PB2000-105200

COMMONWEALTH OF PENNSYLVANIA
DEPARTMENT OF TRANSPORTATION

OFFICE OF PLANNING & RESEARCH

BICYCLE-FRIENDLY SHOULDER RUMBLE STRIPS

University-Based Research, Education and Technology Transfer Program

AGREEMENT NO. 359704, WORK ORDER 25

FINAL REPORT

MARCH 2000

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PENNSTATE

1855

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REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. Agency Use Only (Leave Blank)	2. Report Date	3. Report Type and Dates Covered
	March 2000	Final Report

4. Title and Subtitle
Bicycle-Friendly Shoulder Rumble Strips

5. Funding Numbers
Agreement No. 359704
Work Order No. 25

6. Author(s)
L. Elefteriadou, M. El-Gindy, D. Torbic, P. Garvey, A. Homan, Z. Jiang, B. Pecheux, and R. Tallon

7. Performing Organization Name(s) and Address(es)
The Pennsylvania State University
The Pennsylvania Transportation Institute
201 Transportation Research Building
University Park, PA 16802-4710

8. Performing Organization Report No.
PTI 2K15

9. Sponsoring/Monitoring Agency Name(s) and Address(es)
Pennsylvania Department of Transportation
Bureau of Planning and Research
Division of Research
555 Walnut Street-6th Floor Forum Place
Harrisburg, PA 17101-1900

10. Sponsoring/Monitoring Agency Report Number

11. Supplementary Notes

12a. Distribution / Availability Statement
Available from National Technical Information Service, Springfield, VA

12b. Distribution Code
N/A

13. Abstract (Maximum 200 words)
Shoulder rumble strips have proven to be an effective way to reduce run-off-the-road (ROR) crashes on urban and rural freeways. As the use of shoulder rumble strips is being extended to non-freeway facilities, bicyclists will encounter rumble strips more frequently in the future. Bicyclists are concerned about maneuverability problems while traversing rumble strips, because they can be very uncomfortable to ride over and may cause loss of control of the bicycle.

The objective of this project was to develop new rumble strip configurations that decrease the level of vibration experienced by bicyclists when traversing rumble strips, while at the same time providing an adequate amount of stimuli to alert inattentive or drowsy motorists. Four primary steps were involved in the development of the new rumble strip configurations. The first step was to evaluate and assess the existing rumble strip configuration. The second step was to develop, evaluate, and rank different configurations for their potential to be "bicycle-friendly" yet at the same time not degrade the alerting properties for drivers in motor vehicles. A simulation model was developed and validated to evaluate various new designs. The third step was to install several of the recommended configurations that had the greatest potential to be "bicycle-friendly" and conduct field experiments to further evaluate their effectiveness. The final step of the project was to analyze the data and rank the configurations that were installed based on their ability to alert inattentive or drowsy motorists and on their ability to provide a comfortable and controllable ride for bicyclists.

Researchers recommended two new "bicycle-friendly" rumble patterns for implementation along non-freeway facilities—one for non-freeway facilities with higher operating speeds near 55 mph (88 km/h), and one for non-freeway facilities with lower operating speeds near 45 mph (72 km/h).

14. Subject Terms	15. No. of Pages	16. Price Code
		N/A

17. Security Classification of Report	18. Security Classification of this Page	19. Security Classification of Abstract	20 Limitation of Abstract
None	None	None	None

BICYCLE-FRIENDLY SHOULDER RUMBLE STRIPS

University-Based Research, Education and Technology Transfer Program
Agreement No. 359704
Work Order 25

FINAL REPORT

Prepared for

Commonwealth of Pennsylvania
Department of Transportation
Office of Planning & Research

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March 2000

This work was sponsored by the Pennsylvania Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.

PTI 2K15

ACKNOWLEDGMENT

A reviewing task force was formed as part of this project to guide the development of bicycle-friendly rumble strips. The following individuals served on this task force:

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The authors would like to thank the members of the task force for their time and assistance throughout this project.

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EXECUTIVE SUMMARY

Shoulder rumble strips have proven to be an effective measure in reducing run-off-the-road (ROR) crashes on urban and rural freeways. ROR crashes may be reduced by as much as 20 to 50 percent when rumble strips are installed. As the use of shoulder rumble strips is extended to non-freeway facilities, bicyclists will encounter rumble strips more frequently in the future. Bicyclists are concerned about maneuverability problems while traversing rumble strips because they can be very uncomfortable to ride over and may cause loss of control of the bicycle.

This research was initiated to develop new rumble strip configurations that could alert inattentive/drowsy motorists and be safely and comfortably traversed by bicyclists. Thus, the objective of this project was to develop new rumble strip configurations that decrease the level of vibration experienced by bicyclists when traversing rumble strips, while at the same time, provide an adequate amount of stimuli to alert inattentive/drowsy motorists.

To achieve this objective, two different perspectives needed to be considered throughout the research, that of the bicyclist and that of the motorist. From the bicyclist's perspective, rumble strips should not generate too much vibration or shake the bicycle as the bicyclist traverses the rumble strip, causing discomfort and possibly loss of control. From the motorist's perspective, rumble strips should transmit a sufficient amount of auditory and vibrational stimuli to warn an inattentive/drowsy motorist who drifts from the travel lane.

Four primary steps were involved in the development of the new rumble strip configurations. The first step was to evaluate and assess the Pennsylvania Department of Transportation's existing rumble strip configuration. The second step was to develop, evaluate, and rank different configurations for their potential to be "bicycle-friendly" yet at the same time not degrade the alerting properties for drivers in motor vehicles. A simulation model was developed and validated to evaluate various new designs. The third step was to install several of the recommended configurations that had the greatest potential to be "bicycle-friendly" and conduct field experiments to further evaluate their effectiveness. The final step of the project was to analyze the data and rank the configurations that were installed, based on their ability to alert inattentive/drowsy motorists and provide a comfortable and controllable ride for bicyclists.

The research team developed, installed, and assessed the following milled rumble strip test patterns at the Pennsylvania Transportation Institute's test track.

Table E1. Rumble strip configurations tested.

Test Pattern	Groove Width Inches (mm)	Flat Portion between Cuts inches (mm)	Depth inches (mm)
1*	7" (178 mm)	5" (127 mm)	0.5" (13 mm)
2	5" (127 mm)	7" (178 mm)	0.5" (13 mm)
3	5" (127 mm)	7" (178 mm)	0.375" (10 mm)
4	5" (127 mm)	6" (152 mm)	0.5" (13 mm)
5	5" (127 mm)	6" (152 mm)	0.375" (10 mm)
6	5" (127 mm)	7" (178 mm)	0.25" (6.3 mm)

*PennDOTs current standard

The evaluation experiments involved testing several bicycles and a motor vehicle. To measure the effects of the different configurations on bicyclists, volunteer participants rode different types of bicycles over the rumble strip configurations at different speeds and different angles. Objective data, such as vertical and pitch angular accelerations, were collected to evaluate the comfort and control levels of bicyclists traversing the different configurations. In addition, bicyclists' perceptions were recorded through a subjective questionnaire rating the comfort and controllability of the configurations. To assess the effectiveness of various rumble strip configurations on alerting inattentive/drowsy motorists, measurements were taken of the auditory and vibrational stimuli generated by the rumble strip configurations.

From the bicyclist's perspective, test pattern 6 was the most "bicycle-friendly." However, from the motor vehicle standpoint, test pattern 6 generated the least amount of noise in the passenger compartment, in both the high-speed testing conducted at 55 mph (88 km/h) and the low-speed testing conducted at 45 mph (72 km/h). Because test pattern 6 was ranked the worst test pattern from the motor vehicle standpoint, it is not recommended for installation.

Test pattern 3 was ranked the second most "bicycle-friendly" configuration from the bicyclist's perspective. From the motor vehicle standpoint, test pattern 3 performed well during the high-speed testing and ranked second overall at 55 mph (88 km/h) with an average maximum sound level of 81.3 dB(A) versus 88.9 dB(A) for the existing configuration. Therefore, test pattern 3 is recommended for implementation along non-freeway facilities with higher operating speeds.

During the low speed testing at 45 mph (72 km/h), however, test pattern 3 generated 74.7 dB(A) of noise, less than 7 dB(A) above the ambient noise. As a result, test pattern 3 ranked only fifth overall at this speed. Watts (1977) indicated that rumble strips which produce 4 dB(A) or above can be readily detected by motorists who are awake, but there are no data indicating the sound level difference above the ambient noise necessary to alert a drowsy motorist. Given Watts' study, 7 dB(A) was not considered an adequate difference, so test pattern 3 is not recommended for implementation on non-freeway facilities with lower operating speeds.

The third ranked test pattern from the bicyclist's perspective (test pattern 2) was considered for low-speed facilities. A close examination of the average normalized values for test pattern 2 and test pattern 5 showed very little difference between the two. Essentially, test patterns 2 and 5, perform equivalently from the bicyclist's perspective. From the motor vehicle standpoint, however, test pattern 5 generates slightly more sound in the passenger compartment of lower operating speeds than test pattern 2. Therefore, test pattern 5 is recommended for implementation along non-freeway facilities with lower operating speeds (near 45 mph or 72 km/h).

In summary, based on the results of the motor vehicle testing and the bicycle testing, two new "bicycle-friendly" rumble patterns are recommended for implementation along non-freeway facilities. Test pattern 3 is recommended along non-freeway facilities with higher operating speeds, near 55 mph (88 km/h). Test pattern 5 is recommended along non-freeway facilities with lower operating speeds, near 45 mph (72 km/h).

1. INTRODUCTION

To address the problem of run-off-the-road (ROR) crashes, many agencies are currently using milled shoulder rumble strips (MSRS) to alert motorists who are drifting to the right or to the left, out of the travel lane. This type of rumble strip consists of a continuous pattern ground into the asphalt or concrete. As a motor vehicle's tires pass over the rumble strips, auditory and tactile warnings are received by the drifting motorist.

Since the use of MSRS is being extended to non-freeway facilities on a limited basis, there are legitimate bicyclist concerns that need to be addressed. These concerns revolve around both the design of the rumble strips and their applications, i.e., the location of the rumble strip on the shoulder and the roads selected. Bicyclists who have ridden over MSRS complain that the sensation is extremely uncomfortable, even painful, and that MSRS may cause loss of control of the bicycle.

To address these problems, Work Order 25: Bicycle-Friendly Shoulder Rumble Strips was initiated to develop several rumble strip configurations that can alert inattentive/drowsy motorists and be safely and comfortably traversed by bicyclists. The primary objective was to develop new rumble strip configurations that decrease the level of vibration experienced by the bicyclist when traversing the rumble strips. At the same time, an adequate amount of stimuli, both auditory and tactile, must be maintained to alert an inattentive/drowsy motorist. To achieve this objective, the research team developed, installed, and assessed selected rumble strip designs at the Pennsylvania Transportation Institute (PTI) test track.

This report is the final product of this project and summarizes the research conducted to develop and evaluate potential "bicycle-friendly" rumble strips. It consists of seven sections. Following the introduction, section 2 contains a summary of the literature related to the shoulder rumble strips. Section 3 presents the research methodology. Section 4 discusses the evaluation of the existing rumble strip design. Section 5 outlines the development of a simulation model used to develop and select new rumble strip configurations to be installed at PTI's test track for further evaluation. Section 6 presents the experimental plan to evaluate the selected new configurations installed at PTI's test track. Section 7 summarizes the data analysis, and section 8 presents the conclusions and recommendations.

2. LITERATURE REVIEW

This section contains a summary of the literature identified that is related to rumble strips and provides information on:

- the purpose of rumble strips,
- the types of rumble strips (i.e., milled and raised) and their respective applications and designs,
- previous studies that tested the safety effectiveness of rumble strips in reducing vehicular ROR crashes,
- problems encountered after rumble strips applications,

- previous studies that measured vibration and noise levels of motor vehicles as generated by different rumble strip configurations, and motorists' and bicyclists' perceptions of vibration and/or noise generated from rumble strips, and
- a sample of current rumble strip policies from around the United States, focusing on various bicycle considerations.

A number of studies have been conducted to determine the most effective rumble strip designs. These studies focused, though, on designing rumble strips for cars and, in some instances, trucks and motorcycles. Few studies considered the effect of rumble strip designs on bicycles. Previous results from vibration, noise, and motorist reaction testing with vehicles, however, can be used in developing new "bicycle-friendly" rumble strip designs. Some of the more relevant findings from these tests are presented in this report.

2.1 Purpose of Rumble Strips

A rumble strip is a raised or grooved pattern placed on the pavement surface of a travel lane or shoulder (Harwood 1993). Rumble strips are intended to provide motorists with an audible and tactile warning that they are approaching a decision point of critical importance to their safety or that their motor vehicles have partially or completely left the travel lane. Noise generated as the motor vehicle tires pass over the rumble strip provides an audible warning to the motorist, while vibration induced in the motor vehicle by the rumble strips provides a tactile warning. Although rumble strips alert motorists of potential decision points or roadside hazards, rumble strips do not identify what type of action is appropriate.

Rumble strip applications fall into two general categories:

1. Rumble strips placed in the travel lane
2. Rumble strips placed on highway shoulders (or other areas outside the travel lane)

When rumble strips are placed in the travel lane, their purpose is to alert motorists of approaching intersections, toll plazas, horizontal curves, work zones, or any other unexpected conditions. When rumble strips are placed on highway shoulders or other areas outside of the traveled way, they are used to alert motorists that they have left the travel lane and that a steering correction is necessary to return to the travel lane. This study focuses on shoulder applications of rumble strips, which are most likely to affect bicyclists.

The use of rumble strips on highway shoulders is becoming increasingly common (Harwood 1993). Most installations are at specific locations of critical importance to the driving task. However, several highway agencies do provide rumble strips continuously or intermittently along extended highway sections of urban and rural freeways. In addition, several highway agencies have placed shoulder rumble strips on multilane divided freeways, multilane undivided nonfreeways, and two-lane highways. Rumble strips have been placed on both the right (outside) and left (median) shoulders of highways.

2.2 Types of Rumble Strips

There are four types of rumble strips: milled, rolled, formed, and raised. They differ primarily in the installation method, their shapes and sizes. Different amounts of vibration and noise levels are produced by each of the four types. Table 1 summarizes typical dimensions and shapes employed by highway agencies around the country. Installation concerns are also addressed related to the types of rumble strips.

Milled rumble strips are currently the prevalent type of rumble strip among highway agencies (http://www.ohs.fhwa.dot.gov/rumblestrips/). They are easily installed on new or existing asphalt and portland cement concrete shoulders, and they produce a great amount of noise and vibration. This type of rumble strip is made by a machine, which cuts a smooth, uniform groove in the shoulder surface.

Rolled rumble strips must be installed when the constructed or reconstructed shoulder surface is compacted. Grooves are pressed into the hot asphalt surface by a roller with steel pipes welded to the drums. Depressions are created as the roller passes over the hot asphalt surface.

Formed, or corrugated, rumble strips are installed along portland cement concrete (PCC) shoulders. Grooves or indentations are formed into the concrete surface during the finishing process.

Raised rumble strips are strips of material that adhere to new or existing shoulder surfaces. Different materials that have been used include asphalt bars and raised pavement markers. Use of raised rumble strips is usually restricted to warmer climates due to maintenance difficulties resulting from snow removal in the northern climates.

2.2.1 Shapes and Dimensions

Shoulder rumble strips are constructed in various shapes. Figure 1 illustrates the typical shapes of rumble strips on asphalt shoulders and concrete shoulders. Typically, along asphalt shoulders, rounded or v-shaped grooves are installed, but the strips may also take rectangular and tapered shapes. Along PCC shoulders, rectangular and "wave-like" or corrugated shapes are used.

Rumble strips may be placed continuously along the shoulder or spaced intermittently. Figure 2 illustrates typical rumble strip applications on asphalt shoulders, and figure 3 illustrates typical applications on PCC shoulders.

Table 1 presents typical values for the dimensions shown in figure 2. The table summarizes the design practices of 18 state highway agencies. This table was assembled by Harwood (1993) while synthesizing information on rumble strips during a National Cooperative Highway Research Program (NCHRP) project in 1993. Dimensions of rumble strips on asphalt shoulders range from having groove widths between 0.875" to 4" (22 mm to 102 mm) and depths ranging from 0.5" to 1" (13 mm to 25 mm). The center-to-center spacing between grooves ranges from 6" to 36" (152 mm to 914 mm), with a typical range between 8" to 9" (203 mm to 229 mm).

Table 1. Dimensions and design criteria for rumble strips on asphalt shoulders (Harwood 1993).

State	Rumble Strip Frequency	Spacing Between Patterns A	Length of Pattern B	No. of Grooves per Pattern	Groove Spacing (CL-CL) C	Groove Width D	Groove Depth E	Groove Shape	Distance from Traveled Way To Pattern F	Width of Pattern G	Distance from Pattern to Outside Edge of Shoulder H	Comments
California	Continuous	-	-	-	8"- 9"	1"	1-2"	Rounded	1-5'	3'	-	
Colorado	Continuous	-	-	-	8"- 9"	.75"-1	0.75"-1"	Rounded	1'	2'	6	
Florida	Intermittent	200'	5.17'	6	12"	2"	0.50"	Tapered	0'	Fwys: full shldr Nonfwys: Full shldr-1.5'	-	
Hawaii	Continuous	-	-	-	36"	-	-	RPM	0.25'	1'	-	used only on approaches to horizontal curves
Idaho	Intermittent	60'	4.50'	8	6"	-	-	-	-	-	-	8 rumble strips at 6" centers every 60'
Illinois	Continuous	-	-	-	8"	2-5"	1"	Rounded	1'	3'	-	
Kansas	Continuous	-	-	-	8"	2"	1"	Rounded	0.5"	3'	-	
Michigan	Continuous	-	-	-	8"	2.5"	1"	Rounded	1'	3'	-	
Mississippi	Continuous	-	-	-	8"-9"	0.875"	0.875"	Rounded	1'	2'	4'	
Nevada	Continuous	-	-	-	8"-9"	0.875"	0.875"	Rounded	1'	3'	4'	
New Mexico	Continuous	-	-	-	8"-9"	0.500"	0.500"	Rounded	1'	2'	4'	
Oklahoma		-	-	-	8"	2.25"	0.875"	V	1'	2'	-	AC continuous - multilane
		-	-	-	8"	2.25"	0.875"	Rounded	1'	2'	-	
	Continuous	-	-	-	12"	4"	0.500"	Rectangular	1'	2'	-	
		-	-	-	8"	2.25"	0.875"	V	1'	2'	6'	AC continuous - 2-lane
		-	-	-	8"	2.25"	0.875"	Rounded	1'	2'	6'	
	Continuous	-	-	-	12"	4"	0.500"	Rectangular	1'	2'	6'	
		52.8'	2.85'	5	8"	2.25"	0.875"	V	1'	3.33'	-	AC Intermittent-multilane
		52.8'	2.85'	5	8"	2.25"	0.875"	Rounded	1'	3.33'	-	
	Intermittent	52.8'	4.33'	5	12"	4"	0.500"	Rectangular	1'	3.33'	-	
		52.8'	2.85'	5	8"	2.25"	0.875"	V	1'	2'	6'	AC Intermittent - 2-lane
		52.8'	2.85'	5	8"	2.25"	0.875"	Rounded	1'	2'	6'	
	Intermittent	52.8'	4.33'	5	12"	4"	0.500"	Rectangular	1'	2'	6'	
		52.8'	-	1	-	4"	0.75"	Tapered	1'	3.33'	9.33'	AC Intermittant - single-groove
	Intermittent	52.8'	-	1	-	3.5"	0.50"	Rectangular	1'	3.33'	9.33'	multilane or two-lane; alternate angles of grooves 45 or 60 degrees
Oregon	Continuous	-	-	-	9"	-	-	-	-	-	-	
Tennessee	Continuous	-	-	-	8"-9"	0.75"	0.75"	Rounded	-	3'	-	
Utah	Continuous	-	-	-	8"-9"	1.5"	1"	Rounded	1'	2'	-	Used only on rural hwys with design speed of 50 mph or more
Washington	Intermittent	50'	3.5'	6	7.5"	4"	0.75"	Rectangular	0.5'	Right-5'	-	
		50'	3.5'							Left-3.5'	-	
Wisconsin	Continuous	-	-	-	8"	2.5"	0.75"	Tapered or Rounded	2.5'	2.5'	-	
Wyoming	Continuous	-	-	-	8"-9"	2"	1"	Rounded	0.5'	3'		

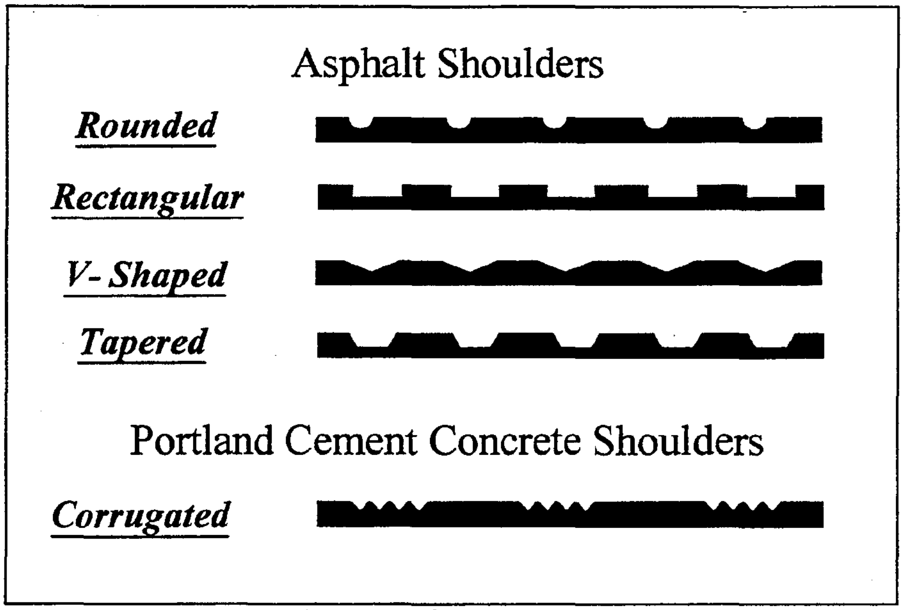


Figure 1. Typical shapes of rumble strips along shoulders.

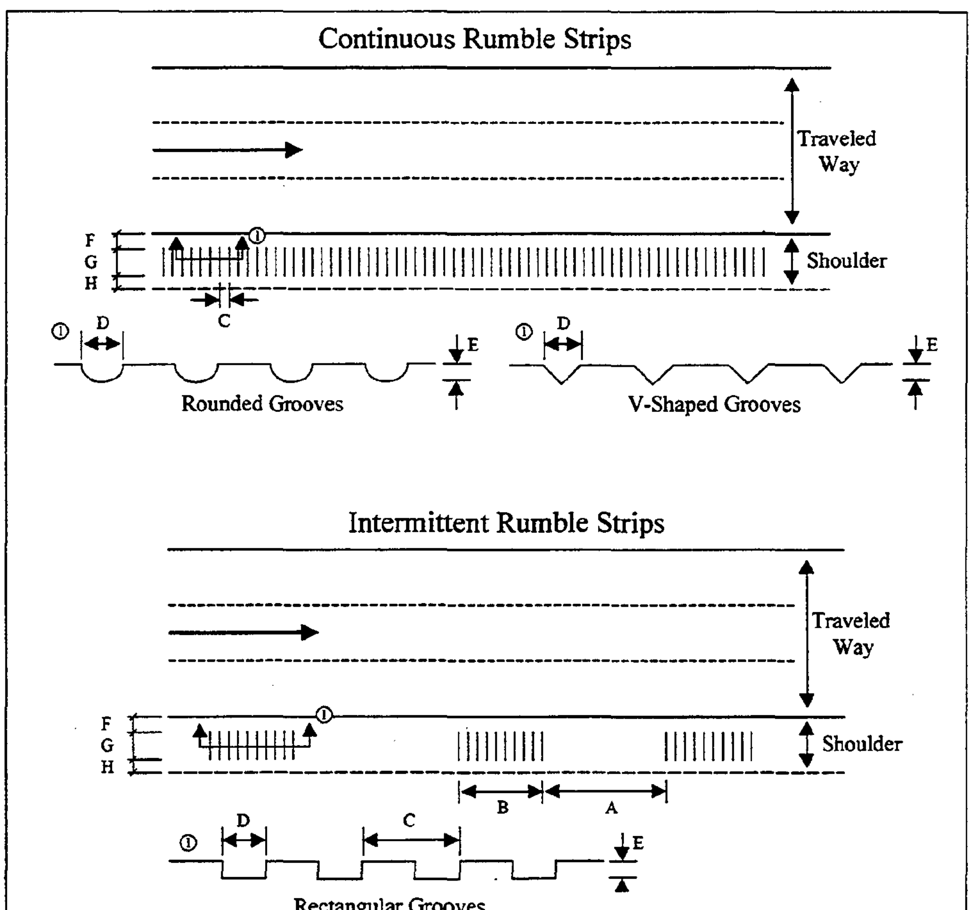


Figure 2. Typical rumble strip applications on asphalt shoulders (Harwood 1993).

Table 2 presents typical values for the dimensions shown in figure 3. The table summarizes the design practices of 21 state highway agencies. The table indicates a wide variation in rumble strip design used for PCC shoulders.

Some problems have been reported associated with the installation of shoulder rumble strips. Reported problems related to the installation of rolled rumble strips include the aggregate being crushed by the ribs of the roller, shoving of the asphalt, and the pipes of the roller flattening with use. The major installation concern with milled rumble strips is the high price of installation, and some problems with asphalt breakup between grooves have been reported.

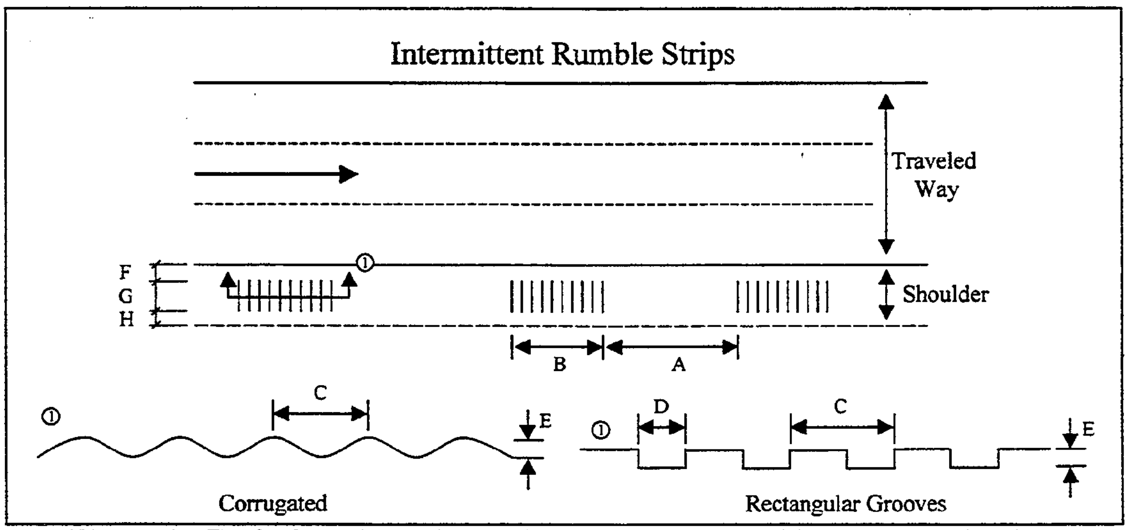


Figure 3. Typical rumble strip application on PCC shoulders (Harwood 1993).

2.3 Safety Effectiveness of Rumble Strips for Vehicular Traffic

This section presents results from previous studies on the safety effectiveness of shoulder rumble strip applications. The studies are presented in chronological order.

2.3.1 Arizona

In 1973, Arizona conducted a study to determine the safety effectiveness of several shoulder treatments along Interstates 8 and 10 (Ligon et al 1985). Results of the analysis indicated that shoulder grooving was the most effective shoulder treatment tested, with a reduction of 61 percent in ROR crashes when compared to other shoulder treatments. Additional analysis concluded that the grooved shoulder sections had 80 percent fewer ROR crashes per mile and 80.2 percent fewer ROR crashes per million vehicle miles traveled (VMT) fewer than the control sections.

Table 2. Dimensions and design criteria for rumble strips on PCC shoulders (Harwood 1993).

State	Spacing Between Patterns (CL-CL) A	Length of Pattern B	No. of Bars per Pattern	Bar Spacing (CL-CL) C	Bar Width D	Bar Height E	Shape	Distance From Travel Lane to Pattern F	Width of Pattern G	Minimum Shoulder Width	Comments
Arizona	30-60'	4'	17	3"	N/A	1'	Rounded	2'	Full shldr width	- -	Pattern spacing depends on design speed; longer spacings used at higher design speeds
Colorado	100'	11.33'	12	12"	4"	0.500"	Rectangular	0'	Full shldr width	6'	Leave outside 3' without strip on bicycle routes
Florida	200'	5.17'	6	12"	2"	0.500"	Tapered	0'	Fwys: Full shldr Nonfwys: Full shldr -1.5'	-	
Georgia	60'	5.83'	16	4.5"	N/A	1"	Rounded 1" radius	0'	Full shldr width	-	
Idaho	60'	3-67'	8	6.0"	-	-	-	-	-	-	8 rumble strips at 6" centers placed every 60'
Illinois	60-100'	3'-6'	5-10	8"	2.5"	1"	Rounded	1'	3'	-	
Kansas	90'	4"	9	6"	4"	0.75"	Tapered	0.5'	Full shldr width	-	
Kentucky	60'	5.33'	6	12"	4"	0.50"	Tapered	1'	4'	-	
Louisiana	60'	6'	16	4.5"	N/A	1"	Rounded 1" radius	0.5'	6'		Minmum distance of 1' from outside edge of Rumble strip to outside edge of shoulder
	-	5.81'	16	4.5'	N/A		Rounded 1" radius	1'	Full shldr width	-	Rural PCC shoulders
Michigan	-	5.81'	16	4.5'	N/A		Rounded 1" radius	1'	Full shldr width	-	Urban PCC shoulders Minimum distance of 1' from outside edge of Rumble strip to outside edge of shoulder
Mississippi	60'	6'	16	4.5"	N/A	1"	Rounded 1" radius	0.17'	2'	-	
Nebraska	-	4'	11	4.5"	N/A	1"	Rounded 1" radius	0.5'	Full shldr-2'	-	
Nevada	54'	6'	16	4.5"	N/A	1"	Rounded 0.5" radius	0'	Full shldr width	-	
North Dakota	-	6'	6	12"	N/A	1"	Rounded 1" radius	3'	4'	-	
		4'	6	8.2"	4"	0.75"	Tapered	1'	3.33'	9.33'	
Oklahoma	52.8'	3.33'	10	4-12"	N/A	0.75"	Rounded	1'	3.33'	9.33'	
Pennsylvania	60'	6'	16	4.5"	N/A	1"	Rounded	0'	Full shldr width	-	
Texas	-	1'	4	3"	N/A	0.50"	Rounded	0'	Full shldr width	-	
Utah	50'	6'	16	4.5"	N/A	0.75"	Rounded	Right-4' Left-1'	Full shldr width	-	Distance from traveled way to rumble strip: 4' on 10' outside shoulder 1' on 4' inside shoulder
West Virginia	40'	3'	12	3"	N/A	1"	Rounded	-	-	-	
		6'	6	12"	4"	0.625"	Rectangular	1.5'	2'	-	Sawed pattern
Wisconsin	30'	6'	6	12"	N/A	1"	Rounded 1" radius	1.5'	2'	-	Formed pattern
		4'	11	4.5"	N/A	1"	Rounded 0.5" radius	3'	Full shldr width	-	
Wyoming	55'	4'	8	3"	1.5"	1"	Rounded taper	3'	Full shldr width	-	

2.3.2 California

A study was initiated in the early 1970s to develop and evaluate rumble strip installations that would alert motorists and prevent ROR crashes. The first part of the research consisted of developing shoulder rumble strip patterns that would alert motorists. The second part involved a one-year before-and-after crash analysis.

After conducting sound, vibrational, and controllability studies on 57 rumble strip patterns, the most effective patterns, in terms of alerting the inattentive/drowsy motorist, were selected for trial installations. Results from the safety evaluation did not provide statistically significant proof that rumble strips are an effective means of reducing ROR crashes.

In the later half of the 1970s and early part of the 1980s, a second study on shoulder rumble strip applications was conducted (Chaudoin et al. 1985). To reduce the number of ROR crashes, grooved rumble strips were installed continuously along the shoulders of 158.5 miles (255 km) of freeways in the Mojave Desert on Interstates 15 and 40. The rumble strips were placed along both the right (outside) and left (median) shoulders.

A one year before-and-after study showed a significant decrease in ROR accidents as a result of the rumble strip installations. On the roadway sections where the rumble strips were installed, 194 ROR crashes occurred in the before period, versus 100 ROR crashes in the after period. On the control sections, 272 ROR crashes occurred in the before period, while 326 ROR crashes were reported in the after period. Thus, ROR crashes were reduced by 49 percent on the freeway sections where continuous shoulder rumble strips were installed, while ROR crashes increased by 20 percent on the control sections. The decrease in ROR crashes was found to be statistically significant at the 99 percent confidence level. In addition, right shoulder rumble strips proved more effective than left shoulder rumble strips. Right shoulder rumble strips reduced ROR crashes by 63 percent as compared to a reduction of 18 percent by left shoulder rumble strips. A 19 percent reduction in total accidents was also attributed to the shoulder rumble strip installations.

2.3.3 Florida

In order to reduce ROR crashes along a 19-mile (31 km) section of U.S. 1, the main highway to Key West, Florida, raised pavement markers were installed four abreast across the shoulder at a 45 degree angle (Ligon et al. 1983). In its 1980 to 1981 annual report, the Florida Department of Transportation (DOT) reported a decrease in fixed object crashes from 19.5 to 11.5 per year due to the rumble strip treatment. Florida DOT also reported a decrease in ran-into-water accidents from 8 to 5.5 per year. Thus, Florida DOT concluded that the raised pavement markers achieved their goal in preventing the inattentive/drowsy motorists from leaving the shoulder.

2.3.4 Multi-State Study

In 1985, AMAF Industries, Inc. conducted a before-and-after safety evaluation of rumble strip installations on rural freeways based on data from 11 states (Ligon et al. 1985). Results of the study indicated that rumble strips significantly reduce ROR crashes. At the sites where rumble strips were installed, the data showed a 20 percent reduction in ROR crash rates. This reduction was statistically significant at the 95 percent confidence level. Meanwhile, the control sites exhibited a 9 percent increase in ROR crash rates over the same time period. The observed safety effectiveness of the rumble strips varied widely among the various test sites. There was no observed difference in crash rates when comparing intermittently spaced treatments versus continuously spaced treatments, and no evidence was found to indicate differences in effectiveness among the four types of treatments considered in the study. The benefit/cost ratio was calculated to be greater than 50 for shoulder rumble strips installed in conjunction with shoulder construction or resurfacing.

2.3.5 Pennsylvania Turnpike

In 1984, 48 percent of the crashes along the Pennsylvania Turnpike were ROR crashes (Wood 1994). The percentage of ROR crashes continued to increase over the next two years, to 51 percent in 1985 and 57 percent in 1986. During this same time period, the Pennsylvania Turnpike Commission was developing the Sonic Nap Alert Pattern (SNAP), a narrow rumble strip to be located continuously in the right shoulder, just outside of the edge line of the pavement. After testing five different milled patterns, the favored pattern was installed along a test section of the turnpike. After 18 months of the initial installation, only one crash was reported along the test section, and it could not even be verified that this crash was a ROR.

Based upon this initial experience, tests were conducted on five more sections of the turnpike totaling 31 miles (50 km). A follow-up study in 1993 confirmed the effectiveness of SNAP. The turnpike experienced a 70 percent reduction in ROR crashes over substantial time periods. As a result of their experiences, the Turnpike Commission initiated a program to have over 80 percent of the turnpike system protected with SNAP by the end of 1994.

In a follow-up study, Hickey (1997) found that a 65 percent reduction in ROR rates could be attributed to SNAP. Hickey also expanded the study to consider all the sections of the turnpike where SNAP were installed and found a 60 percent reduction in ROR crashes over 53 sections of the turnpike totaling 348 miles (560 km).

2.3.6 Washington

The Washington State DOT installed shoulder rumble strips at six locations between 1986 and 1990 (Harwood 1993). A safety evaluation for five of the six locations revealed a statistically significant reduction in crash frequency at only one of the five locations. However, when considering the five sites collectively, crash frequency decreased by 18 percent from before to after rumble strip installation.

2.3.7 Maine

The Maine DOT began installing continuous shoulder rumble strips along rural freeways between 1994 and 1995 (Gårder et al. 1995). Prior to these installations, Gårder and Alexander (1994) assessed the cost effectiveness of continuous shoulder rumble strips as a safety improvement for the DOT. A benefit-cost ratio of around 200 was estimated for rolled rumble strips. The benefit-cost ratio for milled rumble strips was approximately 50, similar to the benefit-cost ratio calculated by AMAF Industries (Ligon et al. 1985). Gårder and Alexander performed a second set of calculations taking an even more conservative approach with some of their assumptions and found the benefit-cost ratios would still be approximately 20 for rolled and 5 for milled rumble strips.

2.3.8 Utah

The Utah DOT evaluated the difference in accident rate experience between highway segments with and without rumble strips (Cheng et al.). Three interstate segments were selected for the study. Results showed that overall crash rates were 33.4 percent higher on the control sections as compared to the sections where rumble strips were installed. Similarly, ROR crash rates were 26.9 percent higher on the sections without rumble strips. In addition, the analysis revealed lower crash rates along highway segments with continuous rumble strips as compared to segments with discontinuous, or intermittent, rumble strips, indicating that the discontinuous design is less effective in alerting motorists to potentially dangerous situations. Finally, the study showed rumble strips to be effective in reducing crash severity.

2.3.9 FHWA

Griffith (1999) examined the safety effects of continuous shoulder rumble strip applications on rural and urban freeways in Illinois and California. Data were extracted from the Highway Safety Information System (HSIS) to perform the evaluation. The evaluation showed that continuous shoulder rumble strips provide a safety benefit to motorists on freeways. The evaluation estimated the average safety effectiveness to be:

1. On all freeways, 18.3 percent reduction in total single vehicle ROR crashes.
2. On all freeways, 13 percent reduction in injury in single vehicle ROR crashes.
3. On rural freeways, 21 percent reduction in total single vehicle ROR crashes.

Griffith also evaluated two types of potential adverse effects related to safety with continuous shoulder rumble strips. One potential adverse effect pertains to the possibility that shoulder rumble strips may cause certain motorists to overreact to the warning, resulting in loss of control of their motor vehicles. The second potential adverse effect is crash migration, which occurs when a motorist is temporarily saved from a crash at a treated site but crashes downstream of the treated area or in another location on the network. Griffith found these potential adverse effects to be insignificant.

2.4 Potential Adverse Effects of Shoulder Rumble Strips

This section discusses the potential adverse effects of shoulder rumble strip applications. It focuses primarily on the safety concerns of bicyclists, but discusses other potential adverse effects as well.

2.4.1 Effects on Bicyclists

Where paved shoulders are provided, many bicyclists prefer to ride on these rather than in the travel lane. As a result, bicyclists and bicycle groups have expressed concerns about shoulder rumble strips. Their main concerns are that a bicyclist may lose control while riding over the rumble strips and also that rumble strips may encourage bicyclists to ride in the travel lane. Many highway agencies have instituted certain policies on the installation of shoulder rumble strips due to these concerns expressed by bicyclists.

Bicyclists are concerned about maneuverability problems while traversing rumble strips for two reasons (Morgan et al. 1997). First, bicyclists are concerned about riders' abilities to control their bicycles when they find themselves rolling across or along rumble strips unexpectedly. Second, bicyclists are concerned about crossing rumble strips when they have to make a left turn or move to avoid an obstacle, which is just one additional task that could distract bicyclists while performing the maneuvers.

Gårder (1995) was the first to document results from tests to verify bicyclist concerns about maneuverability problems associated with rumble strips. Gårder, together with 20 students and staff at the University of Maine, rode over two different configurations of milled rumble strips on several types of bicycles. Gårder found that, "Not a single rider reported any tendency to lose control at any speed or any angle even when not holding on to the handle bars. But every rider reported that riding on the rumble strips was annoying." Thus, these tests did not support bicyclists' fears that shoulder rumble strips would cause them to lose control of their bicycles.

Young's research (1997) contradicts Gårder's findings. Young tested a road bicycle with 90 psi (6.2 x 10^5 Pa) wheels/tires on a section of U.S. 191 in Teton County, Wyoming, that had milled "Pennsylvania Turnpike" style rumble strips. A test rider rode over or across the rumble strips at speeds of less than 5 mph (8 km/h), 10 mph (16 km/h), 20 mph (32 km/h), and 30 mph (48 km/h). In general, at speeds greater than 5mph (8 km/k), the test rider found it dangerous riding over or across the rumble strips.

The other concern bicyclists have with shoulder rumble strips is that they may encourage bicyclists to ride in the travel lane in situations where bicyclists would rather ride on the shoulder (Harwood 1993). Even though rumble strips are typically installed on only about half of the paved shoulder, the remaining area between the outer edge of the rumble strip and the outside edge of the shoulder is often littered with debris. This discourages bicyclists from utilizing that area. Therefore, bicyclists may prefer to ride in the travel lane. A possible solution to this dilemma is to move the rumble strip further from the travel lane to provide bicyclists with adequate room to ride between the travel lane and the rumble strip. This, however, decreases the recovery area available to errant motor vehicles. Another possibility is to make the rumble strips narrower.

Several highway agencies have instituted various policies for use of shoulder rumble strips to protect both the motoring public and bicyclists. In a 1997 survey of 57 transportation agencies in the United States and Canada to which 34 responded, 4 agencies indicated they do not use shoulder rumble strips on routes where bicycles are permitted (Morgan et al. 1997). Thirteen additional agencies have included consideration of bicyclists into their policies. In general, the policies include one or more of the following:

- placing shoulder rumble strips only on shoulders wide enough to provide ample room for bicyclists to ride safely,
- placing rumble strips as close to the pavement edge as the specifications allow, or
- designing narrower rumble strips to provide adequate space.

While most bicyclists and bicycle groups would like to prohibit the use of shoulder rumble strips due to their concerns for bicycle safety, Gårder and Alexander (1995) reported that shoulder rumble strips are especially called for where paved shoulders are used by bicyclists and pedestrians. After making some general assumptions and calculations, Gårder and Alexander concluded that bicyclist safety can be improved with the installation of rumble strips because the strips will wake up motorists before they infringe onto the bicyclists' part of the shoulder. The state of Alabama, in fact, has a policy of using continuous rumble strips to separate lanes for vehicular traffic from shoulders designated for bicyclist and pedestrian use.

2.4.2 Maintenance Issues

Several maintenance problems associated with shoulder rumble strips have been reported by highway agencies (Harwood 1993). The problems are related to winter maintenance, drainage, and surface cracking. Continuous rumble strips that are placed too close to the travel lane have caused snowplowing problems on the travel lane. Shoulder rumble strips may also cause problems while plowing the shoulder, or plows may have to operate at reduced speeds on shoulders with rumble strips.

Surface drainage problems may be created by shoulder rumble strips by disrupting drainage patterns on the shoulder (Harwood 1993). This is particularly true for rumble strips that extend the full width across the shoulder because the water flow may become concentrated at the rumble strips. This may result in erosion of the roadside embankment near the rumble strip area. One possible solution to this problem is not to extend the rumble strip to the outside edge of the shoulder. This solution may remedy the erosion problem, but ponding in the rumble strip may occur.

A few highway agencies have also experienced increased deterioration of the pavement surface to some degree due to shoulder rumble strips (Morgan et al. 1997). Longitudinal cracks may develop along the end of the rumble strip closer to the edge of the pavement. Minor breakup of the asphalt between the rumble strip grooves may also occur.

Future construction projects may also be affected by installation of shoulder rumble strips (Harwood 1993). Shoulder rumble strips limit the ability to use the shoulder as a travel lane during construction and maintenance activities that involve a lane closure.

2.4.3 Noise

The most common problem cited by highway agencies concerning the use of rumble strips is noise that disturbs nearby residents (Harwood 1993). However, noise is not as major a concern for shoulder rumble strips, as it is for rumble strips placed in the travel lane. Noise is generated relatively infrequently by rumble strips placed on the shoulders. It is generated only by errant motor vehicles, not by every motor vehicle.

Although noise created from shoulder rumble strips is not a major concern, several highway agencies have experimented with several alternatives to mitigate the problem in residential areas if the residences are near the highway. One alternative is to construct noise barriers. Several agencies have also moved the rumble strips further away from the edge of the travel lane. This measure, however, provides less time and distance for errant motorists to recover their vehicles.

2.4.4 Motorist Concerns

Complaints about rumble strips have been received by highway agencies both from motorists who do not like rumble strips and from motorists who do not understand the intended purpose of rumble strips (Harwood 1993). Motorists who do not like rumble strips may complain about potential damage to their vehicles from the vibrations caused by rumble strips. Motorists who do not understand rumble strips may mistake the auditory warning as a mechanical problem with their vehicles or may think the rumble strips were an imperfection in the shoulder surface.

2.5 Vibration and Noise Generated by Rumble Strips

2.5.1 Vibration

Chen (1994) studied the effects of milled, rolled, and corrugated rumble strips on motor vehicle dynamics by driving an instrumented test car on them. During the study, Chen developed a theoretical analysis of the tire drop to establish the effectiveness of rumble strips. For rumble strips to be effective, Chen determined that the width of the strip should be large enough for the tire to drop into the groove so as to generate vibration and noise.

A comparison of the theoretical drop of a car tire driven over milled and rolled rumble strips can be calculated as follows. For milled rumble strips, typically, the groove width is about 7" (178 mm) and the depth is about 0.5" (13 mm) (see figure 4). Given that in the United States, the diameter of most car tires is 24" (610 mm), the tire drop may be calculated:

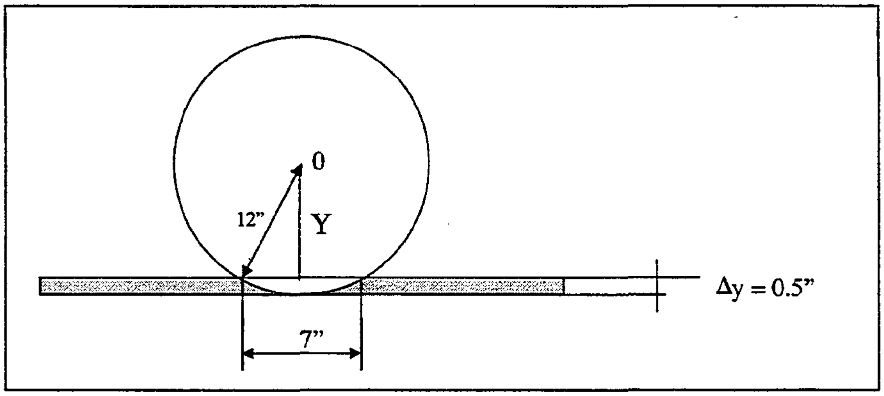


Figure 4. Theoretical tire drop with milled rumble strips (Chen 1994).

$$Y = \sqrt{(12^2 - 3.5^2)} = 11.48"$$

$$\Delta y = 12.00" - 11.48" = 0.52" > 0.5"$$

Because the tire can drop as far as 0.52" (13 mm) in a 7" (179 mm) groove, the tire will drop to the bottom of the groove in this case.

For rolled rumble strips, the width is typically around 1" (25 mm) and the depth is about 0.5" (13 mm). Again, assuming a 24" (610 mm) diameter tire, the tire drop is as shown in figure 5:

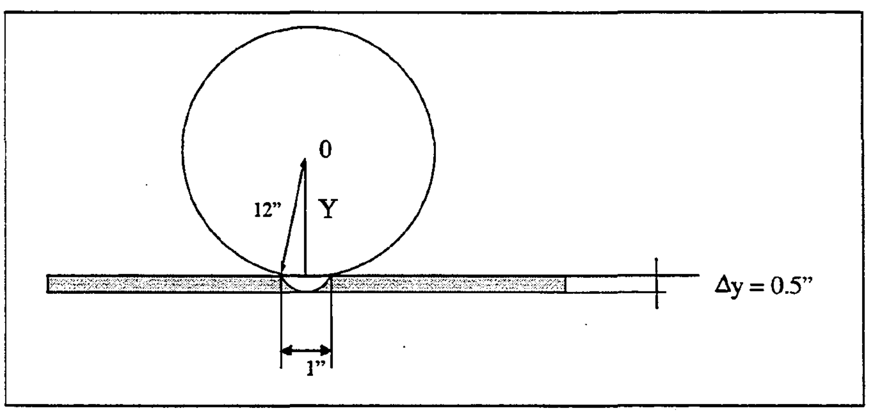


Figure 5. Theoretical tire drop with rolled rumble strips (Chen 1994).

$$Y = \sqrt{(12^2 - 0.5^2)} = 11.99"$$

$$\Delta y = 12.00" - 11.99" = 0.01" < 0.5"$$

In this case, the tire will not drop to the bottom of the groove. It should be noted that this assumption is valid for a solid wheel. In the case of an elastic tire, such as a motor vehicle tire, these calculations are not accurate. The drop will also depend on the tire static and dynamic deflection, which is a function of the load and inflation pressure. The tire drop also depends on the speed of the motor vehicle. When the speed is equal or lower than some critical speed, the tire drops are functions of the width of grooves. When speeds are higher than the critical speed, the tire drops are smaller than the above computed numbers.

The theoretical analysis reveals that the difference between the tire drops for the rolled and milled rumble strips varies by 50 times for speeds less than the critical speed. For speeds higher than the critical speed, such as 55 or 65 mph (88 or 105 km/h), the drops will be less than the computed numbers, yet the difference is still significant based on field observations.

As part of the field testing, Chen conducted pavement roughness tests on three different types of rumble strips: continuous rolled rumble strips on asphalt shoulders, continuous milled rumble strips on asphalt shoulders, and intermittent corrugated rumble strips on concrete shoulders. Pavement roughness measurements were collected at 112 locations on Interstates 85 and 295 in Virginia under the following conditions:

- Testing speed: 55 mph & 65 mph (88 km/h & 105 km/h)
- Angle of departure: 5°
- Road conditions: dry and clean

From the pavement roughness tests and the theoretical analysis, Chen concluded that the milled rumble strips performed better than the rolled or corrugated strips. Roughness levels measured by the International Roughness Index (IRI) were 12.6 times greater for the milled rumble strips than the rolled rumble strips. The milled rumble strips were also 7.16 times greater than the corrugated rumble strips. In addition, Chen noted that rolled rumble strips have very little effect on trucks.

Tye (1976) evaluated three different kinds of rumble strips by instrumenting a test car and driving over various configurations of rumble strips to collect data on sound, vibration, and handling. The test vehicle was instrumented with a tri-axial accelerometer mounted on the front floor over the transmission to measure the vertical, transverse, and longitudinal vibration components. The controllability of the motor vehicle was reasoned to be related to front-wheel bounce. The front wheels were selected for measuring the controllability because steering is done through the front wheels. Also the front wheels are the first to contact a rumble strip and are more sensitive to induced motion. The magnitude of the wheel bounce was measured by a rectilinear potentiometer with a 7" (178 mm) stroke mounted behind the right front wheel.

The instrumented test vehicle was driven over numerous rumble strip designs. The choice was made to test various rumble strip designs using plywood rib rumble strips and milled rumble strips. The plywood rumble strip patterns used had a thickness between 0.25" and 0.75" (6 and 19 mm) and had a rib width ranging from 3" to 8" (76 to 203 mm), in 1" (25 mm) increments. The spacing was varied from 3' to 6' (76 to 152 mm) in 1' (25 mm) increments.

With the plywood rumble strips, 57 rumble strip patterns were driven across at speeds ranging from 30 to 70 mph (48 to 113 km/h). A summary of the test results follows:

- **Right front wheel movement:** The data showed a somewhat erratic pattern of right front wheel movement. However, there was a general tendency for movement to decrease with increasing speed and to increase with increasing rib spacing. Many combinations of rib spacing and speed, however, resulted in little or no difference from the background level of wheel movement on normal pavement.

- **Vertical acceleration:** The 0.75" (19 mm) thick rumble strip ribs produced a generally higher than average increase in vertical acceleration over the background level. The 0.5" (13 mm) thick with 7" (178 mm) wide ribs were the next best. The 0.5" (13 mm) thick by 3" or 5" (76 mm or 127 mm) wide ribs produced vertical accelerations that were 1/3 lower in amplitude than those 0.5" (13 mm) high by 7" (178 mm) wide. The 0.25" (6 mm) thick rumble strip ribs produced an even lower average level of vertical acceleration.

- **Lateral acceleration:** Regardless of rib thickness or width, the greatest increase in amplitude of lateral acceleration was produced by ribs spaced on 5' (1.5 m) centers. The ribs spaced on 8' (2.4 m) centers produced the lowest average increase in amplitude over the background level.

Instrumented drive-over tests were also conducted on a series of milled rumble strips. The grooves varied from 0.5" to 0.75" (6 to 19 mm) in depth. The width of the grooves was either 3", 5", or 7" (76 mm, 127 mm, or 178 mm). All of the grooves were spaced 5' (1.5 m) apart, and the sides of the grooves were vertical. The milled rumble strips, in general, produced lower average differences in wheel movement, and vertical and lateral acceleration from background levels than the raised plywood rumble strips. The 7" (178 mm) wide grooves produced slightly greater average increases in sound and vibration over the background level.

In addition to the instrumented motor vehicle test, a subjective evaluation of the rumble strips was performed by two California highway patrol officers. Their combined opinion was that the 0.25" (6 mm) high plywood rumble strips did not provide adequate vibration. The 0.5" (13 mm) high strips were considered to have adequate alerting properties. The 0.75" (19 mm) high strips were considered to have adequate to good properties. However, the officers reported that the car did tend to loose rear wheel traction while crossing the 0.75" (19 mm) high rumble strips.

The officers' subjective opinions of motor vehicle controllability did not correlate with the instrument data for front wheel bounce. This was understandable because the motorists' sensation of control was related to the wheel spinning and fishtailing. The front wheel bounce data would probably bear a better relationship to vehicle control if the motorists were turning while traversing the rumble strips. All test runs, however, were made with the motor vehicle on a straight path through the rumble strip pattern.

The final portion of the testing involved driving a fully equipped California Highway Patrol Harley-Davidson motorcycle over the plywood rumble strips at speeds of 30, 50, and 60 mph (48, 80, and 97 km/h). Tye reported that control of the motorcycle was not affected by any of the strips. It was speculated that the wheelbase of the motorcycle was such that the motorcycle was affected by only one rib at a time.

Franke (1974) studied the optimum spacing of shoulder rumble strips on the interstate relative to speed. The optimum spacing was determined from vibrational measurements of a car. Heights of 0.5" (13 mm) and 0.375" (10 mm) were evaluated, but the time limitations for the study did not allow evaluation of various strip widths. Various spacings were tested: 1.25', 2', 2.5', 3.25', 3.75', 5', 7.5', 10', 10.5', and 15' (0.38, 0.61, 0.76, 0.99, 1.14, 1.52, 2.29, 3.05, 3.20, and 4.57 m). The test car was driven at the following speeds: 20, 30, 40, 50, 60 and 70 mph (32, 48, 64, 80, 97, and 113 km/h). Conclusions from the study were as follows:

- A spacing of 2' (0.61 m) or less created a large amount of wheel hop and/or did not allow the tires to descend between the rumble strips, which created a situation where the vibration level increased when the speed decreased.
- A 5' (1.52 m) spacing seemed to be the best suited for use on the shoulder of roadways.
- Strips should not be of a height or depth greater than 0.5" (13 mm).

2.5.2 Noise

In addition to doing vibrational testing, Chen (1994) conducted sound level tests on rolled, milled, and corrugated rumble strips. Chen compared the difference in sound levels between driving in the travel lane and driving over the different rumble strips. The sound levels were measured while driving at 65 mph (105 km/h). The tests showed milled rumble strips generated the largest sound excesses. The sound excesses for each type of rumble strip are as follows:

- 2.5 dB between rolled rumble strips and travel lane.
- 7.0 dB between corrugated rumble strips and travel lane.
- 10.87 dB between milled rumble strips and travel lane.

Gupta (1993) evaluated the effectiveness of several rumble strip designs on speed reduction in the travel lane. As part of the evaluation, noise levels associated with the rumble strip designs were measured. Noise data were gathered from four different rumble strip designs for both cars and trucks traveling at an average speed of 55 mph (88 km/h). The four designs are shown in figure 6.

In this study, noise was not measured inside the motor vehicle, but rather it was measured 10' (3.05 m) from the pavement. Tables 3 and 4 show the mean noise level for each rumble strip design. Table 3 considers a car driving at 55 mph (88 km/h) on the asphalt and then on the rumble strips pattern. Table 4 contains the same information for trucks. Clearly pattern A, with an increase of the mean noise level of 6.2 dB for a car and 5.8 dB for a truck, had the best results in terms of generating noise. The results obtained with the trucks were slightly lower than for the cars. This can be explained by the bigger size of the truck wheels.

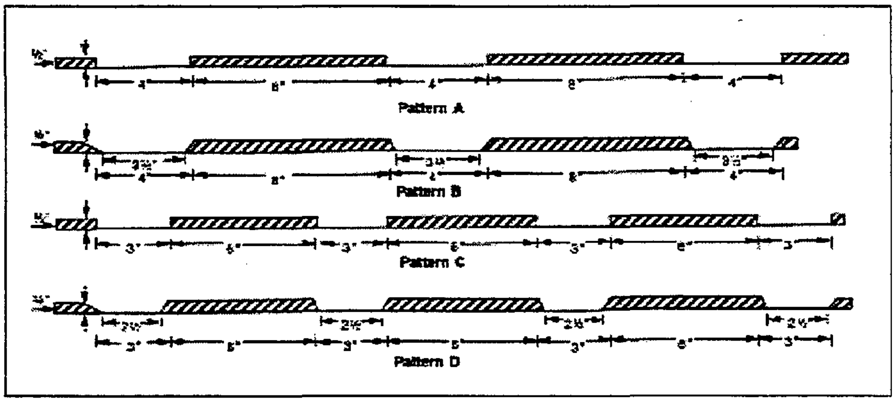


Figure 6. Grooved rumble strips design pattern (Gupta 1993).

Table 3. Mean noise level from a car (Gupta 1993).

Cars	Mean Noise Level (dB)		
	Bare asphalt	**Rumble Strips**	**Increase of the Noise**
Pattern A	72.8	79	6.2
Pattern B	73.2	76.3	3.1
Pattern C	73.15	77.3	4.15
Pattern D	68.5	73.6	5.1

Table 4. Mean noise level from a truck (Gupta 1993).

Trucks	Mean Noise Level (dB)		
	Bare Asphalt	**Rumble strips**	**Increase of the Noise**
Pattern A	80.5	86.3	5.8
Pattern B	77.7	82.2	4.5
Pattern C	80.6	86.1	5.5
Pattern D	78.6	82.5	3.9

In terms of noise, the geometry of pattern A explains its better performance. The width of the groove is the largest compared to the other three patterns. This allows the tires to fall deeper in the grooves. Pattern C, which is similar to pattern A, gave a lower noise level because the tires were not falling low enough in the grooves. Also, the sharp edges of the rectangular groove provide a better excitation of the tire than the v-shaped grooves of patterns B and D.

Before the Pennsylvania Turnpike Commission installed the first SNAP (see figure 7) along the turnpike, various rumble strip designs were tested at their Safety Testing And Research facility, an abandoned roadway section designated for research purposes (Wood 1994, and Hickey 1997). Figure 8 shows the 5 different designs tested during the development of SNAP.

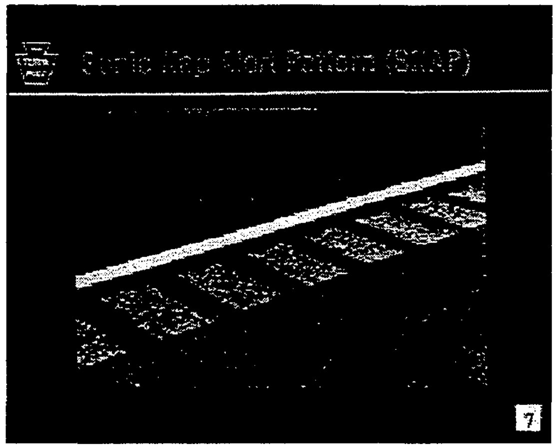


Figure 7. Picture of the SNAP on the Pennsylvania Turnpike (Wood 1994).

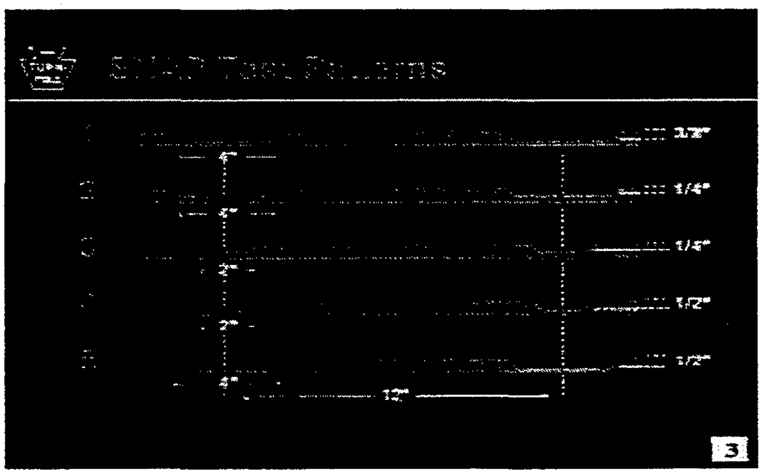


Figure 8. SNAP test patterns (Wood 1994).

The shape of each groove tested was the same. It was a v-shaped groove separated on 12" (305 mm) centers, with only the width and the depth of the groove changing in each pattern. During the testing, a sedan and a truck were driven over the different designs, and the sound level was recorded inside the motor vehicles to compare their effectiveness. Several speeds were tested: 40, 50, 60, and 65 mph (truck only) (64, 80, 97, and 105 km/h). Tables 5 and 6 present the results of the sound measurements.

Tables 5 and 6 do not show the mean noise level inside the sedan or in the truck while it was driven on bare asphalt (travel lane). The average level of noise inside a car being driven on the asphalt was 73 dB at 55 mph (88 km/h), and the average level of noise in the truck was around 79 dB. Considering first the tests with the sedan, pattern 5 gave the highest dB readings for any of the speeds. In the case of the truck tests, only pattern 5 gave a noise level higher than the background noise in the passenger compartment. Pattern 5 had the deepest and the widest groove.

Table 5. Test results for the sedan (Wood 1994).

Sedan Speed	Mean Noise Level (dB)		
	40 mph (64 km/h)	50 mph (80 km/h)	60 mph (97 km/h)
Pattern 1	74	77	80
Pattern 2	70	75	76
Pattern 3	68	74	74
Pattern 4	71	73	74
Pattern 5	75	78	80

Table 6. Test results for the truck (Wood 1994).

Truck Speed	Mean Noise Level (dB)			
	40 mph (64 km/h)	50 mph (80 km/h)	60 mph (97 km/h)	65 mph (105 km/h)
Pattern 1	--	--	--	--
Pattern 2	--	--	--	--
Pattern 3	--	--	--	--
Pattern 4	--	--	--	--
Pattern 5	--	82	82	86

(Note: – not recordable, 79 dB in the truck cab)

In their study of rumble strips on Interstates 15 and 40, Chaudoin and Nelson (1985) gave results on the influence of groove shape and groove spacing on noise. Noise measurements were gathered from 3 different shapes of rumble strips: v-shape, rectangular, and rounded. According to the evaluation, the v-shaped groove gave a good sound effect, and the rounded shape gave a very good sound effect. There were no results concerning the noise generated by the rectangular groove.

Chaudoin and Nelson also studied the effects of four different groove spacings: 4" (102 mm), 8" (203 mm), variable, and 16" (406 mm). The 4" (102 mm) spacing gave a high-pitched sound effect. The 8" (203 mm) spacing provided a good sound effect with a lower pitch than the 4" (102 mm) spacing. The variable spacing provided a sound that was more of a flat tire sound than a tone, and the 16" (406 mm) spacing did not provide adequate sound to be heard.

Higgins and Barbel (Higgins et al. 1984) conducted a study to determine the noise levels in the surrounding neighborhood generated from rumble strips placed in the travel lane. Although this study did not deal with shoulder rumble strips, some of its conclusions can be helpful in shoulder rumble strip design:

- Rumble strips produce a low frequency noise that can increase the Leq noise levels by up to 6 or 7 dB(A) over the noise levels produced by traffic on normal pavement.
- Raised rumble strips rather than milled rumble strips, create better motorist noise perception.

- The groove center-to-center distance has some effect on the motorist's perception of noise. Smaller center-to-center distances appear to be more effective on motor vehicles traveling at higher speeds.

As discussed in the previous section on motor vehicle dynamics, Tye (1976) evaluated three different kinds of rumble strips by instrumenting a test car and driving over various configurations of rumble strips to collect data on sound, vibration, and handling. Focusing on the sound data, the tests indicated that rumble strip ribs a 0.25" (6 mm) thick were marginally effective, producing a sound level that averaged 7 dB(A) above the background level on bare pavement. The 0.5" (13 mm) high rumble strips produced a sound level that averaged 9 dB(A) above the background level, while the 0.75" (19 mm) high strips produced an 11 dB(A) increase.

The sound level generally increased to the highest levels at the fastest speeds, 60 and 70 mph (97 and 113 km/h), for each rumble strip pattern. However, the background level of the bare pavement increased with the speed as well. The difference between the sound levels was greatest in the 30 to 40 mph (48 to 64 km/h) range than at higher speeds for more than 80 percent of the plywood rib rumble strip patterns tested. This difference was lowest at the 60 to 70 mph (97 to 113 km/h) range for over 95 percent of the patterns.

Varying the width of the rumble strip ribs did not produce significantly higher or lower sound levels for any given spacing of ribs.

Rumble strips spacings of 3', 4', and 5' (0.91, 1.22, and 1.52 m) produced significantly different sound levels. Sound levels decreased with the 6' (1.83 m) and greater rib spacing.

2.6 Motorists' and Bicyclists' Perceptions

2.6.1 Motorists' Perceptions of Rumble Strip Noise

Watts (1977) conducted an experiment on motorists' perceptions of rumble strip noise utilizing a driving simulator. A stereo tape player was connected to the driving simulator, and noise pulses were triggered each time the motorist would drift from the lane. The motorist was asked to evaluate the noise patterns on a scale from one to seven, from not noticeable to very noticeable. The motorists were also asked to answer multiple choice questionnaires related to the type of noise they heard and what generated the noise.

Watts concluded that rumble strips that produce 4dB(A) increases or above would be readily detected by motorists if the noise level was sustained for 350 ms or longer. However if the noise increase was only 2dB(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 motorists. The noise increase in the pulses over the ambient levels should be at least 4 dB(A).

2.6.2 Bicyclists' Perceptions of Rumble Strips

Ardekani et al. (1996) conducted a study in which 5 bicyclists rode over 4 different grooved rumble-strip patterns. The bicyclists riding a touring bike and a mountain bike were asked to evaluate the quality of the ride on a scale from 1 (worst ride) to 10 (best ride). Table 7 lists the patterns that were tested, and tables 8 and 9 provide the evaluation results.

The type 3 rumble strip was consistently rated as providing the smoothest and most comfortable ride in 9 out of 10 possible choices. This was reasoned to be so because in type 3, the flush strips were much wider than the flush strips found in type 1 and type 2. Thus, the feeling and perception of the smooth ride appeared to be linked to the width of the smooth surface and not necessarily to the depth or the width of the depression (within given limits).

Table 7. Rumble strip patterns (Ardekai et al. 1996).

Rumble Strip Pattern	
Type 1	8" (198 mm) wide plain flush pavement followed by a 4" (107 mm) wide depressed stripe. The depressions were approximately 0.125" (2.5 mm) deep.
Type 2	7" (183 mm) wide plain flush pavement followed by a 5" (122 mm) wide depressed stripe. The depressions were approximately 0.25" (5.0 mm) deep.
Type 3	18" (457 mm) wide plain flush pavement followed by a 6" (152 mm) wide depressed stripe. The depressions were approximately 0.25" (5.0 mm) deep.
Type 4	6" x 6" (150 mm x 150 mm) square buttons, 1.375" (35 mm) high at one end and 1" (25 mm) high at the other end. These were placed at a distance of 8" (200 mm) center to center.

Table 8. Comfort ratings from a touring bike (Ardekai et al. 1996).

Comfort Rating of Rumble Strips on a Touring Bike						
Pattern	Cyclist 1	Cyclist 2	Cyclist 3	Cyclist 4	Cyclist 5	Mean Score
Type 1	4	4	5	5	7	5.0
Type 2	1	2	3	2	5	2.6
Type 3	7	7	7	6	6	6.6
Type 4	2	4	5	4	6	4.2

Table 9. Comfort ratings from a mountain bike (Ardekai et al. 1996).

Comfort Rating of Rumble Strips on a Mountain Bike						
Pattern	Cyclist 1	Cyclist 2	Cyclist 3	Cyclist 4	Cyclist 5	Mean Score
Type 1	6	6	7	8	9	7.2
Type 2	4	4	5	5	6	4.0
Type 3	8	8	9	7	8	8.0
Type 4	4	5	7	6	7	5.8

2.7 Rumble Strip Policies in Selected States

Tables 1 and 2 in section 2.2.1 provided typical dimensions and design criteria for rumble strips on asphalt and PCC shoulders. These two tables were assembled by Harwood (1993) while synthesizing information on rumble strips during a National Cooperative Highway Research Program (NCHRP) project. These tables provide a good overview of policies around the United States. However, some policies may have changed since this 1993 publication. Therefore, selected states from around the country were contacted to inquire about their current rumble strip designs and to ask if bicyclists' concerns were considered in the rumble strip policy. The states contacted included:

- Arizona
- Colorado
- Connecticut
- Ohio
- Oregon

The following sections discuss the rumble strip configurations currently used, or proposed, from the respective states. If bicyclists' concerns are considered in respective policies, this is noted as well.

2.7.1 Arizona

2.7.1.1 Type and Dimensions

Arizona policy on continuous rumble strips suggests the use of milled rumble strips but does not prohibit the use of other rumble strip types. Arizona's specification for milled rumble strips consists of milling rounded grooves a 0.5" (13 mm) in depth and 7" (178 mm) wide, spaced on 12" (305 mm) centers. The width of the pattern (measured perpendicular to the travel lane) varies from 5" to 12" (127 to 305 mm), depending upon the type of roadway and the area. The rumble strips are to be offset from the edge line by 0" to 12" (0 to 305 mm), depending upon the type of roadway.

2.7.1.2 Bicycle Considerations

Arizona policy indicates that districts are to evaluate when and where shoulder rumble strips should be installed. In the evaluation, heavy bicycle traffic should be considered. Recently, Arizona DOT conducted rumble strip gap studies to allow bicyclists traveling on the roadway or shoulder to cross the rumble strip without having to enter the rumble strip pattern (Moeur, 1999). Based on the study, it is recommended that rumble strips on all non-controlled access highways include periodic gaps of 12' (3.66 m) in length, and that these gaps be placed at periodic intervals at a recommended spacing of 40' (12.19 m) or 60' (18.29 m). This recommendation is being considered for adoption into the current policy.

2.7.2 Colorado

2.7.2.1 Type and Dimensions

Colorado policy permits rumble strips to be installed by milling, rolling, or forming on concrete shoulders and by milling only on asphalt shoulders. Typical dimensions of the milled rumble strips are 6" to 8" (152 to 203 mm) grooved width, 12" (305 mm) spacing, and 0.5" to 0.75" (13 to 19 mm) depth. The typical width of pattern for milled rumble strips is 16" (406 mm), but a minimum width of 12" (305 mm) is permitted when used on shoulders less than 6' (1.83 m) wide. The rumble strips are to be located a maximum of 6" (152 mm) from the edge line.

2.7.2.2 Bicycle Considerations

The regional and bicycle/pedestrian personnel within the DOT are directed to evaluate the state highway system for accommodation of rumble strips and their impact to bicycle use on shoulders. Input from the bicycle community is also to be considered in the evaluation. To accommodate bicycle travel along high priority bicycle corridors, paved shoulders should be at least 6' (1.83 m) wide in order to install rumble strips. Rumble strips may be installed on shoulders that are 4' (1.22 m) or less in width only when there is a history of ROR crashes. Rumble strips may be installed with a pattern width of 12" (305 mm) instead of the typical 16" (406 mm), to accommodate bicyclists. This provides the bicyclists with an additional 4" (102 mm) of smooth shoulder on which to ride and has been advocated by the bicycle community.

2.7.3 Connecticut

2.7.3.1 Type and Dimensions

Connecticut policy permits the use of milled rumble strips along shoulders. The policy specifies finished dimensions of 7" ± 0.5" (178 mm ± 13 mm) in width, 12" ± 0.5" (305 mm ± 13 mm) spacing, 0.5" (13 mm) depth, and 16" (406 mm) width of pattern. The rumble strips are to be located at an offset of approximately 6" (152 mm) on the left shoulder and 12" (305 mm) on the right shoulder, from the outer edge of the edge line.

2.7.3.2 Bicycle Considerations

Connecticut DOT does not state any specific bicycle considerations in its policy.

2.7.4 Ohio

2.7.4.1 Type and Dimensions

Ohio policy permits the use of three types of shoulder rumble strips: milled, rolled, and formed. The policy also states that milled rumble strips are preferred because they are the most effective of the three types in terms of producing a noticeable vibratory and audible warning to motorists. Typical dimensions of the milled rumble strips are 7" (178 mm) grooved width, 12" (305 mm) spacing, 0.5" (13 mm) depth, and 16" (406 mm) width of pattern. On left shoulders, the rumble strips are to be offset from the edge line 6" to 6' (152 mm to 1.83 m), depending upon the width of the shoulder. On right shoulders, the offset ranges from 6" to 10" (152 to 254 mm), depending upon the shoulder width.

2.7.4.2 Bicycle Considerations

Ohio DOT has a section within its "Location and Design Manual" (1990) stating that "Rumble strips generally should not be used on the shoulders of roadways designated as bicycle routes or having substantial volumes of bicycle traffic, unless the shoulder is wide enough to accommodate the rumble strips and still provide a minimum clear path of 4' (1.22 m) from the rumble strip to the outside edge of the paved shoulder or 5' (1.52 m) to adjacent guardrail, curb or other obstacle." The manual also states that rather than using a continuous pattern on routes designated as bicycle routes or having high volumes of bicycle traffic, intermittent rumble strips should be used, consisting of an alternating pattern of gaps and strips, each 10' (3.05 m) in length.

2.7.5 Oregon

2.7.5.1 Type and Dimensions

Oregon policy permits the placement of milled rumble strips on rural interstates only and on non-interstate roadways, if data indicate that a safety problem is correctable by use of milled rumble strips. Raised profile pavement markings may also be considered when milled rumble strips are not allowed due to narrow shoulders or for centerline applications. Oregon's standard design of milled rumble strips calls for a 7" ± 0.5" (178 mm ± 13 mm) grooved width, 12" (305 mm) spacing, 0.5" to 0.625" (13 to 16 mm) depth, and 16" (406 mm) width of pattern. On rural interstates, the rumble strips are to be offset 12" (305 mm) from the outside edge of the edge line on both right and left shoulders. On non-interstate roadways, the rumble strips may be placed between 0" to 6" (0 to 152 mm) from the outside edge of the edge line.

2.7.5.2 Bicycle Considerations

Oregon DOT does not state any specific bicycle considerations in its policy.

2.7.6 Summary of Current Rumble Strip Policies in Selected States

Table 10 provides a summary of the typical milled rumble strip dimensions used in the respective states and also provides the Pennsylvania Department of Transportation's (PennDOT) current rumble strip specification for reference. Comparing table 10 to tables 1 and 2, state practices—or at least the practices of the five states surveyed for this project—have changed significantly since Harwood synthesized information on rumble strips in 1993. In fact, of the five states surveyed (Arizona, Ohio, Colorado, Connecticut, and Oregon), only two states (Colorado and Oregon) had design criteria for rumble strips on asphalt shoulders prior to 1993, and it appears that both Colorado and Oregon previously used rolled rumble strips. In 1993, both Arizona and Pennsylvania had design criteria for rumble strips on portland cement concrete shoulders but had no criteria for asphalt shoulders.

Table 10. Current milled rumble strip configurations from selected states.

State	Groove Shape	Groove Width (D)	Groove Spacing (CL-CL) C	Groove Depth (E)	Width of Pattern (G)	Distance Offset from Edge Line
Pennsylvania	Rounded	7"	12"	0.5" to 0.625"	16" to 17"	- 18" ± 0.5" from pavement/shoulder joint (right shoulder) - 12" ± 0.5" from pavement/shoulder joint (left shoulder)
Arizona	Rounded	7"	12"	0.5"	5" to 12"	0" to 12"
Ohio	Rounded	7"	12"	0.5"	16"	6" to 6' left shoulder 6" to 10" right shoulder
Colorado	Rounded	6" to 8"	12"	0.5" to 0.75"	12" to 16"	6" max
Connecticut	Rounded	6.5" to 7.5"	11.5" to 12.5"	0.5"	16"	6" left shoulder 12" right shoulder
Oregon	Rounded	7" ± 0.5"	12"	0.5" to 0.625"	16"	12" interstates 0" to 6" non-interstates

2.8 Summary

Shoulder rumble strips have proven to be an effective measure in reducing ROR crashes on urban and rural freeways. ROR crashes may be reduced by as much as 20 to 50 percent when rumble strips are installed. However, most of the safety evaluations that have been conducted have focused on freeways. As a result, the effectiveness of shoulder rumble strips in reducing ROR crashes along other types of facilities, such as two-lane rural highways, has yet to be determined.

Previous studies conducted to determine effective rumble strip designs focused on designing rumble strips for cars and, in some instances, trucks and motorcycles. Few studies have considered the effect of rumble strip designs on bicycles. However, results from previous vibrational, noise, and motorist reaction testing with vehicles can be used in developing new "bicycle-friendly" rumble strip designs. Some of the more relevant conclusions from these studies are the following:

1. Milled rumble strips generate the greatest amount of stimuli to alert inattentive/drowsy motorists.

2. 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 rib widths, thicknesses, and spacings using plywood rumble strips, varying the width of the ribs did not produce significantly different sound levels, vertical vibration increased with rib thickness, and varying the spacing of the ribs produced different sound levels. Because varying the rib width of plywood rumble strips did not produce significantly different sound levels and because varying the groove widths of milled rumble strips produced different sound levels, milled rumble strips cannot be simulated using plywood.

3. 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.

4. It seems that the optimal height or depth for rumble strips is about 0.5". It has adequate alerting properties and does not adversely affect the control.

5. Rumble strips which produce 4 dB(A) increases or above will be readily detected by motorists who are awake if the noise level is sustained for 350 ms or longer. If the noise increase is only 2 dB(A), the pulse length should be at least 900 ms. However, no studies have been performed indicating the sound level increase necessary to awake a drowsy or sleeping motorist.

6. The feeling and perception of bicyclists seems to be linked to the width of the smooth surface in between grooves and not necessarily to the depth or width of the depressions (within given limits).

3. METHODOLOGY

To achieve the goal of developing new rumble strip configurations that both alert inattentive/drowsy motorists and can be safely and comfortably traversed by bicyclists, two different perspectives needed to be considered throughout the research, that of the bicyclist and that of the motorist. From the bicyclist's perspective, rumble strips should not generate too much vibration, or shake the bicycle as the bicyclist traverses the rumble strip, causing discomfort and possibly loss of control. From the motorist's perspective, rumble strips should transmit a sufficient amount of auditory and vibrational stimuli to warn an inattentive/drowsy motorist who drifts from the travel lane.

Four primary steps were involved in the development of the new "bicycle-friendly" rumble strip configurations. The first step was to evaluate and assess the existing rumble strip configuration. The second step was to develop, evaluate, and rank different configurations for their potential to be "bicycle-friendly" yet at the same time not degrade the alerting properties for motorists. The third step was to install several of the recommended configurations with the greatest potential to be "bicycle-friendly" and conduct field experiments to further evaluate their effectiveness. These configurations were installed at PTI's test track. The final step was to analyze the data and rank the configurations that were installed based on their ability to alert inattentive/drowsy motorists and on their ability to provide a comfortable and controllable ride for bicyclists. This section outlines the four steps in the following paragraphs.

3.1 Obtain Vibration and Noise Data for Existing Configuration

To design and develop new "bicycle-friendly" rumble strip configurations, the first step was to evaluate and assess the impact of the existing rumble strip configuration on both bicyclists and motorists. This served two purposes:

- It provided a base measure to evaluate the effectiveness of the "bicycle-friendly" configurations.
- The vibration data for the bicyclist gathered during the assessment of the existing rumble strip configuration were used to validate the computer model that was developed to simulate the dynamics of a bicyclist traversing rumble strips. This simulation model was utilized in the next phase of the research to evaluate potential "bicycle-friendly" rumble strip configurations.

3.2 Develop New Configurations

To design new "bicycle-friendly" rumble strip configurations that could be installed at PTI's test track for further evaluation, a computer model was developed that simulated the interactions between a bicycle, its rider, and the pavement surface. The benefit of the simulation model was its ability to evaluate how numerous rumble strip configurations impact the dynamics of a bicycle and its rider. Output from the simulation model included dynamic measures such as vertical acceleration and pitch angular acceleration of the bicycle and rider system.

To validate the simulation model, vibration data from the base measurement testing for the bicyclist were used. Comparisons were made between the vertical accelerations and pitch angular accelerations measured in the field and the respective output from the simulation model. The comparisons verified the ability of the simulation to accurately model the interactions between a bicycle, its rider, and the road surface. Thus, the simulation model could be used as a tool to evaluate different configurations.

By comparing the vertical and pitch angular acceleration of the bicycle/rider system traversing different simulated rumble strip configurations, the simulated configurations could be ranked as having the greatest or least potential to be "bicycle-friendly." Those configurations that had the greatest potential of being "bicycle-friendly" and could also be constructed were selected for installation at PTI's test tract for further evaluation.

3.3 Installation and Testing of Recommended Rumble Strip Configurations

Six rumble strip configurations in all were installed at the test track: PennDOT's existing configuration and five new configurations that had the greatest potential to fulfill the goals of this project, as determined from the simulation model. Following the installation of the rumble strip configurations, test track experiments were performed to further evaluate the five new configurations. The experiments involved testing several bicycles and a motor vehicle. To measure the effects of the different configurations on bicyclists, volunteer participants rode different types of bicycles over the rumble strip configurations at different speeds and different angles. Objective data, such as vertical and pitch angular accelerations, were collected to evaluate the comfort and control levels of bicyclists traversing the different configurations. In addition, bicyclists' perceptions were recorded through a subjective questionnaire rating the comfort and controllability of the configurations. To assess the effectiveness of various rumble strip configurations on alerting inattentive/drowsy motorists, measurements were taken of the auditory and vibrational stimuli generated by the rumble strip configurations.

3.4 Analysis of the Quantitative and Qualitative Assessments

The final task was to analyze the results from the test track experiments. Both objective and subjective measures were used to assess the best configurations in terms of being both "bicycle-friendly" and effective in alerting inattentive/drowsy motorists. The different measurements included:

- Bicycle: vertical acceleration (objective)
- Bicycle: pitch angular acceleration (objective)
- Bicycle: control (objective)
- Bicycle: comfort and control (subjective)
- Motor vehicle: vertical acceleration (objective)
- Motor vehicle: pitch angular acceleration (objective)
- Motor vehicle: noise level (objective)

4. VIBRATION AND NOISE FROM EXISTING RUMBLE STRIPS

This section describes the first step in the methodology, which was to evaluate and assess the impact of the existing rumble strip configuration on both bicyclists and motorists. A base measure was thus established to evaluate the effectiveness of the rumble strip configurations to be installed at PTI's test track. In addition, the vibration data collected during the evaluation were used to validate the bicycle/rider simulation model, which served as a tool to evaluate potential "bicycle-friendly" configurations. The evaluation of the exiting rumble strip configuration involved instrumenting a bicycle with an accelerometer to gather vibrational data, and instrumenting a motor vehicle with an accelerometer and a noise meter to gather vibration and sound levels generated while traversing rumble strips. The data were gathered at a location along US 422 east of Indiana, Pennsylvania.

4.1 Bicycle Testing

To evaluate the effect of the existing rumble strip configuration, on the dynamics of bicycles, a mountain bike was instrumented with a Crossbow DMU-VGS six-axis vertical inertial measurement unit to measure the vertical acceleration and pitch angular acceleration of the bicycle (see figure 9). The Crossbow DMU-VGX has a maximum acceleration range of 6 gs and a maximum angular velocity range of 1.74 rad/s. The measurement unit was connected through a serial cable to a DOLCH PAC PC equipped with a data acquisition card to collect the analog outputs of the sensors. The software CHARTSTREAM was used on a PC to store the data on the hard drive with a sampling rate of 500 Hz. During the measurements, a car carrying the PC and the operator was driven along the bicycle path.

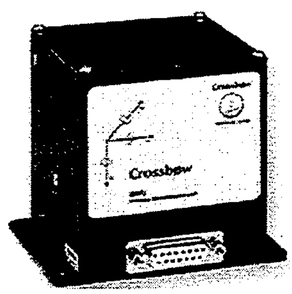


Figure 9. Crossbow DMU-VGX: six-axis inertial measurement unit.

The Crossbow DMU-VGX sensor was placed near the center of gravity of the system, both the bicycle and the rider (see figure 10). For the base measurements, only one type of bicycle was used and one rider. The bicyclist traversed the rumble strips at three different speed ranges: between 3 and 9 mph (5 and 15 km/h) (low speed), between 10 and 15 mph (16 and 25 km/h) (intermediate speed), and speeds greater than or equal to 16 mph (26+ km/h) (high speed). The rider traversed the rumble strips at a 0° angle (the bicyclist approached the rumble strips from straight on) for a distance of approximately 50' to 60' (15.24 to 18.29 m). Five repetitions were performed at each speed.

The speed of the bicycle was measured using a wireless cycle-computer (see figure 11, Cateye model CC-CL200). The cycle-computer can give an estimation of the speed of the bicycle between 0 and 65 mph (0 and 105 km/h), with a precision of 0.3 mph (0.5 km/h). The rider referred to the cycle-computer to control his speed.

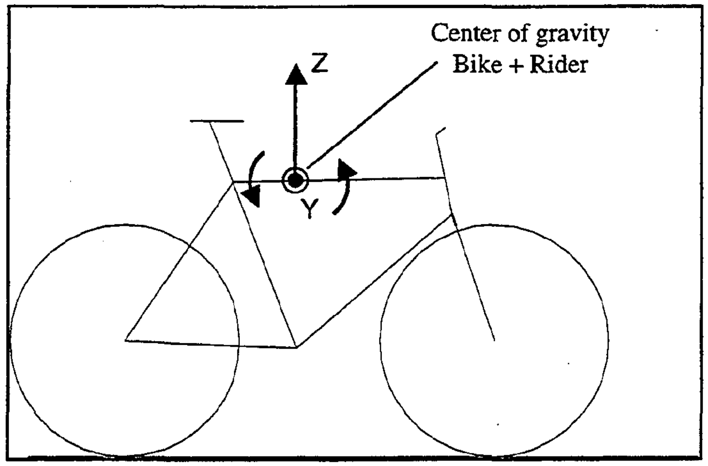


Figure 10. Location of the sensor on the bicycle.

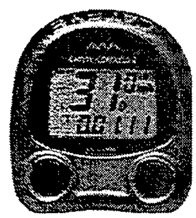


Figure 11. Cateye cycle-computer.

The root-mean-square (RMS) of the bicycle vertical acceleration and pitch angular acceleration are provided in table 11 for the respective repetitions. The RMS is a measure of the magnitude of a set of numbers. It provides a sense for the typical size of the vertical acceleration and pitch angular acceleration. Large RMS values correspond to large vertical accelerations and large pitch angular accelerations. Small RMS values correspond to low levels of vertical accelerations and pitch angular accelerations.

The first column of table 11 shows the trial number, or repetition. Column 2 shows the speed at which the bicyclist traversed the rumble strip. Column 3 indicates the time duration the bicycle was on the rumble strip while vertical acceleration and pitch angular acceleration data were being collected. The data show that the vertical acceleration is lower at the low speed interval (3-9 mph or 5-15 km/h) as compared to the vertical acceleration at the intermediate (10-15 mph or 16-25 km/h) and the high (16+ mph or 26+ km/h) speed intervals. There is not much difference in vertical acceleration between the intermediate and high speed intervals. In general, the pitch angular acceleration decreases as speed increases.

Table 11. RMS of the bicycle vertical and pitch angular acceleration.

Run #	Speed mph (km/h)	Duration sec	RMS Vertical Accel. ft/s^2 (m/s^2)	RMS Pitch Angular Accel. rad/s^2
1	6.2 (10)	12.30	30.3588 (9.2534)	30.9691
2*	6.2 (10)	11.40	31.9015 (9.7236)	29.1941
3	6.2 (10)	11.55	31.3825 (9.5654)	32.2101
4	6.2 (10)	10.70	32.5514 (9.9217)	33.7861
5	6.2 (10)	12.00	32.4284 (9.8842)	31.0843
6	10.6 (17)	6.30	53.4181 (16.2819)	19.0730
7	11.2 (18)	7.00	56.5786 (17.2452)	19.2353
8	11.2 (18)	6.00	57.4060 (17.4974)	14.9948
9	11.2 (18)	6.45	54.3909 (16.5784)	15.7533
10*	11.8 (19)	7.40	54.8151 (16.7077)	20.2982
11	---	---	---	---
12	17.9 (28)	4.50	53.2617 (16.2342)	18.0554
13	18.6 (30)	4.10	55.3801 (16.8799)	17.7884
14	18.0 (29)	3.85	58.4834 (17.8258)	17.2448
15	20.5 (33)	3.50	50.1737 (15.2930)	14.4454

* Indicates that at some point during the trial, the bicycle left the rumble strip for a short duration.

4.2 Motor Vehicle Testing

To measure the amount of noise and vibration generated by the existing rumble strip configuration as motor vehicles traverse it, a 1998 Plymouth Grand Voyager was instrumented to measure the vertical acceleration and pitch angular acceleration of the motor vehicle floor and the noise level within the passenger compartment. The Crossbow DMU-VGS six-axis vertical inertial measurement unit was used to measure the vertical acceleration and pitch angular acceleration. Figure 12 shows the mounting of the crossbow unit between the front two seats within the minivan. A Bruel & Kjaer sound meter (type 2232) was used to measure the sound level (figure 13). The sound meter was held next to the motorist's head.

Table 12 shows the results of the vibration measurements. The RMS for both vertical acceleration and pitch angular acceleration are provided. The results indicate that the vibration of the motor vehicle floor is minimal as the vehicle traverses the rumble strips. There is no significant difference in the magnitude of the RMS vertical acceleration between different speeds, but there is a significant difference in the pitch angular acceleration between speeds. The pitch angular acceleration increases with speed. There is not a significant difference in pitch angular acceleration between 45 and 55 mph (72 and 88 km/h), nor between 55 and 65 mph (88 and 105 km/h), but the pitch angular acceleration at 65 mph (105 km/h) is significantly greater than the pitch angular acceleration at 45 mph (72 km/h).

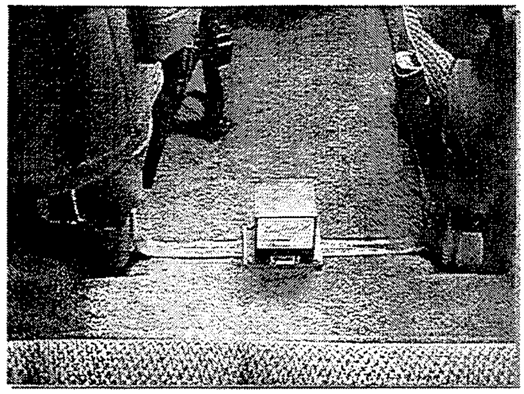


Figure 12. Mounting of crossbow within the minivan.

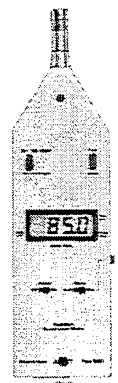


Figure 13. Bruel & Kjaer sound meter.

Table 12. Vibration measurements of the motor vehicle.

Run #	Speed mph (km/h)	RMS Vertical Accel. ft/s^2 (m/s^2)	RMS Pitch Angular Accel. rad/s^2
1	45 (72.4)	0.5180 (0.1579)	0.2271
2	45 (72.4)	0.5433 (0.1656)	0.2390
3	45 (72.4)	0.3658 (0.1115)	0.1625
AVG	45 (72.4)	0.4757 (0.1450)	0.2095
4	55 (88.5)	---	---
5	55 (88.5)	0.4111 (0.1253)	0.3871
6	55 (88.5)	0.4065 (0.1239)	0.2766
AVG	55 (88.5)	0.4088 (0.1246)	0.3318
7	65 (104.6)	0.5463 (0.1665)	0.4114
8	65 (104.6)	0.4534 (0.1382)	0.6714
9	65 (104.6)	0.5318 (0.1621)	0.5408
AVG	65 (104.6)	0.5105 (0.1556)	0.5412

Table 13 shows the results of the noise level tests. The maximum sound level in the passenger compartment was measured using the A-weighting (dB(A)). Sound levels were measured at three different speeds, while the motor vehicle was riding in the travel lane and while the motor vehicle was on the rumble strips. The results indicate that speed does not significantly affect the maximum sound level. In other words, there is no significant difference in the sound levels between the difference speeds. These measurements do indicate, though, that the current rumble strip configuration generates a high amount of noise above the background noise to alert inattentive/drowsy motorists.

Table 13. Maximum sound levels in the passenger compartment.

Maximum Sound Level – dB(A)						
Speed mph (km/h)	Run #1	Run #2	Run #3	Avg. of Runs 1-3	Travel Lane	Difference
45 (72.4)	78.6	82.7	82	81.1	64.8	16.3
55 (88.5)	79	79.8	80.5	79.8	65.6	14.2
65 (104.6)	84	80.5	84.5	83	66.3	16.7

5. NEW CONFIGURATION DEVELOPMENT

This section describes the second step in the methodology, namely the development of new rumble strip configurations. To design the new configurations, a bicycle/rider simulation model was developed, validated, and used to test numerous rumble strip configurations. Output from the simulation was used to select new rumble strip configurations for installation and further evaluation at PTI's test track.

Simulation is a numerical technique for conducting experiments on a digital computer. Mathematical models are used to describe the behavior of a system over time. In this research,.simulation provided the capability to evaluate and assess numerous potential rumble strip configurations prior to installing the configurations at PTI's test track for further testing. By comparing the output from the model, simulated configurations could be ranked as having the greatest or least potential to be "bicycle-friendly." Those configurations that had the greatest potential of being "bicycle-friendly" were selected for installation at PTI's test tract for further evaluation.

5.1 Simulation Model Development

The commercial software package Dynamic Analysis and Design System (DADS) was used to model the interactive rigid body system of a bicycle, its rider, and the road surface. By introducing spring forces and damping forces between the bicycle tires and the road surface and between the rider's hips and the bicycle seat, DADS generated a set of constraint equations to specify the kinematic relationships and a set of differential equations to specify the dynamics of the rider-bicycle-road surface system. To accurately model the interactions between a bicycle, its rider, and the road surface, separate components were developed before the interactions were considered. This model consisted of two components: the bicycle and the rider.

5.1.1 Bicycle/Rider Model

The bicycle model consisted of three components:

- bicycle frame
- front wheel
- rear wheel

The wheels were connected to the bicycle frame with revolutionary joints, rotating freely with respect to the bicycle frame. Figure 14 and table 14 show the dimensions of the simulated bicycle. These were the exact dimensions of the mountain bike used in the validation.

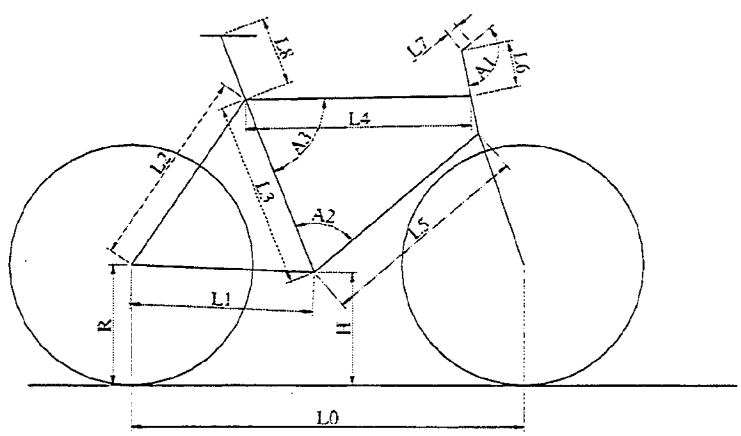


Figure 14. Bicycle dimensions for simulation model.

The rider was modeled as a rigid body system (Wang 1996), consisting of four parts (see figure 15):

- head and torso
- upper arms and lower arms
- lower legs (shins) and feet (the feet are not shown in the figure)
- thighs

Table 14. Bicycle parameters.

Component	Measurement
L0	3.41' (1.040 m)
R	1.07' (0.325 m)
H	0.07' (0.020 m)
L1	1.41' (0.430 m)
L2	1.61' (0.490 m)
L3	1.39' (0.425 m)
L4	1.80' (0.550 m)
L5	2.03' (0.620 m)
L6	0.33' (0.100 m)
L7	0.39' (0.120 m)
L8	1.12' (0.340 m)
Bicycle frame mass	23.04 lb (102.49 N)
Bicycle frame moment of inertia (pitch plane)	37.97 lb-ft^2 (1.60 kg-m^2)
Wheel mass	6.50 lb (28.91 N)
Wheel moment of inertia	3.08 lb-ft^2 (0.13 kg-m^2)

The torso and thighs and the thighs and lower legs were connected with revolutionary joints. Although the upper arms and the lower arms are shown separately in figure 15, they were treated as one unit in the simulation. This was a reasonable assumption because often riders keep their arms straight, with relatively no rotational motion between the upper and lower arms. Table 15 contains the rider parameters pertaining to the rigid body system.

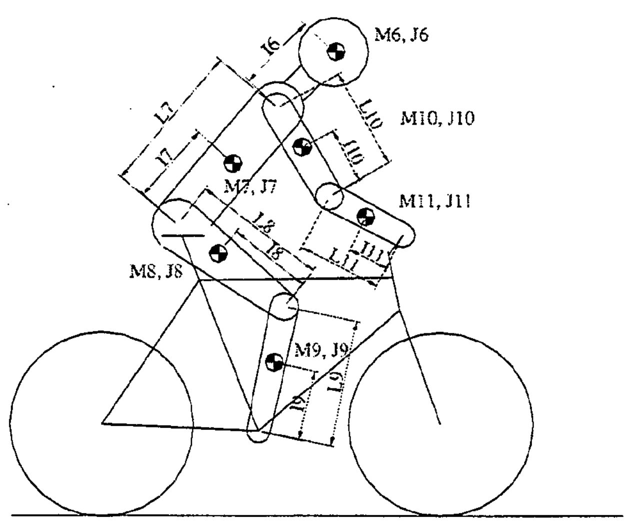


Figure 15. Rider model.

Table 15. Rider parameters.

Component	Measurement
M6 (head mass)	14.77 lb (6.70 kg)
J6 (head momentum of inertial)	0.85 lb-ft^2 (0.036 kg-m^2)
I6 (head center of gravity position)	0.86' (0.262 m)
M7 (torso mass)	135.56 lb (61.49 kg)
J7 (torso momentum of inertial)	67.54 lb-ft^2 (2.846 kg-m^2)
I7 (torso center of gravity position)	0.92' (0.281 m)
M8 (thigh mass)	54.63 lb (24.78 kg)
J8 (thigh momentum of inertial)	6.62 lb-ft^2 (0.279 kg-m^2)
L8 (thigh length)	1.68' (0.513 m)
I8 (high center of gravity position)	1.01' (0.308 m)
M9 (shin mass)	20.75 lb (9.411 kg)
J8 (shin momentum of inertial)	2.11 lb-ft^2 (0.089 kg-m^2)
L9 (shin length)	1.68' (0.513 m)
I9 (shin center of gravity position)	1.08' (0.331 m)
M10 (upper arm mass)	14.18 lb (6.431 kg)
J10 (upper arm momentum of inertial)	0.50 lb-ft^2 (0.021 kg-m^2)
L10 (upper arm length)	1.02' (0.310 m)
I10 (upper arm center of gravity position)	0.49' (0.150 m)
M11 (lower arm mass)	9.56 lb (4.337 kg)
J11 (lower arm momentum of inertial)	0.40 lb-ft^2 (0.016 kg-m^2)
L11 (lower arm length)	0.95' (0.290 m)
I11 (lower arm center of gravity position)	0.56' (0.170 m)

The connections between the rider's hands and the bicycle handle bar and the rider's feet and the bicycle pedals were modeled as revolutionary joints. The connection between the rider's hip and the bicycle seat was modeled as a revolutionary-translational joint. The rider's torso could have vertical motion as well as rotational motion with respect to the bicycle seat, so a translational spring damping force (TSDA) was applied between the rider's hip and the bicycle seat. Both rotational motion and translational motion were permitted between the upper arm and the shoulder. The connection of the torso and the upper arm was modeled as a revolutionary-translational joint. Figure 16 illustrates the difference between a revolutionary joint and a revolutionary-translational joint.

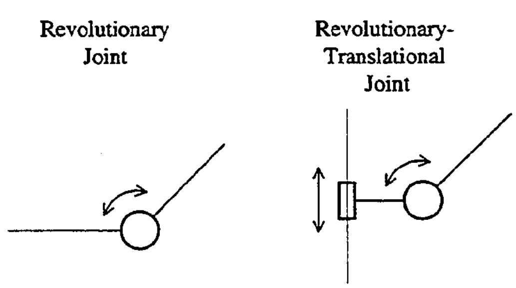


Figure 16. Schematic of joints.

The bicycle wheel was modeled as a circle with a linear radius spring distributed around its peripheral. The contact force between the bicycle tire and the rumble strip was proportional to the tire radial deformation and pointed toward the center of the wheel. Figure 17 indicates four typical wheel and rumble strip contact situations.

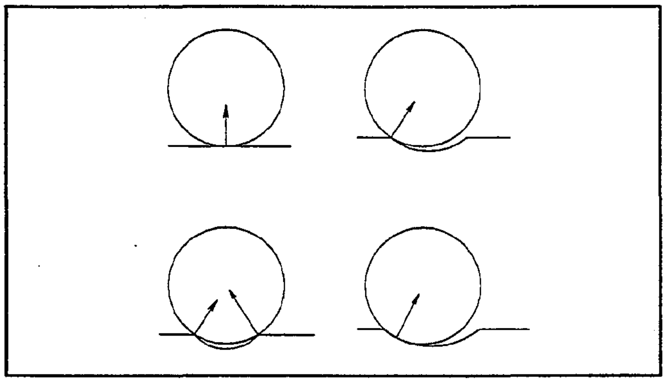


Figure 17. Wheel and rumble strip contact situations.

5.2 Simulation Model Validation

Vibration signals usually look irregular in the time domain and are difficult to compare with each other. Fast fourier transformation (FFT) can be used to transfer signals from the time domain into the frequency domain. It reflects how energy is distributed along the frequency in that signal. Sometimes, there are dominant frequencies in a signal that will appear as peaks in the FFT plot. Typically, the locations of these peaks are more important than the amplitude of the peaks. If two signals have a similar FFT plot (energy distribution), the two signals are similar. Thus, FFT provides an approach to compare two irregular signals.

To validate the bicycle/rider simulation model, a test scenario was run with the model simulating a bicyclist traversing PennDOT's current rumble strip configuration. FFT plots of the vertical acceleration and pitch angular acceleration were created from the simulation results. Likewise, FFT plots of the vertical acceleration and pitch angular acceleration were created from the data gathered during the base measurement tests. Comparisons between the FFT plots from the field data and the simulation showed that the peak locations for both the base measurement results and the simulation results were almost the same (see figures 18 and 19). This verified the proximity between the base measurement results and the simulation results. In the plot of vertical acceleration (figure 18), there was some difference between the peak amplitude of the base frequency of the base measurements and the simulation around 10Hz. This implied that the calculations from the simulation were smaller than the base measurement results. However, the plot reflected the same trends since the peaks were in the same frequency location.

Overall, there was a good comparison between the data from the base measurement tests and the simulation results. Therefore, the bicycle/rider simulation model was used as a tool to evaluate the impact of potential rumble strip configurations on bicycle/rider dynamics.

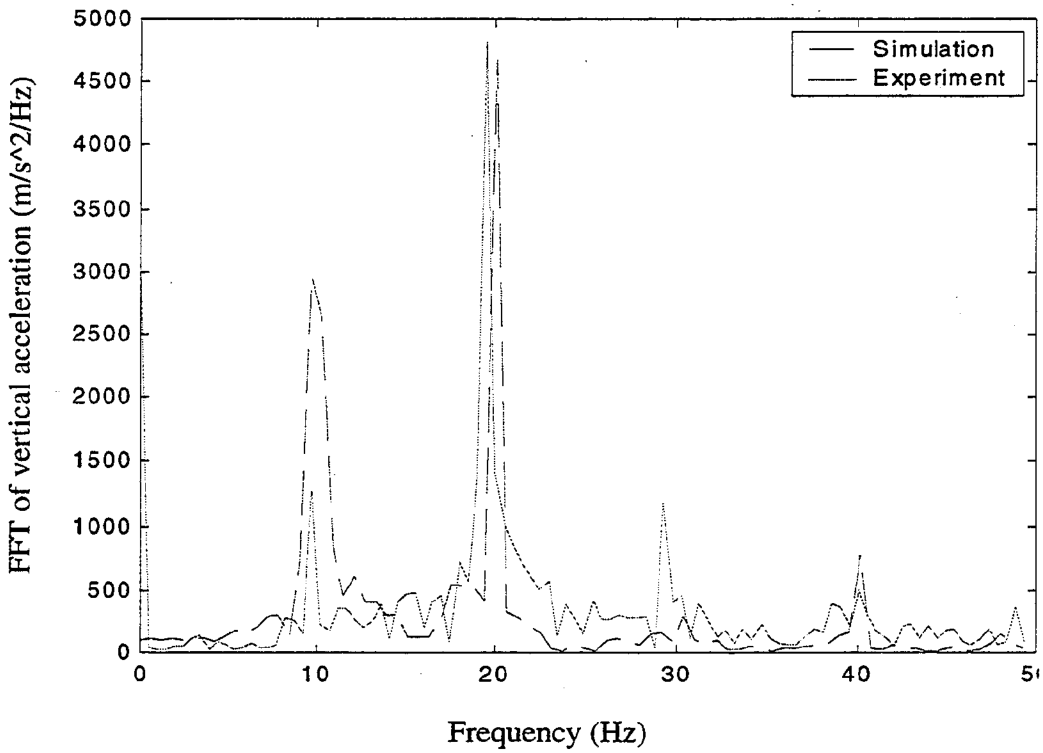


Figure 18. FFT of bicycle vertical acceleration at speed of 6.2 mph (10 km/h).

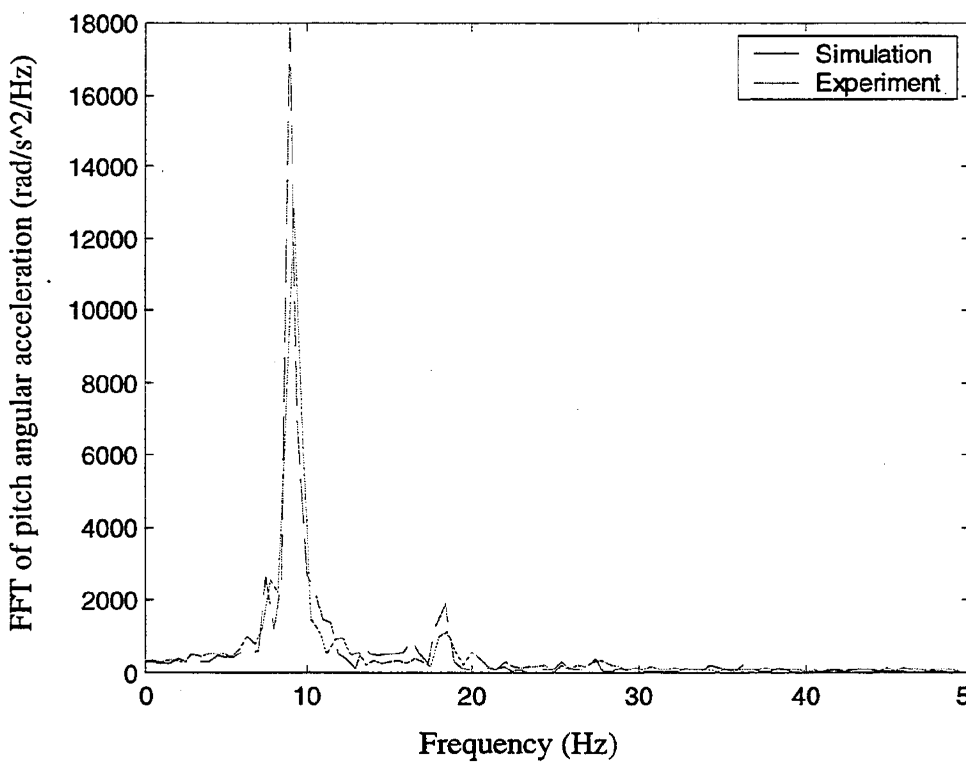


Figure 19. FFT of bicycle pitch angular acceleration at speed of 6.2 mph (10 km/h).

5.3 Testing Potential Configurations with Simulation

The major benefit of the bicycle/rider simulation model was the ability to evaluate the dynamics of a bicycle and rider traversing numerous rumble strip configurations. With milled rumble strips, the primary variables that impact the dynamics of bicycles and motor vehicles include:

- the width of the groove
- the spacing of the groove
- the depth of the groove
- the transverse length of the groove

The simulation focused on varying the width of the groove and the spacing of the grooves. Based on results of the literature review, the depth of the groove was not varied. A depth of less than 0.25" (6 mm) does not generate enough noise and vibration to alert inattentive/drowsy motorists, and a depth equal to or greater than 0.75" (19 mm) generates too much excitation of the motor vehicle. With the range for the depth being so small, the depth of the rumble strips simulated was held constant at 0.5" (13 mm). The transverse length of the groove was irrelevant in the simulation because the simulation was only two-dimensional. Therefore, the transverse length could not be varied within the simulation.

A total of 26 configurations were simulated, varying the width and spacing of the grooves. The groove width was varied from 4" to 8" (102 to 203 mm), and the spacing between the grooves was varied from 2" to 9" (51 to 229 mm). Typically, the spacing of grooves is measured from the center of one groove to the center of the adjacent groove. This is convenient when the groove width is constant, but by varying both the width of the groove and the spacing of the groove, a different convention was developed to keep track of the dimensions of the simulated configurations. Rather than referring to the spacing of the grooves as on centers, the spacing of the grooves refers to the length of the flat portion of pavement between grooves. Table 16 presents all configurations that were simulated using the bicycle/rider simulation model.

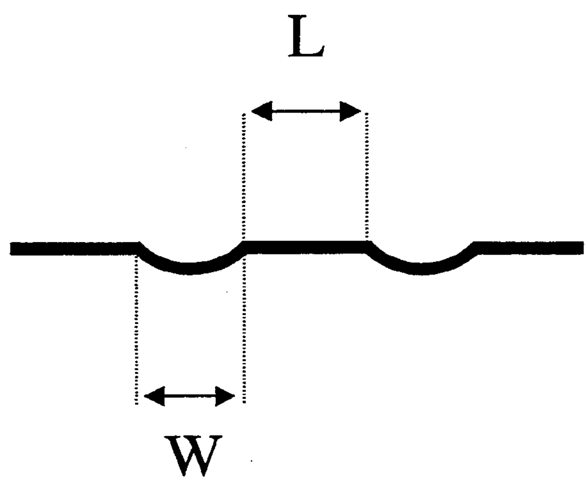
To evaluate the dynamics of the bicycle and rider traversing the various rumble strip configurations, the vertical acceleration and pitch angular acceleration of the bicycle/rider system were measured. Rather than taking an average acceleration or the peak acceleration, the RMS was calculated to measure the magnitude of the vibrations. The formula to calculate RMS is as follows:

$$RMS = \sqrt{\frac{\sum_{i=1}^{n} \ddot{z}_i^2}{n}}$$

Where

$\ddot{z}$ = bicycle acceleration (vertical or pitch angular)
i = i^{th} value bicycle acceleration time history
n = number of values

Table 16. Simulated rumble strip configurations.

Simulation Number	Rumble Strip Pattern*	Rumble Strip Variables
1	RS4_5	
2	RS4_6	
3	RS4_7	
4	RS4_8	
5	RS4_9	
6	RS5_3	
7	RS5_5	
8	RS5_6	
9	RS5_7	
10	RS5_8	
11	RS5_9	
12	RS6_5	
13	RS6_6	
14	RS6_7	
15	RS6_8	
16	RS6_9	
17	RS7_2	
18	RS7_3	
19	RS7_4	
20	RS7_5	
21	RS7_6	
22	RS7_7	
23	RS7_8	
24	RS7_9	
25	RS8_3	
26	RS8_5	

*The first number of the rumble strip pattern represents the width of the groove in inches (W), and the second number represents the spacing between grooves in inches (L).

Using the simulation model, the RMS vertical acceleration and RMS pitch angular acceleration of the bicycle/rider system were calculated for different speeds for the 26 configurations identified in table 16. From the data, plots of RMS vertical acceleration versus speed were created as well as plots of RMS pitch angular acceleration versus speed. To determine which rumble strip configurations were more bicycle-friendly or generated the least amount of vibration, the areas under the RMS curves were calculated for speeds between 9 and 15 mph (15 and 25 km/h). Figure 20 illustrates the area under the RMS curves for rumble strip pattern RS7_5.

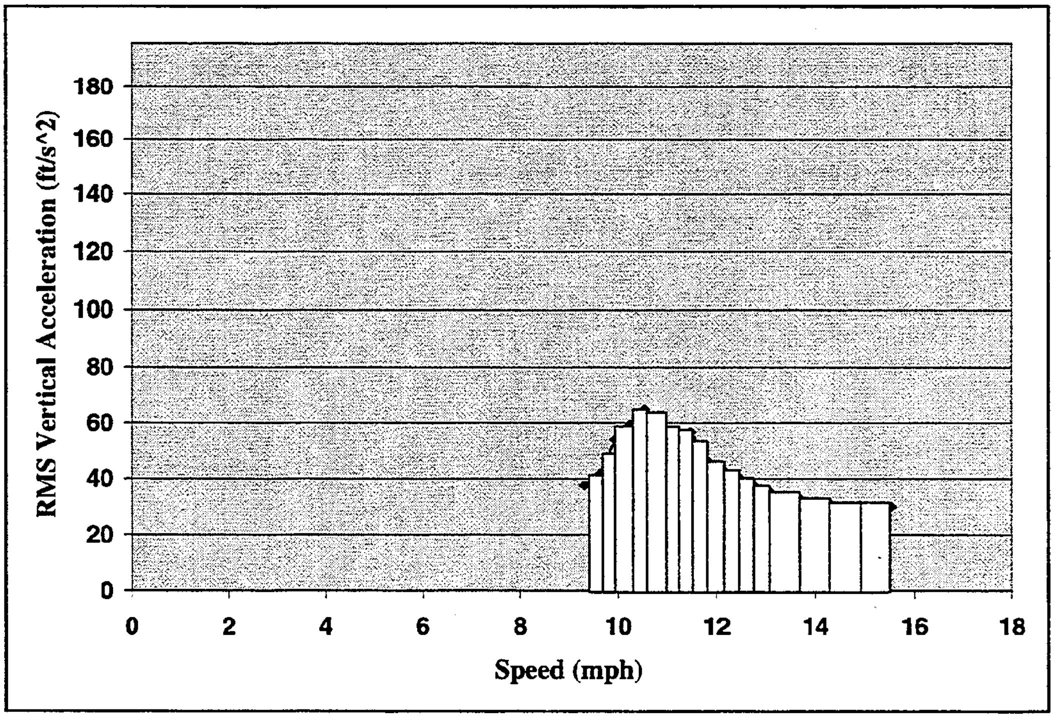


Figure 20. Area under the RMS curve between 9 and 15 mph (15 and 25 km/h).

To consider the influence of both the bicycle/rider vertical acceleration and pitch angular acceleration, the areas under the curves for vertical acceleration and pitch angular acceleration were changed into dimensionless percentages with respect to the maximum value of the area. For each configuration, the percentages from the RMS vertical acceleration and pitch angular acceleration were added together and divided by two, providing an average weighted percentage of RMS. By sorting the configurations by the average weighted percentage of RMS, it was determined which configurations were most bicycle-friendly. The configurations with the lowest average weighted percentages generated the least amount of vibration, and those configurations that had the higher average weighted percentages generated the greatest amount of vibration.

Table 17 shows the sorted list of potential rumble strip configurations that were simulated. The results of this analysis served to prioritize the potential configurations to be installed at PTI's test track. Once installed, additional field tests could be performed. A close analysis of table 17 indicates that groove width impacts the dynamics of the bicycle/rider system more significantly than groove spacing, and by developing potential configurations with narrower grooves, the rumble strips could be more bicycle-friendly.

5.4 Installation of Recommended Rumble Strip Configurations at PTI's Test Track

With a prioritized list of potentially "bicycle-friendly" rumble strip configurations, the contractor, Surface Preparation Technologies (SPT), was contacted to install several of the new configurations at PTI's test track so actual field testing could be performed with both bicycles and a motor vehicle.

Table 17. Simulated configurations sorted by weighted average percentage of RMS.

Rumble Strip Pattern	Vertical Accel. ft^2/s^3 (m^2/s^3)	Pitch Angular Accel. $rad*ft/s^3$ ($rad*m/s^3$)	Percentage of Vert. Accel.	Percentage of Pitch Angular Accel.	Wtd Avg Percentage
RS4_5	78.25 (7.27)	19.00 (5.79)	0.08	0.18	0.13
RS4_7	127.34 (11.83)	14.08 (4.29)	0.12	0.14	0.13
RS4_6	180.94 (16.81)	11.55 (3.52)	0.18	0.11	0.14
RS4_8	104.19 (9.68)	20.47 (6.24)	0.10	0.20	0.15
RS4_9	201.18 (18.69)	18.34 (5.59)	0.20	0.18	0.19
RS5_3	307.63 (28.58)	24.21 (7.38)	0.30	0.24	0.27
RS5_5	372.21 (34.58)	22.44 (6.84)	0.36	0.22	0.29
RS5_7	216.78 (20.14)	45.80 (13.96)	0.21	0.44	0.33
RS5_6	303.86 (28.23)	38.81 (11.83)	0.30	0.38	0.34
RS5_9	467.37 (43.42)	26.15 (7.97)	0.46	0.25	0.36
RS6_6	305.05 (28.34)	69.98 (21.33)	0.30	0.68	0.49
RS7_3	679.52 (63.13)	35.04 (10.68)	0.67	0.34	0.50
RS6_9	452.51 (42.04)	58.17 (17.73)	0.44	0.57	0.50
RS6_8	500.30 (46.48)	57.68 (17.58)	0.49	0.56	0.53
RS5_8	431.63 (40.10)	38.12 (11.62)	0.46	0.68	0.57
RS7_2	214.63 (19.94)	95.73 (29.18)	0.21	0.93	0.57
RS6_7	637.87 (59.26)	53.51 (16.31)	0.62	0.52	0.57
RS7_9	334.22 (31.05)	86.02 (26.22)	0.33	0.84	0.58
RS7_5	388.04 (36.05)	93.21 (28.41)	0.38	0.91	0.64
RS7_4	593.63 (55.15)	73.98 (22.55)	0.58	0.72	0.65
RS7_8	617.52 (57.37)	76.31 (23.26)	0.60	0.74	0.67
RS7_7	917.83 (85.27)	46.19 (14.08)	0.90	0.45	0.67
RS8_3	647.77 (60.18)	80.38 (24.50)	0.63	0.78	0.71
RS7_6	857.13 (79.63)	68.18 (20.78)	0.84	0.66	0.75
RS6_5	636.14 (59.10)	102.92 (31.37)	0.62	1.00	0.81
RS8_5	1020.74 (94.83)	80.45 (24.52)	1.00	0.78	0.89

SPT was called upon to perform the installation because of its highly sophisticated milling equipment, which could be adjusted to mill the different configurations.

Upon arrival at PTI's test track on the day the rumble strips were to be installed, the contractor was provided the prioritized list of the "bicycle-friendly" configurations. However, there were some limitations that prohibited the machine from cutting the exact dimensions of some of the configurations most likely to decrease the vibration levels experienced by bicyclists. The limitations were mainly a function of the size of the cutting head on the machine. Figure 21 shows SPT's milling machine, and figure 22 shows the cutting head. As shown, the milling machine head has a constant diameter, thus decreasing the depth of the grooves also results in decreasing the width of the grooves.

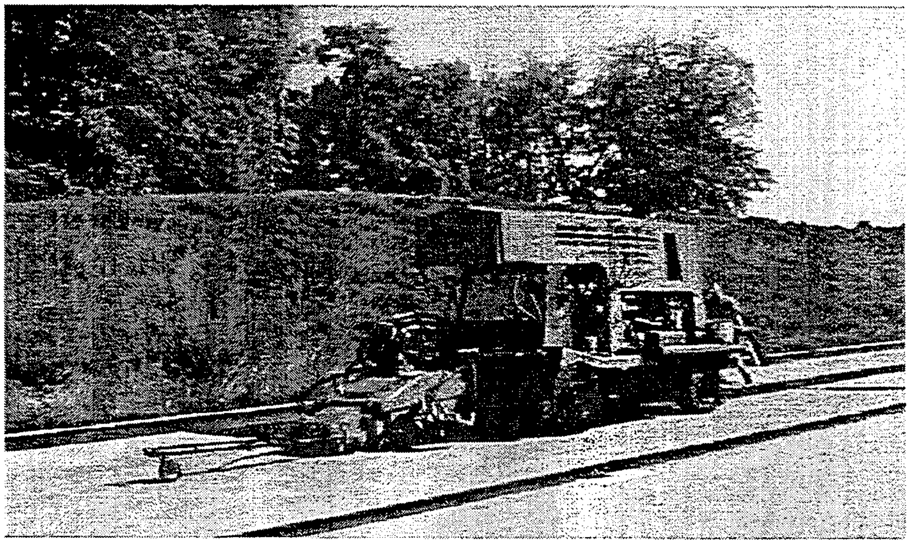


Figure 21. Milling machine used to install rumble strips at PTI's test track.

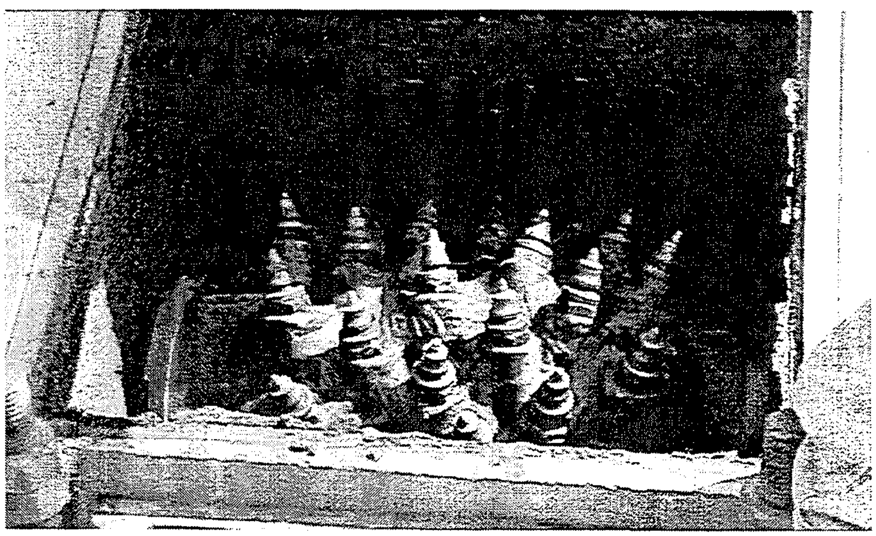


Figure 22. Cutting head on the milling machine.

As previously discussed, the bicycle/rider simulation model simulated only rumble strip configurations with a depth of 0.5" (13 mm). Based on recommendations from the reviewing task force, the depth of some of the rumble strip configurations installed at the test track was to be varied as well. Thus, adjustments were made in the field with respect to the actual dimensions of the new rumble strips configurations. Taking into account the limitations of the milling machine and the recommendations from the reviewing task force, the dimensions of the six rumble strip configurations that were actually installed at PTI's test track for further evaluation are shown in table 18. All of the patterns had a transverse width of 16" (406 mm). The patterns were installed in approximately 125' (38 m) sections.

Table 18. Rumble strip configurations installed at PTI's test track for further evaluation.

Test Pattern	Groove Width inches (mm)	Flat Portion between Cuts inches (mm)	Depth inches (mm)
1*	7" (178 mm)	5" (127 mm)	0.5" (13 mm)
2	5" (127 mm)	7" (178 mm)	0.5" (13 mm)
3	5" (127 mm)	7" (178 mm)	0.375" (10 mm)
4	5" (127 mm)	6" (152 mm)	0.5" (13 mm)
5	5" (127 mm)	6" (152 mm)	0.375" (10 mm)
6	5" (127 mm)	7" (178 mm)	0.25" (6.3 mm)

* PennDOTs current standard

6. EXPERIMENTAL PLAN

This section presents the third step in the methodology. An experimental plan was developed with the assistance of the reviewing task force and PennDOT to gather the appropriate and necessary data during the test track experiments. The test track experiments involved collecting vibration and perception data from volunteer participants bicycling over the various rumble strip configurations and collecting data from a motor vehicle to measure the amount of noise and vibration generated from the new configurations. The following issues were considered while developing the data collection procedures for this aspect of the research, and they are further discussed in the remainder of this section:

Bicycle Testing

- The types of bicycles to be used in the testing (section 6.1.1).
- The speeds and angles at which the bicyclists would be traveling during the tests (section 6.1.2).
- The types of bicyclists to participate in the testing (section 6.1.3).
- The variables to be measured during the tests and the equipment to be used for measuring them (section 6.1.4).
- The test track procedures (section 6.1.5).

Motor Vehicle Testing

- The type of motor vehicle to be used in the testing (section 6.2.1).
- The speeds and angles at which the motor vehicle would be traveling during the tests (section 6.2.2).
- The variables to be measured during the tests (noise, vibration, etc.) and the equipment to be used for measuring them (section 6.2.3).
- The test track procedures (section 6.2.4).

6.1 Bicycle Testing

6.1.1 Types of Bicycles

Bicycles come in many different types and sizes and exhibit varying dynamic characteristics. The following four bicycle types were selected for testing because they represent a large proportion of the bicycles that are in use today:

- Standard adult road bike:
  - 85-120 psi (586 x 10^3 - 827 x 10^3 Pa) tire pressure
- Non-suspended mountain bike:
  - 40-50 psi (276 x 10^3 - 345 x 10^3 Pa) tire pressure
- Hybrid bike:
  - 65-80 psi (448 x 10^3 - 552 x 10^3 Pa) tire pressure
- Tandem
  - 100-110 psi (689 x 10^3 - 758 x 10^3 Pa) tire pressure

Mountain bikes come in two forms: those with active suspensions and those that are non-suspended. Non-suspended mountain bikes theoretically exhibit worse dynamic characteristics as compared to suspended mountain bikes so bicyclists should feel more vibration on non-suspended mountain bikes than suspended mountain bikes. Thus the non-suspended mountain bike was selected so that the new design considers the worst case scenario.

6.1.2 Speeds and Angles for the Bicycle Tests

6.1.2.1 Speed

The speed that a bicyclist rides is dependent upon several factors, such as the type and condition of the bicycle, the purpose of the trip, the speed and direction of the wind, the physical condition of the bicyclist, and the grade and surface condition of the roadway (AASHTO, 1991). In some instances, on downgrade sections, bicyclists may reach speeds approaching 30 to 40 mph (48 to 64 km/h), or even higher. To determine whether speed affects the comfort level of bicyclists and to determine whether speed affects controllability, the bicycle experiments were conducted at various speed levels.

For this research, bicyclists traversed the rumble strip configurations at three speed ranges:

- Low Speed: from 3 to 9 mph (5 to 15 km/h)
- Intermediate Speed: from 10 to 15 mph (16 to 25 km/h)
- High Speed: greater than or equal to 16 mph (26+ km/h)

Speed ranges were used instead of specific speeds because it is difficult for bicyclists to ride at a particular constant speed, say 9 mph (15 km/h). It is possible to do so, but it requires the bicyclist to focus heavily on the speedometer. Rather than trying to control speed, speed ranges were selected, and it was determined that bicyclists could ride within a range of 6 mph (10 km/h) without having to focus too much on their speed. The low value of the speed range was selected because at speeds slower than 3 mph (5 km/h), it is difficult for many bicyclists to keep their balance. The reasoning for the intermediate speed range and the high speed range was that all riders should easily be able to reach the intermediate speed range without much physical exertion. Also, all participants should be able to reach speeds higher than 15 mph (25 km/h) repeatedly, without taking physical condition into consideration. For speeds much higher than 15 mph (25 km/h), the physical condition of the test participants could become a factor in the study. Therefore, 15 mph (25 km/h) seemed a good boundary speed between the intermediate and high speed ranges.

6.1.2.2 Angle

Out on the roadways, it is conceivable that bicyclists traverse rumble strips from all possible angles. Bicyclists may approach rumble strips from straight on, where the rumble strips just begin. Bicyclists may also cross rumble strips at very shallow angles while negotiating from the travel lane to the shoulder or vice versa, or bicyclists may cut across rumble strips at sharp angles to avoid objects or to perform turning maneuvers. Three approach angles were selected for testing:

- 0° (straight on approach)
- 10°
- 45°

6.1.3 Types of Bicyclists

Two issues were considered when selecting the types of bicyclists to be involved in the test track experiments. One issue was safety during the testing. The volunteer participants would be asked to traverse the various rumble strip configurations at speeds up to and exceeding 16 mph (26 km/h). To avoid potential problems, participation in the study was requested from bicyclists with intermediate and advanced skill levels. Bicyclists with minimal riding skills were not asked to participate.

The second issue revolved around considering the types of bicyclists most likely to encounter rumble strips out on the roads. Rumble strips tend to be installed on high speed facilities. In most cases, novice bicyclists do not ride on these types of facilities. Therefore, only intermediate to advanced riders are likely to encounter rumble strips. As such, participation in the testing was only sought from intermediate and advanced skill levels. The following definitions, as provided from the reviewing task force, were used to classify bicyclists as either intermediate or advanced:

> **Intermediate Bicyclist:** Someone who knows how to handle his/her bicycle easily and comfortably--who doesn't fall off, who can shift gears and steer smoothly, and who has a smooth pedaling style and reasonable cadence (at least 60 rpm). Intermediate bicyclists can ride comfortably and confidently in light or moderate traffic environments on adequately wide roads where motor traffic moves at up to legal rural speeds 55 mph (88 km/h) in

Pennsylvania. They can climb most hills without dismounting. A typical intermediate bicyclist might ride 1000 to 4,000 miles (1600 to 6400 km) per year, usually in good weather.

Advanced Bicyclist: Someone who has many years and thousands of miles (km) of bicycling experience, who can do everything the intermediate bicyclist can do, plus ride skillfully, comfortably, and confidently in heavy traffic (urban, suburban, or rural) and on narrow or wide high-speed roads, who can (and at least occasionally does) ride at night and/or in rain, who can negotiate very demanding terrain (both up and down), and who does all this without getting flustered. An advanced bicyclist typically rides 5,000 miles (8000 km) per year or more, although the annual mileage alone is not as good an indicator of skill level as the environments in which the bicyclist rides.

6.1.4 Data Collection

This research evaluated the difference between the potential "bicycle-friendly" rumble strip configurations through both objective and subjective measures. Because the major concerns by bicyclists regarding rumble strips are comfort and control, it was important to gather data for both issues. Previous studies of bicyclists and rumble strips (Ardekani et al. 1996; Garder 1995; and Young 1997) assessed either comfort and/or control through subjective means only.

6.1.4.1 Objective Comfort and Control

To measure comfort and control objectively, the bicycles were instrumented with a Crossbow DMU-VGS six-axis vertical measurement unit to measure both vertical acceleration and pitch angular acceleration. Figure 23 shows the Crossbow secured to the mountain bike, mounted near the center of gravity of the bicycle/rider system (when the bicyclists is in the riding position). Higher vertical and pitch angular accelerations will cause greater discomfort and increase the potential for losing control. Lower levels of acceleration will improve comfort and controllability. Thus the two objective measures used to measure comfort and controllability were:

Objective Comfort and Control Measures
Vertical Acceleration
Pitch Angular Acceleration

6.1.4.2 Objective Control

While vertical and pitch angular accelerations are two good measures to quantify the effects of rumble strips on controllability, it was equally important to obtain objective, verifiable measures of a participant's observable performance. To obtain an observable objective measure of performance, the bicyclists were asked to ride along an 8" (203 mm) white line as they traversed the rumble strips. As the participants traversed the rumble strips at a 0° angle, a video camera was positioned from a perspective that showed both the bicyclists and the white lines. Prior to testing on the rumble strips, the participant rode along an 8" (203 mm) white line which was

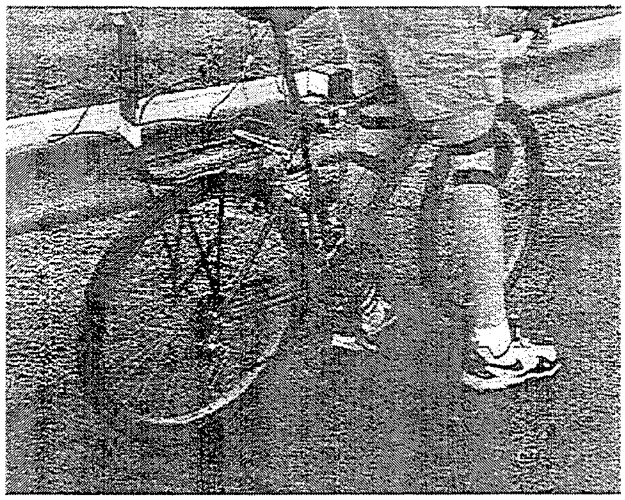


Figure 23. Crossbow mounted on bicycle near center of gravity.

painted on a smooth portion of the pavement to provide a baseline for evaluating the effects of the rumble strips.

After data collection, the video tapes were played back and any lateral deviation from the line was noted by recording the amount of time spent off of the 8" (203 mm) white line. In addition, the amount of time to traverse the entire length of the 8" (203 mm) white line was also recorded. By dividing the amount of time deviating from the white line by the traverse time, the percent of time spent deviating from the line, or the amount of time spent off the line, was calculated, and thus an observable measure of controllability was established.

Objective Control
Percentage of Time Spent Off the Line

6.1.4.3 Subjective Comfort and Control

To obtain a subjective, or perceived, measure of comfort level and controllability, the bicyclists were asked to fill-out a questionnaire rating the comfort level of different body parts while traversing the rumble strip configurations. In addition, the bicyclists were asked to rate the overall control level while traversing the configurations. The selection of body parts for the comfort scale was based on research using a stationary bicycle by Christiaans and Bremner (1998). These researchers found that the five areas selected for the present study collectively accounted for between 73 and 89 percent of all reported complaints of bicycle discomfort. Appendix A contains a sample of the questionnaire. In total, seven subjective measures were collected through the questionnaire:

Subjective Measures
Comfort of wrists, fingers, and elbows
Comfort of shoulder and neck
Comfort of back
Comfort of seat area

Comfort of knees, ankles, and feet
Overall comfort level
Overall control level

6.1.5 Test Track Procedures for Bicyclists

When each participant arrived at the test track, the purpose of the study was reiterated to the participant, and some of the basic procedures of the testing were explained. The participant was then asked if he/she had any questions and if he/she was still willing to participate in the study. Minimal information was supplied if the participant did have any questions so as not to bias the participant's data. After receiving a verbal consent to participate, each participant filled out an informed consent form and a questionnaire designed to gather background information such as age, weight, height, skill level, etc. The definitions of intermediate and advanced riders were also provided with the questionnaire to help the participant rate his/her skill level. A sample consent form is provided in Appendix B.

After the participant finished with the background information, the content of the subjective comfort and control questionnaire was reviewed with the participant. This form was used by each participant to subjectively rate the comfort and controllability of each rumble strip configuration.

The participant then selected one of the four bicycles available for the testing. The instrumentation requirements for this study prohibited a participant from using his/her own bicycle. Before any of the actual testing started, the participant was able to ride around the track area for a while to become comfortable with the bicycle.

During the first phase of the testing, the participant rode along an 8" (203 mm) white line which was painted on a smooth portion of the pavement. This initial phase provided a base measure to evaluate a participant's control level. The white line was approximately 45' (13.7 m) in length. The participant was to ride on the line for the entire length. One practice run was permitted at any speed before any data were gathered. Following the practice run, the participant was video taped riding on the line at the low speed range, the intermediate speed range, and the high speed range. Only one run was made at each speed range.

In the second phase of the testing, the participant actually traversed the six rumble strip patterns at the three speed intervals and the three angles. Starting with a randomly selected rumble strip configuration, the participant traversed the rumble strip at 0° for a length of approximately 45' (13.7 m) along an 8" (203 mm) white line, at the low speed range. The participant then stopped and subjectively rated the comfort and control level of the rumble strip while riding at low speed. Next, the participant followed the same approach for the same pattern but this time at the intermediate speed range. The participant then stopped and subjectively rated the comfort and control of the configuration while riding at the intermediate speed. Finally, the participant made a third run at 0° at the high speed for the same configuration and then filled out the subjective comfort and control questionnaire for the high speed case. Each run at 0° was video taped. Figure 24 shows a participant traversing one of the rumble strip configurations at 0°.

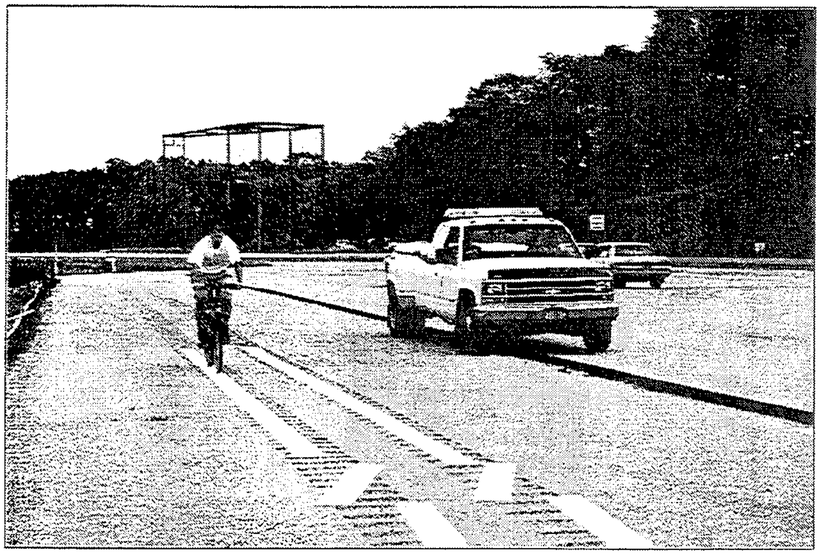


Figure 24. Bicyclist traversing test configuration at 0° angle.

The participant then traversed the same rumble strip pattern at 10° at the three speeds, and finally he/she traversed the same rumble strip pattern at 45° at the three speeds. An 8" (203 mm) white line was painted on the rumble strip configuration at the respective angles, and the participant was instructed to ride on the lines. For the 10° and 45° runs, the participant did not fill out a subjective questionnaire, nor were the runs video taped. In total, nine runs were completed at the same configuration as summarized in table 19.

Table 19. Order of runs at each rumble strip configuration.

Run	Approach Angle	Speed Range	Fill-Out Subjective Questionnaire	Video Taped
1	0°	Low	Yes	Yes
2	0°	Intermediate	Yes	Yes
3	0°	High	Yes	Yes
4	10°	Low	No	No
5	10°	Intermediate	No	No
6	10°	High	No	No
7	45°	Low	No	No
8	45°	Intermediate	No	No
9	45°	High	No	No

After completing all nine runs at the initial pattern, the participant proceeded to a second rumble strip pattern and repeated the process, until 9 runs were completed for all 6 patterns installed at the test track. Thus, the participant made a total of 54 runs over the rumble strips. The order of the rumble strip configurations followed by each participant was randomly generated.

To collect the vertical acceleration and pitch angular acceleration for each run, a 25' (7.6 m) cable was attached to the crossbow (mounted on the bicycle) and a PC-based data acquisition system. The data acquisition system was contained in a motor vehicle that was driven parallel to the bicycle so as to maintain the 25' (7.6 m) distance.

The final phase of the testing was a repeat of the first phase. Each participant rode along the 8" (203 mm) white line painted on the smooth surface at the three speed ranges. Once again, these runs were video taped.

6.1.5.1 Modified Procedures When Vibration Data Were Not Gathered

For the first five participants on each of the bicycles, all 10 subjective and objective measures were collected. After the fifth participant on the respective bicycles, only subjective data and objective control data were gathered. Vibrational data were not collected. When vibration data were not collected, there was only a slight modification to the original procedures. Rather than performing nine runs at each of the configurations, only three runs were performed, at 0° for the three speed ranges. The participant did not traverse the rumble strips at angles of 10° and 45° because the subjective questionnaire was not to be filled out during these runs, nor were the runs at 10° and 45° to be video taped.

6.2 Motor Vehicle Testing

6.2.1 Type of Motor Vehicle

The motor vehicle portion of the test track experiments involved gathering both vibration and noise data while traversing the various rumble strip configurations. Due to the instrumentation needs (drilling holes into the test vehicle to install the measurement equipment) to gather the vibration data, only one motor vehicle—which was the property of PTI—was used in the testing. The motor vehicle was a 1998 Plymouth Grand Voyager (figure 25).

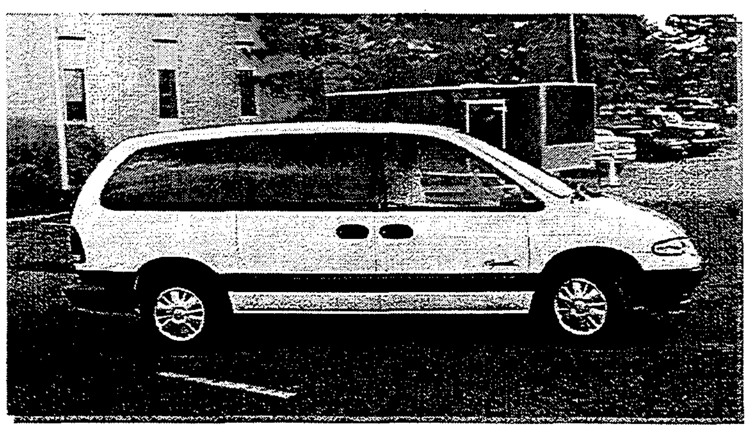


Figure 25. Test vehicle used to gather vibration and noise data.

6.2.2 Speeds and Angles for the Motor Vehicle Tests

Vibration and noise data were collected at two speeds, 45 and 55 mph (72 and 88 km/h). The minivan was driven at a small departure angle, approximately 3 to 5°. Studies have shown that ROR crashes typically occur at these angles.

6.2.3 Data Collection

To assess the effectiveness of various rumble strip configurations on alerting inattentive/drowsy motorists, measurements were taken of the auditory and vibrational stimuli generated by the rumble strips. To measure vibrational stimuli, a Crossbow DMU-VGS six-axis vertical measurement unit was secured to the frame of the minivan between the two front seats (as seen in figure 12 and once again illustrated here in figure 26). The crossbow was used to measure the vertical acceleration and pitch angular acceleration of the motor vehicle frame. To measure auditory stimulus generated from the rumble strips, a Bruel & Kjaer sound meter (type 2232) was used to measure the maximum level of noise, using the A-weighting (dB(A)), in the passenger compartment. Thus, the effectiveness of the potential rumble strip configurations on alerting inattentive/drowsy motorists was evaluated based on three objective measures:

<u>Objective Measures</u>
Vertical Acceleration of the Motor Vehicle Frame
Pitch Angular Acceleration of the Motor Vehicle Frame
Maximum Noise Level in the Passenger Compartment of the Motor Vehicle

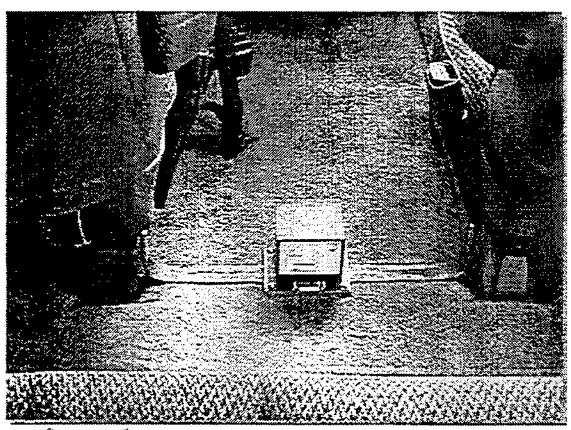


Figure 26. Mounting of crossbow to measure vertical and pitch angular accelerations.

6.2.4 Test Track Procedures for Motor Vehicle

There were two phases in the test track experiments with the motor vehicle. The first phase involved collecting the vibrational data. The second phase involved the noise testing.

6.2.4.1 Vibration Testing

Based on the results of the base measurement testing, which showed minimal levels of vibration for the motor vehicle generated by the existing rumble strip configuration, the minivan was instrumented with the Crossbow DMU-VGS six-axis vertical measurement unit and driven over each rumble strip configuration once at speeds of 45 and 55 mph (72 and 88 km/h). The vertical acceleration data and pitch angular acceleration data were then analyzed to determine if additional vibration testing was necessary. It was determined that the levels of vertical acceleration and pitch angular acceleration of the motor vehicle frame generated by the different rumble strips were insignificant, and no additional vibration tests were performed. Thus, the effectiveness of the different rumble strips in alerting inattentive/drowsy motorists was assessed based upon the results of the noise level tests.

6.2.4.2 Noise Level Testing

To measure the amount of auditory stimulus generated by the respective rumble strip patterns, a Bruel & Kjaer sound meter was used to measure the maximum sound level in the passenger compartment of the minivan. Measurements were gathered at speeds of 45 and 55 mph (72 and 88 km/h). Three runs were made at each speed. In addition to gathering sound levels while traversing the rumble strips, sound levels were measured while riding over the "smooth" pavement surface to determine the amount of noise generated over and above that of the background noise generated while traveling at the respective speeds.

7. ANALYSIS OF THE QUANTITATIVE AND QUALITATIVE MEASURES

This section presents results from the analyses to evaluate and assess the relative effects of the six rumble strip patterns installed at PTI's test track on bicycle and motor vehicle dynamics. Analysis results from the bicycle testing are presented first, followed by the results from the motor vehicle tests. A more detailed statistical analysis of each objective and subjective measure collected for the motor vehicle and bicycle is provided in Appendix C.

7.1 Analysis of Bicycle Measures

Ten measures were gathered to assess the effect of the six rumble strip configurations on bicyclists' comfort and control:

Objective Measure	Subjective Measure
Vertical acceleration	Comfort of wrists, fingers, and elbows
Pitch angular acceleration	Comfort of shoulder and neck
Percentage of time spent off the line	Comfort of back
	Comfort of seat area
	Comfort of knees, ankles, and feet
	Overall comfort level
	Overall control level

For some of the participants involved in the bicycle testing, data for all measures were gathered. For the other participants, data were collected for all the measures except for the vibrational data (vertical and pitch angular acceleration). Twenty five subjects actually participated in the bicycle testing at PTI's test track. Table 20 shows the number of tests conducted with each bicycle type. A total of 27 bicycle tests were conducted. In several cases, subjects rode more than one bicycle type. Thirteen of the participants had "intermediate" riding experience, while 12 participants had "advanced" riding skills. A majority of participants' riding experience was on-road riding, as compared to off-road riding. Twenty males and five females participated in the bicycle testing. Very few of the participants indicated any type of recurring pain in particular body parts or any general health related problems, and about two-thirds of the participants had ridden a bicycle over rumble strips prior to participating in the research. (Appendix D contains additional information and statistics related to the bicycle testing participants.)

Table 20. Tests conducted with each bicycle type.

Bicycle Type	Number of Tests
Mountain	8
Road	9
Hybrid	5
Tandem	5

7.1.1 Objective Measures of Comfort and Control

7.1.1.1 Vertical Acceleration

Analysis of the vertical acceleration data was divided into two parts. One analysis was performed on the data from the mountain, road, and hybrid bicycles, while a separate analysis was performed on the data from the tandem bicycle. Two separate analyses were performed because the Crossbow DMU-VGS six-axis vertical measurement unit had to be mounted at a different location on the tandem, other than the center of gravity of the bicycle/riders system. The crossbow was mounted on the tandem using one of the water bottle fixtures to secure it to the bicycle frame. Because the reference location of the crossbow was different for the tandem, the vertical acceleration for the tandem was not directly comparable with the vertical acceleration data from the mountain, road, and hybrid bicycles.

Vertical acceleration data were collected for the first five participants on each bicycle type. The RMS vertical acceleration was calculated over all speeds and rumble strip types, but only at a 0° angle. The RMS was not be calculated for the 10° and 45° runs due to the short duration actually spent on the rumble strips. There was too much "noise" in the raw data to accurately calculate the RMS. The maximum vertical acceleration was also recorded over all speeds, angles, and rumble strip patterns. RMS is a more stable measure of the vertical acceleration than the maximum values so only the RMS vertical acceleration was used to assess the effect of the rumble strip configurations on vertical acceleration.

Table 21 presents the rankings of the test configurations based upon the vertical acceleration levels measured on mountain, road, and hybrid bicycles across all speed ranges. Similarly, table 22 presents the rankings from the tandem bicycle across all speed ranges. From the bicyclist's perspective, lower vertical accelerations make for a smoother, more comfortable ride and better control of the bicycle. Higher vertical accelerations cause more discomfort and increase the potential of losing control. Therefore, the rumble strip configurations were ranked according to the levels of vertical acceleration generated. The rumble strip configuration that generated the lowest amount of vertical acceleration received the best ranking (#1), and the rumble strip configuration that generated the highest amount of vertical acceleration received the worst ranking (#6).

Table 21. Ranking of test configurations based on vertical acceleration (mountain, road, and hybrid bicycles).

	Rank	Test Pattern	Average RMS - Vertical Acceleration ft/s^2 (m/s^2)
Best	1	6	37.123 (11.315)
	2	3	43.228 (13.176)
	3	2	55.613 (16.951)
	4	5	63.396 (19.323)
	5	1	71.880 (21.909)
Worst	6	4	71.988 (21.942)

Table 22. Ranking of test configurations based on vertical acceleration (tandem bicycle).

	Rank	Test Pattern	Average RMS – Vertical Acceleration ft/s^2 (m/s^2)
Best	1	6	29.327 (8.939)
	2	3	34.003 (10.364)
	3	2	40.850 (12.451)
	4	1	55.131 (16.804)
	5	5	58.940 (17.965)
Worst	6	4	62.605 (19.082)

From the bicyclist's perspective, test patterns 6, 3, and 2 generated the lowest levels of vertical acceleration, and pattern 4 generated the greatest amount of vertical acceleration. For the mountain, road, and hybrid bicycles, test pattern 5 generated less vertical acceleration than test pattern 1. However, for the tandem, test pattern 1 generated less vertical acceleration than test pattern 5.

7.1.1.2 Pitch Angular Acceleration

Similar to the analysis for vertical acceleration, the analysis of the pitch angular acceleration data was divided into two parts. One analysis was performed combining the data from the mountain, road, and hybrid bicycles, and a separate analysis was performed on the data from the tandem bicycle. As discussed previously, the separate analyses were performed because of the different mounting locations of the crossbow on the tandem as compared to the mountain, road, and hybrid bicycles.

Pitch angular acceleration data were collected for the first five participants on each bicycle type. The RMS pitch angular acceleration was calculated over all speeds and rumble strip types, but only at a 0° angle. The maximum pitch angular acceleration was also recorded over all speeds, angles, and rumble strip patterns. Only the RMS pitch angular acceleration was used to assess the effect of the rumble strip configurations on pitch angular acceleration.

Table 23 presents the rankings of the test configurations based upon the pitch angular acceleration levels measured on mountain, road, and hybrid bicycles across all speed ranges. Table 24 presents the rankings from the tandem bicycle across all speed ranges. Similar to vertical acceleration, lower pitch angular accelerations make for a smoother, more comfortable ride and better control of the bicycle, while higher pitch angular accelerations cause more discomfort and increase the potential of losing control. Thus, the rumble strip configurations were ranked according to the levels of pitch angular acceleration generated. The rumble strip configuration that generated the lowest amount of pitch angular acceleration received the best ranking (#1), and the rumble strip configuration that generated the highest amount of pitch angular acceleration received the worst ranking (#6).

Table 23. Ranking of test configurations based on pitch angular acceleration (road, mountain, and hybrid bicycles).

	Rank	Test Pattern	Average RMS – Pitch Angular Acceleration rad/s^2
Best	1	6	13.288
	2	3	15.809
	3	5	18.994
	4	2	21.230
	5	4	21.711
Worst	6	1	30.593

Table 24. Ranking of test configurations based on pitch angular acceleration (tandem bicycle).

	Rank	Test Pattern	Average RMS – Pitch Angular Acceleration rad/s^2
Best	1	6	10.912
	2	3	13.171
	3	5	15.407
	4	2	16.404
	5	4	17.829
Worst	6	1	22.006

Although the actual values of the pitch angular accelerations are different for the analysis of the mountain, road, and hybrid bicycles and the analysis of the tandem bicycle, the test patterns received the same rankings. Test pattern 6 generated the least amount of pitch angular acceleration across all bicycle types, and test pattern 1 generated the greatest amount of pitch angular acceleration across all bicycle types.

7.1.2 Objective Measure of Control

To obtain an observable objective measure of lateral stability, the bicyclists were asked to ride along an 8" (203 mm) white line as they traversed the rumble strips. As the participants traversed the rumble strips at a 0° angle, a video camera was positioned from a perspective that showed both the bicyclists and the white lines. After data collection, the video tapes were played back, and any lateral deviation from the line was noted by recording the amount of time spent off the 8" (203 mm) white line. The amount of time to traverse the entire length of the 8" (203 mm) white line was also recorded. The percent of time spent off the line was calculated by dividing the amount of time deviating from the white line by the traverse time. Lower percentages of time spent off the line indicate better control while traversing the rumble strip configuration. Higher percentages of time spent deviating from the white line indicate greater loss of control. A baseline for controllability was also established by having the participants ride along an 8" (203 mm) white line that was painted on a smooth portion of the pavement.

Videos from 25 of the bicycle tests were used to obtain the rankings of the test configurations based on the objective control measure. Table 25 presents the rankings of the respective test patterns, with the average percent of time off the line combining data across all bicycle types and all speed ranges. On average, participants deviated about 8.14 percent of the time from the 8" (203 mm) white line painted on the smooth portion of the pavement. In comparison, all the new rumble strip configurations caused the participants to deviate from the line a higher percentage of the time. From the standpoint of percentage of time off the line, test patterns 3 and 6 caused the least amount of lateral deviations, while test pattern 1 caused the greatest amount of lateral deviation from the lines.

Table 25. Ranking of test configurations based on objective control (all bicycles).

	Rank	Test Pattern	Percentage of Time Off the Line	
			Average	Difference (Pattern – Base)
		Smooth	0.0814	
Best	1	3	0.1228	0.0414
	2	6	0.126	0.0446
	3	4	0.1644	0.0830
	4	5	0.1922	0.1108
	5	2	0.1956	0.1142
Worst	6	1	0.2535	0.1721

7.1.3 Subjective Measure of Comfort and Control

Subjective rider comfort and control were assessed following trials where the participants traversed the rumble strips at a 0° angle over an extended distance of approximately 45' (13.7 m). After each trial, participants stopped and filled out a questionnaire subjectively rating the comfort and control levels of the rumble strip pattern. Subjective comfort and control were not assessed when the participants traversed the rumble strip patterns at 10° and 45°. At these angles, the participants were on the rumble strip patterns for only a short duration of time, making it very difficult to subjectively rate the comfort and control levels.

To evaluate the perceived, or subjective, level of comfort and loss of control on the rumble strip patterns installed at the test track, a continuous scale with anchors was established. Participants were asked to rank the level of comfort or discomfort for five key body parts for each trial, immediately after the end of the trial. A subjective measure of comfort was obtained for each body section and overall for each rumble strip pattern at each speed level. Subjects were also asked to rate the trial on the relative difficulty or ease in controlling the bicycle when traversing the rumble strip.

The qualitative scale used in this portion of the research was based on studies conducted on subjective truck ride evaluation (O'Hagan 1969) and bicycle comfort (Ng, Cassar, and Gross 1995; Christiaans and Bremner 1998). Qualitative scales were selected over the use of numerical ranking (e.g., 10-point scale) to provide the participants with descriptive categories deemed appropriate for evaluating the manipulated variables, such as rumble-strip type and speed. Qualitative scales were also selected in an attempt to reduce the intersubject variability that results from response bias in numerical scale interpretation (i.e., individuals assign subjective value to points on the scale differently from one another).

The statistical analysis was based on the research of O'Hagan (1969) who used a similar scale to assess subjective truck ride evaluation. Each point on the scale was assigned a numerical value for the analysis. An equal interval scale was used ranging from zero for the lowest comfort or control level to twenty-five for the highest level of comfort and control. In other words, a low score corresponds to being very uncomfortable and causing loss of control. A high score corresponds to being comfortable and causing no control problems.

Comfort Level	Control Level
0 – Very Uncomfortable	0 - Uncontrollable
25 - Very Comfortable	25 – No Effect on Handling

As mentioned above, a total of 25 volunteer subjects participated in the subjective evaluation of the rumble strip patterns. Table 26 presents the average ranking (based on a 25-point scale) of the comfort level for the different body parts, the overall comfort level, and the overall control level across all test patterns, all bicycle types, and all speed ranges. The table indicates the body parts that are most affected while traversing rumble strips. Lower values indicate greater discomfort, while higher values indicate better comfort. Based on the subjective results, the ordered list below ranks the body parts most affected while traversing rumble strips:

- Wrists, fingers, and elbows (most uncomfortable)
- Seat area

- Shoulders and neck
- Back
- Knees, ankles, and feet (most comfortable)

Table 26. Overall average subjective ranking of comfort and control levels.

	Wrists, Fingers, and Elbows	Shoulders and Neck	Back	Seat Area	Knees, Ankles, and Feet	Overall Comfort	Overall Control
Average Value	11.26	12.90	13.47	12.02	13.57	11.64	11.30

To obtain an assessment of the relative effects of the different rumble strip configurations based on the subjective ratings of the participants, three measures were utilized: overall comfort level, overall control level, and comfort level of the wrists, fingers, and elbows. The comfort level of the wrists, fingers, and elbows was selected because these are the body parts most affected while traversing rumble strips. Once again, the "bicycle-friendly" rumble strip configuration should be design-based upon the worst case scenario.

Tables 27, 28, and 29 present the rankings of the test configurations based on the subjective wrist comfort level, overall comfort level, and overall control level, respectively. The average values combine the ratings across all bicycle types and all speeds. From the perceptions of the participants, test configurations 6, 3, and 5 in that order consistently ranked the best from the standpoint of comfort and control. PennDOT's current rumble strip configuration, test pattern 1, was consistently perceived as the worst test pattern from the standpoint of comfort and control.

Table 27. Ranking of test configurations based on subjective wrist comfort level (all bicycles).

	Rank	Test Pattern	Average Wrist Comfort Level*
Best	1	6	14.3
	2	3	13.7
	3	5	11.9
	4	4	10.5
	5	2	10.1
Worst	6	1	7.1

* Comfort scale: very uncomfortable (0) and very comfortable (25)

Table 28. Ranking of test configurations based on subjective overall comfort level (all bicycles).

	Rank	Test Pattern	Average Overall Comfort Level*
Best	1	6	14.8
	2	3	14.5
	3	5	12.1
	4	2	11.0
	5	4	10.0
Worst	6	1	7.3

* Comfort scale: very uncomfortable (0) and very comfortable (25)

Table 29. Ranking of test configurations based on subjective overall control level (all bicycles).

	Rank	Test Pattern	Average Overall Control Level*
Best	1	6	14.3
	2	3	13.4
	3	5	11.5
	4	2	10.8
	5	4	9.5
Worst	6	1	7.4

* Control scale: uncontrollable (0) and no effect on handling (25)

7.1.4 Overall Ranking of Test Patterns Based on Bicycle-Related Measures

To combine the results of the analyses for the objective comfort and control measures, the objective control measure, and the subjective comfort and control measures, a normalized value for each of the measures was established. In so doing, each measure listed below received the same weight in calculating the overall ranking of the test configurations based on the bicycle-related measures:

<u>Objective Comfort and Control Measures</u>

- Average RMS vertical acceleration (mountain, road, and hybrid bicycles)
- Average RMS vertical acceleration (tandem bicycle)
- Average RMS pitch angular acceleration (mountain, road, and hybrid bicycles)
- Average RMS pitch angular acceleration (tandem bicycle)

<u>Objective Control Measure</u>

- Average percentage of time off the line (all bicycles combined)

<u>Subjective Comfort and Control Measures</u>

- Average comfort level of wrists, fingers, and elbows (all bicycles combined)
- Average overall comfort level (all bicycles combined)
- Average overall control level (all bicycles combined)

For each measure, the normalized value was calculated as follows:

$$Normalized\ Value = \frac{Actual\ Value - Minimum\ Value}{Maximum\ Value - Minimum\ Value} \quad (1)$$

or

$$Normalized\ Value = 1 - \left[\frac{Actual\ Value - Minimum\ Value}{Maximum\ Value - Minimum\ Value}\right] \quad (2)$$

For those measures in which a low average value was better from the bicyclist's perspective, such as vertical acceleration, pitch angular acceleration, and percent of time spent off the line, equation 1 was used to calculated the normalized value. For those subjective measures for which a higher subjective rating indicated better comfort and controllability, equation 2 was used to calculate the normalized value. In this manner, the test pattern that received the best ranking for the respective measures obtained a normalized value of 0, and the test pattern that received the worst ranking for the respective measures obtained a normalized value of 1. The normalized value for the other test patterns indicated the relative difference between the maximum and minimum values. By summing the normalized values for the 8 bicycle-related measures and dividing by 8, the average normalized value for each test pattern was calculated. A lower average normalized value for the test pattern corresponds to better comfort and control for the bicyclists. A higher average normalized value for the test pattern indicates worse levels of comfort and increased potential for loss of control.

Table 30 presents the overall ranking of the test configurations based on the bicycle-related measures. From the bicyclist's perspective, test pattern 6 provides the highest level of comfort and controllability, followed by test pattern 3. Test pattern 2 was next, closely followed by test pattern 5. From the normalized value, it appears there is not much difference in the comfort and control levels between test patterns 2 and 5. Test pattern 4 and test pattern 1 (PennDOT's current configuration) received the worst ratings of comfort and controllability from the bicyclist's perspective.

Table 30. Overall ranking of test configurations based on bicycle-related measures.

	Rank	Test Pattern	Sum of Normalized Values	Average Normalized Value
Best	1	6	0.025	0.003
	2	3	0.919	0.115
	3	2	3.972	0.497
	4	5	4.015	0.502
	5	4	5.303	0.663
Worst	6	1	7.772	0.972

7.2 Analysis of Motor Vehicle Measures

Three objective measures were collected during the motor vehicle testing at PTI's test track:

- vertical acceleration of the body frame
- pitch angular acceleration of the body frame
- maximum sound level in the passenger compartment

However, based on the results of the base measurement tests and the preliminary testing at the test track, only the maximum sound level in the passenger compartment of the minivan was used to assess the relative effect of the six rumble strip patterns on the dynamics of the minivan.

Table 31 presents the results of the noise level testing. The maximum sound level in the passenger compartment was measured at speeds of 45 and 55 mph (72 and 88 km/h). Three runs were made at each speed. In addition to gathering sound levels while traversing the rumble strips, sound levels were measured while riding over the "smooth" pavement surface.

Table 31. Van: noise level testing.

Test Pattern	Speed mph (km/h)	Maximum Sound Level – dB(A)				
		Run 1	Run 2	Run 3	Average	Difference (Pattern – Smooth)
Smooth	45 (72)	68.9	68.5	67.8	68.4	
1	45 (72)	79.6	79.8	80.7	80.0	11.6
2	45 (72)	78.5	78.8	77.8	78.4	10.0
3	45 (72)	76.1	74.1	75.3	75.2	6.8
4	45 (72)	83.7	83.7	83.3	83.6	15.2
5	45 (72)	79.6	79.1	79.1	79.3	10.9
6	45 (72)	74	75.2	75	74.7	6.3
Smooth	55 (88)	66.9	64.5	64.1	65.2	
1	55 (88)	88.6	89.3	88.8	88.9	23.7
2	55 (88)	84.2	83	84	83.7	18.5
3	55 (88)	82.3	80.3	81.4	81.3	16.1
4	55 (88)	82	80.6	81	81.2	16.0
5	55 (88)	79.2	79	79	79.1	13.9
6	55 (88)	77.9	77.9	78.9	78.2	13.0

Looking at the sound levels generated while driving on the smooth pavement versus the sound levels generated by each of the rumble strip configurations, there is a greater amount of noise generated above the background noise at 55 mph (88 km/h) as compared to traveling at 45 mph (72 km/h). This may be a result of the high sound level measured on the smooth surface at 45 mph (72 km/h). Typically, the sound level in the passenger compartment increases with speed. However, the average maximum sound level in the passenger compartment was higher (68.4 dB(A)) at 45 mph (72 km/h), as compared to the average maximum sound level (65.2 dB(A)) at 55 mph (88 km/h).

Table 32 presents the rankings of the test configurations based upon the noise level testing for the motor vehicle. One set of rankings is provided based upon the low speed testing at 45 mph (72 km/h), and a second set of rankings is provided based upon the high speed testing at 55 mph (88 km/h). From the motor vehicle standpoint or the motorist's perspective, rumble strips that generate the highest amount of noise are most effective in alerting inattentive/drowsy motorists. Therefore, the rumble strip configuration that generated the highest average maximum sound level at 45 mph (72 km/h) received the best ranking, the rumble strip configuration that generated the next highest average maximum sound level received the second highest ranking, and so on. Likewise, the rumble strip configurations were ranked for the high speed tests at 55 mph (88 km/h).

Table 32. Ranking of test configurations based on noise level testing.

	Rank	Test Pattern	Speed Mph (km/h)	Avg. Max. Sound Level dB(A)	Difference (Pattern – Smooth)
Best	1	4	45 (72)	83.6	15.2
	2	1	45 (72)	80.0	11.6
	3	5	45 (72)	79.3	10.9
	4	2	45 (72)	78.4	10.0
	5	3	45 (72)	75.2	6.8
Worst	6	6	45 (72)	74.7	6.3
		Smooth	45 (72)	68.4	
Best	1	1	55 (88)	88.9	23.7
	2	2	55 (88)	83.7	18.5
	3	3	55 (88)	81.3	16.1
	4	4	55 (88)	81.2	16.0
	5	5	55 (88)	79.1	13.9
Worst	6	6	55 (88)	78.2	13.0
		Smooth	55 (88)	65.2	

Based on the noise level tests at 45 mph (72 km/h), test pattern 4 generated the greatest amount of noise (83.6 dB(A)) in the passenger compartment at this speed, so it received the #1 ranking. The sound level generated by test pattern 4 was approximately 15 dB(A) greater than the ambient sound generated while traveling on the smooth pavement. Test pattern 1, PennDOT's current rumble strip configuration, was ranked #2, generating the next highest sound level at 80.0 dB(A). Test patterns 3 and 6 generated the lowest amount of noise at 45 mph (72 km/h) and received the lowest rankings at this speed, generating only about 6-7 dB(A) above the ambient noise level.

Based on the noise level tests at 55 mph (88 km/h), PennDOT's current configuration, test pattern 1 received the #1 ranking, generating almost 24 dB(A) of noise above the ambient sound. Test pattern 2 generated the next highest noise level, almost 19 dB(A) above the ambient sound. Test patterns 5 and 6 generated the least amount of noise in the passenger compartment of the motor vehicle at 55 mph (88 km/h).

8. CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

The goal of this research was to develop several rumble strip configurations that would both alert inattentive/drowsy motorists and could be safely and comfortably traversed by bicyclists. The objective was to develop new rumble strip configurations that decrease the level of vibration experienced by bicyclists when traversing rumble strips, while at the same time provide an adequate amount of stimuli to alert inattentive/drowsy motorists.

From the bicyclist's perspective, test pattern 6 was the most "bicycle-friendly." The average normalized value of the bicycle-related measures for test pattern 6 was 0.0031, significantly lower than the next best test pattern (test pattern 3). However, from a motor vehicle standpoint, test pattern 6 generated the least amount of noise in the passenger compartment, in both the high speed testing conducted at 55 mph (88 km/h) and the low speed testing conducted at 45 mph (72 km/h). Because test pattern 6 was ranked the worst test pattern from the motor vehicle standpoint, test pattern 6 is not recommended for implementation on any type of facility.

From the bicyclist's perspective, test pattern 3 was ranked the second most "bicycle-friendly" configuration. It had an average normalized value for the bicycle-related measures of 0.1149. Considering test pattern 3 from the motor vehicle standpoint, it performed well during the high speed testing and ranked second overall at 55 mph (88 km/h) with an average maximum sound level of 81.3 dB(A) versus 88.9 dB(A) for the existing configuration. Therefore, test pattern 3 is recommended for implementation along non-freeway facilities with higher operating speeds.

During the low speed testing at 45 mph (72 km/h), however, test pattern 3 generated 74.7 dB(A) of noise, less than 7 dB(A) above the ambient noise. As a result, test pattern 3 ranked only fifth overall at this speed. Watts (1977) indicated that rumble strips producing 4 dB(A) increases or above can be readily detected by motorists who are awake, but there are no data indicating the sound level difference above the ambient noise necessary to alert a drowsy motorist. 7 dB(A) was not considered adequate enough, so test pattern 3 is not recommended for implementation on non-freeway facilities with lower operating speeds.

The third ranked test pattern from the bicyclist's perspective (test pattern 2) was considered for low speed facilities. A close examination of the average normalized values for test pattern 2 and test pattern 5 shows very little difference between the two. Essentially, test patterns 2 and 5, from the bicyclist's perspective, perform equivalently, but from the motor vehicle standpoint, at lower operating speeds, test pattern 5 generates slightly more sound in the passenger compartment as compared to test pattern 2. Thus, test pattern 5 appears to be a better compromise between the bicyclists and the motorists along non-freeway facilities with lower operating speeds than test pattern 2. Some additional analyses were performed to examine specific cases for these two configurations, before proceeding to final recommendations.

It was assumed that, from a bicyclist's perspective, riding a road bicycle at high speeds generated the greatest discomfort and control problems compared to riding other types of bicycles at lower speeds. Some of the data support this assumption, but no detailed statistical analysis was performed to verify it. With that, two analyses were performed to evaluate the bicycle-related measures under this assumed worst-case scenario. One analysis was performed with data from all of the bicyclists who rode the road bicycle, combining data from both intermediate and advanced bicyclists. A second analysis was performed with data from intermediate bicyclists only.

Tables 33 to 38 show the results of the bicycle-related measures for the road bicycle at high speed conditions, for all participants who rode the road bicycle. Note that the sample sizes are different for some of the measures because vibration data were not collected for all subjects. Tables 33 and 34 show the average RMS vertical acceleration and pitch angular acceleration, respectively, based on data from five subjects. Table 35 provides the objective control measure based on data from nine subjects, and tables 36, 37, and 38 show the subjective comfort and control ratings based upon data from eight subjects.

Table 33. RMS – vertical acceleration (road bicycle; high speed; combined intermediate and advanced bicyclists).

Test Pattern	Average RMS – Vertical Acceleration ft/s^2 (m/s^2)	Normalized Value
1	109.094 (33.252)	1.000
2	90.000 (27.432)	0.668
3	64.705 (19.722)	0.229
4	89.153 (27.174)	0.654
5	97.742 (29.792)	0.803
6	51.525 (15.705)	0.000

Table 34. RMS – pitch angular acceleration (road bicycle; high speed; combined intermediate and advanced bicyclists).

Test Pattern	Average RMS – Pitch Angular Acceleration rad/s^2	Normalized Value
1	34.590	1.000
2	27.150	0.575
3	20.706	0.207
4	31.614	0.830
5	25.562	0.485
6	17.072	0.000

Table 35. Objective control (road bicycle; high speed; combined intermediate and advanced bicyclists).

Test Pattern	Average Percentage of Time Off the Line	Normalized Value
1	0.404	1.000
2	0.209	0.080
3	0.306	0.538
4	0.192	0.000
5	0.265	0.344
6	0.196	0.019

Table 36. Subjective wrist comfort level (road bicycle; high speed; combined intermediate and advanced bicyclists).

Test Pattern	Average Wrist Comfort Level*	Normalized Value
1	4.4	1.000
2	7.4	0.535
3	9.8	0.165
4	7.5	0.523
5	7.7	0.481
6	10.8	0.000

* Comfort scale: very uncomfortable (0) and very comfortable (25)

Table 37. Subjective overall comfort level (road bicycle; high speed; combined intermediate and advanced bicyclists).

Test Pattern	Average Overall Comfort Level*	Normalized Value
1	3.4	1.000
2	7.1	0.513
3	10.4	0.079
4	7.0	0.526
5	7.4	0.474
6	11.0	0.000

* Comfort scale: very uncomfortable (0) and very comfortable (25)

Table 38. Subjective overall control level (road bicycle; high speed; combined intermediate and advanced bicyclists).

Test Pattern	Average Overall Control Level*	Normalized Value
1	4.5	1.000
2	8.3	0.457
3	10.8	0.100
4	5.4	0.871
5	6.6	0.700
6	11.5	0.000

* Control scale: uncontrollable (0) and no effect on handling (25)

Table 39 shows the overall ranking of the test patterns based upon the six bicycle-related measures for the road bicycle at high speed using data from both intermediate and advanced bicyclists. Once again, patterns six and three are the most "bicycle-friendly" for this assumed worst case scenario, and pattern 2 has a slightly lower average normalized value than test pattern 5. However, a pairwise comparison test between the average normalized values for test patterns 2 and 5 indicates there is no significant difference in the average normalized values (confidence coefficient = 0.95). Test patterns 2 and 5 are both more bicycle-friendly than test pattern 1 (PennDOT's current configuration).

Table 39. Overall ranking of test configurations based on bicycle-related measures for assumed worst case scenario (road bicycle; high speed; combined intermediate and advanced bicyclists).

	Rank	Test Pattern	Sum of Normalized Values	Average Normalized Value
Best	1	6	0.019	0.003
	2	3	1.318	0.220
	3	2	2.829	0.472
	4	5	3.286	0.548
	5	4	3.404	0.567
Worst	6	1	6.000	1.000

Tables 40 to 45 show the results of the bicycle-related measures for the road bicycle at high speed conditions, based upon data from intermediate bicyclists. Tables 40 and 41 show the average RMS vertical acceleration and pitch angular acceleration, respectively, based on data from two intermediate bicyclists. Table 42 provides the objective control measure based on data from five intermediate bicyclists, and tables 43, 44, and 45 show the subjective comfort and control ratings based upon data from five intermediate bicyclists.

Table 40. RMS – vertical acceleration (road bicycle; high speed; intermediate bicyclists).

Test Pattern	Average RMS – Vertical Acceleration ft/s^2 (m/s^2)	Normalized Value
1	103.346 (31.500)	1.000
2	86.548 (26.380)	0.705
3	70.554 (21.505)	0.423
4	81.315 (24.785)	0.613
5	90.633 (27.625)	0.776
6	46.489 (14.170)	0.000

Table 41. RMS – pitch angular acceleration (road bicycle; high speed; intermediate bicyclists).

Test Pattern	Average RMS – Pitch Angular Acceleration Rad/s^2	Normalized Value
1	36.950	1.000
2	24.445	0.358
3	17.485	0.000
4	31.560	0.723
5	26.810	0.479
6	17.585	0.005

Table 42. Objective control (road bicycle; high speed; intermediate bicyclists).

Test Pattern	Average Percentage of Time Off the Line	Normalized Value
1	0.462	1.000
2	0.247	0.136
3	0.336	0.496
4	0.213	0.000
5	0.429	0.867
6	0.270	0.228

Table 43. Subjective wrist comfort level (road bicycle; high speed; intermediate bicyclists).

Test Pattern	Average Wrist Comfort Level*	Normalized Value
1	4.2	1.000
2	6.7	0.402
3	7.2	0.270
4	6.1	0.547
5	6.3	0.487
6	8.3	0.000

* Comfort scale: very uncomfortable (0) and very comfortable (25)

Table 44. Subjective overall comfort level (road bicycle; high speed; intermediate bicyclists).

Test Pattern	Average Overall Comfort Level*	Normalized Value
1	3.8	1.000
2	6.2	0.473
3	7.2	0.258
4	5.7	0.591
5	6.0	0.511
6	8.3	0.000

* Comfort scale: very uncomfortable (0) and very comfortable (25)

Table 45. Subjective overall control level (road bicycle; high speed; intermediate bicyclists).

Test Pattern	Average Overall Control Level*	Normalized Value
1	4.5	0.902
2	7.0	0.392
3	7.9	0.204
4	4.0	1.000
5	4.8	0.833
6	8.8	0.000

* Control scale: uncontrollable (0) and no effect on handling (25)

Table 46 shows the overall ranking of the test patterns based upon the six bicycle-related measures for the road bicycle at high speed using data from intermediate bicyclists only. Patterns 6 and 3 are the most "bicycle-friendly," followed by pattern 2. Under this scenario however, test pattern 4 is more "bicycle-friendly" than test pattern 5, which is ranked fifth overall. A pairwise comparison test between the average normalized values for test patterns 2, 4, and 5 indicates there is no significant difference in the average normalized values (confidence coefficient = 0.95) between all three patterns. Under this scenario, test pattern 1 once again is the worst configuration from the bicyclist's perspective.

Table 46. Overall ranking of test configurations based on bicycle-related measures for assumed worst case scenario (road bicycle; high speed; intermediate bicyclists).

	Rank	Test Pattern	Sum of Normalized Values	Average Normalized Value
Best	1	6	0.233	0.039
	2	3	1.651	0.275
	3	2	2.465	0.411
	4	4	3.474	0.579
	5	5	3.954	0.659
Worst	6	1	5.902	0.984

The analysis of assumed worst case scenarios shows that both test patterns 2 and 5 are more "bicycle-friendly" than the current rumble strip configuration, test pattern 1, under the worst case scenarios. Test pattern 2 was ranked third overall from the bicyclist's perspective under the assumed worst case scenario (road bicycle; high speed; intermediate bicyclists), while test pattern 5 was ranked fifth overall from the bicyclist's perspective. Given the very small sample size of intermediate bicyclists tested using the road bicycle, test pattern 5 is still more "bicycle-friendly" under the assumed worst case scenarios than the existing configuration and generates slightly more sound under lower operating speeds to alert inattentive/drowsy motorists than test pattern 2. Therefore, it is recommended for implementation along non-freeway facilities with lower operating speeds. It should also be noted that the analysis of assumed worst case scenarios shows test pattern 3 is still ranked as the second most "bicycle-friendly" configuration.

In summary, based on the results of the motor vehicle testing and the bicycle testing, two new "bicycle-friendly" rumble patterns are recommended for implementation along non-freeway facilities. Test pattern 3 is recommended along non-freeway facilities with higher operating speeds, near 55 mph (88 km/h). Test pattern 5 is recommended along non-freeway facilities with lower operating speeds, near 45 mph (72 km/h). Table 47 summarizes the dimensions and applications for these two recommended configurations.

Table 47. Recommended "bicycle-friendly" rumble strip configurations.

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

8.2 Recommendations

To solidify and improve the research presented in this report, additional research is recommended in the following areas. An evaluation of the newly recommended "bicycle-friendly" rumble strip configurations in the field is required to ensure that the fully controlled environment (PTI's test track) results are consistent with the field implementation. Before these rumble strip configurations are installed, they should be installed in several selected locations and further evaluations should be performed. Crash data should be analyzed, and bicyclists should be polled for their evaluation and opinions of the new rumble strip designs.

Output from the simulation model developed during this research indicated that 4" (102 mm) wide grooves would provide the smoothest ride for bicyclists. However, the cutting head on milling machines is a standard diameter, limiting the ability to vary the width of cut and depth of cut concurrently. Until a cutting head is developed that can cut a 4" (102 mm) wide groove, the effects on bicyclists and motor vehicles will never be fully known. By design a cutting head with a variable diameter, different rumble strip designs could be developed to better accommodate both bicyclists and motorists.

A recurring question asked by the reviewing task force was, "What level of sound needs to be generated by the rumble strip to alert a drowsy or sleeping motorist?" Watts (1977) did some research related to this question but never fully answered the question. Without knowing the answer to this question, a vital piece of information is missing in order to develop effective rumble strip configurations.

Finally, future research efforts should also focus on the lateral width of the cut. PennDOT's current standard specifies a 16" to 17" (406 to 432 mm) lateral width. Many state DOTs allow for variable lateral widths in their rumble strip designs. Narrower rumble strips provide additional space on the shoulders for bicyclists to ride. However, no research has been conducted to measure the differences in motor vehicle dynamics while traversing rumble strips of varying lateral widths.

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APPENDIX A

SUBJECTIVE RIDER COMFORT AND CONTROL QUESTIONNAIRE

Trial Characteristics		RIDER COMFORT AND CONTROL RATING	
Rumble Strip Type: 1 Bicycle Speed: 5-15 km/h	**Body Part**	Very Uncomfortable	Very Comfortable
	Wrist/Fingers/Elbows		
	Shoulder/Neck		
	Back		
	Seat Area		
	Knee/Ankle/Foot		
	Overall		
	CONTROL LEVEL	Uncontrollable	No Effect on Handling
Rumble Strip Type: 1 Bicycle Speed: 15-25 km/h	**Body Part**	Very Uncomfortable	Very Comfortable
	Wrist/Fingers/Elbows		
	Shoulder/Neck		
	Back		
	Seat Area		
	Knee/Ankle/Foot		
	Overall		
	CONTROL LEVEL	Uncontrollable	No Effect on Handling
Rumble Strip Type: 1 Bicycle Speed: 26+ km/h	**Body Part**	Very Uncomfortable	Very Comfortable
	Wrist/Fingers/Elbows		
	Shoulder/Neck		
	Back		
	Seat Area		
	Knee/Ankle/Foot		
	Overall		
	CONTROL LEVEL	Uncontrollable	No Effect on Handling

Trial Characteristics		RIDER COMFORT AND CONTROL RATING	
Rumble Strip Type: 2 Bicycle Speed: 5-15 km/h	**Body Part**	Very Uncomfortable	Very Comfortable
	Wrist/Fingers/Elbows		
	Shoulder/Neck		
	Back		
	Seat Area		
	Knee/Ankle/Foot		
	Overall		
	CONTROL LEVEL	Uncontrollable	No Effect on Handling
Rumble Strip Type: 2 Bicycle Speed: 15-25 km/h	**Body Part**	Very Uncomfortable	Very Comfortable
	Wrist/Fingers/Elbows		
	Shoulder/Neck		
	Back		
	Seat Area		
	Knee/Ankle/Foot		
	Overall		
	CONTROL LEVEL	Uncontrollable	No Effect on Handling
Rumble Strip Type: 2 Bicycle Speed: 26+ km/h	**Body Part**	Very Uncomfortable	Very Comfortable
	Wrist/Fingers/Elbows		
	Shoulder/Neck		
	Back		
	Seat Area		
	Knee/Ankle/Foot		
	Overall		
	CONTROL LEVEL	Uncontrollable	No Effect on Handling

Trial Characteristics		RIDER COMFORT AND CONTROL RATING	
Rumble Strip Type: 3 Bicycle Speed: 5-15 km/h	**Body Part**	Very Uncomfortable	Very Comfortable
	Wrist/Fingers/Elbows		
	Shoulder/Neck		
	Back		
	Seat Area		
	Knee/Ankle/Foot		
	Overall		
	CONTROL LEVEL	Uncontrollable	No Effect on Handling
Rumble Strip Type: 3 Bicycle Speed: 15-25 km/h	**Body Part**	Very Uncomfortable	Very Comfortable
	Wrist/Fingers/Elbows		
	Shoulder/Neck		
	Back		
	Seat Area		
	Knee/Ankle/Foot		
	Overall		
	CONTROL LEVEL	Uncontrollable	No Effect on Handling
Rumble Strip Type: 3 Bicycle Speed: 26+ km/h	**Body Part**	Very Uncomfortable	Very Comfortable
	Wrist/Fingers/Elbows		
	Shoulder/Neck		
	Back		
	Seat Area		
	Knee/Ankle/Foot		
	Overall		
	CONTROL LEVEL	Uncontrollable	No Effect on Handling

Trial Characteristics		RIDER COMFORT AND CONTROL RATING	
Rumble Strip Type: 4 Bicycle Speed: 5-15 km/h	**Body Part**	Very Uncomfortable	Very Comfortable
	Wrist/Fingers/Elbows		
	Shoulder/Neck		
	Back		
	Seat Area		
	Knee/Ankle/Foot		
	Overall		
	CONTROL LEVEL	Uncontrollable	No Effect on Handling
Rumble Strip Type: 4 Bicycle Speed: 15-25 km/h	**Body Part**	Very Uncomfortable	Very Comfortable
	Wrist/Fingers/Elbows		
	Shoulder/Neck		
	Back		
	Seat Area		
	Knee/Ankle/Foot		
	Overall		
	CONTROL LEVEL	Uncontrollable	No Effect on Handling
Rumble Strip Type: 4 Bicycle Speed: 26+ km/h	**Body Part**	Very Uncomfortable	Very Comfortable
	Wrist/Fingers/Elbows		
	Shoulder/Neck		
	Back		
	Seat Area		
	Knee/Ankle/Foot		
	Overall		
	CONTROL LEVEL	Uncontrollable	No Effect on Handling

Trial Characteristics		RIDER COMFORT AND CONTROL RATING
Rumble Strip Type: 5 Bicycle Speed: 5-15 km/h	**Body Part**	Very Uncomfortable ... Very Comfortable
	Wrist/Fingers/Elbows	+------+------+
	Shoulder/Neck	+------+------+
	Back	+------+------+
	Seat Area	+------+------+
	Knee/Ankle/Foot	+------+------+
	Overall	+------+------+
	CONTROL LEVEL	Uncontrollable ... No Effect on Handling +------+------+
Rumble Strip Type: 5 Bicycle Speed: 15-25 km/h	**Body Part**	Very Uncomfortable ... Very Comfortable
	Wrist/Fingers/Elbows	+------+------+
	Shoulder/Neck	+------+------+
	Back	+------+------+
	Seat Area	+------+------+
	Knee/Ankle/Foot	+------+------+
	Overall	+------+------+
	CONTROL LEVEL	Uncontrollable ... No Effect on Handling +------+------+
Rumble Strip Type: 5 Bicycle Speed: 26+ km/h	**Body Part**	Very Uncomfortable ... Very Comfortable
	Wrist/Fingers/Elbows	+------+------+
	Shoulder/Neck	+------+------+
	Back	+------+------+
	Seat Area	+------+------+
	Knee/Ankle/Foot	+------+------+
	Overall	+------+------+
	CONTROL LEVEL	Uncontrollable ... No Effect on Handling +------+------+

Trial Characteristics		RIDER COMFORT AND CONTROL RATING	
Rumble Strip Type: 6 Bicycle Speed: 5-15 km/h	**Body Part**	Very Uncomfortable	Very Comfortable
	Wrist/Fingers/Elbows		
	Shoulder/Neck		
	Back		
	Seat Area		
	Knee/Ankle/Foot		
	Overall		
	CONTROL LEVEL	Uncontrollable	No Effect on Handling
Rumble Strip Type: 6 Bicycle Speed: 15-25 km/h	**Body Part**	Very Uncomfortable	Very Comfortable
	Wrist/Fingers/Elbows		
	Shoulder/Neck		
	Back		
	Seat Area		
	Knee/Ankle/Foot		
	Overall		
	CONTROL LEVEL	Uncontrollable	No Effect on Handling
Rumble Strip Type: 6 Bicycle Speed: 26+ km/h	**Body Part**	Very Uncomfortable	Very Comfortable
	Wrist/Fingers/Elbows		
	Shoulder/Neck		
	Back		
	Seat Area		
	Knee/Ankle/Foot		
	Overall		
	CONTROL LEVEL	Uncontrollable	No Effect on Handling

APPENDIX B

INFORMED CONSENT FORM

INFORMED CONSENT FORM FOR CLINICAL RESEARCH STUDY
The Pennsylvania State University

Title of Project: Bicycle-Friendly Shoulder Rumble Strips

Principal Investigator(s): Dr. Lily Elefteriadou. Dr. Moustafa El-Gindy

Other Investigators: Darren Torbic. Allen Homan. Robin Tallon

This is to certify that I, ____________________, have been given the following information with respect to my participation as a volunteer in a program of investigation under the supervision of Drs. Elefteriado and El-Gindy.

1. **Purpose of the study:**

This project will attempt to develop several rumble strip configurations that will both alert inattentive/drowsy drivers and be safely and comfortably traversed by bicyclists. To develop effective and safe rumble strips for Pennsylvania highways, the researchers propose to identify, develop, install and assess selected rumble strips designs at the Pennsylvania Transportation Institute (PTI) test track.

2. **Procedures to be followed:**

Volunteers will be contacted by telephone to schedule a test time convenient to them and corresponding with available test track time. To minimize the potential for injury, each subject will be required to wear a bicycle helmet, elbow pads, and knee pads, during the bicycle testing. During all testing, a first aid kit and a cellular telephone will be onsite in the event emergency services are required. At least one of the research staff will be trained in first aid procedures and will be present during testing. In the event of an injury, standard first aid protocol will be followed to assess the extent of the injury and provide initial treatment. Medical assistance (911) will be called immediately for a serious or life-threatening emergency. During each subject's scheduled time, the following exercises will be completed. A Reviewing Task Force consisting of bicyclists, human factors researchers, and automotive researchers will provide guidance throughout various stages of the project.

One of the research team members will drive a vehicle at highway speed over the rumble strips, parallel to the highway and perpendicular to the direction of the rumble strips. The vehicle will be instrumented with a Crossbow DMU to measure accelerations (vibrations), yaw, pitch, and roll and a B&K sound level meter to measure the noise level inside the vehicle while traversing the normal travel lane and the rumble strips. The instrumentation does not interfere with normal operation of the vehicle.

Upon completion of the test using the vehicle, subjects will be asked to complete a matrix of tests navigating a bicycle over the rumble strips. The test matrix for each subject will include four bicycle types, five rumble strip designs, three test speeds (5-15, 16-25 and 26+ km/h), and three traverse angles. The traverse angles will include 0°, which corresponds to the parallel to the highway and perpendicular to the direction of the rumble strip, as well as 10°, and 45°. The bicycle will be instrumented with a Crossbow DMU to measure accelerations (vibrations), yaw, pitch, and roll. The equipment, mounted on the bicycle frame and a rack, does not interfere with normal operation of the bicycle.

Dynamic data will be collected using a PC-based data acquisition system. The data from the sensors mounted on the bicycle will be transmitted through a 25-foot-long cable to a PC contained in a vehicle. The vehicle will travel parallel to the bicycle so that the 25-foot distance is maintained. Data files will be given names that reflect the conditions of the test run, and not the identity of the subject.

To evaluate the perceived, or subjective, loss of control on the rumble strips to be tested, a continuous scale with anchors was established. Subjects will be asked to rate the trial on the relative difficulty or ease in controlling the bicycle when traversing the rumble strip. Subjective bicycle control will be assessed following trials where the subjects traversed the rumble strips at a 90-degree angle over an extended distance. A subjective measure of bicycle control will be obtained for each rumble strip type, each speed, and each bicycle type.

In addition to measuring bicycle control, rider comfort will be assessed, again using a continuous qualitative scale with end-point anchors. Subjective comfort will be assessed following trials where the subjects traversed the rumble strips at a 90-degree angle over an extended distance. Subjects will be asked to rank the level of comfort or discomfort for two key body parts for each trial. The experimenter will instruct the subject to concentrate on the target body part prior to that test trial and ratings will occur immediately after the trial's end. A subjective measure of comfort will be obtained for each body section and overall for each rumble strip type, each speed, and each bicycle type.

While it is important to know how bicyclists perceive their ability to traverse rumble strips safely, it is equally, if not more, important to obtain objective, verifiable measures of their observable performance. Therefore, in addition to the subjective rating of loss of control, the present research will include an objective assessment of bicyclists' ability to maintain lateral stability on the rumble strips tested. To obtain this objective measure of performance, two four inch wide parallel lines spaced four inches apart will be painted along each rumble strip type and the subjects will be asked to keep the bicycle between the lines as they traverse that rumble strip. Each trial will be videotaped from a perspective that will show both the bicyclist and the lines. Prior to testing on the rumble strips, the subject will be asked to ride the bicycle between a pair of lines painted on a non-rumble strip section of roadway to provide a baseline for evaluating the effects of the rumble strips. After data collection, the video tapes will be played back and any lateral deviation will be noted, compared to the baseline for that subject and the difference used as the dependant measure of performance for that trial. The fewer the deviations onto the painted lines in relation to the baseline, the higher the performance, the more frequent the deviations, the greater the loss of control. Anonymity of the subjects will not be possible because of this video recording; however, data reported will not contain any confidential information.

The test results (quantitative and qualitative assessments) obtained will be processed, analyzed and submitted to PennDOT and the Reviewing Task Force. It is impossible to maintain complete confidentiality of the subjects due to the necessity of video recording each test run. However, only members of the research team will be able to identify the data files that correspond to the subject's videotape.

The majority of the testing will be performed at the Pennsylvania Transportation Institute's test track. However, initial base measurements were obtained on Pennsylvania Route 422 in Indiana County, Pennsylvania. The sponsor of the project, Pennsylvania Department of Transportation (PennDOT), provided the necessary traffic control during the on-road testing.

3. **Discomforts and risks:**

While the subject is traversing the rumble strips on the bicycle, there is the possibility of discomfort or pain in the fingers, hands, wrists, knees, ankles, feet, and/or posterior. As is true during any bicycling activity, there is also the risk of loss of control of the bicycle resulting in the person falling from the bicycle. Injuries resulting from such an occurrence could range in severity from a scratch or cut to a head injury. Because the rumble strip design criteria includes being safe and comfortable for bicyclists to traverse, it is anticipated that there is only a small additional risk to the subjects during testing compared to a typical bicycle ride.

The risk associated with the subject traversing the rumble strips in the automobile is that of the subject loosing control of the vehicle. The likelihood of this is extremely small considering rumble strips are regularly used on public highways to alert drivers of oncoming dangers.

4. a. **Benefits to me:**
   b. **Potential benefits to society:**

The benefit of this project will be the development of several rumble strip configurations that will both alert inattentive/drowsy drivers and be safely and comfortably traversed by bicyclists.

5. **Alternative procedures which could be utilized:**

The methodology proposed for this research has been thoroughly considered. The only identifiable alternative to reduce risk to human subjects would be to replace "real world" testing with computer modeling and simulation. The investigation team is currently developing a computer simulation of the rumble strip scenario for predicting the response of the bicycle to the rumble strips. This simulation will be used to design rumble strips that are less likely to result in discomfort or injury to bicycle riders (i.e.. subjects). However. levels of human comfort during the expected bicycle response must be obtained through subject feedback since individual's responses to the same experience will be different.

6. Time duration of the procedures and study:

The average amount of time required for participation is 2 hours. During this time. the subject may be asked to complete as many as 180 test runs and questionnaires. The first testing date is scheduled for June 3. 1999. The sponsor has requested that all testing be completed prior to November 15. 1999.

7. Statement of confidentiality:

Video recordings will be made of each test run. It is impossible to maintain complete confidentiality of the subjects because of this video recording; however. data reported will not contain any confidential information. The test results (quantitative and qualitative assessments) obtained will be processed. analyzed and submitted to PennDOT and the Reviewing Task Force. Only members of the research team will be able to identify the data files that correspond to the subject's videotape.

Your participation in this research is confidential. Only the investigator. and his/her assistants will have access to your identity and to information that can be associated with your identity. In the event of publication of this research. no personally identifying information will be disclosed.

8. Right to ask questions:

I have been given an opportunity to ask any questions I may have, and all such questions or inquiries have been answered to my satisfaction.

9. Compensation:

I understand that medical care is available in the event of injury resulting from research but that neither financial compensation nor free medical treatment is provided. I also understand that I am not waiving any rights that I may have against the University for injury resulting from negligence of the University or investigators.

10. Voluntary participation:

I understand that my participation in this study is voluntary, and that I may withdraw from this study at any time by notifying the investigator. My withdrawal from this study or my refusal to participate will in no way affect my care or access to medical services.

This is to certify that I consent to and give permission for my participation as a volunteer in this program of investigation. I understand that I will receive a signed copy of this consent form. I have read this form. and understand the content of this consent form.

Volunteer or Parent/Legal Guardian — Date

I. the undersigned. have defined and explained the studies involved to the above volunteer.

Investigator (Moustafa El-Gindy) — Date
Telephone: 814-863-7930
E-mail: mxe15@psu.edu

APPENDIX C

STATISTICAL ANALYSIS RESULTS

Table C-1. ANOVA – van: noise level testing at 72 km/h (45 mph).

```
Analysis of Variance for Maximum Noise Level Generated (dBA) at 72 km/h (45 mph)
Source      DF        SS        MS        F        P
Pattern      6   425.238    70.873   200.04    0.000
Error       14     4.960     0.354
Total       20   430.198
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  -----+---------+---------+---------+-
1           3    80.033     0.586                        (*-)
2           3    78.367     0.513                    (-*)
3           3    75.167     1.007              (*-)
4           3    83.567     0.231                               (*-)
5           3    79.267     0.289                     (-*)
6           3    74.733     0.643             (*-)
Smooth      3    68.400     0.557  (-*)
                                   -----+---------+---------+---------+-
Pooled StDev =    0.595               70.0      75.0      80.0      85.0

Tukey's pairwise comparisons
    Family error rate = 0.0500
Individual error rate = 0.00419
Critical value = 4.83

Intervals for (column level mean) - (row level mean)
                 1           2           3           4           5           6
      2      0.007
             3.326
      3      3.207       1.540
             6.526       4.860
      4     -5.193      -6.860     -10.060
            -1.874      -3.540      -6.740
      5     -0.893      -2.560      -5.760       2.640
             2.426       0.760      -2.440       5.960
      6      3.640       1.974      -1.226       7.174       2.874
             6.960       5.293       2.093      10.493       6.193
   Smooth    9.974       8.307       5.107      13.507       9.207       4.674
            13.293      11.626       8.426      16.826      12.526       7.993
```

Table C-2. ANOVA – van: noise level testing at 88 km/h (55 mph).

```
Analysis of Variance for Maximum Noise Level Generated (dBA) at 88 km/h (55 mph)
Source      DF        SS        MS         F        P
Pattern      6   958.756   159.793    237.65    0.000
Error       14     9.413     0.672
Total       20   968.170
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level        N      Mean     StDev --------+---------+---------+-------
1            3    88.900     0.361                                  (*)
2            3    83.733     0.643                           (-*)
3            3    81.333     1.002                        (*-)
4            3    81.200     0.721                        (*)
5            3    79.067     0.115                     (*)
6            3    78.233     0.577                   (-*)
Smooth       3    65.167     1.514  (*-)
                                   --------+---------+---------+-------
Pooled StDev =     0.820                70.0      77.0      84.0

Tukey's pairwise comparisons
    Family error rate = 0.0500
Individual error rate = 0.00419
Critical value = 4.83

Intervals for (column level mean) - (row level mean)
                    1           2           3           4           5           6
       2        2.880
                7.453
       3        5.280       0.113
                9.853       4.687
       4        5.413       0.247      -2.153
                9.987       4.820       2.420
       5        7.547       2.380      -0.020      -0.153
               12.120       6.953       4.553       4.420
       6        8.380       3.213       0.813       0.680      -1.453
               12.953       7.787       5.387       5.253       3.120
  Smooth       21.447      16.280      13.880      13.747      11.613      10.780
               26.020      20.853      18.453      18.320      16.187      15.353
```

Table C-3. GLM: maximum vertical acceleration (mountain, road, and hybrid bicycles).

General Linear Model

Factor	Levels	Values					
Pattern	6	1	2	3	4	5	6
Wt-Group	5	1	2	3	4	6	
Bike	3	Road	Hybrid	Mountain			
Speed	3	High	Inter	Low			
Angle	3	0	10	45			

Analysis of Variance for Maximum Vertical Acceleration (m/s²) (rad/s²)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Pattern	5	32779	32779	6556	77.39	0.000
Wt-Group	4	16955	4487	1122	13.24	0.000
Bike	2	34543	34543	17272	203.89	0.000
Speed	2	91816	91816	45908	541.95	0.000
Angle	2	7697	7697	3849	45.43	0.000
Error	848	71833	71833	85		
Total	863	255623				

Means for Maximum Vertical Acceleration (m/s²)

Pattern	Mean	StDev	Wt-Group	Mean	StDev
1	48.92	0.8015	1	35.45	0.9210
2	40.33	0.8015	2	39.70	0.6385
3	33.76	0.8015	3	42.80	0.5113
4	46.56	0.8015	4	40.74	0.7817
5	39.36	0.8015	6	42.00	1.3354
6	31.90	0.8015			
Bike			Speed		
Road	49.62	0.6811	High	49.91	0.5901
Hybrid	37.82	0.6639	Inter	44.62	0.5901
Mountain	32.98	0.5196	Low	25.88	0.5901
Angle					
0	43.87	0.5901			
10	39.99	0.5901			
45	36.56	0.5901			

Table C-4. GLM: RMS vertical acceleration (mountain, road, and hybrid bicycles).

General Linear Model

Factor	Levels	Values					
Pattern	6	1	2	3	4	5	6
Wt-Group	5	1	2	3	4	6	
Bike	3	Road	Hybrid	Mountain			
Speed	3	High	Inter	Low			

Analysis of Variance for RMS Vertical Acceleration (m/s^2)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Pattern	5	4786.66	4786.66	957.33	39.06	0.000
Wt-Group	4	636.13	134.36	33.59	1.37	0.244
Bike	2	1833.36	1833.36	916.68	37.40	0.000
Speed	2	4225.87	4225.87	2112.94	86.21	0.000
Error	274	6715.55	6715.55	24.51		
Total	287	18197.57				

Means for RMS Vertical Acceleration (m/s^2)

Pattern	Mean	StDev
1	22.01	0.7467
2	17.05	0.7467
3	13.27	0.7467
4	22.04	0.7467
5	19.42	0.7467
6	11.41	0.7467

Wt-Group	Mean	StDev
1	16.11	0.8580
2	17.34	0.5949
3	18.22	0.4764
4	17.54	0.7282
6	18.45	1.2441

Bike	Mean	StDev
Road	21.22	0.6345
Hybrid	16.84	0.6186
Mountain	14.54	0.4841

Speed	Mean	StDev
High	20.60	0.5498
Inter	19.86	0.5498
Low	12.13	0.5498

Table C-5. ANOVA: maximum vertical acceleration (mountain, road, and hybrid bicycles).

```
Analysis of Variance for Maximum Vertical Acceleration (m/s²)
Source     DF        SS         MS        F        P
Pattern     5     32779       6556    25.24    0.000
Error     858    222845        260
Total     863    255623
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean      StDev  ---------+---------+---------+-------
1         144     49.01      19.12                           (---*---)
2         144     40.41      16.40               (---*--)
3         144     33.85      14.96      (--*---)
4         144     46.65      16.33                         (---*--)
5         144     39.44      16.22              (--*---)
6         144     31.98      13.03   (---*--)
                                    ---------+---------+---------+-------
Pooled StDev =    16.12                  35.0      42.0      49.0
Tukey's pairwise comparisons
    Family error rate = 0.0500
Individual error rate = 0.00448

Critical value = 4.03
Intervals for (column level mean) - (row level mean)

                  1           2           3           4           5
       2       3.19
              14.01
       3       9.75        1.15
              20.58       11.98
       4      -3.05      -11.65      -18.21
               7.78       -0.82       -7.39
       5       4.16       -4.44      -11.01        1.79
              14.98        6.38       -0.18       12.62
       6      11.61        3.01       -3.55        9.25        2.04
              22.44       13.84        7.27       20.07       12.87
```

Table C-6. ANOVA: RMS vertical acceleration (mountain, road, and hybrid bicycles).

```
Analysis of Variance for RMS Vertical Acceleration(m/s²)
Source     DF        SS         MS        F        P
Pattern     5    4786.7      957.3    20.13    0.000
Error     282   13410.9       47.6
Total     287   18197.6
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean      StDev  -------+---------+---------+---------
1          48    21.909      8.725                              (----*----)
2          48    16.951      6.729                 (----*----)
3          48    13.176      5.261      (----*----)
4          48    21.942      7.495                              (----*----)
5          48    19.323      7.893                        (----*----)
6          48    11.315      4.214  (----*----)
                                    -------+---------+---------+---------
Pooled StDev =    6.896                12.0      16.0      20.0
Tukey's pairwise comparisons
    Family error rate = 0.0500
Individual error rate = 0.00470
Critical value = 4.03

Intervals for (column level mean) - (row level mean)

                   1           2           3           4           5
       2       0.947
               8.969
       3       4.722      -0.236
              12.745       7.787
       4      -4.044      -9.002     -12.778
               3.978      -0.979      -4.755
       5      -1.425      -6.383     -10.159      -1.392
               6.597       1.640      -2.136       6.630
       6       6.582       1.624      -2.151       6.615       3.996
              14.605       9.647       5.872      14.638      12.019
```

Table C-7. GLM: maximum vertical acceleration (tandem).

General Linear Model

Factor	Levels	Values					
Pattern	6	1	2	3	4	5	6
Weight	5	332	333	341	345	367	
Speed	3	Low	Inter	High			
Angle	2	0	10				

Analysis of Variance for Maximum Vertical Acceleration (m/s^2)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Pattern	5	9200.6	8923.4	1784.7	32.40	0.000
Weight	4	2243.1	2180.5	545.1	9.90	0.000
Speed	2	32240.4	32273.6	16136.8	292.99	0.000
Angle	1	220.4	220.4	220.4	4.00	0.047
Error	166	9142.7	9142.7	55.1		
Total	178	53047.3				

Means for Maximum Vertical Acceleration (m/s^2)

Pattern	Mean	StDev	Weight	Mean	StDev
1	39.90	1.3550	332	33.71	1.2553
2	34.07	1.3550	333	36.12	1.2369
3	27.03	1.3550	341	41.93	1.2369
4	44.98	1.3550	345	32.53	1.2369
5	40.67	1.3550	367	32.87	1.2369
6	25.97	1.3791			

Speed			Angle		
Low	17.65	0.9581	0	36.54	0.7870
Inter	38.54	0.9581	10	34.32	0.7823
High	50.12	0.9667			

Table C-8. GLM: RMS vertical acceleration (tandem).

General Linear Model

Factor	Levels	Values					
Pattern	6	1	2	3	4	5	6
Weight	5	332	333	341	345	367	
Speed	3	High	Inter	Low			

Analysis of Variance for RMS Vertical Acceleration (m/s²)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Pattern	5	1324.52	1268.42	253.68	21.02	0.000
Weight	4	324.01	312.54	78.14	6.47	0.000
Speed	2	2417.96	2417.96	1208.98	100.19	0.000
Error	77	929.19	929.19	12.07		
Total	88	4995.68				

Means for RMS Vertical Acceleration (m/s²)

Pattern	Mean	StDev	Weight	Mean	StDev
1	16.804	0.8969	332	13.577	0.8446
2	12.451	0.8969	333	14.716	0.8188
3	10.364	0.8969	341	17.737	0.8188
4	19.082	0.8969	345	13.277	0.8188
5	17.965	0.8969	367	12.339	0.8188
6	9.309	0.9308			

Speed		
High	20.266	0.6463
Inter	15.172	0.6342
Low	7.549	0.6342

Table C-9. ANOVA: maximum vertical acceleration (tandem).

```
Analysis of Variance for Maximum Vertical Acceleration (m/s^2)
Source     DF         SS         MS         F         P
Pattern     5       9201       1840      7.26     0.000
Error     173      43847        253
Total     178      53047
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N       Mean      StDev  -+---------+---------+---------+-----
1          30      39.90      18.84                 (-----*-----)
2          30      34.07      14.34           (-----*-----)
3          30      27.03      10.26    (-----*-----)
4          30      44.98      20.96                      (-----*-----)
5          30      40.67      17.68                  (-----*----)
6          29      25.48       9.88   (----*-----)
                                     -+---------+---------+---------+-----
Pooled StDev =      15.92            20        30        40        50
Tukey's pairwise comparisons
    Family error rate = 0.0500
Individual error rate = 0.00445
Critical value = 4.08
Intervals for (column level mean) - (row level mean)

                  1           2           3           4           5
       2      -6.03
              17.69
       3       1.01       -4.82
              24.73       18.90
       4     -16.94      -22.77      -29.81
               6.78        0.95       -6.09
       5     -12.63      -18.46      -25.50       -7.55
              11.09        5.26       -1.78       16.17
       6       2.46       -3.38      -10.42        7.53        3.22
              26.38       20.54       13.50       31.46       27.15
```

Table C-10. ANOVA: RMS vertical acceleration (tandem).

```
Analysis of Variance for RMS Vertical Acceleration (m/s^2)
Source      DF        SS          MS         F        P
Pattern      5    1324.5       264.9      5.99    0.000
Error       83    3671.2        44.2
Total       88    4995.7
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level        N      Mean       StDev  ----------+---------+---------+------
1           15    16.804       7.658                 (------*-----)
2           15    12.451       5.599          (------*------)
3           15    10.364       4.429      (------*------)
4           15    19.082       9.231                       (------*------)
5           15    17.965       7.493                     (------*------)
6           14     8.939       3.483   (------*------)
                                      ----------+---------+---------+------
Pooled StDev =     6.651                        10.0      15.0      20.0
Tukey's pairwise comparisons
    Family error rate = 0.0500
Individual error rate = 0.00453
Critical value = 4.13

Intervals for (column level mean) - (row level mean)

                 1           2           3           4           5
       2    -2.739
            11.445
       3    -0.652      -5.005
            13.532       9.179
       4    -9.370     -13.723     -15.810
             4.814       0.461      -1.626
       5    -8.253     -12.605     -14.693      -5.975
             5.931       1.579      -0.509       8.209
       6     0.648      -3.705      -5.792       2.926       1.809
            15.083      10.730       8.643      17.361      16.244
```

Table C-11. GLM: maximum pitch angular acceleration (mountain, road, and hybrid bicycles).

General Linear Model

Factor	Levels	Values					
Pattern	6	1	2	3	4	5	6
Wt-Group	5	1	2	3	4	6	
Bike	3	Road	Hybrid	Mountain			
Speed	3	High	Inter	Low			
Angle	3	0	10	45			

Analysis of Variance for Maximum Pitch Angular Acceleration (rad/s^2)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Pattern	5	69196	69196	13839	27.22	0.000
Wt-Group	4	53098	61062	15265	30.03	0.000
Bike	2	46059	46059	23030	45.30	0.000
Speed	2	2529	2529	1265	2.49	0.084
Angle	2	43150	43150	21575	42.44	0.000
Error	848	431130	431130	508		
Total	863	645163				

Means for Maximum Pitch Angular Acceleration (rad/s^2)

Pattern	Mean	StDev	Wt-Group	Mean	StDev
1	75.39	1.963	1	78.12	2.256
2	56.74	1.963	2	51.61	1.564
3	51.02	1.963	3	52.38	1.253
4	58.45	1.963	4	51.13	1.915
5	49.32	1.963	6	51.07	3.272
6	50.24	1.963			

Bike			Speed		
Road	65.56	1.668	High	58.18	1.446
Hybrid	58.36	1.627	Inter	54.44	1.446
Mountain	46.67	1.273	Low	57.95	1.446

Angle		
0	66.41	1.446
10	54.65	1.446
45	49.52	1.446

Table C-12. GLM: RMS pitch angular acceleration (mountain, road, and hybrid bicycles).

General Linear Model

Factor	Levels	Values					
Pattern	6	1	2	3	4	5	6
Wt-Group	5	1	2	3	4	6	
Bike	3	Road	Hybrid	Mountain			
Speed	3	High	Inter	Low			

Analysis of Variance for RMS Pitch Angular Acceleration (rad/s^2)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Pattern	5	8632.46	8632.46	1726.49	66.39	0.000
Wt-Group	4	393.91	350.79	87.70	3.37	0.010
Bike	2	1824.30	1824.30	912.15	35.08	0.000
Speed	2	226.67	226.67	113.33	4.36	0.014
Error	274	7125.18	7125.18	26.00		
Total	287	18202.51				

Means for RMS Pitch Angular Acceleration (rad/s^2)

Pattern	Mean	StDev	Wt-Group	Mean	StDev
1	31.12	0.7691	1	23.30	0.8838
2	21.76	0.7691	2	20.68	0.6128
3	16.34	0.7691	3	20.14	0.4907
4	22.24	0.7691	4	19.01	0.7501
5	19.52	0.7691	6	20.87	1.2815
6	13.82	0.7691			

Bike	Mean	StDev	Speed	Mean	StDev
Road	23.09	0.6536	High	21.57	0.5663
Hybrid	22.21	0.6371	Inter	19.56	0.5663
Mountain	17.10	0.4987	Low	21.28	0.5663

Table C-13. ANOVA: maximum pitch angular acceleration (mountain, road, and hybrid bicycles).

```
Analysis of Variance for Maximum Pitch Angular Acceleration (rad/s^2)
Source      DF        SS        MS        F        P
Pattern      5     69196     13839    20.62    0.000
Error      858    575967       671
Total      863    645163
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level        N      Mean     StDev  --------+---------+---------+--------
1          144     72.98     40.02                              (---*---)
2          144     54.33     20.78          (---*----)
3          144     48.61     19.25    (----*---)
4          144     56.04     25.01            (---*---)
5          144     46.91     20.87   (---*---)
6          144     47.83     23.72    (---*---)
                                    --------+---------+---------+--------
Pooled StDev =     25.91                    50        60        70
Tukey's pairwise comparisons
    Family error rate = 0.0500
Individual error rate = 0.00448
Critical value = 4.03

Intervals for (column level mean) - (row level mean)

                  1           2           3           4           5
       2       9.94
              27.35
       3      15.67       -2.98
              33.07       14.43
       4       8.23      -10.41      -16.14
              25.64        6.99        1.27
       5      17.36       -1.28       -7.01        0.43
              34.77       16.12       10.40       17.83
       6      16.44       -2.20       -7.93       -0.49       -9.62
              33.84       15.20        9.47       16.91        7.78
```

Table C-14. ANOVA: RMS pitch angular acceleration (mountain, road, and hybrid bicycles).

```
Analysis of Variance for RMS Pitch Angular Acceleration (rad/s^2)
Source     DF        SS        MS        F        P
Pattern     5    8632.5    1726.5    50.87    0.000
Error     282    9570.1      33.9
Total     287   18202.5
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev --+---------+---------+---------+-----
1          48    30.593     7.868                                (--*--)
2          48    21.230     5.672               (-*--)
3          48    15.809     4.264      (-*--)
4          48    21.711     6.551               (--*--)
5          48    18.994     6.087           (--*-)
6          48    13.288     3.375 (--*--)
                                  --+---------+---------+---------+-----
Pooled StDev =    5.825         12.0      18.0      24.0      30.0
Tukey's pairwise comparisons
    Family error rate = 0.0500
Individual error rate = 0.00470
Critical value = 4.03

Intervals for (column level mean) - (row level mean)

                1           2           3           4           5
       2     5.975
            12.752
       3    11.395       2.032
            18.173       8.809
       4     5.493      -3.870      -9.291
            12.270       2.907      -2.514
       5     8.210      -1.153      -6.573      -0.671
            14.988       5.625       0.204       6.106
       6    13.917       4.554      -0.867       5.035       2.318
            20.694      11.331       5.910      11.812       9.095
```

Table C-15. GLM: maximum pitch angular acceleration (tandem).

General Linear Model

Factor	Levels	Values					
Pattern	6	1	2	3	4	5	6
Weight	5	332	333	341	345	367	
Speed	3	Low	Inter	High			
Angle	2	0	10				

Analysis of Variance for Maximum Pitch Angular Acceleration (rad/s^2)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Pattern	5	6817.0	6590.5	1318.1	1.90	0.096
Weight	4	24499.1	24659.3	6164.8	8.91	0.000
Speed	2	7920.2	7995.6	3997.8	5.78	0.004
Angle	1	14338.6	14338.6	14338.6	20.72	0.000
Error	166	114860.2	114860.2	691.9		
Total	178	168435.1				

Means for Maximum Pitch Angular Acceleration (rad/s^2)

Pattern	Mean	StDev	Weight	Mean	StDev
1	71.51	4.803	332	70.93	4.449
2	66.02	4.803	333	64.11	4.384
3	56.81	4.803	341	69.76	4.384
4	73.23	4.803	345	42.70	4.384
5	61.95	4.803	367	76.42	4.384
6	59.21	4.888			

Speed			Angle		
Low	70.16	3.396	0	73.74	2.789
Inter	55.38	3.396	10	55.84	2.773
High	68.82	3.426			

Table C-16. GLM: RMS pitch angular acceleration (tandem).

General Linear Model

Factor	Levels	Values					
Pattern	6	1	2	3	4	5	6
Weight	5	332	333	341	345	367	
Speed	3	High	Inter	Low			

Analysis of Variance for RMS Pitch Angular Acceleration (rad/s^2)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Pattern	5	1081.37	1055.36	211.07	26.20	0.000
Weight	4	277.78	277.79	69.45	8.62	0.000
Speed	2	243.61	243.61	121.81	15.12	0.000
Error	77	620.22	620.22	8.05		
Total	88	2222.99				

Means for RMS Pitch Angular Acceleration (rad/s^2)

Pattern	Mean	StDev	Weight		
1	22.01	0.7328	332	16.05	0.6901
2	16.40	0.7328	333	14.63	0.6689
3	13.17	0.7328	341	17.70	0.6689
4	17.83	0.7328	345	13.47	0.6689
5	15.41	0.7328	367	18.07	0.6689
6	11.08	0.7605			

Speed		
High	18.33	0.5280
Inter	14.94	0.5182
Low	14.68	0.5182

Table C-17. ANOVA: maximum pitch angular acceleration (tandem).

```
Analysis of Variance for Maximum Pitch Angular Acceleration (rad/s^2)
Source     DF        SS         MS         F        P
Pattern     5      6817       1363      1.46    0.206
Error     173    161618        934
Total     178    168435
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean      StDev  --+---------+---------+---------+----
1          30     71.51      38.22              (---------*--------)
2          30     66.02      32.52          (--------*--------)
3          30     56.81      23.44  (--------*---------)
4          30     73.23      34.53                (--------*--------)
5          30     61.95      21.79      (---------*--------)
6          29     58.55      29.45   (---------*--------)
                                    --+---------+---------+---------+----
Pooled StDev =    30.56               48        60        72        84
Tukey's pairwise comparisons
    Family error rate = 0.0500
Individual error rate = 0.00445
Critical value = 4.08

Intervals for (column level mean) - (row level mean)

                 1           2           3           4           5
       2      -17.27
               28.26
       3       -8.06      -13.56
               37.47       31.98
       4      -24.48      -29.97      -39.18
               21.06       15.56        6.35
       5      -13.20      -18.70      -27.91      -11.49
               32.33       26.84       17.63       34.04
       6      -10.00      -15.49      -24.70       -8.29      -19.56
               35.93       30.43       21.22       37.64       26.36
```

Table C-18. ANOVA: RMS pitch angular acceleration (tandem).

```
Analysis of Variance for RMS Pitch Angular Acceleration (rad/s²)
Source     DF        SS        MS        F        P
Pattern     5    1081.4     216.3    15.72    0.000
Error      83    1141.6      13.8
Total      88    2223.0
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  ---+---------+---------+---------+---
1          15    22.006     2.475                       (---*---)
2          15    16.404     2.989             (---*---)
3          15    13.171     3.404        (--*---)
4          15    17.829     6.227                (---*--)
5          15    15.407     3.455           (---*---)
6          14    10.912     2.124   (---*---)
                                   ---+---------+---------+---------+---
Pooled StDev =    3.709            10.0      15.0      20.0      25.0
Tukey's pairwise comparisons
    Family error rate = 0.0500
Individual error rate = 0.00453
Critical value = 4.13

Intervals for (column level mean) - (row level mean)

                  1           2           3           4           5
       2      1.647
              9.557
       3      4.880      -0.722
             12.789       7.187
       4      0.223      -5.379      -8.612
              8.132       2.530      -0.703
       5      2.644      -2.958      -6.191      -1.533
             10.553       4.951       1.719       6.376
       6      7.069       1.467      -1.766       2.892       0.470
             15.119       9.517       6.284      10.941       8.520
```

Table C-19. ANOVA: objective control (percent of time off the line).

```
Analysis of Variance for Percent of Time Off the Line
Source      DF        SS        MS        F        P
Pattern      6    1.4218    0.2370     7.66    0.000
Error      497   15.3797    0.0309
Total      503   16.8014
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level        N      Mean     StDev  -+---------+---------+---------+--
0           72    0.0814    0.0905   (-----*----)
1           72    0.2535    0.2210                         (-----*-----)
2           72    0.1956    0.1921                  (-----*-----)
3           72    0.1228    0.1669        (-----*----)
4           72    0.1644    0.1715              (----*-----)
5           72    0.1922    0.1993                  (----*-----)
6           72    0.1260    0.1602        (-----*-----)
                                    -----+---------+---------+---------+--
Pooled StDev =    0.1759               0.070     0.140     0.210     0.280
Tukey's pairwise comparisons
    Family error rate = 0.0500
Individual error rate = 0.00334
Critical value = 4.17

Intervals for (column level mean) - (row level mean)

                    0           1           2           3           4           5
       1      -0.2585
              -0.0856
       2      -0.2006     -0.0285
              -0.0277      0.1444
       3      -0.1278      0.0442     -0.0137
               0.0451      0.2171      0.1592
       4      -0.1695      0.0026     -0.0553     -0.1281
               0.0034      0.1755      0.1176      0.0448
       5      -0.1973     -0.0252     -0.0831     -0.1559     -0.1142
              -0.0244      0.1477      0.0898      0.0170      0.0587
       6      -0.1310      0.0410     -0.0169     -0.0896     -0.0480     -0.0202
               0.0419      0.2140      0.1560      0.0833      0.1249      0.1527
```

Table C-20. Repeated measures analysis: comfort level of wrists, fingers and elbows.

```
Two-way Analysis of Variance
Analysis of Variance for Wrists, Fingers, and Elbows
Source        DF        SS        MS
Pattern        5    860.21    172.04
Observer      24   4549.91    189.58
Error        120   1077.19      8.98
Total        149   6487.31

                       Individual 95% CI
Pattern         Mean   -------+---------+---------+---------+----
1                7.13    (----*---)
2               10.14                (----*---)
3               13.70                              (----*----)
4               10.47                 (----*----)
5               11.86                       (---*----)
6               14.29                                (----*----)
                       -------+---------+---------+---------+----
                           7.50     10.00     12.50     15.00
```

Table C-21. Repeated measures analysis: comfort level of shoulder and neck.

Two-way Analysis of Variance

```
Analysis of Variance for Shoulder and Neck
Source        DF        SS        MS
Pattern        5   2097.79    419.56
Observer      24  15448.98    643.71
Interaction  120   2438.50     20.32
Error        300   1772.70      5.91
Total        449  21757.97

                          Individual 95% CI
Pattern          Mean   -------+---------+---------+---------+----
1                9.25    (-*--)
2               12.16                 (--*--)
3               14.94                               (--*-)
4               11.55              (--*--)
5               13.89                           (-*--)
6               15.58                                  (--*--)
                        -------+---------+---------+---------+----
                             10.00     12.00     14.00     16.00
```

Table C-22. Repeated measures analysis: comfort level of back.

Two-way Analysis of Variance

Analysis of Variance for Back

Source	DF	SS	MS
Pattern	5	2077.73	415.55
Observer	24	15340.69	639.20
Interaction	120	2377.01	19.81
Error	300	1860.19	6.20
Total	449	21655.62	

```
                          Individual 95% CI
Pattern          Mean    -----+---------+---------+---------+------
1                 9.71    (--*-)
2                12.72                   (--*-)
3                15.45                                (--*--)
4                12.42                 (--*--)
5                14.35                           (--*--)
6                16.15                                    (--*--)
                         -----+---------+---------+---------+------
                          10.00     12.00     14.00     16.00
```

Table C-23. Repeated measures analysis: comfort level of seat area.

```
Two-way Analysis of Variance
Analysis of Variance for Seat Area
Source        DF        SS        MS
Pattern        5   2411.09    482.22
Observer      24  15042.43    626.77
Interaction  120   2641.11     22.01
Error        300   2165.30      7.22
Total        449  22259.93

                       Individual 95% CI
Pattern         Mean   ----+---------+---------+---------+-------
1               8.01    (--*--)
2              11.21                    (--*--)
3              14.24                                   (--*--)
4              10.98                   (--*--)
5              12.65                           (--*--)
6              15.02                                       (--*--)
                       ----+---------+---------+---------+-------
                        8.00     10.00     12.00     14.00
```

Table C-24. Repeated measures analysis: comfort level of knees, ankles, and feet.

Two-way Analysis of Variance

Analysis of Variance for Knees, Ankles, and Feet

Source	DF	SS	MS
Pattern	5	2000.41	400.08
Observer	24	12801.01	533.38
Interaction	120	2669.08	22.24
Error	300	1932.59	6.44
Total	449	19403.10	

```
                             Individual 95% CI
Pattern            Mean    --+---------+---------+---------+---------
1                 10.19   (--*--)
2                 12.58               (--*--)
3                 15.80                               (--*--)
4                 12.39              (--*--)
5                 14.17                        (--*--)
6                 16.32                                  (--*-)
                          --+---------+---------+---------+---------
                          10.00     12.00     14.00     16.00
```

Table C-25. Repeated measures analysis: overall comfort level.

Two-way Analysis of Variance

Analysis of Variance for Overall

Source	DF	SS	MS
Pattern	5	1014.44	202.89
Observer	24	4524.34	188.51
Error	120	905.68	7.55
Total	149	6444.47	

```
                            Individual 95% CI
Pattern         Mean    ------+---------+---------+---------+-----
1               7.30     (---*----)
2              11.05                   (---*----)
3              14.53                                 (---*---)
4              10.03               (---*---)
5              12.11                       (---*----)
6              14.84                                  (---*----)
                        ------+---------+---------+---------+-----
                           7.50     10.00     12.50     15.00
```

Table C-26. Repeated measures analysis: overall control level.

Two-way Analysis of Variance

Analysis of Variance for Control

Source	DF	SS	MS
Pattern	5	689.42	137.88
Observer	21	3830.73	182.42
Error	105	750.78	7.15
Total	131	5270.93	

```
                        Individual 95% CI
Pattern          Mean   -----+---------+---------+---------+------
1                7.44   (----*---)
2               10.83                 (---*----)
3               13.36                            (---*----)
4                9.46           (----*---)
5               11.50                   (----*----)
6               14.25                               (----*----)
                        -----+---------+---------+---------+------
                           7.50     10.00     12.50     15.00
```

APPENDIX D

BACKGROUND INFORMATION ON THE SUBJECTS WHO PARTICIPATED IN THE BICYCLE TESTS

RUMBLE STRIPS RIDER SURVEY
SUMMARY OF CLASSIFICATION RESULTS

This appendix summarizes the classification results of the rumble strip rider survey. Twenty-five bicycle riders were surveyed as part of this project; of those, 24 fully answered the classification questions. The last page of this appendix contains a sample of the survey.

SURVEY RESULTS

Riding Comfort in Traffic

The first set of questions was used to assess riders' comfort while riding in traffic. The results are shown in Tables D-1 and D-2. As shown in table D-1, nearly all the respondents felt comfortable riding in traffic. Only 20 of the 24 respondents answered the follow-up question, assessing comfort riding in heavy traffic. As shown in table D-2, only 10 of the respondents felt comfortable riding in heavy traffic.

Table D-1. Do you ride comfortably in traffic?

Yes	23
No	1

Table D-2. Do you ride comfortably in traffic in heavy traffic?

Yes	10
No	10
No Response	4

Riding in Inclement Weather

The next set of questions was used to assess riders' attitudes toward riding in inclement weather. The results are shown in tables D-3 and D-4. As shown in table D-3, two-thirds (16) of the 24 respondents ride in inclement weather. Of these 16, seven indicated that they were bothered by the weather. One person did not respond to this question.

Table D-3. Do you ride in inclement weather?

Yes	16
No	8

Table D-4. Does it bother you to ride in inclement weather?

Yes	7
No	8
No Response	1

Hill Climbing Ability

Next, riders' hill-climbing abilities were assessed. The results are shown in table D-5. As shown in table D-5, 20 of the 24 respondents indicated that they were able to climb hills without dismounting their bicycles. One person did not respond to this question.

Table D-5. Can you climb most hills without dismounting?

Yes	20
No	3
No Response	1

Annual Miles Traveled

Riders were asked to estimate the number of miles they cycle annually. Table D-6 shows the results. As shown in table D-6, 23 of the 24 respondents (96 percent) estimated cycling less than 3,000 miles annually. One respondent estimated traveling between 4,000 and 5,000 miles annually.

Table D-6. Estimated annual number of miles ridden.

Annual Miles Ridden	Respondents	Percent of Total
< 1,000	11	46 %
1,000 – 2,000	10	42 %
2,000 – 3,000	2	8 %
3,000 – 4,000	0	0 %
4,000 – 5,000	1	4 %
> 5,000	0	0 %

Riding Experience

Riders were asked to estimate their own riding experience as either "intermediate" or "advanced." No novice cyclists were surveyed as part of this study. The results are shown in table D-7. As shown in table D-7, of the 24 respondents, one-half described themselves as having intermediate riding experience and the other half described themselves as having advanced riding experience.

Table D-7. Riding experience.

Intermediate	12
Advanced	12

Off-Road Riding

Riders were asked to estimate the percentage of time they spent riding off-road. The results are shown in table D-8. As shown in table D-8, the majority of the respondents (59 percent) indicated riding off-road no more than 10 percent of the time. Eighty-three percent of the respondents indicated riding off-road less than half of the time. The remaining 17 percent indicated riding off-road between 70 and 80 percent of the time.

Table D-8. Percentage of time spent off-road riding.

Percent Time Off-Road	Respondents	Percent of Total Respondents
0 - 10 %	14	59 %
11 – 20 %	1	4 %
21 – 30 %	2	8 %
31 – 40 %	2	8 %
41 – 50 %	1	4 %
51 – 60 %	0	0 %
61 – 70 %	0	0 %
71 – 80 %	4	17 %
81 – 90 %	0	0 %
91 – 100 %	0	0 %

Age Distribution

Table D-9 illustrates the age distribution of the riders surveyed. All riders were under age 55.

Table D-9. Age distribution.

Age Range (years)	Respondents	Percent of Total
20 – 25	3	13 %
26 – 30	7	28 %
31 – 35	1	4 %
36 – 40	2	8 %
41 – 45	3	13 %
46 – 50	4	17 %
51 – 55	4	17 %
56 - 60	0	0 %

Gender

Table D-10 shows the gender distribution of the respondents. As shown in table D-10, 20 men and 5 women were surveyed.

Table D-10. Gender distribution.

Male	20
Female	5

Weight Distribution

Table D-11 shows the distribution in weights among the respondents. As shown in table D-11, approximately two-thirds (68 percent) of the respondents weighed between 116 and 175 pounds. Approximately one-third (32 percent) weighed between 176 and 235 pounds. None of the respondents weighed less than 116 pounds or more than 235 pounds.

Table D-11. Weight distribution.

Weight Range (lbs)	Respondents	Percent of Total
100 – 115	0	0 %
116 – 130	4	17 %
131 – 145	4	17 %
146 – 160	4	17 %
161 – 175	4	17 %
175 – 190	2	9 %
191 – 205	2	9 %
206 – 220	2	9 %
221 – 235	1	5 %
236 – 250	0	0 %

Height Distribution

Table D-12 shows the height distribution among the respondents. As shown in table D-12, 88 percent of the respondents were between 5'4" and 6'1". The remaining 12 percent were over 6'1". No respondents were under 5'4".

Table D-12. Height distribution.

Height Range	Respondents	Percent of Total
< 5' 4"	0	0 %
5' 4" – 5' 5"	3	13 %
5' 6" – 5' 7"	7	29 %
5' 8" – 5' 9"	2	8 %
5' 10" – 5' 11"	6	25 %
6' 0" – 6' 1"	3	13 %
6' 2" – 6' 3"	2	8 %
6' 4" – 6' 5"	0	0 %
> 6' 5"	1	4 %

Health Problems --General and Specific

Riders were asked if they had any general health problems. As shown in table D-13, only one of the respondents indicated having a general health problem (a lower back problem).

Table D-13. General health problems.

Yes	1
No	23

Riders were then asked if they had any pain in particular body parts or areas. The results for these questions are summarized in tables D-14 through D-18.

Table D-14. Do you have pain in your wrists, fingers, or elbows?

Yes	1
No	23

Table D-15. Do you have pain in your neck or shoulders?

Yes	0
No	24

Table D-16. Do you have pain in your back?

Yes	4
No	20

Table D-17. Do you have pain in your seat area?

Yes	0
No	24

Table D-18. Do you have pain in your knees, ankles, or feet?

Yes	4
No	20

Rumble Strip Experience

Tables D-19 and D-20 show the results of questions asked to assess riders' awareness and experience with rumble strips. As shown in table D-19, only 1 of the 24 respondents did not know what a rumble strip is. As table D-20 shows, two-thirds (16) of the respondents had ridden a bicycle over rumble strips.

Table D-19. Do you know what a rumble strip is?

Yes	23
No	1

Table D-20. Have you ever ridden your bicycle over rumble strips?

Yes	16
No	8