

Locations	State Highway Agencies	Local Agencies	Toll Roads	Total
Intersections	37 (82.2)	7 (46.7)	0 (0.0)	44 (60.3)
Toll Plazas	12 (26.7)	0 (0.0)	7 (53.8)	19 (26.0)
Horizontal Curves	10 (22.2)	5 (33.3)	0 (0.0)	15 (20.5)
Lane Drops	2 (4.4)	2 (13.3)	0 (0.0)	0 (0.0)
Work Zones	11 (24.4)	1 (6.7)	5 (38.5)	17 (23.3)
Other Applications	6 (13.3)	9 (60.0)	0 (0.0)	17 (20.3)
Note: The numbers in parentheses represent the percentage of highway agencies that have used each rumble strip application. Percentages add to more than 100 percent because of multiple responses.				

Approaches to Intersections

The most common usage of transverse rumble strips is on approaches to stop-controlled intersections. They have also been utilized at signalized intersections, but to a lesser extent. Transverse rumble strips are applicable to conditions where, because of limited sight distance, drivers are not expecting an intersection. The use of rumble strips may reduce right-angle accidents, which are commonly associated with running through a stop sign or signal, by alerting drivers to an upcoming condition (*1*,*19*).

Approaches to Toll Plazas

Transverse rumble strips have been used on approaches to toll plazas where drivers are expected to stop. Rumble strips are used on approaches to toll plazas when long hours of monotonous driving cause drivers to be unaware of upcoming toll facilities (*19*).

Approaches to Horizontal Curves

Transverse rumble strips have been used at approaches to sharp horizontal curves, especially where advisory speed limits are posted or sharp curves that are present at the end of long tangent sections of roadways. The purpose of this usage is to alert drivers and therefore reduce skidding or run-off-the-road accidents that occur when drivers do not see the curve or enter a curve at too high of a speed (*19*).

Approaches to Lane Drops

In a few instances, transverse rumble strips were used by highway agencies where the right or left lane is to be dropped from the mainstream freeway. In this case, rumble strips are used to alert drivers of the need to vacate the lane. Rumble strips may be a source of confusion when used on approaches to lane drops prior to freeway exits. It may be unclear to exiting drivers who do not need to change lanes. Thus, rumble strips should be used with caution on approaches to lane drops (*19*).

Approaches to Work Zones

Transverse rumble strips have been utilized on approaches prior to and within work zones. The rumble strips aid in warning drivers of lane closures or restrictions, width restrictions, or sharp detour transitions. The rumble strips are used to warn drivers to either change lanes or reduce speed prior to coming to one of the aforementioned conditions (*19*).

Effectiveness of Transverse Rumble Strips

This section summarizes known information on the safety and operational effects of transverse rumble strips. The discussion addresses effects of rumble strips on traffic accident mitigation, traffic control device compliance, and work zone safety. A separate section will address the effect of transverse rumble strips on vehicle speeds.

Accident Mitigation Effectiveness

Studies show that rumble strips are very effective in reducing accidents. The majority of studies found reported large reductions (40 percent to 100 percent) of accidents after installing transverse rumble strips. The studies focused on the usage of transverse rumble strips on approaches to stop-controlled T-intersections and stop-controlled four-way intersections. However, it was stated that these studies were generally small and varied greatly in quality and completeness (*2*,*19*). Only two of the studies found in the literature review reported statistically significant (95 percent confidence level) accident reductions from rumble strip installation. The majority of the studies did not state whether the results were statistically significant.

Despite weaknesses in the accident evaluation designs, the study results indicate that transverse rumble strip installation can be an effective form of traffic control for accident mitigation. The literature suggests that transverse rumble strips are effective in reducing accident types that are susceptible to correction by more than 50 percent. The recommendations suggest the use of rumble strips placed in the traveled way at locations where rear-end accidents and ran-stop-sign accidents are prevalent (*19*).

Compliance with Traffic Control Devices

Transverse rumble strips have been evaluated as to the effectiveness of inducing compliance with traffic control devices. The locations studied included stop-controlled intersections at T- and four-way intersections. The criteria studied were drivers making a full stop, making a partial (rolling) stop, or not stopping. The results showed that drivers made significantly more full stops in the post-treatment period than in the pre-treatment period. Table 7 shows the results of the five studies involving stop-sign compliance.

Table 7. Study Results of Stop-Sign Compliance.

Study Location	Percentage of Full Stop		Percentage Change
	Pre-Treatment	Post-Treatment	
California	46%	76%	30%
Minnesota	37%	63%	26%
Illinois	91%	95%	4%
Iowa	66%	77%	11%
Israel	91%	95%	4%

Work Zone Applications

A review of the effectiveness of transverse rumble strips for the Federal Highway Administration indicated that the studies have reviewed only a limited number of applications and that these studies have produced inconsistent findings. In a majority of instances involving work zones, rumble strips have been used to identify lane closures, crossovers, significant changes in speeds, and transition of driving lanes (*21*). Two studies were performed, after the FHWA report, to study the effectiveness of rumble strip applications in work zones.

A study performed by the Texas Transportation Institute (TTI) evaluated the effectiveness of portable rumble strips and speed displays at reducing speeds in rural work zones. The results for the portable rumble strips were mixed. Passenger cars experienced a lesser reduction (2 mph) than that of trucks, whose speeds were reduced by 7.2 mph (11.6 km/hour). It was reported that the percent of vehicles exceeding the speed limit in the advance warning area reduced when rumble strips were present (*22*).

Another study in Kansas evaluated orange removable rumble strips used for highway work zones. The work zone was a bridge repair site in Kansas. Vehicle speeds were recorded with standard asphalt rumble strips in place; then removable rumble strips were installed, and additional speed data were collected. The orange rumble strips were reported to have a significant effect at reducing vehicle speed, which was attributable to their visibility (*23*).

Effect of Transverse Rumble Strips on Speed

There have been five studies performed involving transverse rumble strips, and all have used speed reduction as a surrogate for safety. The objectives of those studies were to determine if transverse rumble strips had an effect on vehicle speed on approaches to intersections, roundabouts, villages, and other roadway junctions. All the studies utilized a before-and-after study design.

The previous studies indicate that transverse rumble strips result in a small reduction in vehicle speeds. Reduction in vehicle speeds varied between studies, and it appears that speed variance on the junction approaches increased. This section outlines the study methodology and results from the available studies involving vehicle speeds and transverse strips.

Contra Costa County, California, Study

Kermit and Hein (*24*) studied the effects of rumble strips installed at four locations. The locations were at the end of a controlled-access expressway that ended at a T-intersection, an urban T-intersection, a Y-intersection of a county road and a former state highway, and another county road with a four-way intersection. The "rumble strips" used in this study were a series of 25 feet (7.6 m) long areas of rough-textured aggregate placed on the appropriate lanes at 50- to 100-foot (15.2- to 30.5-meter) intervals.

The goal of the study was to determine if drivers began to slow down farther from the intersection after treatment of the rumble areas. The speeds at three locations were measured. The three locations were 1000 feet (304.8 m) upstream of the intersection, 450 feet (137.2 m) upstream of the intersection, and at the subject intersection. The 85th percentile speeds were reported as well as the deceleration rates between points. Table 8 shows the results of the study (*24*).

Table 8. Study Results from Contra Costa County Study.

Speed Measurement Location	Measurement	Before Rumble Strip Installation	After Rumble Strip Installation
1000 feet (304.8 m) Upstream	85th Percentile Speed (mph/kph)[1]	44.0 (70.8)	46.0 (74.0)
	Deceleration Rate (fpsps/mpsps)[2]	0.57 (0.17)	1.43 (0.44)
450 feet (137.2 m) Upstream	85th Percentile Speed (mph/kph)[1]	41.0 (66.0)	37.0 (59.5)
	Deceleration Rate (fpsps/mpsps)[2]	3.46 (1.05)	2.70 (0.82)
Intersection	85th Percentile Speed (mph/kph)[1]	14.8 (23.8)	15.1 (24.3)
Note: The metric values are in parenthesis.			

1 Miles per hour (mph), km per hour (kph)
2 Feet per second per second (fpsps), meters per second per second (mpsps)

The before-and-after study design in Contra Costa County was performed one week before treatment and two months after treatment. The study summarizes the results; however, it fails to report statistical analysis procedures or if reductions were statistically significant. Traffic volumes were not reported for the study.

TRRL Study

The United Kingdom Department of Transport and Road Research Laboratory (TRRL) studied the effects of rumble strips on vehicle speeds at 10 sites (*25*). The rumble areas were upstream of such junctions as roundabouts, four-way intersections, T-intersections, horizontal curves, and small towns. The speeds were measured upstream from the junction at 1,312 feet (400 m) and 164 feet (50 m). The mean speeds were identified at these locations.

The speed measurement analysis between the 1,312-foot (400-meter) station and the 164-foot (50-meter) station found that the effects of the rumble areas were inconsistent. In some instances, the rumble areas caused drivers to use larger deceleration between the two stations, and at other sites, a lesser deceleration rate was used. The data for all sites combined only showed a small decrease in the amount of speed chosen by drivers between the two stations. None of the decreases in speed were reported to be statistically significant (*25*).

Israeli Study

Zaidel et al. (*26*) evaluated the use of rumble strips on one stop-controlled intersection approach in Israel. Thirty-eight rumble strips were placed over a distance of 883 feet (269 m) upstream of the intersection. The speeds were measured at eight locations along the approach to the intersection. The mean speeds and standard deviation were reported at each data collection station. The mean speeds were reported to be reduced by 5 to 50 percent after the installation of the rumble strips. Table 9 shows the sample data collected from the study.

Table 9. Study Results of Israeli Study.

Distance from Intersection	*(ft)*	128	101	87	78	50	32	14	5
	(m)	420	330	285	255	165	105	45	15
Mean Speed (Before)	*(mph)*	117.8	116.0	113.9	112.8	104.0	92.5	66.9	39.8
	(kph)	73.2	72.1	70.8	70.1	64.6	57.5	41.6	24.7
Mean Speed (After)	*(mph)*	111.8	101.5	86.9	70.0	52.9	50.9	39.4	23.7
	(kph)	69.5	63.1	54.0	43.5	32.9	31.6	24.5	14.7
Percent Change	*(%)*	-5.1	-12.5	-23.7	-37.9	-49.1	-45.0	-41.1	-40.5

Zaidel et al. believed that drivers generally begin to slow down sooner and that some drivers slowed down more, which would account for the increase in speed variance. However, these findings only considered one site.

Minnesota Study

The Minnesota Department of Highways studied the effect of rumble areas to approaches to seven stop-controlled intersections. The rumble areas consisted of coarse aggregate with a minimum size stone of 0.75 inch aggregate and cationic asphalt emulsion. The rumble areas were laid out in differing patterns. Four rumble areas were 25 feet (7.6 m) long and spaced 100 feet (30.5 m) apart, six rumble areas were 25 feet (7.6 m) long and 50 feet apart (15.2 m), and one rumble area was 50 feet long (15.2 m) and placed at the intersection (*27*).

Speed data were collected at each site at the following upstream distances: 300 feet (91.4 m), 500 feet (152.4 m), 1,000 feet (304.8 m), 1,500 feet (457.2 m), and a free-flow station. The amount of speed data collected ranged from 30 passenger vehicles to 101 passenger vehicles. Table 10 shows the results of the analysis for the mean speed with all seven approaches combined. The results show a 95-percent confidence interval for each of the mean speeds. An overall reduction in approach speed was found at each point of observance. The amount of dispersion, however, increased in some cases after the installation of rumble areas. Researchers speculated that some drivers slowed down considerably more than others (*27*).

Table 10. Study Results from Minnesota Study.

Distance from Intersection (ft/m)	Average Speed (mph/kph)			Significant?
	Before Installation	After Installation	Difference	
300 (91.4)	31.01 (49.91)	27.99 (45.05)	3.02 (4.86)	Yes
500 (152.4)	36.57 (58.85)	33.59 (54.06)	2.98 (4.80)	Yes
1,000 (304.8)	43.70 (70.33)	41.39 (66.61)	2.31 (3.72)	Yes
1,500 (457.2)	47.26 (76.06)	44.47 (71.57)	2.79 (4.49)	Yes
Free Flow	52.09 (83.83)	52.58 (84.62)	-0.49 (-0.79)	No
Note: The metric values are in parenthesis.				

University of Toledo Study

A study performed at the University of Toledo evaluated the effect of rumble strips in reducing speeds on approaches to stop-controlled intersections. Seven approaches were used in the before-and-after study design. The mean speeds were determined at a location 300 feet (91.4 m) downstream of the first rumble strip. After gathering the before-and-after data sets, the reduction in speed was compared to determine if it was statistically significant at the 95 percent confidence level. Of the seven sites, five locations produced statistically significant reductions in speed at the 95 percent confidence level. Table 11 shows the results of the study (*19*).

Table 11. Study Results from the University of Toledo Study.

Location of Rumble Strips	Mean Speed (mph)			Significant?
	Before	After	Reduction	
SR 281, East of SR 108	41.9 (67.4)	35.9 (57.8)	6.0 (9.7)	Yes
SR 281, West of SR 108	47.9 (77.1)	39.9 (64.2)	8.0 (12.9)	Yes
SR 576, North of SR 34	43.9 (70.7)	45.9 (73.9)	-2.0 (-3.2)	No
SR 576, South of SR 34	45.9 (73.9)	41.9 (67.4)	4.0 (6.4)	Yes
US 20, East of US 127	51.9 (83.5)	49.9 (80.3)	2.0 (3.2)	Yes
US 20, West of US 127	53.9 (86.7)	51.9 (83.5)	2.0 (3.2)	No
US 20, West of US 108	53.9 (86.7)	49.9 (80.3)	4.0 (6.4)	Yes
Note: The metric values are in parenthesis.				

The previous five before-and-after speed studies performed involving transverse rumble strips have reported statistically significant reductions in mean and/or 85th percentile speeds. However, the actual reductions in speeds have been in the range of 2 to 8 mph (3.2 to 12.9 km/hr), which may be barely perceptible to the traveling public. There have been no studies that evaluate the reduction of excessive speeds. In a report of traffic calming devices used in Minnesota, the effectiveness of traffic calming should be defined using the combination of the following (*28*):

- reduction in mean speeds;
- reduction in the 85th percentile speeds; and
- reduction in the highest speeds.

CHAPTER 3
SAFETY ANALYSES

This chapter presents the safety analyses that were conducted in order to determine the relative effectiveness of centerline and edgeline rumble strips in the applications associated with this research. The numbers are compared against other states to show some potential comparisons. It should be noted that the Pennsylvania Department of Transportation provided the numbers for all of the states shown except Texas.

Figures 7 and 8 show the potential safety impacts for centerline rumble strips. The figures are based on the latest statistics for costs for crashes, depending on severity. They are split into four classes of roadway volume and show benefit/cost ratios for each class of roadway volume. The results indicate that the higher the roadway volume, the more benefit of centerline rumble strips.

The B/C ratios shown assume a 20 percent reduction in the pertinent crash rates as a result of the centerline rumble strips. This threshold was chosen based on the literature review presented previously. However, the tables were developed in a spreadsheet format so that this assumption could be studied in sensitivity analysis. The spreadsheet was provided to the project director for additional analyses and policy-making decisions.

Figures 9 and 10 show the potential safety impacts of edgeline rumble strips on two-lane highways. These figures are similar to the previous figures except that they are classified by roadway volume and shoulder width. Unlike the centerline rumble strip results, the results for the edgeline rumble strips vary depending on volume and shoulder width. The reasons for these fluctuations can be traced to the distribution of two-lane mileage in Texas and the related run-off-the-road crashes that occur on them (Figures 11 and 12).

	Costs per Crash ($)
Fatal	3,883,811 *
A Injury	1,043,826
B Injury	69,990
C Injury	5,543
PDO	2,217
Fatalities/Fatal Crash	1.35
Cost of Rumble Strips/Foot	1.50
Reduction from Rumble Strips	0.2

* Cost of Fatal Crashes ($2,882,516) x 1.35 Fatalities/Fatal crash

Table 1: ADT=< 1500

	Head-on and opposing flow side swipe crashes **	WASH	NC	IL	PA	TX
a.	Fatal	3	6	0	8	36
b.	A Injury	6	24	1	23	50
c.	B Injury	7	38	1	43	76
d.	C Injury	3	16	3	79	60
e.	PDO	24	21	3	66	50
f.	Annual Crash Cost	18,474,156	51,149,555	1,137,096	58,672,275	197,771,167
g.	Miles	1,971	13,776	1,325	9,862	41,923
h.	Estimated Rumble Strip Cost/Mile	7,920	7,920	7,920	7,920	7,920
i. (g x h)	Estimated Rumble Strip Total Cost	15,612,696	109,103,544	10,490,832	78,107,040	332,029,764
j.	Estimated Pvmnt Life (yrs)	8	8	8	8	8
k. (f x j)	Total Crash cost over Pvmnt Life	147,793,249	409,196,442	9,096,768	469,378,202	1,582,169,337
l.	Annual Cost Reduction Due to Rumble Strips***	3,694,831	10,229,911	227,419	11,734,455	39,554,233
m. (j x l)	Total Cost reduction over Pvmnt Life	29,558,650	81,839,288	1,819,354	93,875,640	316,433,867
n. (m / i)	**Estimated B/C**	**1.89**	**0.75**	**0.17**	**1.20**	**0.95**
o. (a x 1.35 x 0.2)	Expected Annual Lives Saved	0.81	1.62	0.00	2.16	9.70
p. (j x o)	Expected Lives Saved over life of Pvmnt	6.47	12.93	0.00	17.25	77.61

** Crash data from HSIS except for Pennsylvania and Texas

*** Assumes 20% reduction in head-on and opposing flow side swipe crashes and related costs

Table 2: ADT 1500-2999

	Head-on and opposing flow side swipe crashes **	WASH	NC	IL	PA	TX
a.	Fatal	5	12	7	17	47
b.	A Injury	16	18	18	32	58
c.	B Injury	24	36	15	49	74
d.	C Injury	9	12	0	79	60
e.	PDO	32	14	28	68	74
f.	Annual Crash Cost	37,920,862	68,011,794	47,087,471	103,445,383	248,756,924
g.	Miles	1,197	5,080	2,163	3,182	9,067
h.	Estimated Rumble Strip Cost/Mile	7,920	7,920	7,920	7,920	7,921
i. (g x h)	Estimated Rumble Strip Total Cost	9,478,498	40,232,808	17,128,584	25,201,440	71,815,984
j.	Estimated Pvmnt Life (yrs)	8	8	8	8	9
k. (f x j)	Total Crash cost over Pvmnt Life	303,366,897	544,094,355	376,699,770	827,563,060	2,238,812,320
l.	Annual Cost Reduction Due to Rumble Strips***	7,584,172	13,602,359	9,417,494	20,689,077	49,751,385
m. (j x l)	Total Cost reduction over Pvmnt Life	60,673,379	108,818,871	75,339,954	165,512,612	447,762,464
n. (m / i)	**Estimated B/C**	**6.40**	**2.70**	**4.40**	**6.57**	**6.23**
o. (a x 1.35 x 0.2)	Expected Annual Lives Saved	1.35	3.23	1.89	4.58	12.67
p. (j x o)	Expected Lives Saved over life of Pvmnt	10.78	25.87	15.09	36.65	113.99

** Crash data from HSIS except for Pennsylvania and Texas

*** Assumes 20% reduction in head-on and opposing flow side swipe crashes and related costs

Figure 7. Safety Analysis of Centerline Rumble Strips (1 of 2).

Costs per Crash ($)	
Fatal	0 *
A Injury	1,043,826
B Injury	69,990
C Injury	5,543
PDO	2,217
Fatalities/Fatal Crash	0.00
Cost of Rumble Strips/Foot	1.50
Reduction from Rumble Strips	0.2

* Cost of Fatal Crashes ($2,882,516) x 1.35 Fatalities/Fatal crash

Table 3: ADT 3000-4499

	Head-on and opposing flow side swipe crashes **	WASH	NC	IL	PA	TX
a.	Fatal	9	12	10	17	62
b.	A Injury	17	10	53	27	56
c.	B Injury	20	20	33	53	57
d.	C Injury	15	14	3	61	61
e.	PDO	41	11	28	56	65
f.	Annual Crash Cost	54,273,183	58,545,781	96,549,263	98,379,835	303,722,198
g.	Miles	585	2,370	1,144	1,831	4,575
h.	Estimated Rumble Strip Cost/Mile	7,920	7,920	7,920	7,920	7,921
i. (g x h)	Estimated Rumble Strip Total Cost	4,634,784	18,769,608	9,060,480	14,501,520	36,236,436
j.	Estimated Pvmnt Life (yrs)	8	8	8	8	9
k. (f x j)	Total Crash cost over Pvmnt Life	434,185,466	468,366,251	772,394,107	787,038,676	2,733,499,782
l.	Annual Cost Reduction Due to Rumble Strips***	10,854,637	11,709,156	19,309,853	19,675,967	60,744,440
m. (j x l)	Total Cost reduction over Pvmnt Life	86,837,093	93,673,250	154,478,821	157,407,735	546,699,956
n. (m / i)	**Estimated B/C**	**18.74**	**4.99**	**17.05**	**10.85**	**15.09**
o. (a x 1.35 x 0.2)	Expected Annual Lives Saved	2.43	3.23	2.69	4.58	16.71
p. (j x o)	Expected Lives Saved over life of Pvmnt	19.40	25.87	21.56	36.65	150.37

** Crash data from HSIS except for Pennsylvania and Texas

*** Assumes 20% reduction in head-on and opposing flow side swipe crashes and related costs

Table 4: ADT >4500

	Head-on and opposing flow side swipe crashes **	WASH	NC	IL	PA	TX
a.	Fatal	33	36	17	65	190
b.	A Injury	54	57	35	94	260
c.	B Injury	66	34	26	133	324
d.	C Injury	58	37	9	193	291
e.	PDO	107	17	50	171	333
f.	Annual Crash Cost	189,710,421	201,937,719	104,539,175	361,324,937	1,034,346,890
g.	Miles	979	3,539	994	2,801	8,897
h.	Estimated Rumble Strip Cost/Mile	7,920	7,920	7,920	7,920	7,921
i. (g x h)	Estimated Rumble Strip Total Cost	7,750,433	28,028,088	7,870,104	22,183,920	70,473,929
j.	Estimated Pvmnt Life (yrs)	8	8	8	8	9
k. (f x j)	Total Crash cost over Pvmnt Life	1,517,683,368	1,615,501,753	836,313,396	2,890,599,496	9,309,122,010
l.	Annual Cost Reduction Due to Rumble Strips***	37,942,084	40,387,544	20,907,835	72,264,987	206,869,378
m. (j x l)	Total Cost reduction over Pvmnt Life	303,536,674	323,100,351	167,262,679	578,119,899	1,861,824,402
n. (m / i)	**Estimated B/C**	**39.16**	**11.53**	**21.25**	**26.06**	**26.42**
o. (a x 1.35 x 0.2)	Expected Annual Lives Saved	8.89	9.70	4.58	17.52	51.20
p. (j x o)	Expected Lives Saved over life of Pvmnt	71.14	77.61	36.65	140.13	460.80

** Crash data from HSIS except for Pennsylvania and Texas

*** Assumes 20% reduction in head-on and opposing flow side swipe crashes and related costs

Figure 8. Safety Analysis of Centerline Rumble Strips (2 of 2).

		Costs per Crash ($)
	Fatal	3,193,376 *
	A Injury	1,043,826
	B Injury	69,990
	C Injury	5,543
	PDO	2,217
q.	Fatalities/Fatal Crash	1.11
r.	Cost of Rumble Strips/Foot	0.25
s.	Reduction from Rumble Strips	0.2

* Cost of Fatal Crashes = ($2,882,516 * q)

Table 1: ADT=< 1500

	Shoulder Width	0.0-1.5	2.0-4.0	4.5-6.0	6.5-8.0	8.5-9.0	9.5-10.0	>10.0
a.	Fatal	6	3	7	7	1	2	0
b.	A Injury	13	15	20	22	10	2	0
c.	B Injury	42	26	34	23	17	7	0
d.	C Injury	13	31	22	20	9	6	2
e.	PDO	51	38	45	36	17	17	4
	(Total Crashes)	125	113	128	108	54	34	6
f.	Annual Crash Cost	35,854,697	27,313,336	45,831,520	47,118,243	14,909,042	9,035,280	19,954
g.	Miles	349	299	516	373	158	110	13
h. (5280 * r)	Estimated Rumble Strip Cost/Mile	1,320	1,320	1,320	1,320	1,320	1,320	1,320
i. (g * h)	Estimated Rumble Strip Total Cost	460,643	394,322	681,094	491,753	208,089	144,866	17,428
j.	Estimated Pvmnt Life (yrs)	8	8	8	8	8	8	8
k. (f * j)	Total Crash cost over Pvmnt Life	286,837,579	218,506,686	366,652,160	376,945,944	119,272,333	72,282,241	159,632
l. (f * s)	Annual Cost Reduction Due to Rumble Strips**	7,170,939	5,462,667	9,166,304	9,423,649	2,981,808	1,807,056	3,991
m. (j * l)	Total Cost reduction over Pvmnt Life	57,367,516	43,701,337	73,330,432	75,389,189	23,854,467	14,456,448	31,926
n. (m / i)	**Estimated B/C**	**125**	**111**	**108**	**153**	**115**	**100**	**2**
o. (a * q * s)	Expected Annual Lives Saved	1.33	0.66	1.55	1.55	0.22	0.44	0.00
p. (j * o)	Expected Lives Saved over life of Pvmnt	10.64	5.32	12.41	12.41	1.77	3.55	0.00

** Assumes 20% reduction in head-on and opposing flow side swipe crashes and related costs

Table 2: ADT 1500-2999

	Shoulder Width	0.0-1.5	2.0-4.0	4.5-6.0	6.5-8.0	8.5-9.0	9.5-10.0	>10.0
a.	Fatal	2	5	4	7	4	2	0
b.	A Injury	12	21	16	19	14	10	4
c.	B Injury	26	58	34	61	32	34	6
d.	C Injury	25	28	27	61	28	33	2
e.	PDO	41	53	46	86	42	42	7
	(Total Crashes)	106	165	127	234	120	121	19
f.	Annual Crash Cost	20,961,875	42,219,349	32,106,021	46,984,498	29,875,064	19,480,704	4,621,849
g.	Miles	228	407	345	610	397	322	47
h. (5280 * r)	Estimated Rumble Strip Cost/Mile	1,320	1,320	1,320	1,320	1,320	1,320	1,320
i. (g * h)	Estimated Rumble Strip Total Cost	300,865	536,646	455,828	805,824	523,480	424,930	61,875
j.	Estimated Pvmnt Life (yrs)	8	8	8	8	8	8	8
k. (f * j)	Total Crash cost over Pvmnt Life	167,695,001	337,754,791	256,848,170	375,875,984	239,000,514	155,845,633	36,974,792
l. (f * s)	Annual Cost Reduction Due to Rumble Strips**	4,192,375	8,443,870	6,421,204	9,396,900	5,975,013	3,896,141	924,370
m. (j * l)	Total Cost reduction over Pvmnt Life	33,539,000	67,550,958	51,369,634	75,175,197	47,800,103	31,169,127	7,394,958
n. (m / i)	**Estimated B/C**	**111**	**126**	**113**	**93**	**91**	**73**	**120**
o. (a * q * s)	Expected Annual Lives Saved	0.44	1.11	0.89	1.55	0.89	0.44	0.00
p. (j * o)	Expected Lives Saved over life of Pvmnt	3.55	8.86	7.09	12.41	7.09	3.55	0.00

** Assumes 20% reduction in head-on and opposing flow side swipe crashes and related costs

Figure 9. Safety Analysis of Edgeline Rumble Strips (1 of 2).

		Costs per Crash ($)
	Fatal	3,193,376 *
	A Injury	1,043,826
	B Injury	69,990
	C Injury	5,543
	PDO	2,217
q.	Fatalities/Fatal Crash	1.11
r.	Cost of Rumble Strips/Foot	0.25
s.	Reduction from Rumble Strips	0.2

* Cost of Fatal Crashes = ($2,882,516 * q)

Table 3: ADT 3000-4499

	Shoulder Width	0.0-1.5	2.0-4.0	4.5-6.0	6.5-8.0	8.5-9.0	9.5-10.0	>10.0
a.	Fatal	0	1	3	7	2	1	1
b.	A Injury	8	9	7	27	18	11	3
c.	B Injury	23	23	28	55	25	23	8
d.	C Injury	23	20	8	40	28	22	1
e.	PDO	29	57	40	63	42	34	8
	(Total Crashes)	83	110	86	192	115	91	21
f.	Annual Crash Cost	10,152,160	14,434,809	18,979,653	54,747,772	27,173,687	16,482,556	6,908,053
g.	Miles	216	230	181	445	237	221	38
h. (5280 * r)	Estimated Rumble Strip Cost/Mile	1,320	1,320	1,320	1,320	1,320	1,320	1,320
i. (g * h)	Estimated Rumble Strip Total Cost	284,828	303,238	239,538	587,690	313,079	291,946	50,089
j.	Estimated Pvmnt Life (yrs)	8	8	8	8	8	8	8
k. (f * j)	Total Crash cost over Pvmnt Life	81,217,280	115,478,469	151,837,222	437,982,176	217,389,497	131,860,445	55,264,421
l. (f * s)	Annual Cost Reduction Due to Rumble Strips**	2,030,432	2,886,962	3,795,931	10,949,554	5,434,737	3,296,511	1,381,611
m. (j * l)	Total Cost reduction over Pvmnt Life	16,243,456	23,095,694	30,367,444	87,596,435	43,477,899	26,372,089	11,052,884
n. (m / i)	**Estimated B/C**	**57**	**76**	**127**	**149**	**139**	**90**	**221**
o. (a * q * s)	Expected Annual Lives Saved	0.00	0.22	0.66	1.55	0.44	0.22	0.22
p. (j * o)	Expected Lives Saved over life of Pvmnt	0.00	1.77	5.32	12.41	3.55	1.77	1.77

** Assumes 20% reduction in head-on and opposing flow side swipe crashes and related costs

Table 4: ADT >4500

	Shoulder Width	0.0-1.5	2.0-4.0	4.5-6.0	6.5-8.0	8.5-9.0	9.5-10.0	>10.0
a.	Fatal	0	2	3	12	7	12	1
b.	A Injury	9	16	16	43	26	38	1
c.	B Injury	30	29	30	103	52	69	13
d.	C Injury	25	25	40	100	45	69	11
e.	PDO	60	55	79	187	87	108	21
	(Total Crashes)	124	127	168	445	217	296	47
f.	Annual Crash Cost	11,765,729	25,378,187	28,777,906	91,382,874	53,574,899	83,437,108	5,254,602
g.	Miles	148	155	342	687	451	505	106
h. (5280 * r)	Estimated Rumble Strip Cost/Mile	1,320	1,320	1,320	1,320	1,320	1,320	1,320
i. (g * h)	Estimated Rumble Strip Total Cost	195,998	204,182	451,292	907,343	594,944	666,048	139,391
j.	Estimated Pvmnt Life (yrs)	8	8	8	8	8	8	8
k. (f * j)	Total Crash cost over Pvmnt Life	94,125,832	203,025,497	230,223,246	731,062,991	428,599,192	667,496,863	42,036,813
l. (f * s)	Annual Cost Reduction Due to Rumble Strips**	2,353,146	5,075,637	5,755,581	18,276,575	10,714,980	16,687,422	1,050,920
m. (j * l)	Total Cost reduction over Pvmnt Life	18,825,166	40,605,099	46,044,649	146,212,598	85,719,838	133,499,373	8,407,363
n. (m / i)	**Estimated B/C**	**96**	**199**	**102**	**161**	**144**	**200**	**60**
o. (a * q * s)	Expected Annual Lives Saved	0.00	0.44	0.66	2.66	1.55	2.66	0.22
p. (j * o)	Expected Lives Saved over life of Pvmnt	0.00	3.55	5.32	21.27	12.41	21.27	1.77

** Assumes 20% reduction in head-on and opposing flow side swipe crashes and related costs

Figure 10. Safety Analysis of Edgeline Rumble Strips (2 of 2).

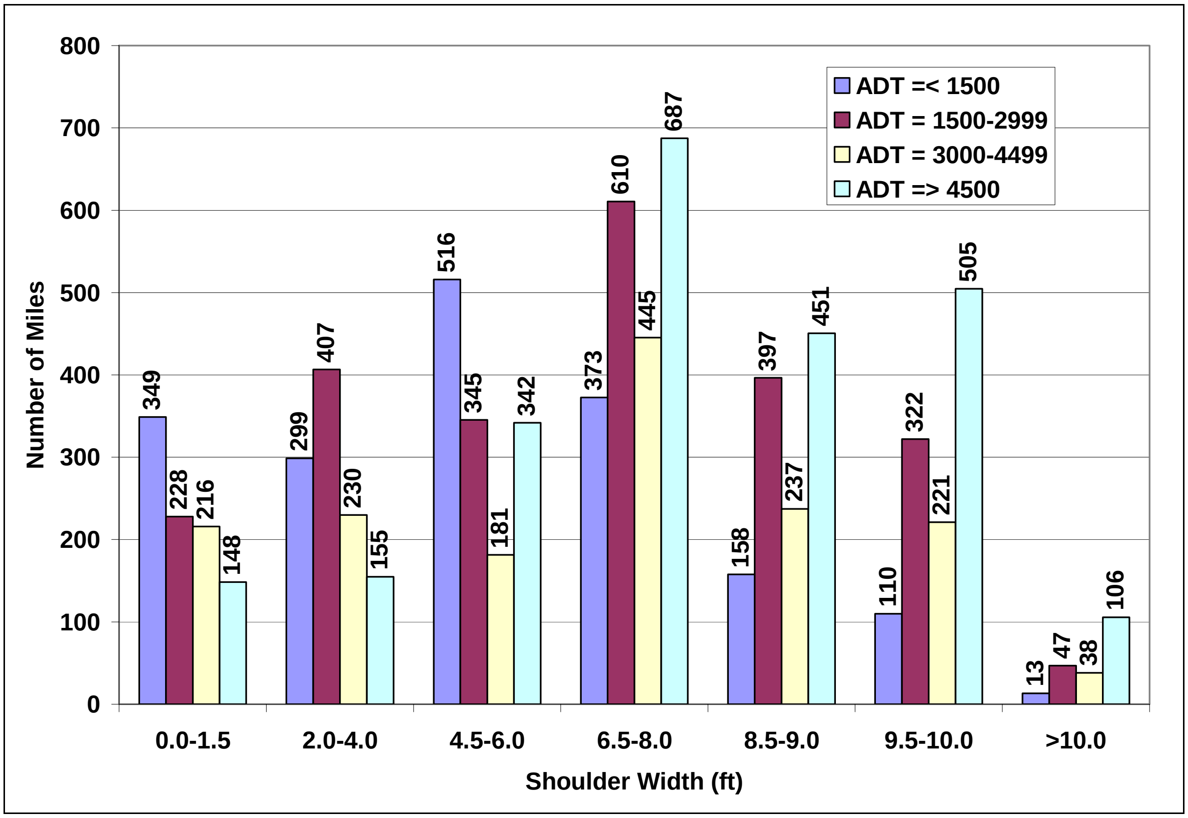

Figure 11. Distribution of Two-Lane Highway Mileage by Shoulder Width.

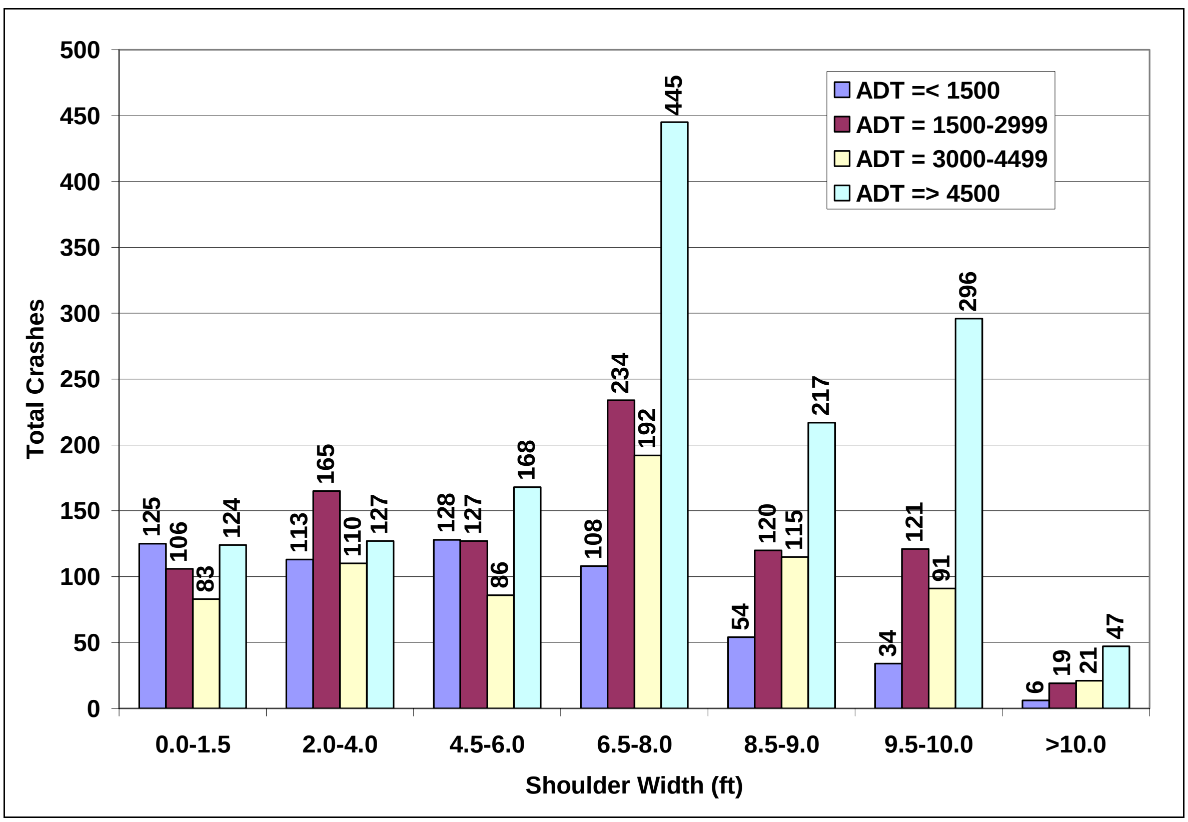

Figure 12. Distribution of Two-Lane Crashes by Shoulder Width.

CHAPTER 4
PRELIMINARY RECOMMENDATIONS

This chapter includes the draft recommendations of the researchers based on the state-of-the-art review and discussions with the project director and advisory panel. These guidelines are subject to change based on the ongoing and planned research as described in the following chapter.

DEFINITIONS

Rumble strips are devices designed to generate audible and tactile vibrations as vehicles pass over them. They consist of raised (bumps) or lowered (divots) breaks in the level surface of a roadway and are placed in proximity to the edge of a roadway, to the centerline of a roadway, or in the lane of a roadway.

Raised rumble strips are rumble strips that are created by the placement and forming of additional roadway material or by placing prefabricated materials on the finished roadway surface. For example, one method would be affixing prefabricated material such as high-density-polyurethane (HDPE) plastic strips to the roadway. In some cases, raised pavement markings serve as raised rumble strips.

Milled rumble strips are a type of rumble strip that is ground (cut) into the finished surface of a roadway and constitutes a divot.

Rolled rumble strips are a type of rumble strip that is rolled into the finished surface of a roadway and constitutes a divot. This method is only for freshly placed asphalt concrete.

Transverse rumble strips (TRSs) are rumble strips that are placed in the lane and generally traverse more than two-thirds of the travel path perpendicular to the direction of travel. These strips are generally raised rumble strips.

Centerline rumble strips (CCRSs) are rumble strips that are installed along the specified roadway centerline.

Length (L) is the dimension of an individual rumble strip as it runs parallel to the direction of travel.

Width (W) is the dimension of an individual rumble strip as it runs perpendicular to the direction of travel.

Spacing is the term for distance in the direction of travel from the front of one rumble strip to the front of the next successive rumble.

On-centers spacing (OCS) is the term for the distance in the direction of travel from the center of one rumble strip to the center of the next rumble strip. This term refers to a similar distance that the term *spacing* refers to, except that the points of measure are different. *Spacing* is the preferred method of measure for it is simpler and more time efficient with regard to field measures.

Gap spacing (GS) describes the distance between two sections of rumble strips, and it is associated with intermittent rumble strip placement.

Depth (D) refers to vertical distance of a rumble strip from the roadway surface to the bottom of a rumble strip. For formed, above ground rumble strips, this dimension will be referred to as *height (H)*.

Intermittent describes an installation of rumble strips that consists of groupings of rumble strips that are broken up by gaps (see gap spacing).

Continuous describes an installation of rumble strips that uses a set spacing between individual rumble strips that is consistent from the start to finish of the installation treatment.

Two-way-left-turn-lane is a lane placed along the centerline of the roadway that allows turning in both directions. The center of the TWLTL commonly coincides with the true centerline of the roadway.

Edgeline is the term for pavement marking that delineates the edge of the lane with the edge of the shoulder of a roadway.

Centerline (CL) is the term for the location of the center of the roadway and is usually delineated by pavement markings on an undivided roadway. The exceptions are turn lanes and TWLTL. In the exceptions, the pavement delineation may not follow the true centerline of the roadway.

Lane lines are the travel-way delineators between the *edgelines* and the *centerlines* on multilane roadways with more than one lane of travel in one direction (this excludes TWLTL).

Offset is a term that describes the distance that an object (i.e., a pavement marking or rumble strip) may be placed laterally or longitudinally from a referenced location such as from another object (i.e., an edgeline). This distance will be measured from the two closest adjacent inside edges of the object unless specified otherwise.

CENTERLINE RUMBLE STRIPS DESIGN RECOMMENDATION

Centerline rumble strips (CRSs) are a countermeasure designed to reduce the occurrence of head-on, opposite direction sideswipe and/or single vehicle crossover crashes on two-way undivided roadways.

Installation Guidelines

- All CRS should be placed on undivided roadways that have shown a high-incidence crash rate with regard to head-on, opposite direction sideswipe and/or single vehicle crossover crashes. Any additional installations may be assessed on a case-by-case basis.

- All CRS should be installed to the following standard dimensions:
  - Rolled rumble strips of the same dimensions as milled rumble strips may be used in place of milled on asphalt concrete (hot-mix) overlays of at least 2 inches (51 mm) of thickness.
  - Non-retroreflective raised pavement markers (RPM) may be used in place of milled rumble strips. See item "CRS RPM Supplement."
  - 0.5 ± 0.125 inch in depth (13 ± 3 mm).
  - 16 ± 0.5 inch in width (406 ± 13 mm), measured perpendicular to the travel path.
  - 7 ± 0.5 inch in length (178 ± 13 mm), measured with the direction of the travel path.
  - 17 ± 0.5 inch (432 ± 13 mm) longitudinal spacing between adjacent rumble strips or 24 ± 0.5 inch (610 ± 13 mm) on-centers spacing.
  - See the detailed drawings in Figures 13 through 15.

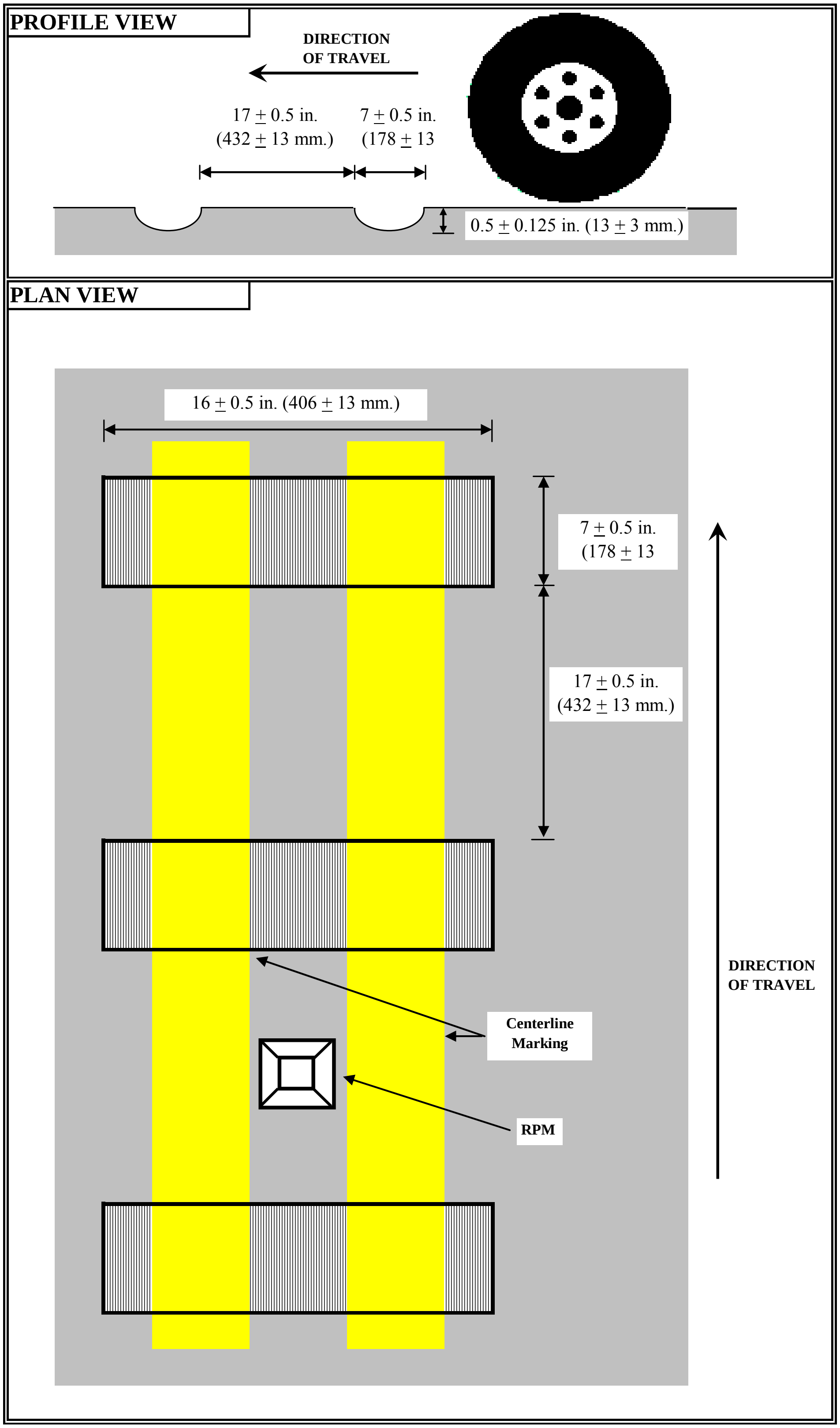

Figure 13. Centerline Rumble Strip (Detail 1).

- CRSs should be installed along the delineated CL on undivided roadways without TWLTL.

- CRSs may be installed along the edgeline delineating pavement stripes for TWLTL. The TWLTL should have at least a 14-foot (4.3-meter) width from the outside edges of the solid edgelines, and the CRSs will be reduced to 12 ± 0.5 inches (305 ± 13 mm) in width for each edgeline. Alternatively, CRSs may be installed down the middle of a TWLTL.

- In areas where delineated left-turning bays are installed, the CRSs should follow the outside CL pavement marking to the direction of travel with the left-turn bay.

- All CRSs should be continuous and will be installed in both passing and no-passing zones (CRSs).

- Breaks in the CRSs will start at least 50 feet (15.2 m) and no more than 150 feet (45.7 m) prior to each approach for the following instances:
    - Bridges
    - Roadways with guardrails that do not provide at least 2 feet (0.6 m) of shoulder width.
    - Intersections
    - Driveways with high usage or large trucks

- CRSs should not be cut into joints; they should be placed to one side of the joint, or the particular individual rumble strip should be skipped.

- RPM and lane striping should be placed according to current TxDOT standards as addressed in the Texas Manual of Traffic Control Devices (TMUTCD) and TxDOT Standard Sheets.
    - When specifying RPM placement, the project engineer should use the standard specifications as depicted in TxDOT standard drawing PM(2)–00A, "Position Guidance Using Raised Pavement Markers" and should not use the supplemental standard PM(3)-00A.
    - The individual CRS closest to the placement of an individual RPM should be skipped, and the RPM should be placed equidistant from the two remaining adjacent CRSs.
    - Profile markings should not be used in conjunction with CRSs.

- CRSs should not be installed in areas with the following conditions unless approved by the Traffic Operations Division:
    - Roadways with less than 12-foot (3.7-meter) wide lanes.
    - Roadways with less than 2-foot (0.6-meter) wide paved shoulders.
    - Roadways with less than 2.5 inches (64 mm) in slab thickness for asphalt concrete.
    - Roadways with less than 2.5 inches (64 mm) in slab thickness between the top of the roadway surface to the top of the rebar or structural reinforcement in Portland cement concrete.
    - Roadways with significant deterioration and/or raveling ("significant" will be defined by the project engineer with regards to current TxDOT engineering practices).
    - Current construction projects are not complete and may conflict (i.e., an overlay or widening are scheduled or under construction).

- The following considerations are suggested before installing CRSs:
  - Look at noise impacts to the community. This does not mean do not install, only access any problems, be prepared to respond to public concern, and look for any applicable and practical noise mitigation techniques.
  - Coordinate CRS installation with other design projects, such as schedule after roadway resurfacing and prior to pavement striping.

- CRS RPM Supplement
  - The RPM should be:
    - A standard 4-inch-diameter (102 mm) round button.
    - Laterally offset 0 inches (0 mm) from the outside of the centerline striping (the RPM will encroach on the travelway by 4 inches (102 mm)).
    - 24 ± 0.5 inches (610 ± 13 mm) longitudinal spacing between adjacent RPM or 24 ± 0.5 inches (610 ± 13 mm) on-center spacing.
    - Yellow, black or gray when it is placed directly on the pavement with the applicable binder.
    - Yellow when it is placed over centerline pavement strips with the applicable binder.

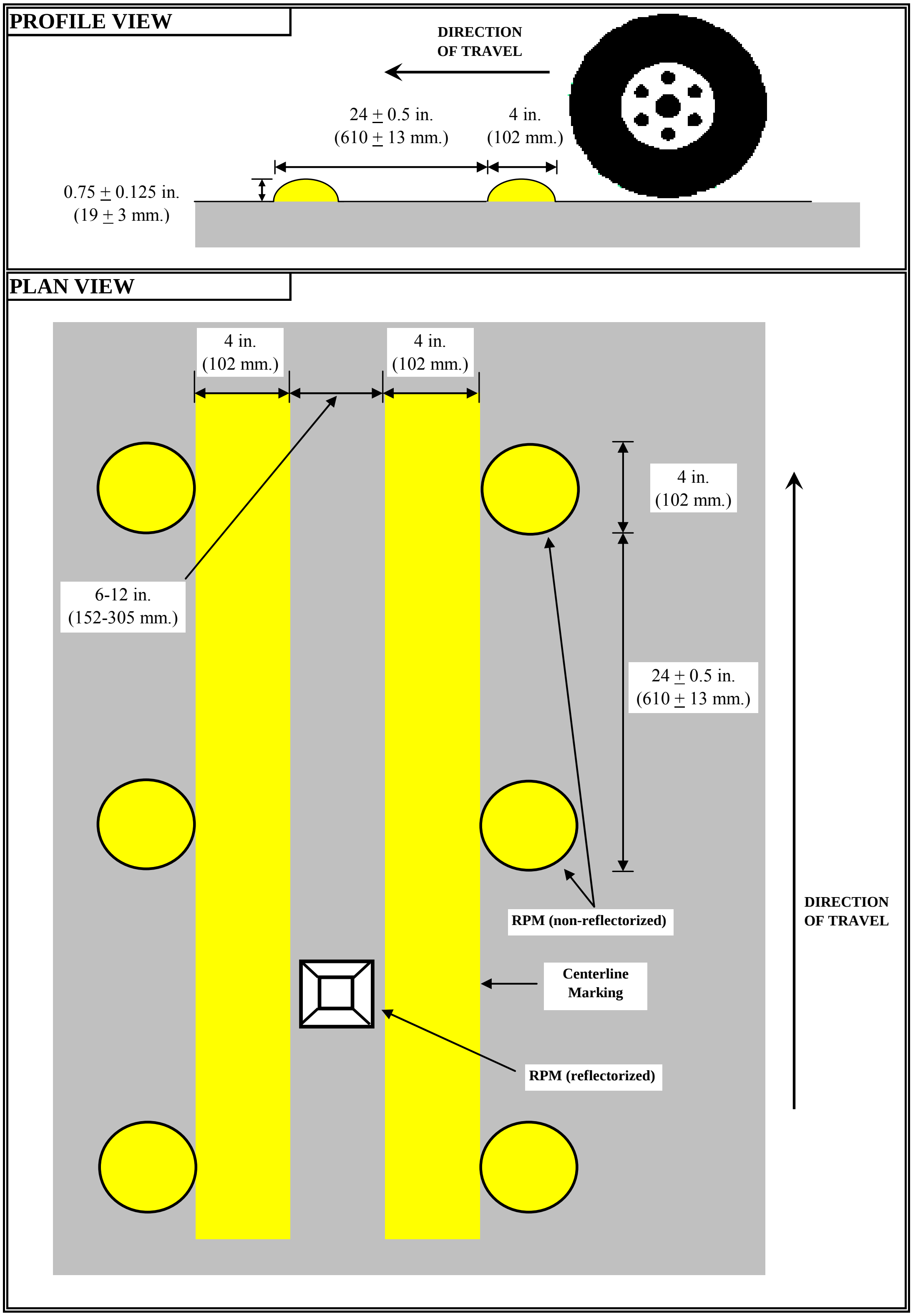

Figure 14. Centerline Rumble Strip (Detail 2).

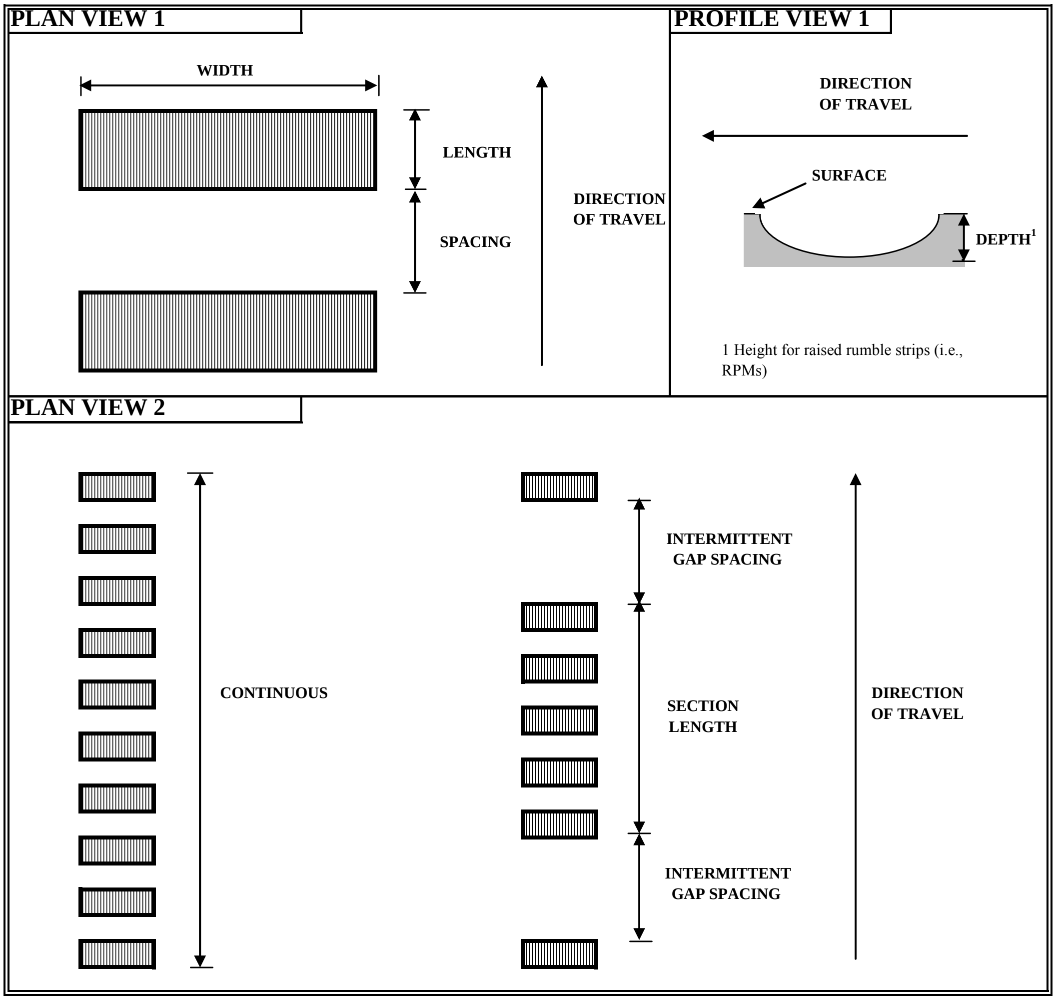

Figure 15. Centerline Rumble Strip (Detail 3).

TRANSVERSE RUMBLE STRIPS DESIGN RECOMMENDATION

Transverse rumble strips are a countermeasure designed to reduce the occurrence of single and multi-vehicle crashes that occur as a result of inattentive motorists approaching stop-controlled intersections or horizontal curves. The preliminary recommendations that are being tested are based on the design shown in Figure 16. This design was based on the findings in the literature as well as the researchers' initial recommendations and the subsequent changes as a result of project advisory input.

One of the benefits of this design is that the location of the rumble strips is based on the warning sign location and not on the intersection of the horizontal curve location. This situation is primarily because the intent or the rumble strips is to get inattentive drivers to become aware of the approaching conditions. The warning signs at these locations are already positioned in accordance with the vehicle speeds. Therefore, the use of the warning sign as a base measuring point for locating the rumble strips will provide drivers ample time to become aware of their conditions and react in time to be safe.

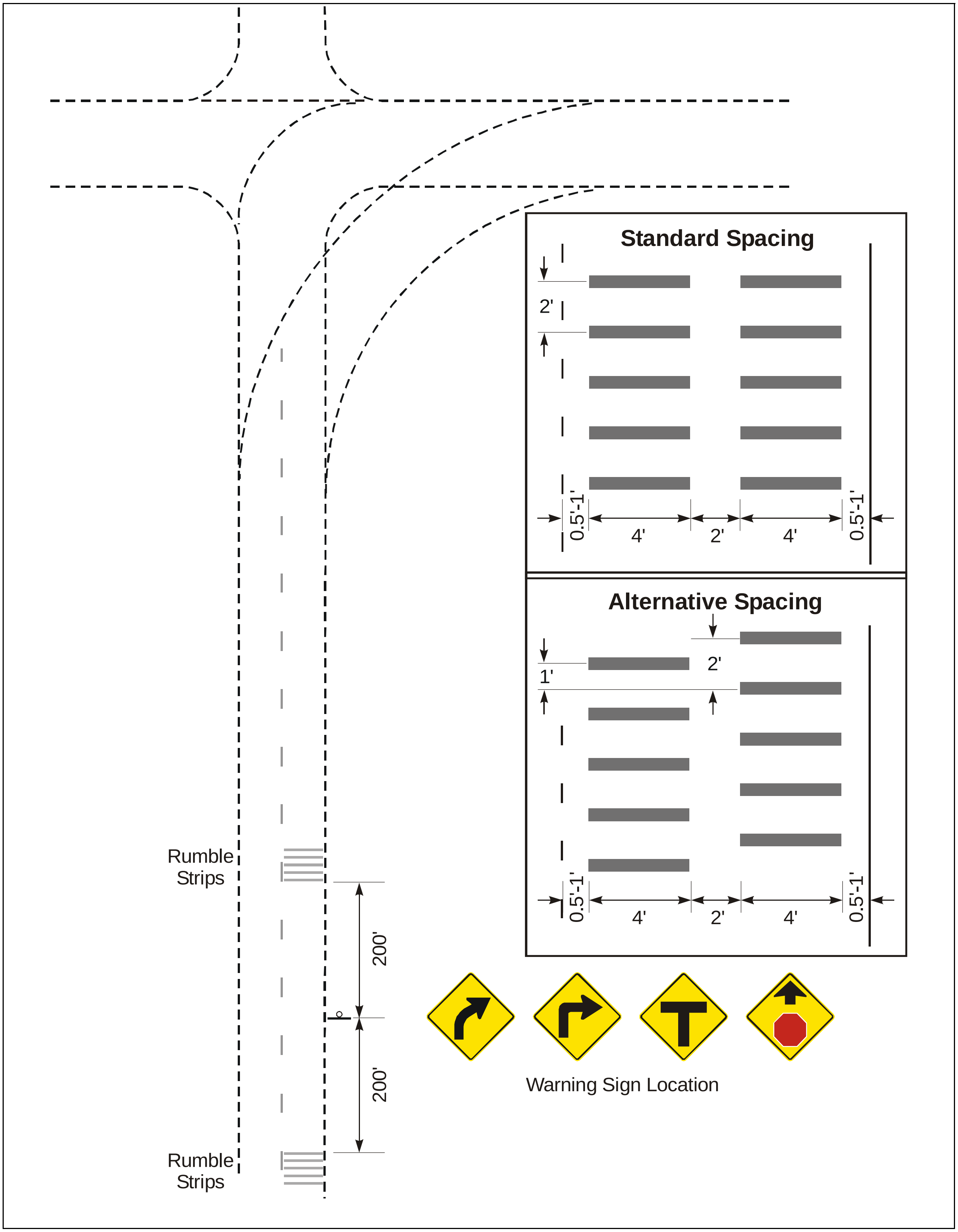

Figure 16. Preliminary Transverse Rumble Strip Application.

CHAPTER 5
CURRENT STATUS AND PLANNED YEAR-TWO ACTIVITIES

CURRENT STATUS

Once the literature was reviewed and the pertinent state policies were obtained and reviewed, the researchers developed preliminary recommendations for TxDOT. Since then, the researchers have been testing the in-lane rumble strip recommendations at several sites throughout the state. Table 12 shows the progress of this research as of August 20, 2003. The work for in-lane rumble strips is planned to be completed by the end of the calendar year.

Table 12. Progress of In-Lane Rumble Strip Field Studies.

Site Location	Study Approach	Intersecting Arterial	Approach	Before Data			Rumble Strips Installed	VIDEO	After Data		
				Weekday	Weekend	Analyzed			Weekday	Weekend	Analyzed
Colorado City	FM 208	SH 20	SB	5/14/2003	--	7/7/2003	5/21/2003	--	6/26/2003	--	7/22/2003
Colorado City	FM 208	SH 20	NB	5/14/2003	--	7/8/2003	5/21/2003	--	6/26/2003	--	7/22/2003
Millican	FM 2154	FM 159	SB	7/10/2003	8/17/2003	8/19/2003		***			
Millican	FM 2154	FM 159	NB	7/10/2003	8/17/2003	8/19/2003		***			
Snook	FM 60	FM 50	SB					--			
Snook	FM 60	FM 50	NB					--			
Hearne	FM 2549	FM 391	SB					***			
Hearne	FM 2549	FM 391	NB					***			
Bosque Co. (Waco)	FM 3118	SH 22	T					--			
Shiro/Richards	FM 1486	FM 149	T	4/10/2003	--	4/21/2003	4/29/2003	--	7/23/2003	--	8/14/2003
Shiro/Richards	FM 2819	FM 1486	T	4/10/2003	--	5/9/2003	4/29/2003	--	7/23/2003	--	8/15/2003

NOTE: *** = data to be collected

Once the draft guidelines for the centerline rumble strips were developed, the researchers began contacting TxDOT districts in an attempt to find situations where centerline rumble strip installations could be installed within the timing of the project. Currently, there are no centerline rumble strips installed. However, there are at least two districts where significant progress has been made in terms of finding appropriate sites and beginning the proper paperwork to have the research project cover or at least subsidize the costs of the installation. The researchers had hoped to have centerline rumble strips installed along at least two roadway sections before the end of the calendar year. However, the installations were slightly delayed. Raised centerline rumble strips were installed in the Austin District in January 2004, and milled centerline rumble strips were installed in February 2004 in the Brownwood District.

SECOND-YEAR ACTIVITIES

Based on the results of the first year's activities, several future activities have been planned. These following activities will provide TxDOT with a set of recommended guidelines that will be field tested and ready for implementation:

1. Continue to study the effect of transverse rumble strips at locations to stop-controlled intersections and hazardous horizontal curves. It is too early in the research to determine the effectiveness of this application. However, the literature review and the increasing number of state agencies using transverse rumble strips indicate that there is promise in this application. If needed, the preliminary guidelines will be modified as necessary.

2. Continue to identify potential study sites for the study of centerline rumble strips. Although there are currently several potential study sites on the horizon, additional sites will be needed as back-up plans. It is critical that study sites are determined as soon as possible as this application of rumble strips has been determined by the project director and advisory panel to be the most emphasized element of this research project. However, success in this realm is contingent on the cooperation of the districts in terms of identifying sites and working with the researchers to get CRSs installed.
3. Determine locations where profiled markings have been installed and perform an ad-hoc safety analysis study to determine the effectiveness of the markings. The identification of these sites will be achieved through a district-wide email to the traffic engineers.

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APPENDIX
AN EXAMPLE RUMBLE STRIP POLICY

This appendix includes the Pennsylvania Department of Transportation's policy for centerline and edgeline rumble strips. This policy is included because it represents the most comprehensive policy of any state DOT. However, policies from many other states were obtained and reviewed during the first year of this research project.

Attachment A

MILLED CENTERLINE RUMBLE STRIPS
(For Non-Interstate and Non-Expressways Use)

Responsibilities:

District Safety Engineer is the process Owner.

Guidelines for Use:

1. The purpose of milled Center Line Rumble Strips (CLRS) is to reduce the occurrence of head-on and/or sideswipe crashes on undivided two-lane or four-lane highways.

2. Consider CLRS on the following locations and under following conditions:

Roadway Description	Typical Drawing Detail
Roadway with 12 feet or greater lane width and minimum of 3 feet of paved shoulder.	Detail # 1
Roadway with 11 feet lane width and minimum of 3 feet of paved shoulder.	Detail # 1 or Detail # 2
Roadway with 11 feet lane width and less than 3 feet of shoulder or no shoulder.	Detail # 2
Roadway with 10 feet lane width with or without shoulder.	Detail # 2
Roadway with less than 10 feet lane width	Consult BHSTE

3. Milled centerline rumble strips (CLRS) are for use on bituminous pavement.

4. Installing CLRS on bituminous pavement requires an ID-2 or ID-3 surface with BCBC base or better.

5. If it is desired to retrofit CLRS on existing pavement, the pavement should be in sufficiently good condition, as determined by the District, to effectively accept the milling process without raveling or deteriorating. Otherwise the pavement needs upgraded prior to milling any desired CLRS.

6. CLRS should not be installed on existing concrete pavements with overlay less than 2 ½” in depth.

PennDOT CLRS Policy – Pg 1

7. Do not install CLRS on bridge decks.

8. CLRS may be installed in passing zones where deemed appropriate by District safety personnel. Consider reducing depth of cut to 3/8" in areas where passing is permitted. If CLRS are being discontinued for a passing zone, use engineering judgment as to where to terminate CLRS in advance of a passing zone.

9. CLRS are to be broken for intersections. Also consider breaking for driveways according to engineering judgment. When breaking CLRS pattern, discontinue CLRS 25 feet from the Point of Curvature of any such highway or driveway (refer to Typical Detail #3).

10. Coordinate the milling of CLRS with all necessary project phases. Do not mill the CLRS until all appropriate construction phases are completed.

11. Coordinate the milling of CLRS with traffic line painting operations a) to avoid milling newly applied traffic lines and b) to install new yellow centerlines within two weeks of CLRS completion.

12. Consult the Bureau of Highway Safety & Traffic Engineering before installing CLRS on highways with travel lane widths that are less than 10 feet.

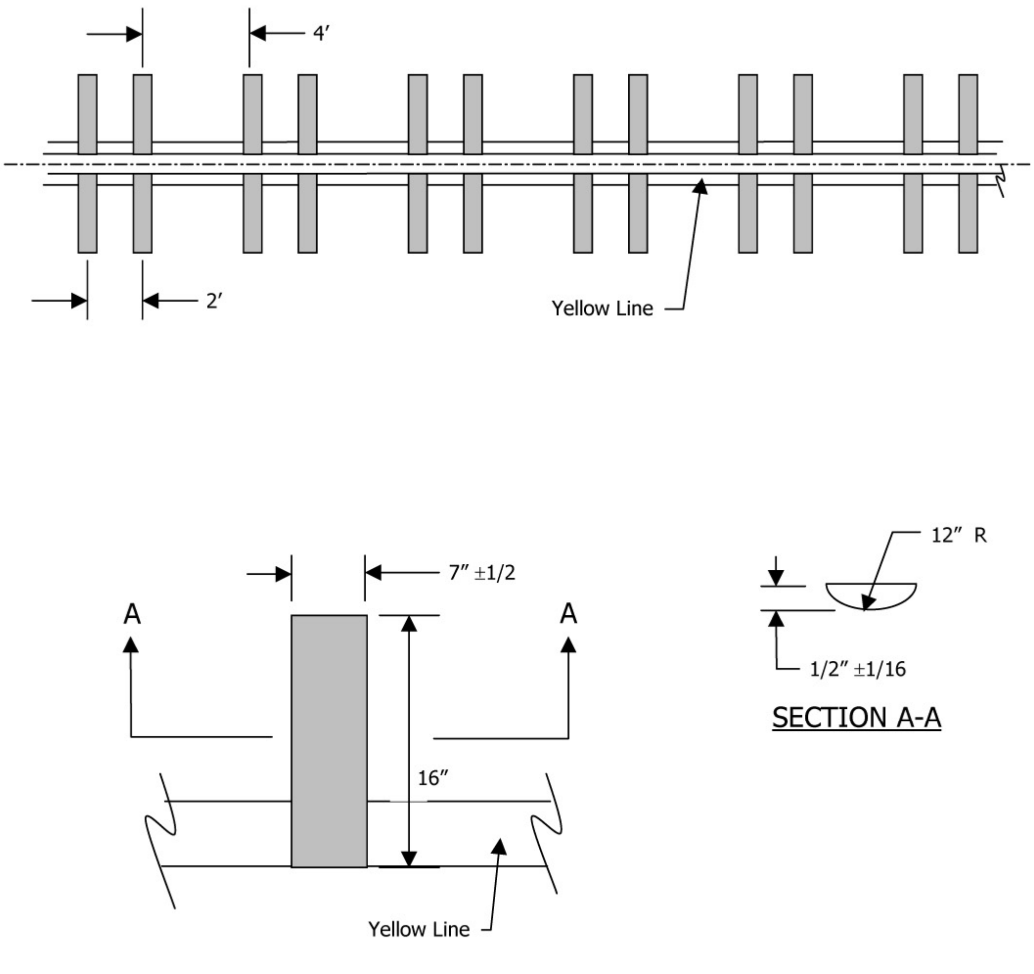
13. Take into consideration potential noise impacts when contemplating the installation of CLRS in residential or urban areas.

DESIGN DEVIATION

Deviation from the above specifications and guidelines may be considered by the district; however, they must be approved by the Bureau of Highway Safety & Traffic Engineering prior to being implemented.

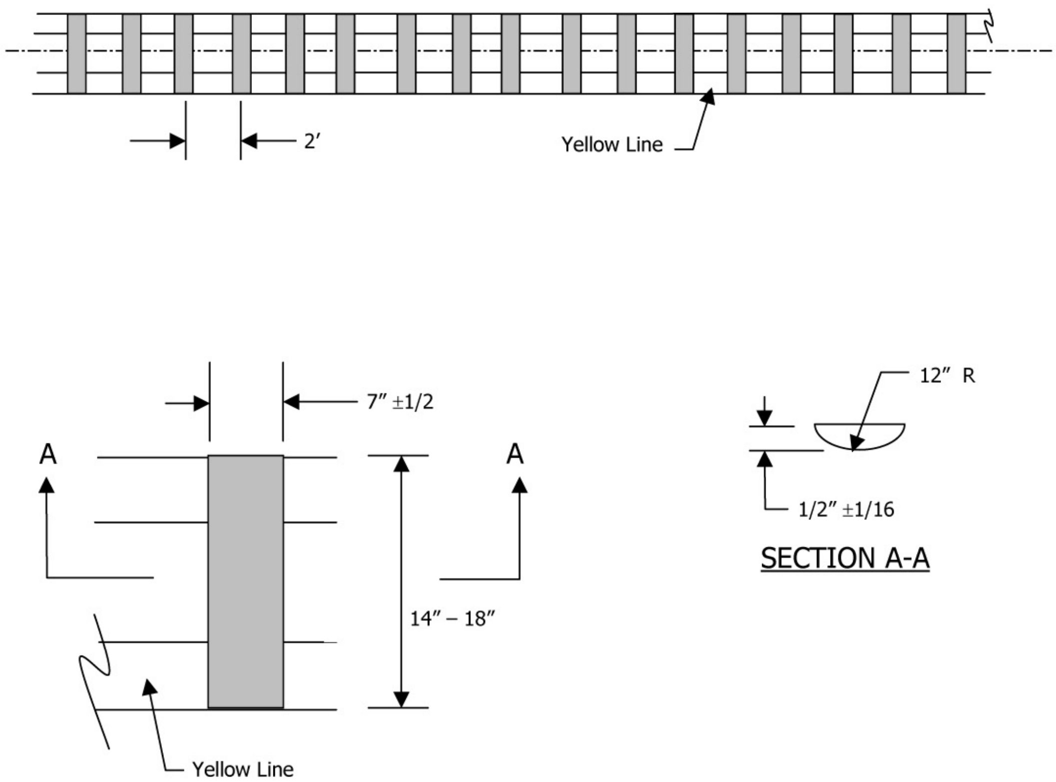
PennDOT CLRS Policy – Pg 2

Attachment A (cont.)
Milled Centerline Rumble Strips
Typical Drawing Detail # 1



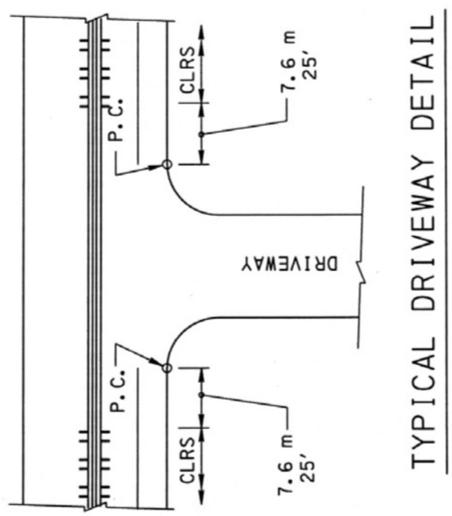
PennDOT CLRS Policy – Pg 3

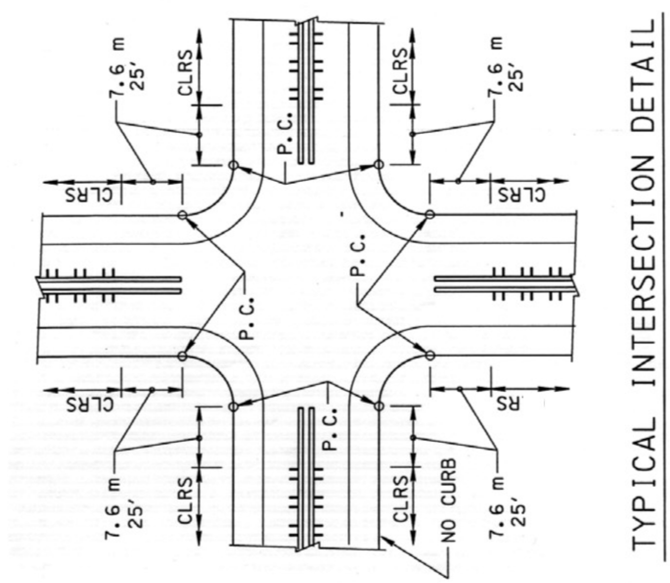
Attachment A (cont.)
Milled Centerline Rumble Strips
Typical Drawing Detail # 2



PennDOT CLRS Policy – Pg 4

Attachment A (cont.)
<u>Center Line Rumble Strips</u>
Typical Drawing Detail # 3





Attachment B

BICYCLE TOLERABLE SHOULDER RUMBLE STRIPS (BTSRS)
(For Non-Interstate and Non-Expressways Use)

Responsibilities:

District Safety Engineer is the process owner.

District Pedestrian/Bicycle Coordinator shall jointly review the areas to be targeted.

Guidelines for Use:

Consider Bicycle Tolerable Shoulder Rumble Strips (BTSRS) on the following locations and under following conditions:

1. The purpose of BTSRS is to reduce run-off-the-road crashes on highways (except interstates and expressways).

2. Consider BTSRS for the following types of two-four lane highways (except Interstate & Expressways):

   - Where the roadway lane width is 11 feet or greater, 6 feet or more of paved shoulder and the posted speed is 55 MPH or greater, the BTSRS shall be installed on the shoulder as shown in Typical Drawing Detail # 1.

   - Where the roadway lane width is 11 feet or greater, 6 feet or more paved shoulder and the posted speed is less than 55 MPH, the BTSRS shall be installed on the shoulder as shown in Typical Drawing Detail #2.

   - If the shoulder width is less than 6 feet in any case, consider the Edgeline Rumble Strips (ERS), outlined in Attachment C.

3. The paved shoulder must be equal in smoothness to that of the adjacent travel lane.

4. Installing BTSRS on bituminous pavement requires an ID-2 or ID-3 surface with BCBC base or better.

5. If it is desired to retrofit BTSRS on existing pavement, the pavement & shoulder should be in sufficiently good condition, as determined by the District, to effectively accept the milling process without raveling or

deteriorating the pavement. Otherwise both the pavement & shoulders need to be upgraded prior to milling BTSRS.

6. Do not install BTSRS on bridge decks.

7. BTSRS are to be broken for intersections. Also consider breaking for driveways according to engineering judgment. When breaking BTSRS pattern, discontinue BTSRS 25 feet from the Point of Curvature of any such highway or driveway (refer to Typical Detail #3).

8. Coordinate the milling of BTSRS with all necessary project phases. Do not mill the BTSRS until all appropriate construction phases are completed.

9. Take into consideration potential noise impacts when contemplating the installation of BTSRS in residential or urban areas.

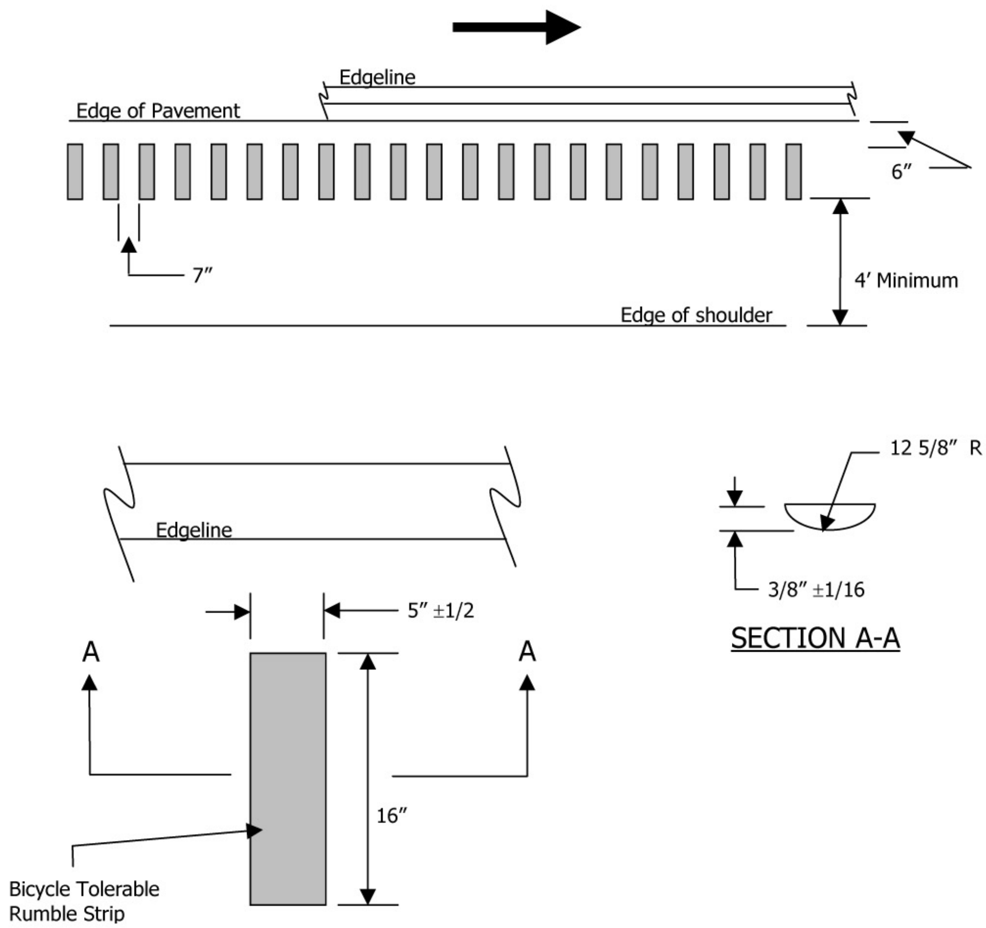
10. As part of multi-modal transportation system planning, consult the District Pedestrian/Bicycle Coordinator where BTSRS are being planned for installation, and determine if the District Coordinator has any concerns. These concerns may include Bicycle PA routes, other local bike routes, Adventure Cycling Association, National Bike routes in Pennsylvania, proposed bike routes from MPO/LDD regional plans, potential ADA violations and others.

DESIGN DEVIATION
Deviation from the above specifications and guidelines may be considered by the District; however, they must be approved by the Bureau of Highway Safety & Traffic Engineering prior to being implemented.

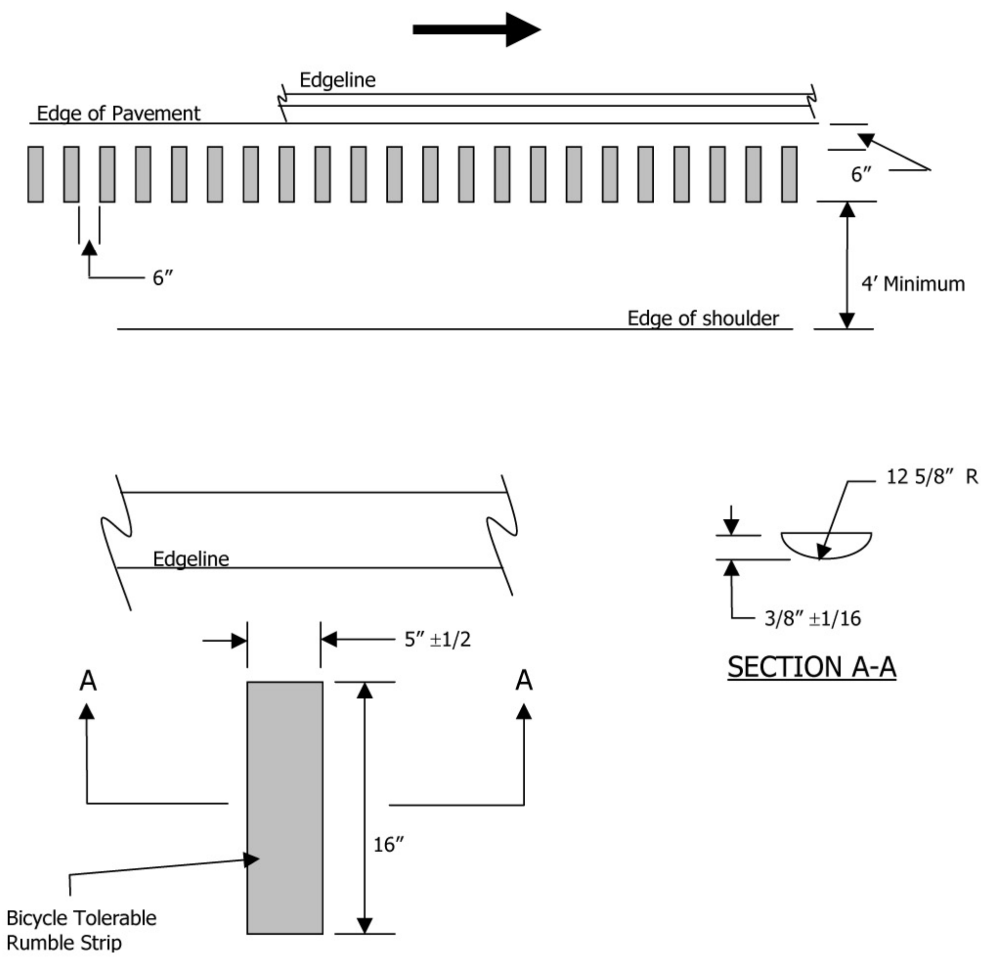
Attachment B (cont.)

BTSRS Detail (55 MPH or More Posted Speed)

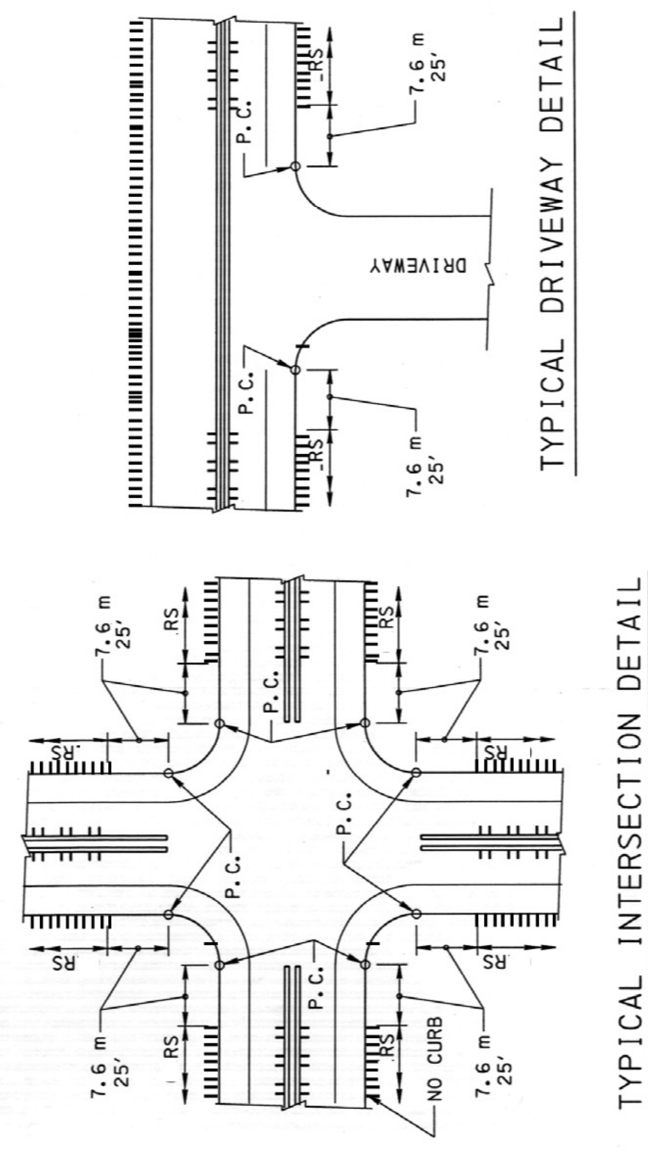
Typical Drawing Detail # 1



Attachment B (cont.)
BTSRS Detail (Less than 55 MPH Posted Speed)
Typical Drawing Detail # 2



Attachment B (cont.)
<u>Bicycle Tolerable Rumble Strips</u>
Typical Drawing Detail # 3



Attachment C

PENNSYLVANIA EDGELINE RUMBLE STRIP (ERS) GUIDELINES
(For Non-Interstate and Non-Expressways Use)

Responsibilities:

District Safety Engineer is the process owner.

District Pedestrian/Bicycle Coordinator shall jointly review the areas to be targeted.

Guidelines for Use:

Consider milled Edgeline Rumble Strips on the following locations and under the following conditions:

1. The purpose of ERS is to reduce run off the road crashes on highways (except interstates and expressways).
2. Consider ERS for the following types of two-to-four lane highways (except Interstate & Expressways):
   - On highways with 11 feet or greater lane width and 4-6 feet of paved shoulder, ERS shall be installed on the edge of the roadway as shown in Typical Drawing Detail # 1.
   - If the shoulder width is greater than or equal to 6 feet, consider the Bicycle Tolerable Rumble Strips shown in Attachment B.
3. If there is concern with the pavement joint between the roadway and the shoulder, district may consider the following options:
   - Where shoulder width is between 5-6 feet, offset ERS 2-4 inches from the joint into the shoulder surface.
   - Where shoulder width is less than 5 feet, district may offset ERS 2-4 inches from the joint into the travel lane surface.
4. The ERS shall be discontinued 50 feet before and after adjacent guiderail, where the face of the guiderail is located less than 4 feet from the edge line of the roadway.
5. The paved shoulder and the adjacent travel lane should be of equal smoothness.

6. Installing ERS on bituminous pavement requires an ID-2 or ID-3 surface with BCBC base or better.

7. If it is desired to retrofit ERS on existing pavement, the pavement & shoulder should be in sufficiently good condition, as determined by the District, to effectively accept the milling process without raveling or deteriorating the pavement. Otherwise both the pavement & shoulders need to be upgraded prior to milling any desired ERS.

8. Do not install ERS on bridge decks.

9. ERS are to be broken for intersections. Also consider breaking for driveways according to engineering judgment. When breaking ERS pattern, discontinue ERS 25 feet from the Point of Curvature of any such highway or driveway (refer to Typical Detail #2).

10. Coordinate the milling of ERS with all necessary project phases. Do not mill the ERS until all appropriate construction phases are completed.

11. Coordinate the milling of ERS with traffic line painting operations a) to avoid milling newly applied traffic lines and b) to install new white edge lines within two weeks of ERS completion.

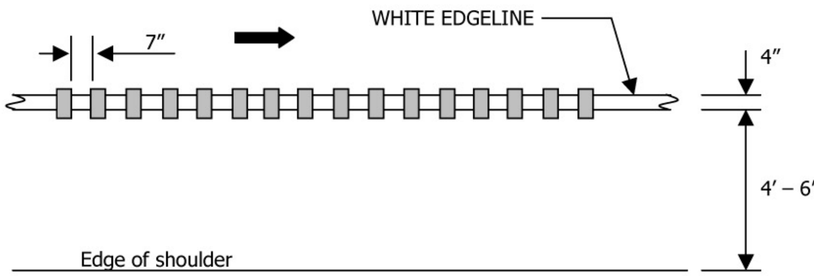
12. Take into consideration potential noise impacts when contemplating the installation of ERS in residential or urban areas. Do not install ERS on the inside of moderate to sharp curves which are in the immediate vicinity of any residence.

13. As part of multi-modal transportation system planning, consult the District Pedestrian/Bicycle Coordinator where ERS are being planned for installation, and determine if the District Coordinator has any concerns. These concerns may include Bicycle PA Routes, other local bike routes, Adventure Cycling association, National Bike Route segments in Pennsylvania, proposed bike routes from MPO/LDD regional plans, potential ADA violations and others.

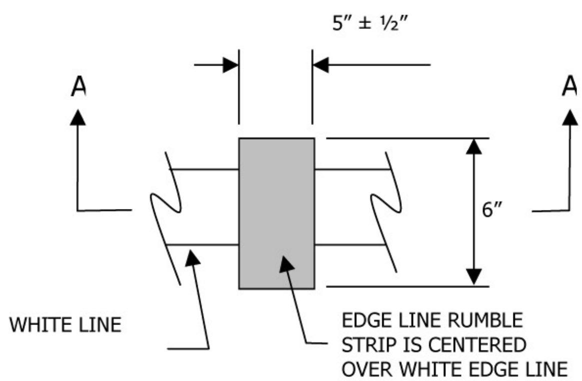
DESIGN DEVIATIONS

Deviation from the above specifications and guidelines may be considered by the District; however, they must be approved by the Bureau of Highway Safety & Traffic Engineering prior to being implemented.

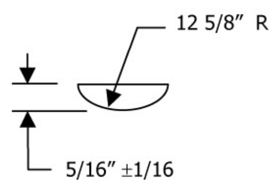
Attachment C (cont.)
Edgeline Rumble Strips
Typical Drawing Detail # 1



TYPICAL PLAN VIEW FOR MILLED EDGE LINE RUMBLE STRIP PATTERN



RUMBLE STRIP DETAIL



SECTION A-A

Attachment C (cont.)
Edgeline Rumble Strips
Typical Drawing Detail # 2