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RUMBLE STRIPS FOR ROADS WITH NARROW OR NON-EXISTENT SHOULDERS

University-Based Research, Education, and Technology Transfer Program

AGREEMENT NO. 359704, WORK ORDER 87

FINAL REPORT

September 2001

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16. Abstract

The goal of this project is to develop conceptual designs for rumble strips to be placed on roads with narrow or non-existent shoulders, so that: a) their installation does not compromise the integrity of the pavement, b) their location and/or type are acceptable for bicyclists, and c) they can alert inattentive drivers. Very little information was found in the literature specifically related to the installation of rumble strips on roads with narrow or non-existent shoulders. However, several states have written or unwritten policies related to the installation of rumble strips on two-lane roadways. These policies were reviewed to gain a broader perspective of the issues related to the application of rumble strips along roads with narrow shoulders.

Assuming the roadway to be a non-freeway facility with good pavement conditions, once a site has been identified for the installation of rumble strips to reduce run-off-the-road crashes, two procedures are developed to determine the preferred lateral width of the rumble strip and the optimum placement of rumble strips within the roadway cross-section. These procedures can be used in combination with the findings from the *Bicycle-Tolerable Shoulder Rumble Strips* project (Elefteriadou et al., 2000) to determine the exact pattern and placement for rumble strips on roads with narrow or non-existent shoulders.

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Prepared for

Commonwealth of Pennsylvania
Department of Transportation
Office of Planning & Research

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PTI

TABLE OF CONTENTS

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EXECUTIVE SUMMARY

The goal of this project is to develop conceptual designs for rumble strips to be placed on roads with narrow or non-existent shoulders, so that: a) their installation does not compromise the integrity of the pavement, b) their location and/or type are acceptable for bicyclists, and c) they can alert inattentive drivers. Very little information was found in the literature specifically related to the installation of rumble strips on roads with narrow or non-existent shoulders. However, several states have written or unwritten policies related to the installation of rumble strips on two-lane roadways. These policies were reviewed to gain a broader perspective of the issues related to the application of rumble strips along roads with narrow shoulders.

Assuming the roadway to be a non-freeway facility with good pavement conditions, once a site has been identified for the installation of rumble strips to reduce run-off-the-road crashes, two procedures are developed to determine the preferred lateral width of the rumble strip and the optimum placement of rumble strips within the roadway cross-section. These procedures can be used in combination with the findings from the *Bicycle-Tolerable Shoulder Rumble Strips* project (Elefteriadou et al., 2000) to determine the exact pattern and placement for rumble strips on roads with narrow or non-existent shoulders.

The methodology for determining the preferred lateral width of the rumble strip and the optimum placement of rumble strips within the roadway cross-section is as follows:

1) Determine the preferred lateral width of the rumble strip.

Determining the preferred lateral width of a rumble strip depends upon a desired exposure time of the stimuli (noise and/or vibration) generated by the rumble strips. The exposure time of the stimuli is a function of vehicle speed, departure angle, the lateral width of the rumble strips, and the contact area of the tire.

2) Determine the preferred placement of the rumble strips.

The placement of rumble strips within the roadway cross-section is a function of the clear zone and the steering adjustment area. For rumble strips to fulfill their intended purpose, the clear zone should be greater than the steering adjustment area. Such information however may be difficult to obtain and estimate for an entire roadway section. Thus, two methods were developed for determining the optimum placement of rumble strips within the roadway cross-section. It can be determined based upon the clear zone and steering adjustment areas, or it can be determined based upon the roadside hazard rating. The simplified procedure for determining the optimum placement of rumble strips based upon the roadside hazard rating is recommended.

The roadside hazard rating is a seven-point scale that takes into account the overall hazard of the site as well as the potential frequency and severity of roadside crashes.

Roadsides are rated according to accident damage likely for errant vehicles on a scale from one (low likelihood of off-road collision or overturn) to seven (high likelihood of a crash resulting in fatality or severe injury).

A) If the roadside hazard rating is 5 or higher, the site has the potential for more severe crashes. Therefore, the rumble strips should be placed within the roadway cross-section to provide the greatest amount of paved recovery area so the rumble strips should be centered along the center of the edge line.

B) If the hazard rating is 4 or lower, the site has a lower potential for severe crashes. Therefore, the rumble strips should be placed on the outside (right) portion of the shoulder. The rumble strips should be placed as far as possible to the edge of the paved shoulder without compromising the integrity of the paved shoulder. Pavement cross-section on the shoulder and the capabilities of the milling machine should be taken into consideration when determining this distance.

Appendix C is a stand-alone concise guide for practitioners that want to use the simplified method for determining the preferred lateral width and optimum placement of rumble strips within the roadway cross-section.

An experimental plan is provided to evaluate the conceptual design of rumble strips for roads with narrow or non-existent shoulders. The plan consists of four types of evaluations to determine whether the goal of the research is achieved. A before-after crash analysis should be conducted with comparison sites to estimate the safety effectiveness of the rumble strip installations while controlling for time trend effects. To assess the effectiveness of the rumble strip configurations on alerting inattentive motorists, field tests of motor vehicles should be conducted to measure the auditory and vibrational stimuli generated by the rumble strips. To assess the impacts of the rumble strip configurations on bicyclists, bicycle tests should consist of measuring the accelerations experienced by the bicyclists while traversing the rumble strip configurations, and a survey should be filled-out by bicyclists local to the area to determine bicyclists' perception of ride quality along route prior to installation of the rumble strips and afterwards. Finally, the impacts on pavement performance of the rumble strips under investigation should be assessed through real-time and accelerated field testing.

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

To address the problem of frequent run-off-the-road types of crashes on Pennsylvania highways, the Pennsylvania Department of Transportation (PENNDOT) is currently using milled shoulder rumble strips (MSRS) to alert inattentive/drowsy drivers who are drifting to the right and/or to the left, out of the travel lane. MSRS are a pattern of grooves ground into asphalt or concrete shoulders, which transmit auditory and vibrational warnings to the drifting motorist.

Within Pennsylvania, MSRS have been installed primarily along limited access highways and in some cases four-lane highways and two-lane roads. To extend the use of MSRS to roads with narrow or non-existent shoulders, several issues need to be addressed. These issues revolve around the design of the rumble strips and their placement along the highway. The goal of this project is to develop conceptual designs for rumble strips to be placed on roads with narrow or non-existent shoulders, so that: a) their installation does not compromise the integrity of the pavement, b) their location and/or type are acceptable for bicyclists, and c) they can alert inattentive drivers.

This report summarizes the research conducted to develop these conceptual designs. The report consists of seven sections. Following this introduction, section two presents the research methodology. Section three presents findings from the literature review and the survey of highway agencies conducted to learn more about the experiences and policies related to rumble strips on roads with narrow shoulders. Section four presents procedures to determine the preferred lateral width of rumble strips and the placement of rumble strips within the roadway cross-section. Section five presents several examples of how the methodology is used to determine the preferred lateral width and placement of rumble strips. Section six discusses an experimental plan to field test these conceptual designs, and section seven provides final conclusions and recommendations from the research.

2. RESEARCH METHODOLOGY

The following tasks were undertaken to develop effective and safe rumble strips for placement on roads with narrow or non-existent shoulders:

Task 1: Reviewing task force
Task 2: Literature review
Task 3: Conceptual design
Task 4: Experimental plan development

The first task of the project was to establish a reviewing task force to provide guidance during various stages of the project. PENNDOT selected the task force representatives. The task force consisted of representatives from the highway safety and traffic engineering community, the bicycle community, and human factor research community. Appendix A lists the names and affiliations of the individuals who served on the task force.

The second task was to document the following:

a) The application and/or types of rumble strips on roads with narrow or non-existent shoulders and issues relative to location, width, spacing, noise and vibration, and curve vs. tangent placement.
b) Studies of pavement integrity relative to rumble strip installation.
c) Studies of driver reactions to rumble strips.

First, a thorough literature review was conducted to identify references that had been added to the literature since the completion of Work Order 25: Bicycle-Tolerable Rumble Strips (Elefteriadou et al., 2000). Next, representatives from several state departments of transportation (DOTs) and the Federal Highway Administration (FHWA) were contacted to identify any existing installations of rumble strips on roads with narrow or non-existent shoulders and inquire about state rumble strip policies. In addition, a survey was sent to rumble strip providers/contractors to document their experiences of installing rumble strips on roads with narrow or non-existent shoulders.

The third task was to develop a conceptual design for rumble strips, considering human factors issues, pavement integrity, bicyclist comfort, and driver alertness. The preliminary conceptual design was presented to the reviewing task force at a meeting in Harrisburg, Pennsylvania on May 8, 2001. The conceptual design was modified to incorporate comments discussed during the May 8, 2001 meeting and subsequent discussions with members of the reviewing task force. The conceptual design for rumble strips consists of a methodology to determine the preferred lateral width of the rumble strips and the optimum placement of rumble strips within the roadway cross-section.

The objective of the fourth task was to develop an experimental plan to field test the conceptual designs. The experimental plan was developed taking into consideration the following issues:

a) The types of roadways on which the rumble strips will be appropriate and could be installed for testing.
b) A list of the performance measures to be obtained during the tests, and the equipment to be used for measuring them.
c) Issues relative to speeds, bicyclist types/bicycles and vehicle types, and their respective sample sizes.
d) Human factors issues.
e) Issues relative to pavement integrity.

3. LITERATURE REVIEW

A literature review and a survey of state rumble strip policies was conducted to identify issues related to the installation of rumble strips on roads with narrow shoulders. The research team first conducted a thorough literature review to identify references that have been added to the literature since the completion of Work Order 25: Bicycle-Tolerable Rumble Strips (Elefteriadou et al., 2000). Next, the research team contacted representatives from several state DOTs and FHWA to identify any existing installations of rumble strips on roads with narrow, or non-existent shoulders and inquire about state rumble strip policies. The points of contact for shoulder rumble strip information, by state, were obtained from the FHWA web page on rumble strips (http://safety.fhwa.dot.gov/programs/rumble.htm). The information was requested via e-mail. In addition, an e-mail survey was sent to rumble strip providers/contractors to document their experiences of installing rumble strips on roads with narrow or non-existent shoulders. The list of rumble strips providers was also obtained from the FHWA web page on rumble strips. The next three sections summarize the findings.

3.1 Application of Rumble Strips on Roads with Narrow Shoulders

The literature review and survey of states confirmed there is a very limited amount of information available on the application of rumble strips on roads with narrow or non-existent shoulders. In a few cases, state policies and/or documentation on rumble strips indicate rumble strips have been installed, or may be considered for installation, along two-lane roads. However, no references specifically addressed the application of rumble strips on roadways with narrow or non-existent shoulders.

Table 1 is based upon the responses obtained through the e-mail survey and three rumble strip surveys/reports (Perrillo, 1998; FHWA, 1998; and Isackson, 2000). Thirty-nine states responded to the survey (see appendix B). The responses were grouped into three main categories: no policy, unwritten policy, and written policy. States with policies or standard procedures provided a copy with their responses. The responses were sorted to identify states that did not restrict the use of rumble strips on two-lane roads. From these policies, information regarding the type of rumble strip treatment; the minimum requirements for placement; and the rumble strip dimensions were extracted. In several instances installation practices have evolved, but the written policies have not been updated.

Table 1 is divided into three sections. The pattern characteristics section includes information on the type of rumble strip used by each state, whether states have tried centerline treatments, and details of a skip pattern if preferred over continuous placement. The next section provides information regarding minimum requirements for rumble strip placement such as speed, average daily traffic (ADT), clear space, and shoulder width, distance to travel way, and asphalt thickness. The final section provides dimensions of the rumble strips used by various states that install rumble strips on two-lane roads. Figure 1 illustrates the tabulated dimensions.

Table 1. Summary of state rumble strip practices

State	Pattern Characteristics			Minimum Requirements for Installation							Rumble Strip Dimensions			
	Rumble Type*	Centerline Treatment	Skip Pattern	ADT (vpd)	Speed	Clear Path	Bicycle Considerations	Shoulder Width	Distance to Travel Way (A)	Asphalt Thickness	Groove Length (B)	Groove Width (C)	Groove Spacing (D)	Groove Depth (E)
Alaska	M	--	--	--	--	--	N	6'	4"	--	16"	7"	19"	0.5"
Arizona	M	--	28' rumble strips 12' clear space	--	--	--	Y	4'	0" to 12"	--	6", 8", or 12"	7"	12"	0.5"
California	M,RL	Y	--	--	--	5'	Y	--	6"	--	18"	5" to 8"	12"	0.5"
Colorado	M	--	--	--	--	3'	Y	4'	6"	--	12" to 24"	6" to 8"	12"	0.5" to 0.75"
Delaware	M	Y	--	--	--	--	N	--	--	--	--	--	--	--
Georgia	M	--	28' rumble strips 12' clear space	400	50 mph	--	Y	4'	12"	--	16"	7"	12"	0.5"
Idaho	M	--	48' rumble strips	--	--	3'	Y	--	8"	--	16" to 24"	7"	12"	0.5"
Kansas	M	Y	mill 5, skip 5	--	--	--	N	8'	6"	1.5"	36"	--	--	--
Maryland	M	Y	--	--	--	--	N	--	--	--	--	--	--	--
Minnesota	M	--	48' rumble strips 12' clear space	--	--	--	Y	4'	4"	--	12" to 16"	7"	12"	0.5"
Missouri	RL	--	--	--	--	--	Y	4'	24"	--	36"	1.5"	8"	0.75"
Montana	M	--	--	--	--	--	Y	4'	6"	--	12" to 16"	--	12"	0.5" to 0.75"
Nebraska	M	--	--	--	--	--	N	--	6"	--	16"	7"	12"	0.5"
New Mexico	M	Y	--	--	--	--	N	--	--	--	--	--	--	--
North Dakota	M	--	--	--	--	--	N	--	2" to 6"	--	18"	6" to 7"	12"	0.5" to 0.75"
Oklahoma	M	--	--	--	50 mph	--	N	4'	12"	2"	16"	7"	12"	0.5"
Oregon	M,RS	Y	--	--	--	--	Y	4'	12"	--	--	--	--	--
Pennsylvania	M	Y	--	--	--	--	Y	6'	18"	--	16"	7"	12"	0.5"
South Dakota	RL	--	--	2500	--	--	N	--	8"	--	15"	--	8"	1.2"
Utah	RL	--	--	--	50 mph	--	N	4'	12"	--	24"	1.5"	8"	1"
Virginia	M	--	--	--	--	--	Y	8'	6"	--	16"	6.5"	12"	0.5"
Washington	M	Y	--	--	--	--	Y	6'	6"	--	16"	7"	12"	0.5"
Wyoming	M	Y	10' rumble strips 10' clear space	--	45 mph	4'	Y	2'	18"	--	20"	7"	12"	0.5"

* Rumble Strip Type Abbreviations: M = Milled RL= Rolled RS = Raised

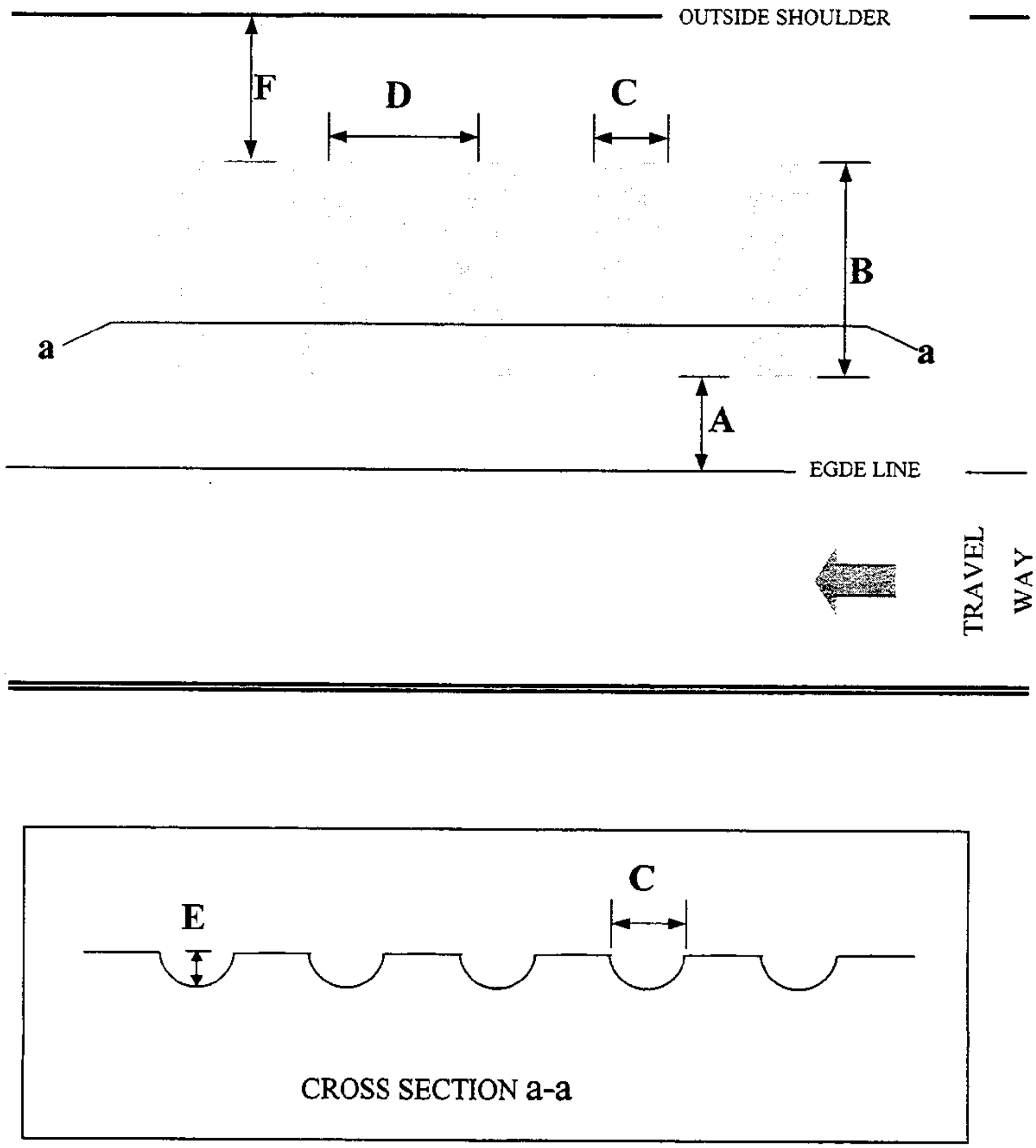

Figure 1. Rumble Strip Dimensions

Two states, Arizona, and Oregon, reported installation of rumble strips on two-lane roads with narrow shoulders. Neither state reported the safety effectiveness of the installations. Arizona DOT reported milled rumble strips on narrow right hand shoulders along stretches of US 93 between I-40 and Wikieup, SR 260 near Forest Lakes, US 89 north of Flagstaff, and a few other locations statewide. At these locations the shoulders are less than 4' (1.2-m) in width (measured perpendicular to the travel way), and the rumble strips are 6" (150-mm) in lateral width (measured perpendicular to the travel way). The rumble strips are placed adjacent to, or directly under, the edge line. The most recent Arizona DOT policy on shoulder grooving does not permit the installation of rumble strips on right hand shoulders of less than 4′ (1.2-m), unless justified by an approved written evaluation. Arizona DOT also indicated while the 6" (150-mm) lateral width minimizes the impact of the rumble strips on vehicular traffic, their placement in the same location as the wheel track of bicyclists significantly affects the comfort of bicyclists. Oregon DOT reported the use of profiled durable lines along two-lane roads with narrow shoulders. Profiled lines were used due to bicyclist considerations. A FHWA representative reported during his travels that he saw rumble strips used extensively on two-lane roads with narrow shoulders in Kentucky, but Kentucky DOT provided no information on their experience.

An international report from New Zealand (Dravitzki et al., 1998) stated raised pavement markers or discrete mounds of thermoplastics could be applicable on roads with narrow shoulders to produce an edge line. Raised rumble strips of these types are commonly used in the United Kingdom and Australia along the edge line.

Three rumble strip providers/contractors responded to the survey (appendix B). One rumble strip provider/contractor (Thomas Grinding, Inc.) had practical experience with installing rumble strips on roads with narrow shoulders. This contractor has installed milled rumble strips on roads with narrow shoulders in numerous states including: Alabama, Colorado, Florida, Louisiana, Mississippi, Montana, and Oregon. Placement of the rumble strips was in direct relation to the shoulder width, and typically the rumble strips were 16" (400-mm) in lateral width (measured perpendicular to the travel way). However, the contractor has installed rumble strips anywhere from 10" (254- mm) to 18" (457-mm) in lateral width. Pavement integrity was only an issue on very old shoulders or shoulders that had not been maintained. The contractor has a milling machine that can grind within 36" (0.9-m) of any obstruction, and the machine has special attachments to allow it to mill rumble strips on almost any width shoulder provided the rumble strip will fit between the edge line and the edge of the pavement.

3.2 Pattern Characteristics

3.2.1 Rumble Strip Type

There are four types of rumble strips: milled, rolled, formed, and raised (Elefteriadou et al., 2000). They differ primarily in the installation method and dimensions. Milled rumble strips are installed on new or existing asphalt and Portland cement concrete (PCC) shoulders by a machine, which cuts a smooth, uniform groove in the shoulder surface. Rolled rumble strips must be installed during the construction or reconstruction of the shoulder surface. Grooves are pressed into the hot asphalt surface by a roller with steel pipes welded to the drums. Formed rumble strips are installed along PCC shoulders. Indentations are formed into the concrete surface during the finishing process. Raised rumble strips are strips of material (asphalt, thermoplastics, etc.) that adhere to new or existing shoulder surfaces. Based on the survey, milled rumble strips are used more frequently than the other types of rumble strips on two-lane roads. This trend is consistent with reports from FHWA (http://safety.fhwa.dot.gov/programs/rumble.htm) that milled rumble strips are the prevalent type of rumble strip currently being installed.

3.2.2 Centerline Application

Based upon the survey results and reports by Perrillo (1998) and Fitzpatrick et al. (1999), centerline rumble strips have been installed along two-lane roads in states such as Delaware, Maryland, Oregon, Pennsylvania, Washington, and Wyoming. The purpose of centerline rumble strips is slightly different than shoulder rumble strips. Centerline rumble strips are installed to mitigate head-on and side-swipe crashes, while the main purpose of shoulder rumble strips is to address the problem of run-off-the-road crashes. Centerline rumble strips are applied using milling technology and applying painted centerline stripes over the milled rumble strips.

A before-after study has shown centerline rumble strips to be effective in reducing the number of head-on crashes on a two-lane, undivided rural highway in Delaware (Perrillo, 1998). Thirty-six months of before-data were collected, and 24 months of after-data were collected. During the before-period there were six fatal crashes, 14 injury crashes, and 19 property damage only crashes. In the after-period there were zero fatal crashes, 12 injury crashes, and six property damage only crashes. Thus, the centerline rumble strips reduced the total number of crashes and the severity of the crashes.

Kansas DOT is planning to install centerline rumble strips during the 2001 construction season on an experimental basis. Kansas DOT has been working with Kansas State University on the development of a rumble strip pattern for centerline applications. The research has been completed, but a final report has not been published to-date. Kansas DOT plans to install centerline rumble strips with a lateral width of 12" (300-mm). Oregon DOT has installed centerline rumble strips with a lateral width of 16" (400-mm).

3.2.3 Skip Pattern

Several states try to accommodate bicyclists by specifying an intermittent or skip pattern of rumble strip, rather than a continuous pattern. A skip pattern provides an area for bicyclists to cross between the shoulder and the travel way without having to traverse grooves. Moeur (1999) conducted research on the optimal gap length between rumble strip clusters. Subjects maneuvered through gaps of various lengths, and Moeur (1999) determined that the rumble strips should include periodic gaps in the rumble strip pattern 12′ (3.7-m) in length, placed at periodic intervals of 40′ (12.2-m) or 60′ (18.3-m). The 60′ (18.3-m) cycle provides greater rumble strip coverage, while the 40′ (12.2-m) cycle provides more frequent gaps for the bicyclists with a small difference in coverage.

Most states that have incorporated a skip pattern within their rumble strip policy have followed Moeur's recommendations. Arizona and Georgia DOTs have adopted the 40′ (12.2-m) skip pattern. With this rumble strip pattern, grooves are cut into the shoulder surface over a distance of 28′ (8.5-m) followed by a gap of 12′ (3.7-m), then another 28′ (8.5-m) series of grooves, and so on. Idaho and Minnesota DOTs have adopted the 60′ (18.3-m) cycle length, still providing a 12′ (3.7-m) gap. Kansas and Wyoming DOTs have adopted the skip pattern, but the patterns vary considerably from Moeur's recommendations. Kansas' policy calls for milling five grooves and skipping five grooves. Wyoming DOT has adopted a 20′ (6.1-m) cycle with rumble strips covering 10′ (3.0-m) followed by a gap of 10′ (3.0-m).

3.3 Minimum Requirements for Installation

Several states have established policies to provide guidance on the types of two-lane roadways on which shoulder rumble strips may be installed. The minimum requirements vary from state to state. In some states (Georgia, Oklahoma, South Dakota, Utah, and Wyoming) the requirements are related to vehicular traffic and/or speed on the roadway, while in most cases the requirements are related to clear path and/or shoulder width requirements, and the thickness of the shoulder surface.

3.3.1 Vehicular Requirements

Most states do not specifically consider the traffic volume or vehicular speeds when determining the applicability of shoulder rumble strips along a facility. The exceptions to this rule are the states of Georgia, Oklahoma, South Dakota, Utah, and Wyoming. Georgia DOT incorporates both volume and speed criteria in their rumble strip installation policy. In Georgia, two of the qualifying criteria for the consideration of rumble strips along two-lane roadways are that the roadways must have in excess of 400 vehicles per day (vpd) and have a posted speed greater than or equal to 50 mph (80 km/h). In Oklahoma and Utah, shoulder rumble strips may only be installed along routes with high design speeds, greater than or equal to 50 mph (80 km/h). In Wyoming, rumble strips may not be installed along routes with posted speed limits at or below 45 mph (70 km/h). In South Dakota, rumble strips are not installed along two-lane roads with ADTs under 2,500 vpd.

3.3.2 Clear Path and Shoulder Width

Many state rumble strip policies specify minimum clear path and/or shoulder width requirements. As illustrated in figure 1, clear path is the smooth portion of shoulder surface between the outside edge of the rumble strip and the outside edge of the shoulder surface (F). In several cases, state policies specify the clear path and/or shoulder width requirements are based upon bicycle considerations and the need to provide sufficient space along the shoulder for bicyclists. However, in other cases, it was difficult to determine the rationale for the clear path and/or shoulder width requirements.

States with minimum clear path requirements are California, Colorado, Idaho, and Wyoming. Colorado and Idaho DOTs require only 3′ (0.9-m) of clear path. Wyoming DOT requires 4′ (1.2-m), and California DOT requires 5′ (1.5-m).

States with minimum shoulder width requirements are Alaska, Arizona, Colorado, Georgia, Kansas, Minnesota, Missouri, Montana, Oklahoma, Oregon, Pennsylvania, Utah, Virginia, Washington, and Wyoming. Most of the state policies specify rumble strips may not be installed along shoulders less than 4′ (1.2-m) in width. However, minimum shoulder width requirements range from a low of 2′ (0.6-m) in Wyoming to a high of 8′ (2.4-m) in Kansas and Virginia.

Two documents, related to designing facilities for bicyclists, may have influenced states' rumble strip policies as related to clear path and/or shoulder width requirements:

- *Selecting Roadway Design Treatments to Accommodate Bicyclists* (FHWA, 1994).
- *Guide for the Development of Bicycle Facilities* (AASHTO, 1999).

These references address clear path and/or shoulder width issues to better accommodate bicycle travel.

AASHTO (1999) indicates that in rural areas, paved shoulders are often the best way to accommodate bicyclists. While experienced bicyclists benefit from shoulder widths as narrow as 1′ to 2′ (0.3 to 0.6-m) (FHWA, 1994), a minimum shoulder width of 4′ (1.2-m) is recommended to accommodate bicycle travel (AASHTO, 1999). As vehicular speeds increase, more trucks are included in the traffic mix, and/or traffic volumes increase, added shoulder width is desirable. AASHTO (1999) recommends increased shoulder widths when speeds exceed 50 mph (80 km/h). FHWA (1994) recommends shoulder widths be increased to 6′ (1.8-m), when vehicle speeds exceed 40 mph (64.4 km/h) and the ADT is 2,000 vpd or more.

AASHTO (1999) does not recommend the use of rumble strips on shoulders used by bicyclists unless one of the following minimum clearances exists:

- 1′ (0.3-m) from the rumble strip to the travel way
- 4′ (1.2-m) from the rumble strip to the outside edge of the shoulder, or
- 5′ (1.5-m) to adjacent guide rail or other obstacle.

When conditions preclude achieving the minimum desirable clearance, alternative solutions should be considered, such as decreasing the lateral width (measured perpendicular to the travel way) of the rumble strip.

3.3.3 Distance to Travel Way

Table 1 shows the distance required by each state between the edge of the travel way and the inside edge of the rumble strip (A). This distance varies considerably between states, ranging from 0" (0-mm) up to 24" (600-mm). Many states require 6" (150-mm) between the travel way and the rumble strips. Arizona permits the option of installing rumble strips directly under the edge line when shoulders are 4' (1.2-m) and it is in a bicycle area.

3.3.4 Bicycle Considerations

Table 1 identifies those states that consider bicyclists when determining clear path and/or shoulder width requirements within their rumble strip policies. The letter 'Y' indicates bicycles or bicyclists were specifically mentioned in relation to clear path and/or shoulder width requirements within the respective DOT's rumble strip policy. The letter 'N' indicates there was no specific mention of bicyclists with respect to clear path and/or shoulder width requirements.

3.3.5 Asphalt Thickness

Although the thickness of the asphalt/concrete shoulder is definitely a critical design criterion for shoulder rumble strips on two-lane roads, most states do not specifically address shoulder pavement requirements in their rumble strip policies. Oklahoma and Kansas are the only states that have rumble strip policies applicable to two-lane roads that specify minimum cross sectional requirements of the shoulder pavement. New York DOT incorporates asphalt thickness requirements into their rumble strip policies, but their rumble strip policy prohibits the installation of rumble strips on two-lane roadways. Section 3.5 provides additional information on pavement integrity issues.

3.4 Rumble Strip Dimensions

Several research efforts (Franke, 1974; Tye, 1976; Chen, 1994, Wood, 1994; and Elefteriadou et al., 2000) have focused on the design of effective rumble strips. Most of these efforts focused on determining effective rumble strip dimensions for cars and, in some instances, trucks and motorcycles. Elefteriadou et al. (2000) was the first study to consider both motor vehicles and bicycles in the design of rumble strips.

There are four dimensions to consider in the design of rumble strips: lateral width, groove width, groove spacing, and groove depth. Lateral width (B) is the dimension of the groove measured perpendicular to the travel way. Groove width (C) is the dimension of the groove measured parallel to the travel way. The spacing of grooves (D) is measured from the center of one groove to the center of the adjacent groove. The groove depth (E) is the maximum depth of the groove, measured at the center of the rounded groove.

Lateral width requirements vary from state to state. Most states install rumble strips with a lateral width of 16' (400-mm). However, there are exceptions to this rule, most notably are the states of Arizona, Colorado, Idaho, Minnesota, and Montana. In each of these states, lateral widths vary primarily because of the clear path requirements, shoulder width requirements, and/or bicycle considerations.

Groove width requirements are consistent from state to state. Generally, groove widths are between 5" (127-mm) to 7" (175-mm), but several states like California and Colorado permit groove widths of up to 8" (200-mm). When a groove width of 1.5" (38-mm) is specified in table 1, the rumble strip is of the rolled type.

Groove spacing requirements are consistent between states. For states that install milled rumble stripes, the grooves are typically spaced 12" (300-mm) on center. For states that install rolled rumble strips, the indentations are typically spaced 8" (200-mm) on center.

As with groove width and groove spacing, groove depth does not vary considerably from state to state. Most states that install milled rumble strips require groove depths between 0.5" (13-mm) and 0.75" (19-mm). South Dakota and Utah permit groove depths of 1.2" (30-mm) and 1" (25-mm), respectively, but these are for the rolled type of rumble strip.

3.5 Pavement Performance Issues

3.5.1 Published Studies

The literature review revealed no published, controlled studies regarding the impact of milled rumble strips on pavement performance (Newcomb, 2001). The installation of rumble strips has generally been initiated by the considerations of traffic and safety teams within highway agencies (Olson, 2001). While pavement impacts have not been ignored, the potential safety improvements have overwhelmed most initial benefit/cost or life-cycle cost calculations (Khan and Bacchus, 1995). Most applications of milled rumble strips have been on shoulder pavements with very small volumes of traffic. In addition, anticipated pavement life cycles are very long compared to the age of most milled rumble strips, so little relevant field data are available.

As the use of rumble strips is extended to roads with narrow or non-existent shoulders, the possibility for adverse effects on pavement performance may be increased. By necessity, those rumble strips would be placed in areas subject to greater contact by vehicles. In addition, those roadways and shoulders are generally of thinner structural cross-sections and often of lower-quality materials.

3.5.2 Current Policies

Several states have pavement considerations in their current rumble strip policies, including New York, Oklahoma, Kansas, and Arizona. Those considerations, as extracted from the policies, are:

> *New York.* Rumble strips should only be installed on shoulders in reasonably good condition and, in the case of asphalt shoulders, having a minimum thickness of 2.5" (60-mm). They should not be milled into existing shoulders that are rated as either deformed or having moderate to high degrees of deformation and/or

cracking distress as defined by the Pavement Rehabilitation Manual. They should also not be installed on Type 1 Optional Flexible Shoulders or other asphalt shoulders with less than 1" (25-mm) of top course (New York DOT, 1997).

Oklahoma. Use only on routes that have 2" (50-mm) minimum asphalt or concrete surfacing depth on the shoulders (Oklahoma DOT, 2000).

Kansas. Rumble strips will also be used when full-width shoulders are overlaid with a minimum of one inch of asphalt . . . The shape of the groove shall be semicircular and have a nominal depth of 1" (25-mm) for an asphalt thickness of 1.5" (38-mm) or more (Kansas DOT, 1991).

Arizona. The make-up of the new pavement or the thickness, condition, and type of existing pavement needs to be determined prior to the application of ground-in rumble strips. The installation of ground-in rumble strip on pavement that is of questionable thickness, condition, or type (e.g., AC over PCCP) needs to be evaluated to ensure that the installation of the rumble strip will be possible without adverse impact to the pavement or the performance of the strip (Arizona DOT, 2000).

In addition, many of the current policies and provisions provide for the sealing or coating of the rumble strips. For example, the Virginia Department of Transportation Special Provision for Rumble Strips (asphalt) states (Virginia DOT, 1999):

> Following cutting and cleaning depressions of waste material, the Rumble Strip area shall be coated entirely with liquid asphalt coating (emulsion) using a pressure distributor at an approximate rate of 0.45 liter-per-square-meter. Over spray shall not extend more than 50-mm beyond the width of cut and/or shall not come in contact with pavement markings.

3.5.3 Pavement Considerations

Some of the potential pavement performance and maintenance impacts to be considered are listed below. No attempt has been made, at this time, to prioritize or rank the potential impact of these issues.

- Rumble strips will reduce, by a significant percentage on the thinner pavements on lower volume roads, the effective structural cross-section of the pavement. This may reduce the overall pavement life, or require greater total pavement thickness, if significant loadings are anticipated to the milled area. This could be important to the consideration of the cost-effectiveness of the rumble strips.
- Milled rumble strips should be sealed to prevent the infiltration of moisture and to coat aggregates. Various types of seals can be used, and should be evaluated, including asphalt emulsions, acrylics, and other fog seals. Minnesota DOT is currently conducting a limited study on the appropriate fog seal material (Olson, 2001).

- The maintenance of the rumble strips may require periodic re-application of the fog seal, particularly when the strips are placed in locations with greater traffic impacts. This may pose problems when the rumble strips are at or near paint stripes. Also, the repeated application of fog seals can potentially reduce skid resistance.
- The rumble strips may allow increased moisture infiltration. This requires greater attention to the stripping potential of aggregates, and the use of anti-stripping agents when necessary.
- Rumble strips at or near longitudinal paving joints may be more prone to raveling and deterioration. Longitudinal paving joints are often the weakest part of the pavement structure, due to the difficulties of obtaining adequate compaction during construction.
- Lower-volume roads are more likely to have thin functional overlays or surface treatments applied (less than 1.5" (38-mm)). In some cases, a milled rumble strip may actually penetrate through the surface layer. This could result in increased chances of delamination or debonding of the layers and raveling, both during construction and over time (Perrillo, 1998). Where appropriate, the application of a thicker overlay may be justified by the potential benefits of the rumble strips. Alternately, shallower groove depths may be considered.
- Lower-volume roads are more likely to be surfaced with lower-quality materials, which are adequate for the anticipated traffic. These materials may be more susceptible to damage by milling rumble strips.
- Lower-volume rural roads may have a greater diversity of traffic, including farm equipment, horses, buggies, and other vehicles not permitted on higher volume roads. These vehicles may adversely affect the durability of the rumble strips.
- Centerline applications on crowned roadways may hinder drainage, and increase freeze-thaw and infiltration problems. (Standing water in a centerline rumble strip over a paving joint has been observed in New Mexico (Worrell, 1999).) Rumble strips in the center of the lane may also interrupt the drainage flow path, unless appropriately considered in the milling pattern. At horizontal curves, where greater cross-slopes and superelevated sections can be expected, this problem would be minimal.
- Maintenance and overlay cycles on lower-volume roads are typically longer, and minimum acceptable pavement conditions are lower than on higher-volume roads. The installation of milled rumble strips on distressed pavements may decrease the performance life of both the rumble strips and the pavement.

3.6 Driver Reaction to Rumble Strips

There are several relevant issues related to driver reaction of rumble strips on roads with narrow or non-existent shoulders. First, the rumble strips should provide sufficient stimuli to alert inattentive/drowsy motorists as they leave the travel way. Second, sufficient time should be provided for the motorists to perceive the alerting stimuli generated by the rumble strip and react to the stimuli by correcting their steering direction.

A summary of previous driver reaction studies that measured vibration and noise levels of motor vehicles generated by different rumble strip configurations, was provided by Elefteriadou et al. (2000). Some of the more relevant conclusions from these studies are as follows:

- Milled rumble strips generate the greatest amount of stimuli to alert inattentive/drowsy motorists.
- When evaluating groove widths of milled rumble strips, the 7" (178-mm) wide groove produced slightly than greater average increases in sound and vibration over the background level as compared to 3" (76-mm) and 5" (127-mm) grooves.
- When evaluating raised rumble strips, sound levels generally increase to the highest levels at higher speeds, but the ambient noise level of the bare pavement also increases as speed increases. The largest difference between background noise levels and noise generated from rumble strips occurs at lower speeds.
- The optimal height or depth for rumble strips is about 0.5" (13-mm). It has adequate alerting properties and does not adversely affect control of the vehicle.

The results of the motor vehicle tests conducted by Elefteriadou et al (2000) are relatively consistent with the findings of the previous studies. Elefteriadou et al. (2000) also noted a question that needs to be addressed in the future: "What level of sound needs to be generated by the rumble strip to alert a drowsy or sleeping motorist?" Watts (1977) conducted some related research, but never fully answered the question. In his research, Watts noted exposure time to the stimulus is an important element in the alerting properties of rumble strips.

Hall (1991) investigated various factors affecting exposure time to rumble strips. The time period for which a motorist is exposed to noise and vibration from the rumble strip is a function of vehicle speed, departure angle, and lateral width of the groove. Assuming that a rumble strip begins to alert a driver just as the front right tire contacts the groove and ceases just after it passes beyond the groove, the exposure time increases if the departure angle is small or if the lateral width of the rumble strip is large and decreases at higher speeds (figure 2). It is important to note that the departure angle is the combined result of the steering angle and the curvature of the road. As a result, rumble strips on a tangent section allow for more time for the driver to correct his/her steering direction than on a horizontal curve to the left.

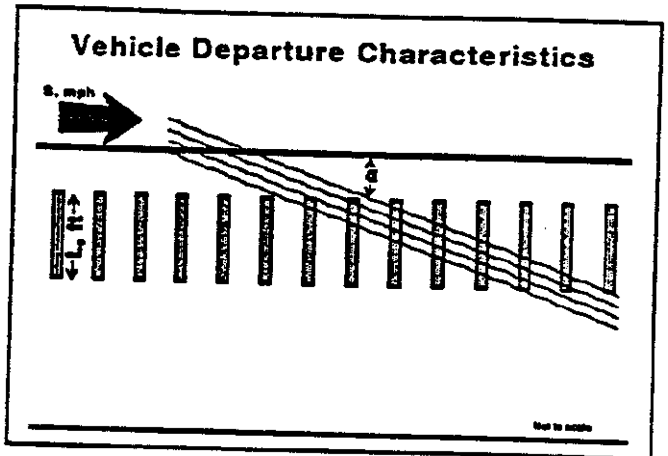

Figure 2. Vehicle departure characteristics (Hall, 1991)

Figure 3 illustrates the relationship between lateral width and the exposure time. The length of time that a vehicle's front tire is exposed to the rumble strip while traveling at 65 mph, or 100 ft/s (105 km/h), is shown as a function of the departure angle and the lateral width. For a small passenger car-encountering rumble strips with a lateral width of 2′ (0.6 m), exposure time is one second for a departure angle of 1.7°, and decreases rapidly at larger angles. Hall (1991) indicated the median encroachment angle in run-off-the-road crashes is about 8°, and that 25 percent of the encroachment angles exceed 15°. However, departure angles tend to be smaller at higher speeds. As seen in figure 3, exposure time is directly proportional to the lateral width of the grooves; an increase in lateral width from 2′ to 3′ (0.6-m to 0.9-m) increases the exposure time by 33 percent.

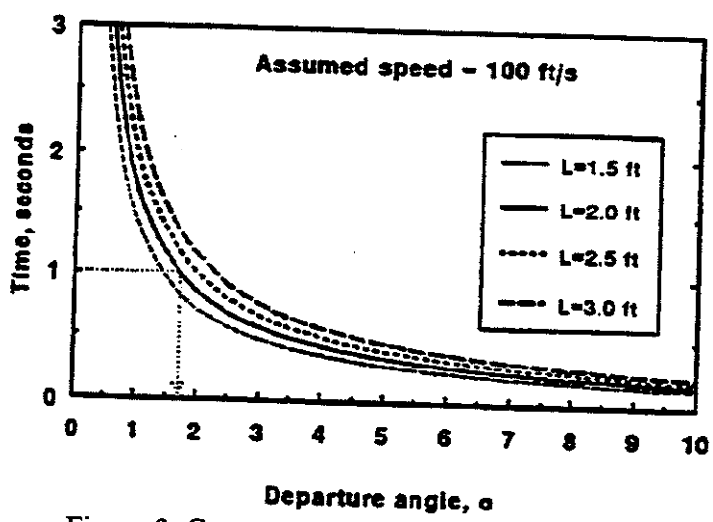

Figure 3. Groove exposure time (Hall, 1991)

It appears that the tires nearest the shoulder are likely to completely cross the grooves before the driver initiates a steering correction. If the shoulder is greater than 6.5′ (2.0-m) wide, tires on the vehicle's left side will contact the grooves prior to the time that right side tires leave the paved surface. If the shoulder is narrower than 6.5′ (2.0-m), the left tires will not contact the grooves before the right side tires travel off of the shoulder. This suggests that rumble strips will provide the most benefit when there is a full shoulder; however, they could still be beneficial on narrower shoulders (Hall, 1991).

3.7 Summary of Literature Review

Very little information was found in the literature specifically related to the installation of rumble strips on roads with narrow or non-existent shoulders. However, several states have written or unwritten policies related to the installation of rumble strips on two-lane roadways, which often have narrow shoulders. These policies were reviewed to gain a broader perspective of the issues related to the application of rumble strips along roads with narrow shoulders.

The major issues related to the application of rumble strips on roads with narrow shoulders concern the pattern characteristics, the minimum requirements for installation, and the dimensions of the rumble strips. Regarding the pattern characteristics, most highway agencies are installing milled type rumble strips due to its superior alerting properties. Several highway agencies are also installing rumble strips along the centerline of two-lane roads to mitigate head-on and side-swipe crashes, and several highway agencies are employing skip patterns versus continuous patterns along the shoulder in an effort to accommodate bicyclists.

Several states have established minimum requirements for the installation of rumble strips along two-lane roads. Most states incorporate some type of shoulder width and/or clear path requirements within their rumble strip policies, mainly due to bicycle considerations. In addition, a few states specifically consider the ADT and/or the operating speed or speed limit of the roadway, and two states address the minimum thickness requirements for the asphalt shoulder.

Rumble strip dimensions do not vary dramatically from state to state. The dimension that tends to vary to the greatest extent is the lateral width of the groove, measured perpendicular to the travel way. Issues related to clear path requirements, shoulder width requirements, and placement of the rumble strips along the shoulders are directly affected by this dimension.

The structural integrity of the pavement surface needs to be considered in the conceptual design of rumble strips for roads with narrow shoulders. These roadways and shoulders are generally constructed with lower-quality materials and thinner structural cross-sections. As a result, the possibility for adverse effects on pavement performance may be increased. The impact of pavement performance is an area that has not been thoroughly documented within the literature.

A final issue that needs to be considered in the conceptual design of rumble strips for roads with narrow shoulders is driver reaction to the stimuli. The stimuli from the rumble strips must possess sufficient properties (sound and/or vibration levels and duration) to alert inattentive/drowsy drivers that a corrective action in their steering is required. In addition, the driver must have an adequate amount of time to perform the corrective maneuver, or the rumble strip will not serve its purpose of preventing the crash.

4. CONCEPTUAL DESIGN OF RUMBLE STRIPS

This section presents the methodology developed to provide recommendations on the placement and design of rumble strips patterns for roads with narrow shoulders. The methodology was formulated assuming the following conditions for the types of roadways on which the rumble strips would be applicable:

- Non-freeway facilities
- Frequent run-of-the-road crashes
- Only pavements with good surfaces

Before a decision is made to install rumble strips on a facility that meets the above conditions, an evaluation should be conducted to determine if rumble strips are an appropriate safety measure. In some cases where the horizontal and/or vertical alignments are poor, sight distance is restricted, and/or the travel way is narrow, other types of safety improvements might be more appropriate for reducing run-off-the-road crashes.

Once a site has been identified for the installation of rumble strips, the methodology can be used to select the placement and pattern of the rumble strips to alert inattentive motorists and accommodate bicyclists. The methodology consists of two procedures. The first procedure is used to determine the preferred lateral width of the rumble strip. The second procedure is used to determine the optimum placement of rumble strips within the roadway cross-section. The methodology does not provide recommendations for rumble strip dimensions of groove width, groove depth, or groove spacing. The impacts of these three rumble strip design elements on motorists and bicyclists were evaluated by Elefteriadou et al. (2000). Table 2 provides the recommended dimensions for groove width, depth, and spacing for the respective facility types so that the rumble strips can alert inattentive/drowsy motorists and be safely and comfortably traversed by bicyclists. These dimensions should be used in combination with the procedures to determine the preferred lateral widths of rumble strips and the optimum placement of rumble strips within the roadway cross-section to determine the exact pattern and placement for rumble strips on roads with narrow or non-existent shoulders. It should be noted that in table 2 the spacing of the grooves refers to the length of the flat portion of pavement between grooves, not the center-to-center spacing.

Table 2. Recommended groove widths, depths, and spacings

Groove Width	Flat Portion between Grooves	Groove Depth	Facility Type
5" (127-mm)	7" (178-mm)	0.375" (10-mm)	High Operating Speeds (55 mph or 88 km/h)
5" (127-mm)	6" (152-mm)	0.375" (10-mm)	Low Operating Speeds (45 mph or 72 km/h)

4.1 Determining the Preferred Lateral Width of Rumble Strips

Determining the preferred lateral width of a rumble strip depends upon a desired exposure time of the stimuli (noise and/or vibration) generated by the rumble strips. The exposure time of the stimuli is a function of vehicle speed, departure angle, the lateral width of the rumble strips, and the contact area of the tire. Figures 4 to 7 illustrate the variation in exposure time as a function of vehicle speed, departure angle, and lateral width of the rumble strip. The figures were developed assuming rumble strips begin to alert a driver when the front right tire contacts the groove and ceases after the front right tire passes beyond the groove. The front tire is assumed to be approximately 5" (127 mm) in width. These figures, or the corresponding tables 3 to 6, can be used to determine the preferred lateral width of rumble strips for a route.

An engineer must use judgment in selecting a desired exposure time, a typical departure angle (which is a function of the horizontal alignment of the roadway), and the operating speed along the route. The desired exposure time will differ depending upon the cognitive state of the driver for which the rumble strips are being designed. Very little information is available to provide guidance on selecting a desired exposure time. Intuitively, inattentive drivers have quicker reaction times than drivers who have fallen asleep or who are extremely tired, thus inattentive drivers need less exposure (magnitude and duration) to noise and vibration generated by rumble strips and less room to fully recover the vehicle than drowsy drivers. On roads with narrow shoulders, there is probably not going to be enough space for drowsy drivers to react to the stimuli generated by the rumble strip and recover the vehicles. However, given that inattentive drivers have quicker reactions, rumble strips have the potential to reduce the frequency of run-off-the-road crashes caused by inattentive drivers on roads with narrow shoulders.

The only research available to help select a desired exposure time for rumble strips was conducted by Watts (1977). Watts concluded rumble strips which produce noise increases of 4 dB(A) or higher would be readily detected by drivers if the noise level was sustained for 350 ms or longer. However, if the noise increase was only 2 dB(A), a pulse length of at least 900 ms would probably be required. Also, a pattern of noise consisting of a regular series of 500 ms pulses separated by 500 ms would be suitable for alerting drivers. The noise increase in the pulses over the ambient levels should be at least 4 dB(A). Based upon Watts' research, the desired exposure time varies from 350 ms to 900 ms depending upon the noise level generated by the rumble strips over the ambient level.

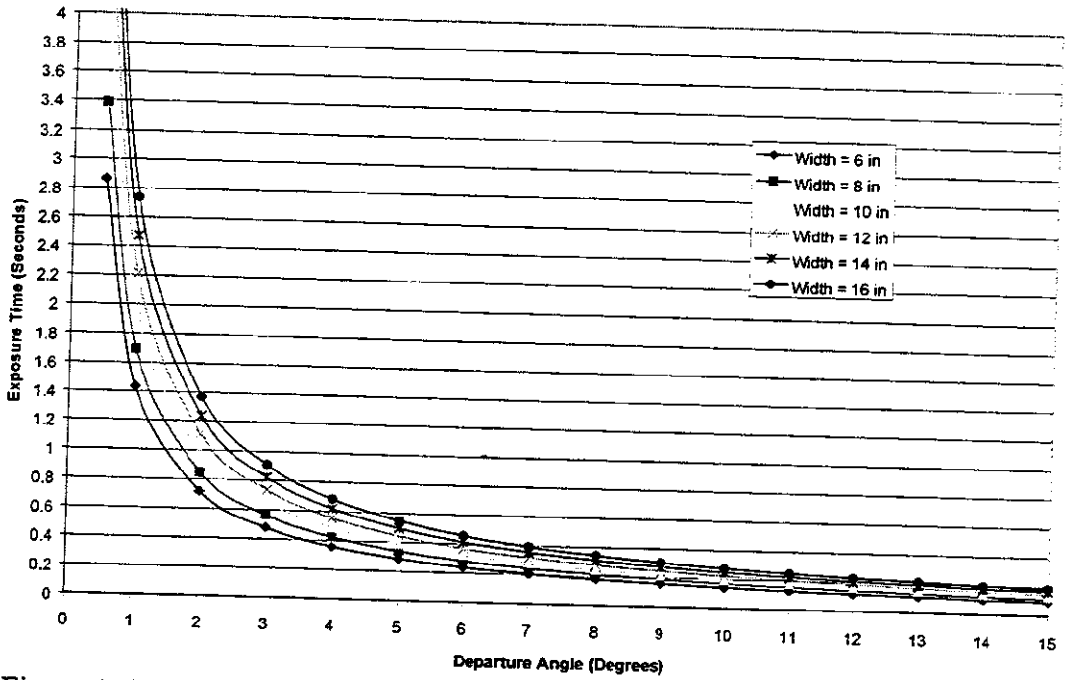

Figure 4. Exposure time as a function of lateral width (speed = 25 mph)

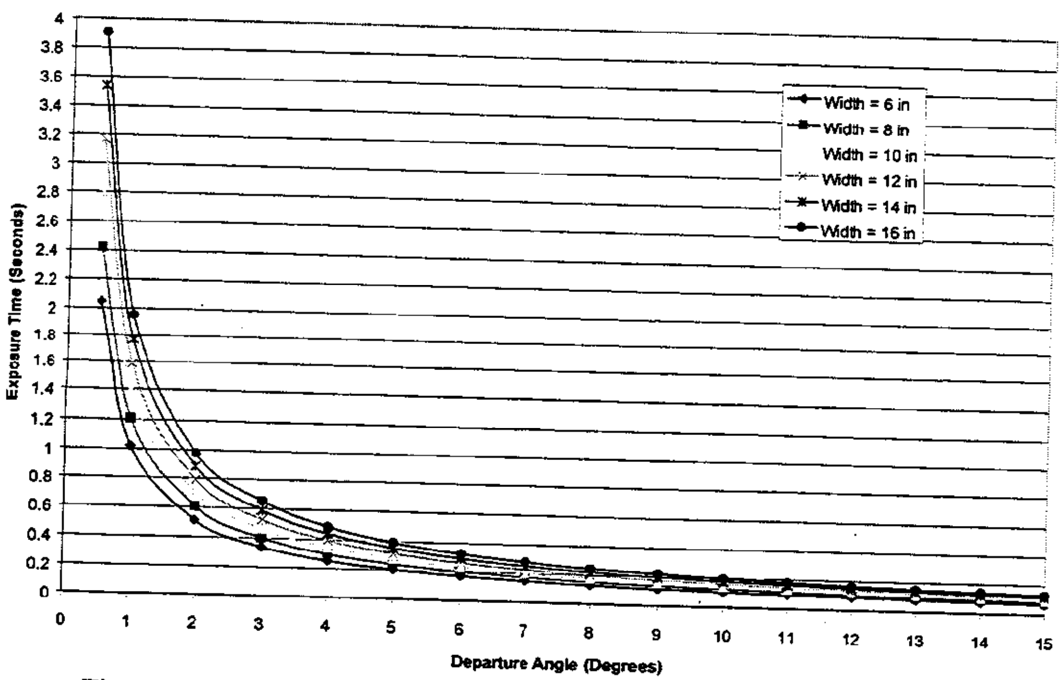

Figure 5. Exposure time as a function of lateral width (speed = 35 mph)

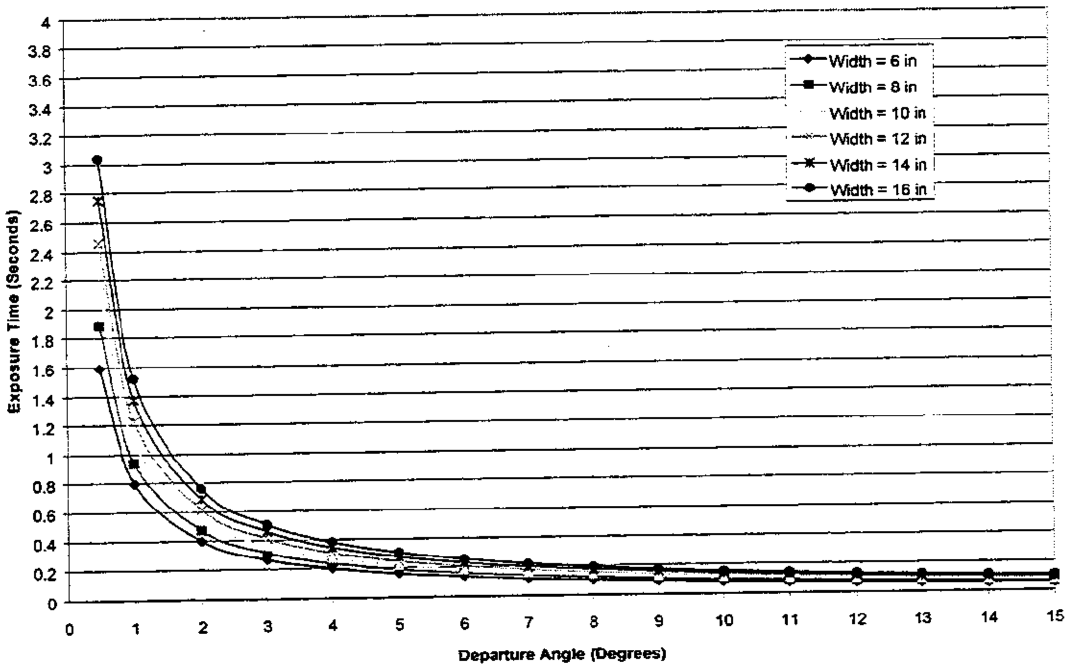

Figure 6. Exposure time as a function of lateral width (speed = 45 mph)

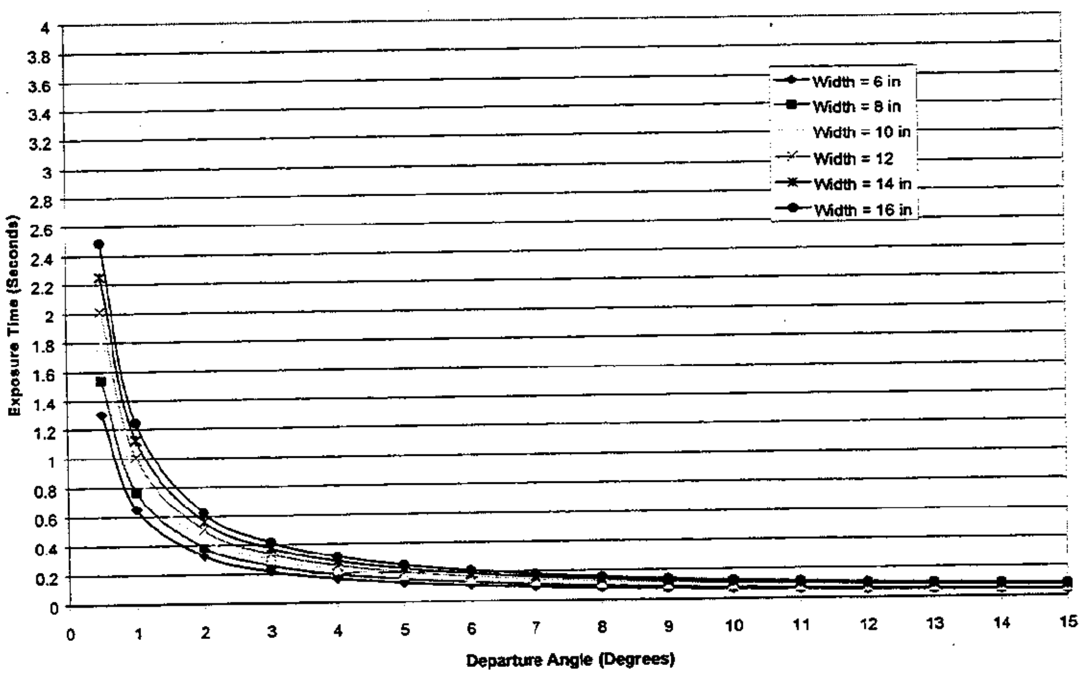

Figure 7. Exposure time as a function of lateral width (speed = 55 mph)

Table 3. Exposure time as a function of lateral width (speed = 25 mph)

Departure Angle (degrees)	Lateral Width of Rumble Strips					
	6 inches (152-mm)	8 inches (203-mm)	10 inches (254-mm)	12 inches (305-mm)	14 inches (356-mm)	16 inches (406-mm)
	Desired Exposure Time (seconds)					
0.5	2.865	3.3386	3.907	4.427	4.948	5.469
1	1.432	1.693	1.953	2.214	2.474	2.735
2	0.716	0.847	0.977	1.107	1.237	1.368
3	0.478	0.565	0.651	0.738	0.825	0.912
4	0.358	0.424	0.489	0.554	0.619	0.684
5	0.287	0.339	0.391	0.443	0.495	0.548
6	0.239	0.283	0.326	0.370	0.413	0.457
7	0.205	0.242	0.280	0.317	0.354	0.392
8	0.180	0.212	0.245	0.278	0.310	0.343
9	0.160	0.189	0.218	0.247	0.276	0.305
10	0.144	0.170	0.196	0.222	0.249	0.275
11	0.131	0.155	0.179	0.202	0.226	0.250
12	0.120	0.142	0.164	0.186	0.208	0.230
13	0.111	0.131	0.152	0.172	0.192	0.212
14	0.103	0.122	0.141	0.160	0.178	0.197
15	0.097	0.144	0.132	0.149	0.167	0.184

Table 4. Exposure time as a function of lateral width (speed = 35 mph)

Departure Angle (degrees)	Lateral Width of Rumble Strips					
	6 inches (152-mm)	8 inches (203-mm)	10 inches (254-mm)	12 inches (305-mm)	14 inches (356-mm)	16 inches (406-mm)
	Desired Exposure Time (seconds)					
0.5	2.046	2.418	2.790	3.162	3.535	3.907
1	1.023	1.209	1.395	1.581	1.767	1.953
2	0.512	0.605	0.698	0.791	0.884	0.977
3	0.341	0.403	0.465	0.527	0.589	0.651
4	0.256	0.303	0.349	0.396	0.442	0.489
5	0.205	0.242	0.279	0.317	0.354	0.391
6	0.171	0.202	0.233	0.264	0.295	0.326
7	0.147	0.173	0.200	0.226	0.253	0.280
8	0.128	0.152	0.175	0.198	0.222	0.245
9	0.114	0.135	0.156	0.176	0.197	0.218
10	0.103	0.122	0.140	0.159	0.178	0.196
11	0.094	0.111	0.128	0.145	0.162	0.179
12	0.086	0.102	0.117	0.133	0.148	0.164
13	0.079	0.094	0.108	0.123	0.137	0.152
14	0.074	0.087	0.101	0.114	0.127	0.141
15	0.069	0.082	0.094	0.107	0.119	0.132

Table 5. Exposure time as a function of lateral width (speed = 45 mph)

Departure Angle (degrees)	Lateral Width of Rumble Strips					
	6 inches (152-mm)	8 inches (203-mm)	10 inches (254-mm)	12 inches (305-mm)	14 inches (356-mm)	16 inches (406-mm)
	Desired Exposure Time (seconds)					
0.5	1.592	1.881	2.170	2.460	2.749	3.038
1	0.796	0.941	1.085	1.230	1.375	1.519
2	0.398	0.470	0.543	0.615	0.687	0.760
3	0.265	0.314	0.362	0.410	0.458	0.507
4	0.199	0.235	0.272	0.308	0.344	0.380
5	0.159	0.188	0.217	0.246	0.275	0.304
6	0.133	0.157	0.181	0.205	0.230	0.254
7	0.114	0.135	0.155	0.176	0.197	0.218
8	0.100	0.118	0.136	0.154	0.172	0.191
9	0.089	0.105	0.121	0.137	0.153	0.169
10	0.080	0.095	0.109	0.124	0.138	0.153
11	0.073	0.086	0.099	0.112	0.126	0.139
12	0.067	0.079	0.091	0.103	0.115	0.128
13	0.062	0.073	0.084	0.095	0.107	0.118
14	0.057	0.068	0.078	0.089	0.099	0.110
15	0.054	0.063	0.073	0.083	0.093	0.102

Table 6. Exposure time as a function of lateral width (speed = 55 mph)

Departure Angle (degrees)	Lateral Width of Rumble Strips					
	6 inches (152-mm)	8 inches (203-mm)	10 inches (254-mm)	12 inches (305-mm)	14 inches (356-mm)	16 inches (406-mm)
	Desired Exposure Time (seconds)					
0.5	1.302	1.539	1.776	2.012	2.249	2.486
1	0.651	0.770	0.888	1.006	1.125	1.243
2	0.326	0.385	0.444	0.503	0.562	0.622
3	0.217	0.257	0.296	0.336	0.375	0.415
4	0.163	0.193	0.222	0.252	0.281	0.311
5	0.130	0.154	0.178	0.202	0.225	0.249
6	0.109	0.128	0.148	0.168	0.188	0.208
7	0.093	0.110	0.127	0.144	0.161	0.178
8	0.082	0.096	0.111	0.126	0.141	0.156
9	0.073	0.086	0.099	0.112	0.125	0.139
10	0.065	0.077	0.089	0.101	0.113	0.125
11	0.060	0.070	0.081	0.092	0.103	0.114
12	0.055	0.065	0.075	0.084	0.094	0.104
13	0.051	0.060	0.069	0.078	0.087	0.096
14	0.047	0.056	0.064	0.073	0.081	0.090
15	0.044	0.052	0.060	0.068	0.076	0.084

4.2 Determining the Optimum Placement of Rumble Strips

The procedure for determining the placement of rumble strips is developed to satisfy the following two objectives:

- Rumble strips should be placed within the roadway cross-section so when an inattentive motorist receives stimuli (sound and/or vibration) from the rumble strips, the motorist has sufficient time to react and perform the necessary and appropriate maneuver to return to the travel way.
- Rumble strips should be placed within the roadway cross-section to accommodate bicyclists.

The first objective is related to the purpose of shoulder rumble strips. Shoulder rumble strips are intended to alert a motorist that his/her vehicle is drifting from the travel way and will strike an object unless an appropriate maneuver is performed. To fulfill this primary purpose, rumble strips must be designed to generate sufficient stimuli to alert an inattentive motorist that his/her vehicle is drifting from the travel way, and once alerted, the motorist needs sufficient time and space to react and perform the appropriate maneuver to return the vehicle to the travel lane. If both of these elements are not present, rumble strips will not serve their intended purpose.

The second objective recognizes that motorists are not the only users of the highway network. Bicyclists also utilize the roadway network as one of their principal riding environments, and thus, highways should be designed to accommodate bicyclists. As stated in section 3.3.2, the *Guide for the Development of Bicycle Facilities* (AASHTO, 1999) recommends a minimum shoulder width of 4′ (1.2-m) to accommodate bicyclists and even wider shoulders are desired if motor vehicle speeds exceed 50 mph (80 km/h) or if there is a high percentage of trucks, buses, and/or recreational vehicles. AASHTO also indicates where minimum desired shoulder widths of 4′ (1.2-m) cannot be achieved any additional shoulder width is better than none at all.

This project addresses the placement of rumble strips on roads with narrow to non-existent shoulders, or shoulder widths less than or equal to 4′ (1.2-m). Thus, the roadways considered will have the minimum or less than the minimum shoulder recommended by AASHTO to accommodate bicyclists. Therefore, the goal is to select the location for the rumble strip having the least amount of impact to the bicycle clear path. In the case where the shoulder width is greater than 4′ (1.2-m), the rumble strip should be placed along the edge line to alert the motorists as soon as possible, as long as a clear path of at least 4′ (1.2-m) remains to accommodate bicycles.

The placement of rumble strips within the roadway cross-section is a function of the clear zone and the steering adjustment area. The clear zone is defined as the total roadside border area, starting at the edge of the travel way, available for safe use by errant vehicles. This area may consist of a shoulder, a recoverable slope, a non-recoverable slope, and/or a clear run-out area. The desired width is dependent upon the traffic volumes and speeds and on the roadside geometry (AASHTO, 1996). For the purposes of this project, the steering adjustment area is defined as the lateral distance traversed by an errant vehicle corresponding to the minimum time required by the driver to recover the vehicle.

For rumble strips to fulfill their intended purpose, the clear zone should be greater than the steering adjustment area. Such information however may be difficult to obtain and estimate for an entire roadway section. Thus, two methods were developed for determining the optimum placement of rumble strips within the roadway cross-section. It can be determined based upon the clear zone and steering adjustment areas, or it can be determined based upon the roadside hazard rating. Each of these concepts (clear zone, steering adjustment area, and roadside hazard rating) is presented below. Next, the simplified procedure for determining the optimum placement of rumble strips based upon the roadside hazard rating is illustrated and applied. Appendix C is a stand-alone concise guide for practitioners that want to use the simplified method for determining the preferred lateral width and optimum placement of rumble strips within the roadway cross-section.

4.2.1 Detailed Method - Clear Zone and Steering Adjustment Concept

Figure 8 provides an illustration of both the clear zone concept and the steering adjustment area. Assuming the roadside is traversable, the clear zone is the lateral distance between the edge line and the nearest fixed object located in the roadside. To estimate the steering adjustment area first, calculate the diagonal distance covered by the errant vehicle. Second, calculate the lateral distance corresponding to the diagonal and the angle of departure. This distance is the steering adjustment area.

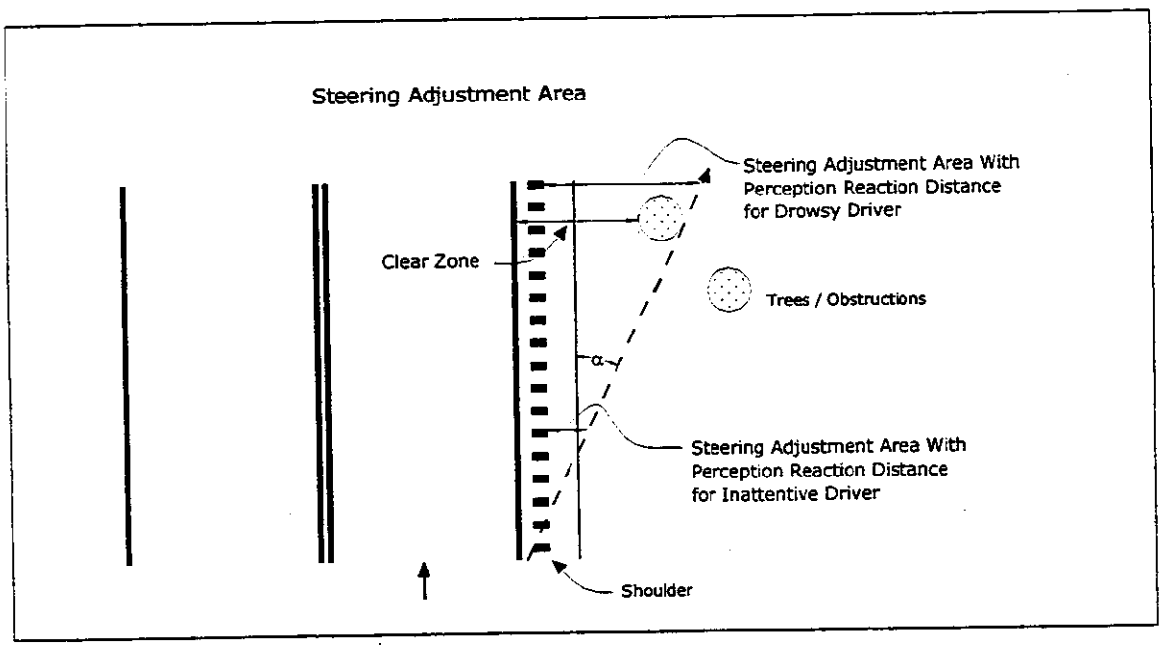

Figure 8. Clear zone and steering adjustment area

The steering adjustment area is a function of:

- Speed
- Angle of departure and horizontal curvature of the roadway - The angle of departure for run-off-the-road crashes can vary. O'Halan and Kelley (1974) report an average departure angle of about 3° for run-off-the-road crashes, while Hall (1991) reports a median departure angle of about 8°. Hall (1991) also reports for a significant portion of run-off-the-road crashes, the departure angle exceeds 15°. The angle of departure is a function of the horizontal alignment as well.
- Perception and reaction time of the driver - Perception and reaction times vary from individual to individual and depend upon a motorist's level of cognition.
- Braking and/or "turning" distance - Braking and/or "turning" distances are dependent upon a driver's cognitive state, the vehicle speed, the braking and steering characteristics of the vehicle, and the roadside terrain.

The steering adjustment area will vary along a route and from driver to driver. In some cases a driver might become inattentive to the position of his/her vehicle within the travel lane, and the vehicle simply begins drifting out of the lane. Upon receiving stimuli from a rumble strip, the driver can quickly perform the necessary steering adjustment to return the vehicle to the travel lane. On the other hand, if a motor vehicle drifts from the travel lane while the driver is extremely drowsy, sleeping, or even under the influence of drugs/alcohol, the driver will require more stimuli to become alert. In addition, the driver's perception/reaction time will be affected by his/her reduced level of cognition, and as a result the driver will require more time to perform the necessary steering adjustment, assuming that he or she is able.

The steering adjustment area also depends upon the placement of the rumble strips within the roadway cross-section. For example, assume a driver of a vehicle drifting from the travel lane becomes alerted to the situation at the moment the vehicle tires contact the rumble strips. If the rumble strips are installed along the edge line, the steering adjustment area begins at the edge line of the travel lane. However, if the rumble strips are installed approximately 2′ (610-mm) from the edge line along the shoulder, the vehicle encroaches 2′ (610-mm) onto the shoulder before the driver receives stimuli from the rumble strips. Thus, the steering adjustment area is effectively shifted to the right of the edge line by 2′ (610-mm).

4.2.1.1 Decision Tree for Detailed Method

The decision tree presented here can be used to determine whether rumble strips should be installed along a roadway and the optimum location for installation within the roadway cross-section. The steps of the decision tree are as follows:

1) Determine the required steering adjustment area and compare to the available clear zone.

A) If the required steering adjustment area is larger than the clear zone, then rumble strips installed along the edge line or on the shoulder will not be effective. Therefore, evaluate whether middle of the lane rumble strips can be effective.

a) If the width of the travel lane is less than 10′ (3-m), do not consider the installation of middle of the lane rumble strips because the steering adjustment area will still extend beyond the boundary of the clear zone (figure 6).

b) If the width of the travel lane is greater than 10′ (3-m), recalculate the steering adjustment area considering the advance warning from the middle of the lane.

- If the recalculated steering adjustment area is within the boundary of the clear zone, then consider installation of middle of the lane rumble strips. Keep in mind that middle of the lane rumble strips might not be favorable to motorcyclists.

- If the recalculated steering adjustment area still extends beyond the boundary of the clear zone, do not install rumble strips.

B) If the theoretical steering adjustment area equals the clear zone, then consider the following:

a) If the shoulder is less than 4′ (1.2-m) wide and the width of the travel lane is greater than 10′ (3-m), then consider installation of middle of the lane rumble strips to accommodate bicyclists, but keep in mind that middle of the lane rumble strips might not be favorable to motorcyclists. (The *Guide for the Development of Bicycle Facilities* (AASHTO, 1999) recommends a minimum shoulder width of 4′ (1.2-m) to accommodate bicyclists.)

b) If the shoulder is less than 4′ (1.2-m) wide AND the width of the travel lane is less than 10′ (3-m), then do not install rumble strips. (If rumble strips are installed on the edge line, there will be insufficient room to accommodate bicyclists. If rumble strips are installed in the middle of the lane, the steering adjustment area still extends beyond the boundary of the clear zone.)

c) If the shoulder width is 4′ (1.2-m) or greater, install rumble strips on the edge line.

C) If the theoretical steering adjustment area is less than the clear zone, then consider the following:

a) If the shoulder width is less than 4′ (1.2-m), install rumble strips on the shoulder at a distance from the edge line such that the steering adjustment area does not extend beyond the clear zone boundary. Note: recalculate the steering adjustment area considering that the area is shifted to the right of the edge line. (Consider narrow rumble strips to provide adequate space for bicyclists, without significantly reducing exposure time).

b) If the shoulder width is between 4′ (1.2-m) and 6′ (1.8-m), install rumble strips close to or on the edge line so that at least 4′ (1.2-m) are provided for the bicyclist, to the right of the rumble strip. Recalculate the steering adjustment area considering that the area is shifted to the right of the edge line. Make sure the recalculated steering adjustment area does not extend beyond the clear zone boundary.

4.2.2 Simplified Method - Roadside Hazard Rating

The roadside hazard rating system was developed by Zegeer et al. (1988) as a measure to quantify the overall roadside hazards of a roadway section. The roadside hazard rating is a seven-point scale that takes into account the overall hazard of the site as well as the potential frequency and severity of roadside crashes. Roadsides are rated according to accident damage likely for errant vehicles on a scale from one (low likelihood of off-road collision or overturn) to seven (high likelihood of a crash resulting in fatality or severe injury). In general, steep side slopes and/or large obstacles close to the roadway correspond to a hazard rating of seven, while clear, level roadsides represent a hazard rating of one. Sample photographs of rural roadsides, with their corresponding hazard rating, are provided in figure 9.

4.2.2.1 Decision Tree for Simplified Method

This decision tree can be used to determine the optimum placement of rumble strips within the roadway cross-section. The steps of the decision tree are as follows:

1) Determine the preferred lateral width of the rumble strip.

2) Determine the roadside hazard rating.

   A) If the roadside hazard rating is 5 or higher, the site has the potential for more severe crashes. In this case the roadside is less likely to safely accommodate an errant vehicle. Therefore, the rumble strips should be placed within the roadway cross-section to provide the greatest amount of paved recovery area so the rumble strips should be centered along the center of the edge line. This placement will provide the maximum room for bicyclists along the shoulder while alerting inattentive drivers as early as possible.

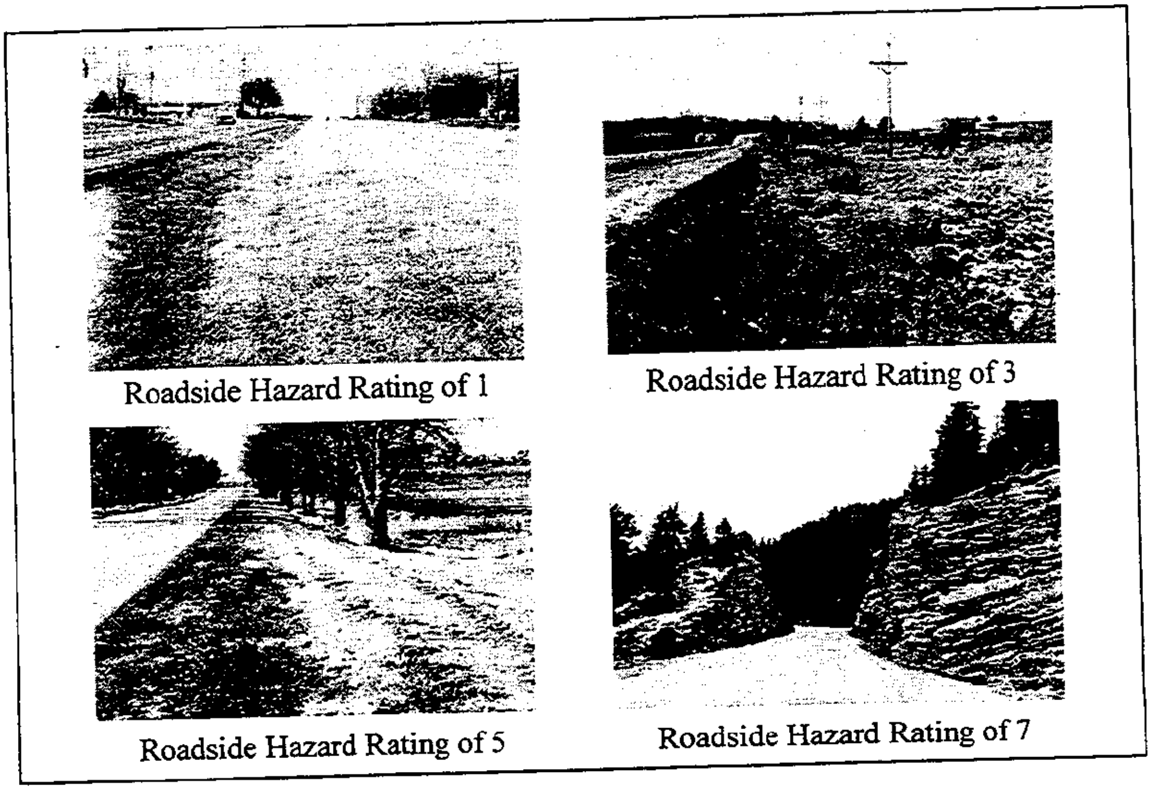

Figure 9. Sample roadside hazard rating photographs (Zegeer et al., 1988)

B) If the hazard rating is 4 or lower, the site has a lower potential for severe crashes. Furthermore, it implies there is no immediate danger to an errant vehicle as it leaves the shoulder. Therefore, the rumble strips should be placed on the outside (right) portion of the shoulder. The rumble strips should be placed as far as possible to the edge of the paved shoulder without compromising the integrity of the paved shoulder. Pavement cross-section on the shoulder and the capabilities of the milling machine should be taken into consideration when determining this distance. By placing the rumble strip on the outside portion of the shoulder, the rumble strips will effectively alert motorists while providing an unobstructed area for bicyclists along the edge of the travel way.

5. SAMPLE CASE STUDIES

Two case studies are presented as examples of how the methodology is used to determine the recommended lateral width and placement of rumble strips. The sites were selected from a database developed during a previous research project (Fitzpatrick et al., 1999). The database contains geometric roadway information such as lane width, shoulder width, and roadside hazard rating. All data used in the examples were taken from the database. The sites were visited to obtain the photographs shown in figures 10 and 12.

Site # 1 (figure 10):

- The roadway has a 3.6′ (1.10m) shoulder.
- The speed limit is 55 mph (88 km/h).
- The roadside hazard rating is 4.

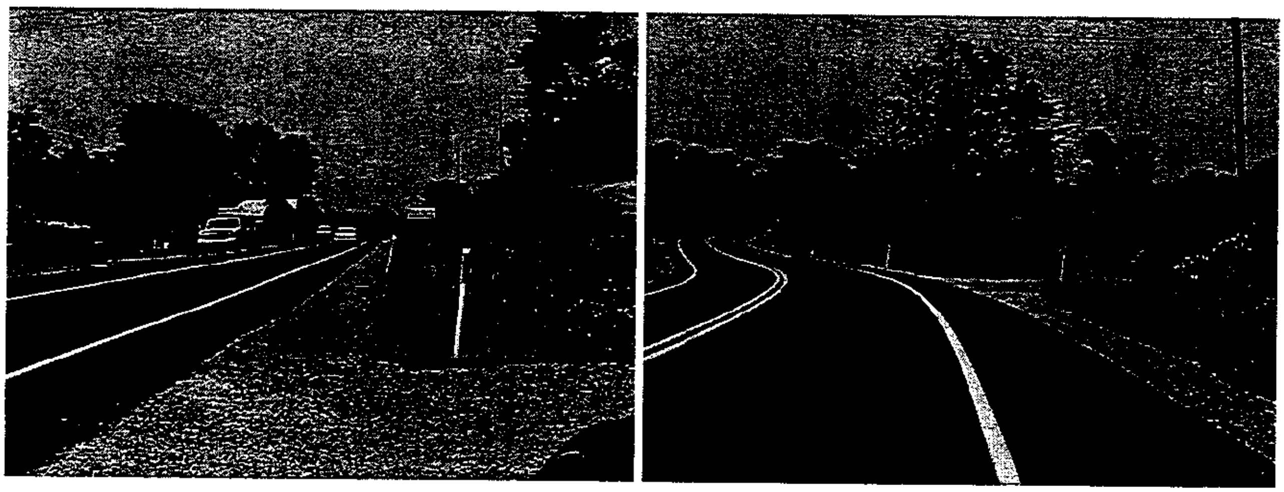

Figure 10. Typical roadside features for site # 1

1. The first step is to determine the preferred lateral width of the rumble strips. Figure 7 is used. Because engineering judgment should be exercised in selecting a desired exposure time, lateral widths are determined for several exposure times to illustrate the effect of desired exposure time on the resulting lateral width. Assuming a typical departure angle of 3° and desired exposure time of 0.15 seconds, the preferred lateral width of the rumble strip would be 6" (150-mm). If the desired exposure time is increased to 0.35 seconds, the preferred lateral width more than doubles to 13" (330-mm). If the desired exposure time were 0.5 seconds, the preferred lateral width of the rumble strip would be greater than 16" (406-mm). Based upon research by Watts (1977) a minimum desired exposure time of 0.35 seconds is selected, so the rumble strip is designed with a lateral width of 13" (330-mm).

2. Step two is to determine the roadside hazard rating. The site was rated as a 4; therefore decision B is followed on the decision tree. Therefore, the rumble strip should be placed as far to the right as possible while not compromising pavement integrity. It was determined that 4" (102-mm) from the rightmost edge of the paved shoulder was adequate considering the cross-section of the shoulder. The cross-section of the rumble strip is shown in figure 11.

For comparison purposes, if the speed limit of site #1 was 45 mph (72 km/h) rather than 55 mph (89 km/h), the rumble strip would be designed with a different lateral width assuming the other conditions remain the same (i.e., desired exposure time is 0.35 seconds, and a 3° departure angle). Under these conditions, the rumble strip would be designed with a lateral width of 10" (254-mm). It would still be placed along the outside portion of the paved shoulder.

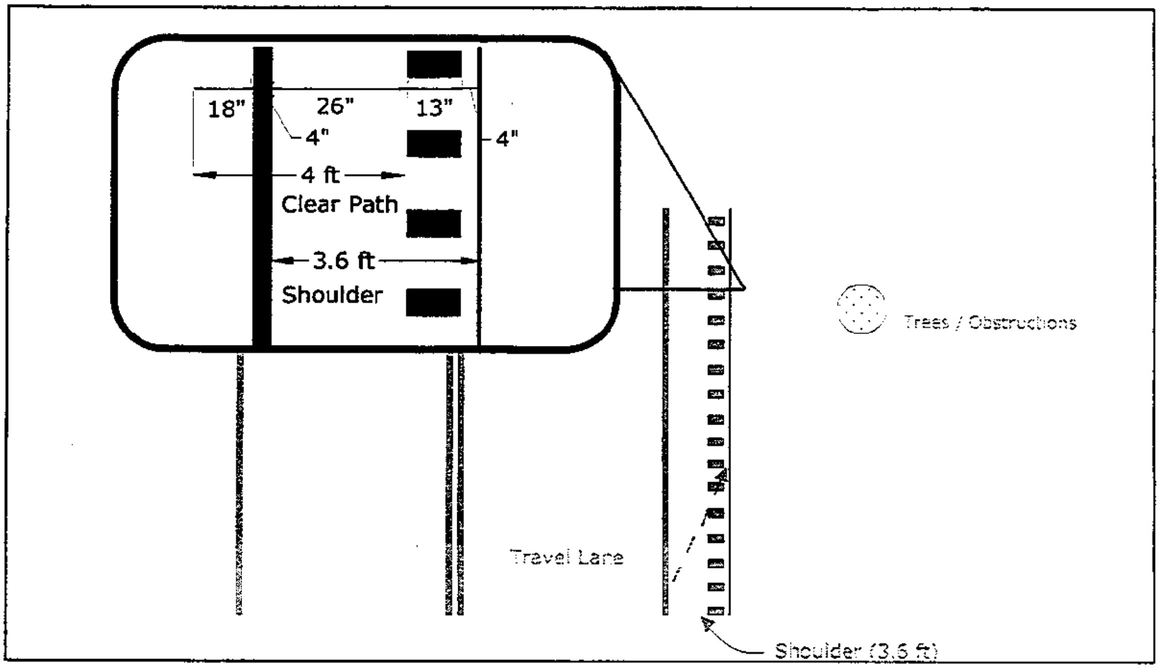

Figure 11. Placement and lateral width of rumble strips for site # 1

Site # 2 (figure 12):

- The roadway has a 3.2' (0.975-m) shoulder.
- The speed limit is 55 mph (88 km/h).
- The roadside hazard rating is 4.

Figure 12. Typical roadside features for site # 2

1. Figure 7 is used to determine the lateral width of the rumble strip to produce a desired exposure time. Using a departure angle of 3° and desired exposure time of 0.35 seconds, a 13" (330-mm) lateral width is selected.

2. Step two consists of determining the roadside hazard rating. The site was rated as having a hazard rating of 4; therefore decision B is followed on the decision tree. Therefore, the rumble strip should be placed as far to the right as possible while not compromising pavement integrity. It was determined that 4" (102-mm) from the rightmost edge of the paved shoulder was adequate considering the cross-section of the shoulder. The cross-section of the shoulder is shown in figure 13.

For comparison purposes, if the site had a hazard rating of 5 or greater, the preferred lateral width of the rumble strip would remain the same (assuming all other conditions remain the same). However, rather than placing the rumble strip on the outside (rightmost) portion of the shoulder, the rumble strips would be centered along the edge line.

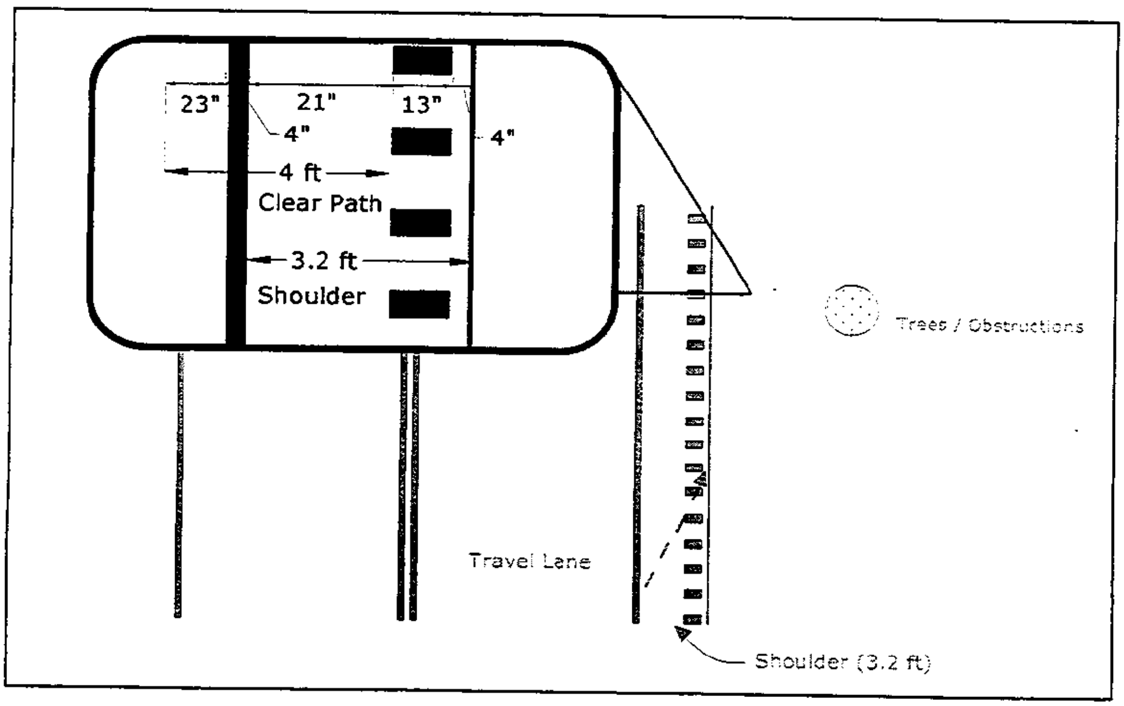

Figure 13. Placement and lateral width of rumble strips for site # 2

6. EXPERIMENTAL PLAN

This section presents an experimental plan developed to evaluate the conceptual design of rumble strips for roads with narrow or non-existent shoulders. The procedures for determining the preferred lateral width of rumble strips and the placement of the rumble strips within the roadway cross-section are applicable to all non-freeway facilities with frequent run-of-the-road crashes and which have pavements with good surfaces. The experimental design is divided into four sections: crash analysis, motor vehicle tests, bicycle tests, and pavement integrity tests.

6.1 Crash Analysis

To evaluate the safety effects of rumble strip installations on roads narrow or non-existent shoulders, a before-after crash analysis should be conducted with comparison sites. With before-after crash analyses, typically the number of crashes "before" the installation of the safety treatment is compared to the number of crashes "after" the installation of the safety treatment, and the difference in frequency is attributed to the safety treatment (Hauer, 1997). This is a naive comparison, however, because it assumes the number of "before" crashes is a good estimate of what would have been the number of "after" crashes, but since traffic, weather, road user demographics, vehicle fleet, and other important factors all change in time, the tacit assumption is incorrect. The simple comparison of "before" crashes to "after" crashes reflects not only the effect of the safety treatment, but also the effect of changes in all the other factors.

To assess the safety effects of rumble strip installations, a comparison should be made between the predicted number of crashes in the "after" period, had the rumble strips not been installed, and the number of actual crashes in the "after" period (Hauer, 1997). In other words, the safety effect of the rumble strip installations is in the comparison of:

What **would have been** the safety of the roadway in the "after" period had the treatment not been applied	with	What the safety of the treated roadway in the "after" period **was**.

To make such a comparison, a before-after crash analysis should be conducted with comparison sites. This approach is well suited to estimating the safety effectiveness of the rumble strip installations while controlling for time trend effects. A minimum of three years "before" crash data should be gathered for each site where rumble strips were installed and the comparison sites. An equal number of years of "after" crash data should be gathered for the respective sites. In addition, ADT data should be gathered for the respective sites for the same time periods.

The reason for including comparison sites in the analysis and for collecting ADT data is to account for the many causal factors that influence road safety over time (Hauer, 1997). The varieties of causal factors that change over time belong to two classes. One set of factors is known to affect safety, and their effect on safety is well understood. For example, the influences of traffic flow can be modeled to account for changes in traffic flow. This is the reason ADT data should be collected during the "before" and "after" periods. The second set of causal factors includes those factors that are either not recognized as affecting safety, are recognized but are not measured, and those whose influence on safety is not well understood. To account for this second set of factors, crash data and ADT data should be gathered from comparison sites.

Ideally, each route where rumble strips were installed which is included in the crash analysis should have at least one corresponding comparison site. The corresponding comparison site should have similar horizontal and vertical alignments, cross-sectional features, traffic flow, and vehicle fleet composition.

6.2 Motor Vehicle Tests

To assess the effectiveness of the rumble strip configurations on alerting inattentive motorists, measurements should be taken of the auditory stimuli generated by the rumble strips. Field tests should be conducted to measure the noise generated by the rumble strips with different lateral widths. It is recommended that three common vehicles be used during the testing, such as small, mid-size and full-size passenger cars. The motor vehicle tests should be conducted under the following conditions:

- Testing speed: 45 mph (72 km/h) & 55 mph (88 km/h)
- Road conditions: dry and clean

To measure the noise generated from the rumble strips, a sound meter (such as a Bruel & Kjaer sound meter-type 2232) can be used to measure the maximum noise level using the A-weighting (dB(A)) generated in the passenger compartment. This maximum noise level should be compared to the ambient noise level while driving within the travel way. A minimum of three tests should be conducted for each rumble strip configuration at each speed and for each test vehicle. The results of these tests can be compared to the noise tests conducted during the *Bicycle-Tolerable Shoulder Rumble Strips* project (Elefteriadou et al., 2000).

The effectiveness of the rumble strip configurations on alerting inattentive motorists can also potentially be evaluated by collecting vibration data. During the *Bicycle-Tolerable Shoulder Rumble Strips* project (Elefteriadou et al., 2000), an accelerometer was mounted to the frame of a motor vehicle (minivan) and vertical and pitch angular accelerations of the vehicle frame were measured as the vehicle was traversed across different rumble strip configurations. These measures did not prove to be effective measures for describing the ability of rumble strips to alert inattentive/drowsy drivers. One possibility would be to once again measure the vertical and pitch angular accelerations of motor vehicle frames while traversing the new rumble strip configurations, either to confirm results from the previous research or to obtain additional information on vibrations of vehicle frames generated by rumble strips. This can be accomplished by securing an accelerometer (such as a Crossbow DMU-VGS six-axis vertical/angular measurement unit) to the frames of the three proposed vehicles, at approximately the center of gravity of the vehicles. In addition, other locations for measuring vibrations should be explored. One possibility is mounting an accelerometer(s) to the steering wheel. A second option is mounting the accelerometer(s) on the driver seat. A third option is to design a harness for the driver to wear and mount the accelerometer(s) on the driver. Thus, the following four possible locations for mounting the accelerometer(s) should be explored to evaluate the effectiveness of the new rumble strip configurations on alerting inattentive drivers, based upon the vibrational stimuli generated by the rumble strips:

- center of gravity of the vehicle frame,
- the steering wheel,
- the driver seat, and/or
- harnessed to the driver

6.3 Bicycle Tests

The bicycle tests should consist of two types. Vibration testing should be conducted to measure the accelerations experienced by the bicyclists while traversing the rumble strip configurations. The vibration portion of the bicycle tests should be conducted in the same manner as the vibration tests conducted during the *Bicycle-Tolerable Shoulder Rumble Strips* project (Elefteriadou et al., 2000). This way the vibrations generated by the rumble strips installed in the field can be compared to the vibration generated by the rumble strips installed in the fully controlled environment. If the new rumble strip configurations have similar groove widths, depths, and spacings as those tested earlier (Elefteriadou et al., 2000), the measurements can be used to validate the previous testing. If the new rumble strip configurations have different groove widths, depths, and spacings, then the accelerations can be compared to the results from the *Bicycle-Tolerable Shoulder Rumble Strips* project (Elefteriadou et al., 2000) to determine which configurations are more tolerable for bicyclists.

To measure the vibrations levels experienced by bicyclists, an accelerometer should be secured to the crossbars of the bicycles, located near the approximate center of gravity of the bicycle/rider systems and near the seat posts. The vertical and pitch angular accelerations should be recorded and reported as the root-mean-square of the acceleration histories. The frequencies of the motions should also be recorded. At least two types of bicycles should be used during the vibration testing. One bicycle should be similar to one of the bicycles tested during the *Bicycle-Tolerable Shoulder Rumble Strips* project (Elefteriadou et al., 2000). In other words, it should be a non-suspended mountain, road, or hybrid bicycle. Since the road bicycle generated the highest vibration levels during the previous research, it is recommended that a road bicycle be used during the testing. This way the worst-case scenario will be evaluated. By testing a road bicycle without active suspension, a direct comparison can be made between the accelerations generated by the new rumble strip configurations and the accelerations generated by the rumble strip configurations tested during the *Bicycle-Tolerable Shoulder Rumble Strips* project (Elefteriadou et al., 2000). The second type of bicycle should have an active suspension system. A bicycle with an active suspension was not tested during the previous research, and an investigation to determine the vibration levels experienced by bicyclists on these types of bicycles would be useful. At least five bicyclists should test the respective bicycles during the vibration testing. Tests should be conducted at one approach angle and three different traverse speeds:

- 0° traverse angle (straight on approach)
- Low Speed: from 3 to 9 mph (5 km/h to 15 km/h)
- Intermediate Speed: from 10 to 15 mph (16 km/h to 25 km/h)
- High Speed: greater than or equal to 16 mph (26 km/h)

To evaluate the effect of the lateral width and placement of the rumble strips on overall ride quality, bicyclists should complete a survey. The questionnaire should be designed to determine bicyclists' perception of ride quality along the route before and after the installation of the rumble strips. Factors that may influence the ride quality along the route include the placement of the rumble, lateral width of the rumble strip, width of clear path, traffic volume, vehicle speeds, and traffic composition.

6.4 Pavement Performance Tests

If the method of installation, placement, or other features of rumble strips decrease pavement performance, unanticipated costs or safety detriments may occur. Reduced pavement performance may include decreased skid resistance, increased roughness, and decreased life. Each of these factors may reduce overall safety both directly, and indirectly, by increasing the frequency of repair and construction work on the roadway section. Therefore, the impacts on pavement performance of the rumble strips under investigation should be assessed through two types of field tests: real-time and accelerated.

6.4.1 Real-Time Assessment

An initial pavement inspection and examination should be conducted immediately before and again after the rumble strips are installed. This will assist in the identification of pavement distresses already existing, and any occurring at the time of installation. This inspection should include the specific characteristics discussed below. This inspection should also include an assessment of the pavement drainage, and any effects on the drainage observed after installation of the rumble strips.

The experimental rumble strip areas should be surveyed periodically (once per year is suggested) for related pavement distresses. This should include careful observation of the pavement directly at the rumble strips, measurement and recording of the overall pavement performance, and corresponding inspection of a control section without rumble strips.

The pavement directly affected by the rumble strips should be carefully examined for evidence of:

- Raveling
- Stripping
- Debonding of the layers
- Localized cracking or rutting

If possible, a core should be taken from an area exhibiting differentially high levels of distress, and compared to a control core from a nearby location without the rumble strips. This would enable confirmation or elimination of the possibility of the rumble strips causing or contributing to the observed problem.

In addition, the overall pavement section should be inspected periodically. This inspection should be conducted using the condition survey techniques already in use by PENNDOT, including skid resistance, roughness, and pavement images. It would be necessary, however, to divide the pavement indices into sections with and without rumble strips, rather than to obtain the summaries as typically reported.

Any routine preventive or restorative maintenance performed to the rumble strips or to the overall pavement section should be carefully recorded for the experimental and control sections. This would be essential to identifying other causes of differential performance. In addition, proper preventive maintenance of milled rumble strips may include periodic seal coats, which may also affect pavement performance and skid resistance.

6.4.2 Accelerated Assessment

The possibility exists to obtain accelerated predictions of the relative future performance of the pavement sections with and without rumble strips. This would require the coring of sections with rumble strips and a nearby control, and the subsequent laboratory testing of those cores.

Cores should be obtained before installation of the rumble strips, immediately after installation, and after one to three years of environmental exposure. The cores would be tested for structural capacity of the bituminous layers. This would determine if the rumble strips have accelerated material and/or structural damage to the pavement even before any surface distresses have been observed.

Falling weight deflectometer testing to assess the relative structural capacity of areas with and without milled rumble strips may also be a feasible technique for accelerated assessment. However, the difficulty of seating the load and sensors directly on an area with rumble strips may be an obstacle.

7. CONCLUSIONS AND RECOMMENDATIONS

The goal of this project was to develop conceptual designs for rumble strips to be placed on roads with narrow or non-existent shoulders, so that: a) their installation does not compromise the integrity of the pavement, b) their location and/or type are acceptable for bicyclists, and c) they can alert inattentive drivers. Assuming the roadway to be a non-freeway facility with good pavement conditions, once a site has been identified for the installation of rumble strips to reduce run-off-the-road crashes, two procedures have been developed to determine the preferred lateral width of the rumble strip and the optimum placement of rumble strips within the roadway cross-section. These procedures can be used in combination with the findings from the *Bicycle-Tolerable Shoulder Rumble Strips* project (Elefteriadou et al., 2000) to determine the exact pattern and placement for rumble strips on roads with narrow or non-existent shoulders.

The methodology for determining the preferred lateral width of the rumble strip and the optimum placement of rumble strips within the roadway cross-section is as follows:

1) Determine the preferred lateral width of the rumble strip.

Determining the preferred lateral width of a rumble strip depends upon a desired exposure time of the stimuli (noise and/or vibration) generated by the rumble strips. The exposure time of the stimuli is a function of vehicle speed, departure angle, the lateral width of the rumble strips, and the contact area of the tire.

2) Determine the preferred placement of the rumble strips.

The placement of rumble strips within the roadway cross-section is a function of the clear zone and the steering adjustment area. For rumble strips to fulfill their intended purpose, the clear zone should be greater than the steering adjustment area. Such information however may be difficult to obtain and estimate for an entire roadway section. Thus, two methods were developed for determining the optimum placement of rumble strips within the roadway cross-section. It can be determined based upon the clear zone and steering adjustment areas, or it can be determined based upon the roadside hazard rating. The simplified procedure for determining the optimum placement of rumble strips based upon the roadside hazard rating is recommended.

The roadside hazard rating is a seven-point scale that takes into account the overall hazard of the site as well as the potential frequency and severity of roadside crashes. Roadsides are rated according to accident damage likely for errant vehicles on a scale from one (low likelihood of off-road collision or overturn) to seven (high likelihood of a crash resulting in fatality or severe injury).

A) If the roadside hazard rating is 5 or higher, the site has the potential for more severe crashes. Therefore, the rumble strips should be placed within the roadway cross-section to provide the greatest amount of paved recovery area so the rumble strips should be centered along the center of the edge line.

B) If the hazard rating is 4 or lower, the site has a lower potential for severe crashes. Therefore, the rumble strips should be placed on the outside (right) portion of the shoulder. The rumble strips should be placed as far as possible to the edge of the paved shoulder without compromising the integrity of the paved shoulder. Pavement cross-section on the shoulder and the capabilities of the milling machine should be taken into consideration when determining this distance.

Appendix C is a stand-alone concise guide for practitioners that want to use the simplified method for determining the preferred lateral width and optimum placement of rumble strips within the roadway cross-section.

An experimental plan is provided to evaluate the conceptual design of rumble strips for roads with narrow or non-existent shoulders. The plan consists of four types of evaluations to determine whether the goal of the research is achieved. A before-after crash analysis should be conducted with comparison sites to estimate the safety effectiveness of the rumble strip installations while controlling for time trend effects. To assess the effectiveness of the rumble strip configurations on alerting inattentive motorists, field tests of motor vehicles should be conducted to measure the auditory and vibrational stimuli generated by the rumble strips. To assess the impacts of the rumble strip configurations on bicyclists, bicycle tests should measure the accelerations experienced by the bicyclists while traversing the rumble strip configurations, and surveys should be filled-out by bicyclists local to the area to determine bicyclists' perception of ride quality along the route prior to installation of the rumble strips and afterwards. Finally, the impacts on pavement performance of the rumble strips under investigation should be assessed through real-time and accelerated field-testing.

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APPENDIX A

REVIEWING TASK FORCE

APPENDIX A

A reviewing task force was formed as part of this project to guide the development of a conceptual design of rumble strips for roads with narrow or non-existent shoulders. The following individuals served on this task force:

Table A.1 Members of the reviewing task force

Name	Affiliation
Dave Bachman	Pennsylvania Department of Transportation
Patti Marshall	Pennsylvania Department of Transportation
James Tenaglia	Pennsylvania Department of Transportation
Devang Patel	Pennsylvania Department of Transportation
Michael Baglio	Pennsylvania Department of Transportation
Gary Modi	Pennsylvania Department of Transportation
James Long	Pennsylvania Department of Transportation
Michael Castellano	Federal Highway Administration
Thomas Helm	Bicycling Federation of Pennsylvania
William Hoffman	Pennsylvania Pedalcycle and Pedestrian Advisory Committee
Martin Pietrucha	The Pennsylvania State University

APPENDIX B

RESPONSES TO SURVEY

APPENDIX B

Responses to the survey were obtained from the following representatives at the respective state and federal highway agencies.

State	Agency	Contact
Alabama	FHWA	Wes Elrod
Arizona	DOT	Richard C. Moeur
	FHWA	Phil Bleyl
Arkansas	DOT	Phillip McConnell
	FHWA	Brent Dather
California	DOT	Craig Copelan, Linus Motumah
Colorado	DOT	Bryan Allery
	FHWA	Peter U. Eun
Connecticut	FHWA	Robert Ramirez
Delaware	FHWA	Patrick Kennedy, David Nicol
Florida	DOT	Jim Mills
	FHWA	Bobby Norburn
Georgia	DOT	Jim Kennerly
	FHWA	Dana Robbins, Terry Chism
Idaho	DOT	Greg M. Laragan
	FHWA	Cathy Satterfield
Indiana	DOT	Jeff James
	FHWA	Edward Ratulowski
Kansas	DOT	Mike Crow
	Kansas State University	Gene Russell, Dr. Margaret Rys
Kentucky	DOT	Gary Sharpe
Louisiana	DOT	Hadi H. Shirazi
Maine	DOT	Stephen Landry
	FHWA	Tracey Praul

Maryland	Maryland State Highway	Tom Hicks
Massachusetts	DOT	Robert Fay, Wesley Blount
Michigan	DOT	Carlos Libiran
Minnesota	DOT	Cassandra Isackson
Missouri	DOT	Kirsten Munck, Pat McDaniel, Joe Jones
Montana	DOT	Gary Gilmore
	FHWA	Craig Genzlinger
New Hampshire	FHWA	Marty Calawa
New Jersey	FHWA	Dave Powell
New Mexico	DOT	Eric Martinez
New York	DOT	John Watson
	FHWA	Emmett McDevitt
North Carolina	DOT	Dewayne Sykeo
North Dakota	FHWA	Steve Busek
Oklahoma	DOT	Brian E. Schmitt
Oregon	DOT	Larry Christianson
Pennsylvania	FHWA	Michael Castellono
South Dakota	FHWA	Roland Stenger, Brett Hestdalen
Tennessee	DOT	David Donoho
	FHWA	Ron Carr
Texas	DOT	Mark Marek, Greg Brinkmeyer, Michael Behrens
Utah	FHWA	Clair Hendrickson
Virginia	FHWA	Bob McCarty
	DOT	Chung Chen
Washington	FHWA	Dennis Eckhart
West Virginia	FHWA	Greg Morris, Ed Compton
Wisconsin	DOT	John Haverberg
	FHWA	Bill Bremer
Wyoming	FHWA	Lee Potter

Responses to the survey were obtained from the following rumble strip providers/contractors.

Contractor	Contact
Thomas Grinding, INC.	Chad Thomas
KLEMMFIX GmbH	Ilse Mann
Davidson Traffic Control Products	Peter Speer

APPENDIX C

CONCISE STAND-ALONE GUIDE FOR CONCEPTUAL DESIGN OF RUMBLE STRIPS

APPENDIX C

This appendix includes a concise guide for determining the preferred lateral width and optimum placement of rumble strips within the roadway cross-section. The methodology consists of two procedures. The first procedure is used to determine the preferred lateral width of the rumble strip. The second procedure is used to determine the optimum placement of rumble strips within the roadway cross-section. The methodology does not provide recommendations for rumble strip dimensions of groove width, groove depth, or groove spacing. The impacts of these three rumble strip design elements on motorists and bicyclists were evaluated by Elefteriadou et al. (2000). Table C.1 provides the recommended dimensions for groove width, depth, and spacing for the respective facility types so that the rumble strips can alert inattentive/drowsy motorists and be safely and comfortably traversed by bicyclists. These dimensions should be used in combination with the procedures to determine the preferred lateral width of rumble strips and the optimum placement of rumble strips within the roadway cross-section to determine the exact pattern and placement for rumble strips on roads with narrow or non-existent shoulders.

Table C.1 Recommended groove widths, depths, and spacings

Groove Width	Flat Portion between Grooves	Groove Depth	Facility Type
5" (127-mm)	7" (178-mm)	0.375" (10-mm)	High Operating Speeds (55 mph or 88 km/h)
5" (127-mm)	6" (152-mm)	0.375" (10-mm)	Low Operating Speeds (45 mph or 72 km/h)

The steps of the decision tree are as follows:

1) Determine the preferred lateral width of the rumble strip.

Determining the preferred lateral width of a rumble strip depends upon a desired exposure time of the stimuli (noise and/or vibration) generated by the rumble strips. The exposure time of the stimuli is a function of vehicle speed, departure angle, the lateral width of the rumble strips, and the contact area of the tire. Figures C.1 to C.4 illustrate the variation in exposure time as a function of vehicle speed, departure angle, and lateral width of the rumble strip. These figures, or the corresponding tables C.2 to C.5, can be used to determine the preferred lateral width of rumble strips for a route.

2) Determine the roadside hazard rating.

The roadside hazard rating is a seven-point scale that takes into account the overall hazard of the site as well as the potential frequency and severity of roadside crashes. Roadsides are rated according to accident damage likely for errant vehicles on a scale from one (low likelihood of off-road collision or overturn) to seven (high likelihood of a crash resulting in fatality or severe injury). In general, steep side slopes and/or large obstacles close to the roadway correspond to a hazard rating of seven, while clear, level roadsides represent a hazard rating of one. Sample photographs of rural roadsides, with their corresponding hazard rating, are provided in figure C.5.

A) If the roadside hazard rating is 5 or higher, the site has the potential for more severe crashes. In this case the roadside is less likely to safely accommodate an errant vehicle. Therefore, the rumble strips should be placed within the roadway cross-section to provide the greatest amount of paved recovery area so the rumble strips should be centered along the center of the edge line. This placement will provide the maximum room for bicyclists along the shoulder while alerting inattentive drivers as early as possible.

B) If the hazard rating is 4 or lower, the site has a lower potential for severe crashes. Furthermore, it implies there is no immediate danger to an errant vehicle as it leaves the shoulder. Therefore, the rumble strips should be placed on the outside (right) portion of the shoulder. The rumble strips should be placed as far as possible to the edge of the paved shoulder without compromising the integrity of the paved shoulder. Pavement cross-section on the shoulder and the capabilities of the milling machine should be taken into consideration when determining this distance. By placing the rumble strip on the outside portion of the shoulder, the rumble strips will effectively alert motorists while providing an unobstructed area for bicyclists along the edge of the travel way.

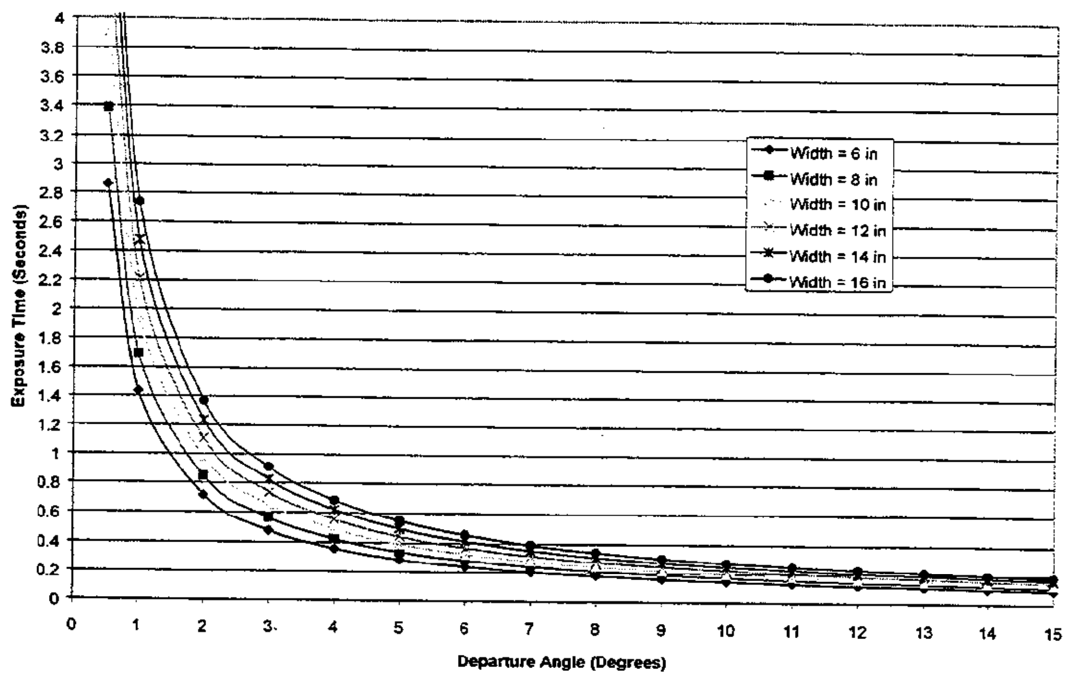

Figure C.1 Exposure time as a function of lateral width (speed = 25 mph)

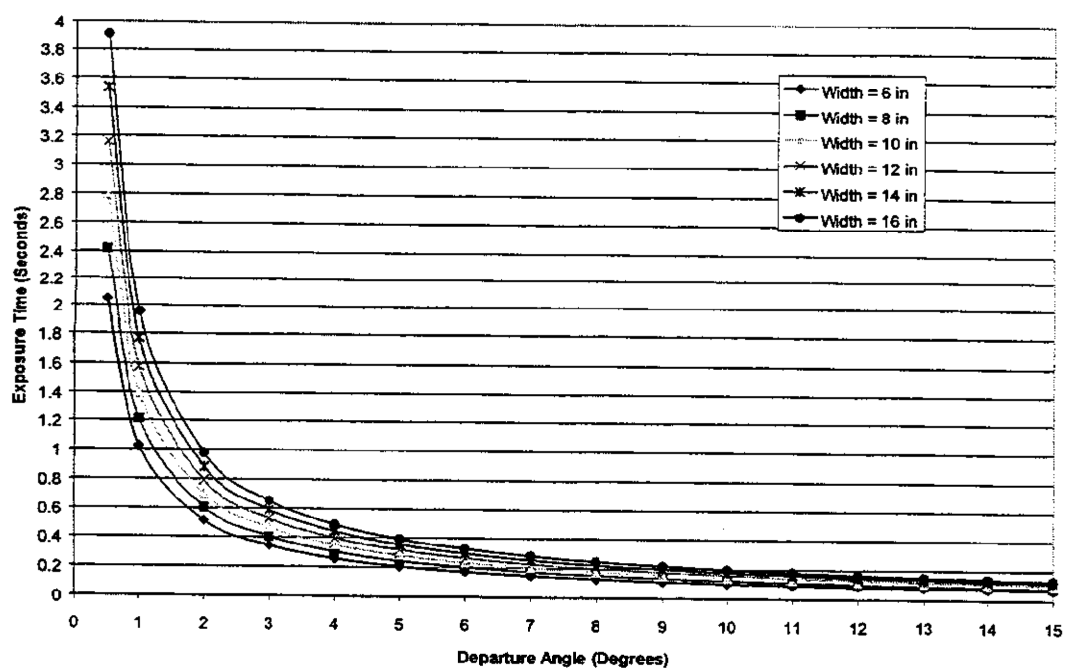

Figure C.2 Exposure time as a function of lateral width (speed = 35 mph)

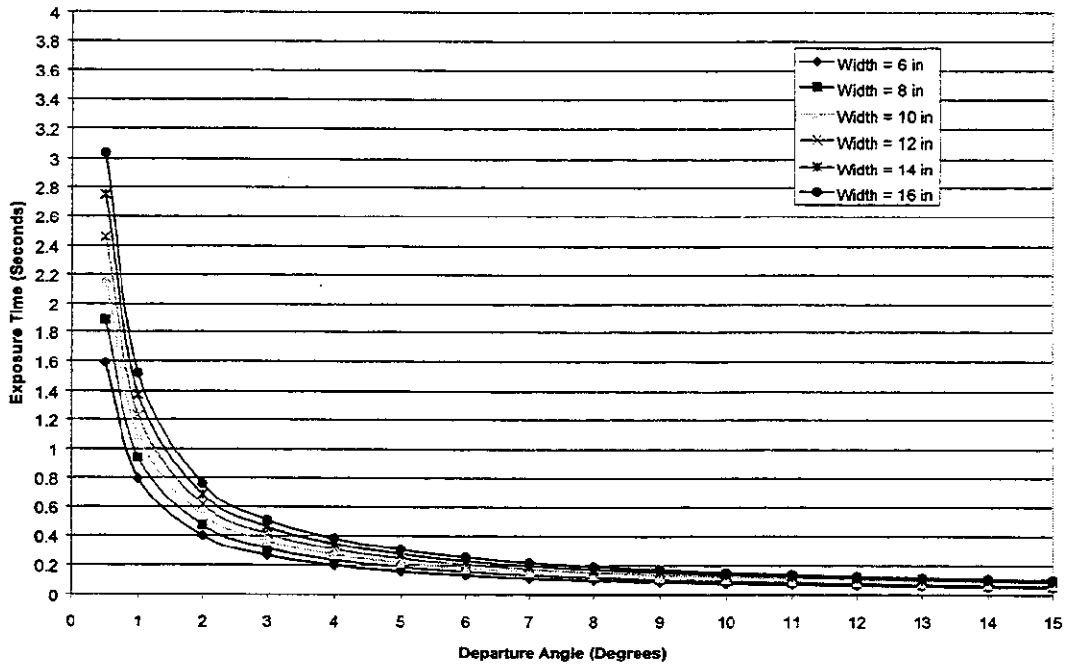

Figure C.3. Exposure time as a function of lateral width (speed = 45 mph)

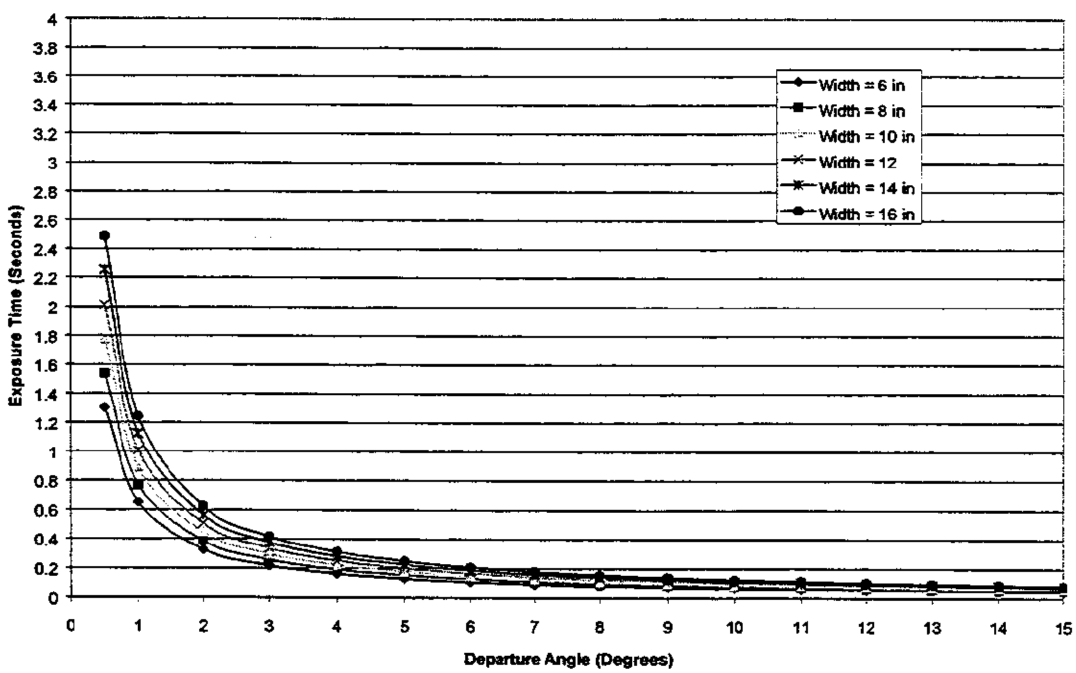

Figure C.4 Exposure time as a function of lateral width (speed = 55 mph)

Table C.2 Exposure time as a function of lateral width (speed = 25 mph)

Departure Angle (degrees)	Lateral Width of Rumble Strips					
	6 inches (152-mm)	8 inches (203-mm)	10 inches (254-mm)	12 inches (305-mm)	14 inches (356-mm)	16 inches (406-mm)
	Desired Exposure Time (seconds)					
0.5	2.865	3.3386	3.907	4.427	4.948	5.469
1	1.432	1.693	1.953	2.214	2.474	2.735
2	0.716	0.847	0.977	1.107	1.237	1.368
3	0.478	0.565	0.651	0.738	0.825	0.912
4	0.358	0.424	0.489	0.554	0.619	0.684
5	0.287	0.339	0.391	0.443	0.495	0.548
6	0.239	0.283	0.326	0.370	0.413	0.457
7	0.205	0.242	0.280	0.317	0.354	0.392
8	0.180	0.212	0.245	0.278	0.310	0.343
9	0.160	0.189	0.218	0.247	0.276	0.305
10	0.144	0.170	0.196	0.222	0.249	0.275
11	0.131	0.155	0.179	0.202	0.226	0.250
12	0.120	0.142	0.164	0.186	0.208	0.230
13	0.111	0.131	0.152	0.172	0.192	0.212
14	0.103	0.122	0.141	0.160	0.178	0.197
15	0.097	0.144	0.132	0.149	0.167	0.184

Table C.3 Exposure time as a function of lateral width (speed = 35 mph)

Departure Angle (degrees)	Lateral Width of Rumble Strips					
	6 inches (152-mm)	8 inches (203-mm)	10 inches (254-mm)	12 inches (305-mm)	14 inches (356-mm)	16 inches (406-mm)
	Desired Exposure Time (seconds)					
0.5	2.046	2.418	2.790	3.162	3.535	3.907
1	1.023	1.209	1.395	1.581	1.767	1.953
2	0.512	0.605	0.698	0.791	0.884	0.977
3	0.341	0.403	0.465	0.527	0.589	0.651
4	0.256	0.303	0.349	0.396	0.442	0.489
5	0.205	0.242	0.279	0.317	0.354	0.391
6	0.171	0.202	0.233	0.264	0.295	0.326
7	0.147	0.173	0.200	0.226	0.253	0.280
8	0.128	0.152	0.175	0.198	0.222	0.245
9	0.114	0.135	0.156	0.176	0.197	0.218
10	0.103	0.122	0.140	0.159	0.178	0.196
11	0.094	0.111	0.128	0.145	0.162	0.179
12	0.086	0.102	0.117	0.133	0.148	0.164
13	0.079	0.094	0.108	0.123	0.137	0.152
14	0.074	0.087	0.101	0.114	0.127	0.141
15	0.069	0.082	0.094	0.107	0.119	0.132

Table C.4 Exposure time as a function of lateral width (speed = 45 mph)

Departure Angle (degrees)	Lateral Width of Rumble Strips					
	6 inches (152-mm)	8 inches (203-mm)	10 inches (254-mm)	12 inches (305-mm)	14 inches (356-mm)	16 inches (406-mm)
	Desired Exposure Time (seconds)					
0.5	1.592	1.881	2.170	2.460	2.749	3.038
1	0.796	0.941	1.085	1.230	1.375	1.519
2	0.398	0.470	0.543	0.615	0.687	0.760
3	0.265	0.314	0.362	0.410	0.458	0.507
4	0.199	0.235	0.272	0.308	0.344	0.380
5	0.159	0.188	0.217	0.246	0.275	0.304
6	0.133	0.157	0.181	0.205	0.230	0.254
7	0.114	0.135	0.155	0.176	0.197	0.218
8	0.100	0.118	0.136	0.154	0.172	0.191
9	0.089	0.105	0.121	0.137	0.153	0.169
10	0.080	0.095	0.109	0.124	0.138	0.153
11	0.073	0.086	0.099	0.112	0.126	0.139
12	0.067	0.079	0.091	0.103	0.115	0.128
13	0.062	0.073	0.084	0.095	0.107	0.118
14	0.057	0.068	0.078	0.089	0.099	0.110
15	0.054	0.063	0.073	0.083	0.093	0.102

Table C.5 Exposure time as a function of lateral width (speed = 55 mph)

Departure Angle (degrees)	Lateral Width of Rumble Strips					
	6 inches (152-mm)	8 inches (203-mm)	10 inches (254-mm)	12 inches (305-mm)	14 inches (356-mm)	16 inches (406-mm)
	Desired Exposure Time (seconds)					
0.5	1.302	1.539	1.776	2.012	2.249	2.486
1	0.651	0.770	0.888	1.006	1.125	1.243
2	0.326	0.385	0.444	0.503	0.562	0.622
3	0.217	0.257	0.296	0.336	0.375	0.415
4	0.163	0.193	0.222	0.252	0.281	0.311
5	0.130	0.154	0.178	0.202	0.225	0.249
6	0.109	0.128	0.148	0.168	0.188	0.208
7	0.093	0.110	0.127	0.144	0.161	0.178
8	0.082	0.096	0.111	0.126	0.141	0.156
9	0.073	0.086	0.099	0.112	0.125	0.139
10	0.065	0.077	0.089	0.101	0.113	0.125
11	0.060	0.070	0.081	0.092	0.103	0.114
12	0.055	0.065	0.075	0.084	0.094	0.104
13	0.051	0.060	0.069	0.078	0.087	0.096
14	0.047	0.056	0.064	0.073	0.081	0.090
15	0.044	0.052	0.060	0.068	0.076	0.084

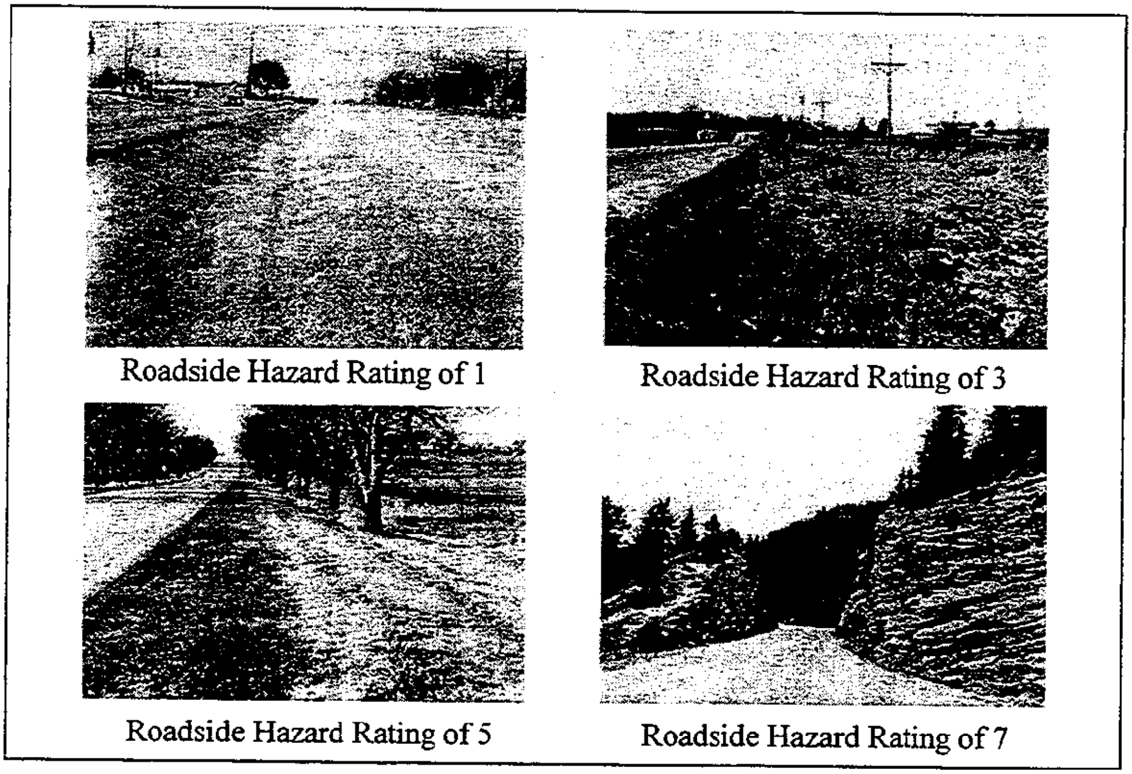

Figure C.5 Sample roadside hazard rating photographs (Zegeer et al., 1988)