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GUIDELINES FOR THE APPLICATION OF REMOVABLE RUMBLE STRIPS

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The University of Kansas
Lawrence, Kansas

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16 Abstract

This work was initiated to assess the viability of removable rumble strips as replacements for asphalt rumble strips, particularly in short term highway work zones. The two rumble strips tested were the Orange Rumble Strip from Advanced Traffic Markings and the Rumbler from Swarco in black.

The removable strips are compared with asphalt strips in terms of the levels of in-vehicle noise, vehicle-body vibration, and roadside noise, their effect on vehicle speeds, and their cost, durability, and installation and removal processes. Sound and vibration levels were measured with a sound/vibration analyzer, microphone, and accelerometer. Speeds were monitored with pneumatic hoses and automatic traffic recorders. Additional tests were performed to explore the effects of changes in deployment configuration with respect to the sound and vibration levels produced by the orange rumble strips. Of the configurations tested, 6 strips with a center-to-center spacing of 0.6 m (2 ft) was the preferred configuration based on the sound and vibration levels produced.

The results of the comparisons indicated that the removable rumble strips tested are similar to asphalt rumble strips in terms of the sound and vibration levels produced and the speed reductions observed. With certain limitations, these removable rumble strips are a viable alternative to asphalt rumble strips.

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GUIDELINES FOR THE APPLICATION OF TEMPORARY RUMBLE STRIPS

Final Report

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A Report on Research Sponsored By

THE KANSAS DEPARTMENT OF TRANSPORTATION
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and

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PREFACE

The Kansas Department of Transportation's (KDOT) Kansas Transportation Research and New-Developments (K-TRAN) Research Program funded this research project. It is an ongoing, cooperative and comprehensive research program addressing transportation needs of the state of Kansas utilizing academic and research resources from KDOT, Kansas State University and the University of Kansas. Transportation professionals in KDOT and the universities jointly develop the projects included in the research program.

NOTICE

DISCLAIMER

ABSTRACT

This work was initiated to assess the viability of removable rumble strips as replacements for asphalt rumble strips, particularly in short term highway work zones. The two rumble strips tested were the Orange Rumble Strip from Advanced Traffic Markings and the Rumbler from Swarco in black.

The removable strips are compared with asphalt strips in terms of the levels of in-vehicle noise, vehicle-body vibration, and roadside noise, their effect on vehicle speeds, and their cost, durability, and installation and removal processes. Sound and vibration levels were measured with a sound/vibration analyzer, microphone, and accelerometer. Speeds were monitored with pneumatic hoses and automatic traffic recorders. Additional tests were performed to explore the effects of changes in deployment configuration with respect to the sound and vibration levels produced by the orange rumble strips. Of the configurations tested, 6 strips with a center-to-center spacing of 0.6 m (2 ft) was the preferred configuration based on the sound and vibration levels produced.

The results of the comparisons indicated that the removable rumble strips tested are similar to asphalt rumble strips in terms of the sound and vibration levels produced and the speed reductions observed. With certain limitations, these removable rumble strips are a viable alternative to asphalt rumble strips.

ACKNOWLEDGEMENTS

Special thanks go to Scott Walton, Graduate Research Assistant, who invested many hours collecting and processing data and wrote the draft document upon which this report is based. Thanks also go to Swarco Industries, Inc., and to Advanced Traffic Markings, Inc., who each contributed time and materials to this study.

The study could not have been completed without the help of KDOT field personnel who helped coordinate the work, monitor the strips over time, drive the test truck, and provide traffic control for installation and removal activities.

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NOMENCLATURE

- A-weighting filter = weighting curve applied to measurements recorded with a microphone to transform them into sound levels that a human would perceive. Figure 3.2 on page 25 shows a plot of the correction factors applied to recorded measurements.
- dB = decibel = 10 log (value)

    herein: value = (Measured pressure/Reference pressure)2

    therefore: decibel = 20 log (Measured pressure/Reference pressure)
- dBA = decibel measured with an A-weighting filter; used for sound measurements
- Leq = equivalent sound level (dB)
- L10 = sound level that is exceeded 10 percent of the time (dB)
- Reference pressure = 20 micropascals (μPa) for sound

CHAPTER 1

BACKGROUND AND MOTIVATION

In 1999, work zone fatalities in the United States hit an all-time high. In 2000, a new record of 1093 fatalities represented an additional increase of 26%. [1] Statistics such as these have served to highlight the need for transportation agencies to continue working to improve work zone safety. The Kansas Department of Transportation (KDOT) is continuously investigating new ways of improving safety for maintenance workers and travelers alike. Removable rumble strips show promise of being an improvement over asphalt rumble strips in some circumstances. This report details a comparative study to assess the viability of removable rumble strips as a substitute for asphalt strips.

Rumble strips have long been used in Kansas in advance of some work zones to help alert drivers of upcoming conditions. While studies have shown that permanent rumble strip deployments have been effective at reducing accidents in other contexts [2, 3], few studies have quantitatively assessed the effect of rumble strips on safety in work zones. Part of the difficulty lies in the limited amount of time that work zones are in place. To accurately determine the effect of a device on accident and fatality rates, several years of data (i.e., preferably 6 years or more) are needed. Most work zone deployments of rumble strips exist for only a few months or even weeks. Although it is difficult to quantify their effectiveness in work zones in terms of accidents or fatalities, rumble strips have been shown to reduce accidents for permanent installations, and they are effective in alerting drivers of potentially unexpected driving conditions. It is reasonable to expect rumble strips to have a positive effect on safety in work zones.

The impetus for investigating removable rumble strips is that the installation and removal is much quicker and easier. Decreasing the time required to install and remove rumble strips improves safety by reducing traffic disruption and decreasing the time workers must spend in the traveled way. Other advantages of removable strips include increased ease of repair, decreased damage to the pavement upon removal, material savings through reuse, the provision of additional visual stimuli to help capture the driver's attention, and possibly the consistency of shape and size, resulting in more consistent sound and vibration levels. Additionally, studies have found rumble strips made of synthetic materials to be more durable than formed in place asphalt strips. [2]

1.1 Introduction

According to the Manual on Uniform Traffic Control Devices (MUTCD) Millennium Edition, "Rumble strips consist of intermittent narrow, transverse areas of rough-textured or slightly raised or depressed road surface that alert drivers to unusual motor vehicle traffic conditions. Through noise and vibration they attract the driver's attention to such features as unexpected changes in alignment and to conditions requiring a stop." [1]

The term rumble strips can imply either shoulder rumble strips or rumble strips in the traveled way. Shoulder rumble strips are changes to only the shoulder of the road and are intended to help prevent run-off-the-road crashes. Rumble strips in the traveled way are strips that are placed within the lane, perpendicular to the direction of travel. The purpose of these strips is primarily to alert the driver that the road ahead requires special attention, and, in some cases, to control speeds, though their effectiveness in this regard is arguable. The focus of this research was the latter of the two applications, and, throughout this report, rumble strips refers to rumble strips in the traveled way.

Rumble strips are often deployed at locations where additional safety measures are needed, such as some work zones. Rumble strips capture the driver's attention by producing auditory and tactile stimuli (sound and vibration), prompting the driver to pay special attention to the upcoming roadway. Many studies of rumble strip installations have found them to be effective in this regard. These studies have found significant speed reductions, increases in stop compliance, reductions in accidents, and reductions in fatalities. [2, 3, 4, 5, 6]

Little research has been done regarding the effectiveness of removable rumble strips. Removable rumble strips are thought to offer many advantages over traditional asphalt rumble strips for removable rumble strip deployments. Quicker installation and removal, additional visual stimuli, and reduced damage to the pavement upon removal are all worthwhile benefits, but they can only justify the use of removable rumble strips if the strips can perform as well as the permanent strips they are intended to replace. This report presents a detailed comparison of two types of removable rumble strips to the more commonly used raised asphalt rumble strips.

1.2 State of the Practice

1.2.1 Rumble Strip Use

The most common locations for rumble strip deployments are:

- Approaches to Intersections
- Approaches to Toll Plazas
- Approaches to Work Zones

These areas most often require vehicles to either stop or to significantly slow down. Rumble strips are intended to draw driver's full attention to the driving task. In the cases mentioned above, the rumble strips may also be intended to decrease the speed at which the driver feels comfortable driving. In other cases, a speed decrease may not be necessary or even desired, such as with rumble strips located just prior to a lane closure, where the strips serve to ensure drivers alert so as to take note of the upcoming merge.

1.2.2 Rumble Strip Cross-Sections

A variety of rumble strip cross-sections are commonly used. Asphalt rumble strips of the appropriate shape and size are often created using wooden forms, and usually have a domed cross-section. Rumble strips, both raised and grooved, can be rectangular, trapezoidal, domed, or any other shape. The width of the strips ranges from 5 to 31 cm (2 to 12 in), though they are most often between 10 and 20 cm (4 and 8 in). The height of the strips ranges from 0.32 to 3.8 cm (0.125 to 1.5 in). [3] Since grooved rumble strips require permanently altering the pavement by cutting or grinding in grooves, most temporary installations are raised strips.

The Kansas Department of Transportation typically uses dome-shaped raised asphalt strips that are between 13 and 19 mm (0.5 and 0.75 in) high and approximately 31 cm (12 in) wide for highway work zones. [7] Rectangular grooved rumble strips 10 mm (0.375 in) deep and 10 cm (4 in) wide are used for approaches to intersections. [3]

1.2.3 Rumble Strip Materials

Raised rumble strips can be made from many materials, although asphalt strips are the most commonly used type of raised rumble strip. [3] Rumble strips can also be made from rubber, plastic, exposed aggregates, etc. Removable rumble strips are typically made from plastic or rubber. Raised pavement markers (RPMs) have also been used to create the rumble effect.

1.2.4 Rumble Strip Layout

The most common rumble strip configurations consist of 1-4 sets with each set containing 1-4 groups of closely spaced strips. In Kansas, the current practice for work zones consists of two sets spaced 152.4–304.8 m (500–1000 ft) apart, with each set containing three groups of strips spaced at 30.5 m (100 ft). Each of the six groups consists of six strips with 0.6 m (2 ft) center-to-center spacing. [7] An installation at an approach to an intersection consists of a single group containing 25, 10 cm (4 in) grooves at a 0.3 m (1 ft) center-to-center spacing. [3]

1.3 Effectiveness of Rumble Strips

Several measures of effectiveness (MOE) have been used to evaluate rumble strips. Typical MOE used in previous studies include:

- Stop compliance,
- Speed compliance,
- Deceleration patterns,
- Number of accidents,
- Number of fatalities, and
- Reductions in speed.

All of these MOE relate to driver behavior. Causation (i.e., the cause-effect relationship between driver behavior and the presence of rumble strips) must be assumed based on the likelihood that the experimental design properly isolated the effects of the rumble strips by keeping all other factors the same or by somehow adjusting the results to compensate for other changes. Driver behavior is an indirect measure of driver perception. Direct measures must be related to sound and vibration levels. While there are many other factors that affect the driver's perception of rumble strips, such as duration and frequency, there exists a direct relationship between the levels and sound and vibration produced and the driver's perception of the strips. There are many site-specific factors that affect driver behavior, but by comparing the levels of sound and vibration produced, the potential effectiveness of rumble strips can be directly compared, even though data were collected at multiple sites. If one set of rumble strips produces more sound and vibration than another set at a different location, then it would be reasonable to assume it to be more noticeable and potentially more effective if deployed under similar conditions. The approach used in this study capitalizes on this relationship, comparing the effectiveness of removable strips and asphalt strips with respect to the sound and vibration levels produced.

1.3.1 Case Studies

Although there are many studies suggesting that rumble strips are effective, [2, 3, 4, 5, 6] there are also studies that find rumble strips to be ineffective. Studies of rumble strips used in work zones are commonly found in both categories. [2, 3, 8, 9, 10] Part of the reason for this apparent discrepancy is that no standard exists for rumble strip dimensions, configuration, and installation. With a wide variety of rumble strip configurations being used, it is not surprising that one set of rumble strips would be effective, and yet a completely different configuration of a different type of strip would be ineffective.

The MOE used can also influence the studies findings. For example, the South Dakota DOT conducted a study of rumble strips at a work zone where drivers were required to come to a complete stop. They found a decrease in means speeds of 4.7 kph (2.9 mph) at the most downstream point. However, the study also found that the number of drivers that came to a complete stop at the work zone decreased by 20% (from 67% to 47%). [9] This deployment could be said to have been both effective and ineffective—effective at reducing speeds and ineffective at increasing stop compliance. It is also possible that both of these changes were due to factors other than the rumble strips, such as drivers becoming familiar with the work zone.

A study of rumble strips used to warn drivers of a lane closure on Interstate 75 in Kentucky found that rumble strips in advance of the lane closure decreased the percentage of vehicles in the closing lane from 11.0% to 4.1%. [12] The rumble strips were placed in the closing lane to warn drivers that they need to switch lanes. Since the number of drivers that were in the closing lane decreased, it was concluded that the rumble strips had effectively alerted drivers. Perhaps the drivers were simply avoiding the strips, rather than being more aware of the roadway. In this application, the cause for the change in driver behavior really does not matter, but it is critically important to consider the mechanism when attempting to relate the results to other applications.

1.3.2 Maximizing the Effectiveness of Rumble Strips

In Kansas, the Department of Transportation uses rumble strips primarily in advance of work zones where two or more lanes of traffic traveling in opposite directions are forced to share a single lane, as is common for two lane bridge repairs. In these situations, temporary traffic signals are used to control traffic movement through the work zone. Rumble strips are used to alert drivers that an unusual situation (i.e., the traffic signal) is ahead. It has been suggested that the effectiveness of rumble strips is dependent upon the quality of the strips and their configuration pattern. [9] Presumably, to increase the effectiveness of rumble strips, the levels of stimuli produced by the strips must be increased, which can be done by varying the configuration and strip cross-section.

Few studies have considered which configuration(s) of rumble strips produce the greatest levels of stimuli. The few studies that have been conducted relied on the results of only a few combinations of cross-sections, vehicles, speeds, and configurations. Since the levels of stimuli produced are directly related to all of these variables, results obtained using one cross-section or one vehicle may not necessarily be indicative of the results that would be obtained using another cross-section or another vehicle.

A study was conducted by the New Jersey DOT to determine the rumble strip spacing that would produce the greatest “rumble” and the greatest “jolt”1. This study used plywood strips that were 76 mm (3 in) wide, 13 mm (0.5 in) thick, and had edges beveled at 45 degrees. The results indicated that a 23 cm (9 in) center-to-center spacing produced the most rumble, and a 318 cm (125 in) center-to-center spacing produced the greatest jolt. Rumble strips using these spacings and cross-sections were placed at one approach to a traffic circle. The accident histories for two years before the deployment and two years after were later compared. The approach with the rumble strips had a 20% reduction in accidents and a 40% reduction in injuries. Another approach to the same traffic circle without the rumble strips had a 113% increase in accidents and a 233% increase in injuries over the same period. [13]

The Virginia Highway and Transportation Research Council performed a similar study that used measurements of in-vehicle sound and axle deflection to determine the spacing that would provide the maximum stimuli. [14] The strips used in the study were 10 cm- (4 in-) wide plywood strips. Three strip heights were used, 6 mm (0.25 in), 10 mm (0.375 in), and 13 mm (0.5 in). The report recommended a spacing of 3 m (10 ft) for a stopping scenario, and a strip height of no greater than or less than 13 mm (0.5 in). The data collected in these tests indicated that the maximum sound and vibration levels were usually observed on configurations with spacings between 38 cm (1.25 ft) and 99 cm (3.25 ft). The variation in the results of these tests using rumble strips with fairly similar cross-sections indicates how much effect the configuration can have on the amount of sound and vibration produced.

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[1] “Rumble” and “Jolt” were not defined, but may correspond to noise and vibration, respectively.

1.4 Goals and Objectives

The use of asphalt rumble strips is a widely accepted practice, and is the standard practice for many agencies. While removable strips have several advantages, substituting them for asphalt strips could have safety—and subsequent legal—implications. This study was initiated to assess whether or not the effectiveness of removable strips is comparable to the current standard practice, asphalt strips, and thus whether or not they should be allowed as a substitute.

The primary MOE used in this study were the sound inside the vehicle and the vibration of the vehicle body. Secondary MOE include sound levels at the roadside, speed-related parameters, and economic parameters. Thus, the goal of this study is to provide a detailed and thorough comparison of removable rumble strips and asphalt rumble strips. The specific objectives are to determine whether or not removable rumble strips are comparable to asphalt rumble strips with respect to the following parameters.

- sound levels inside the vehicle
- vibration levels inside the vehicle
- sound levels at the adjacent roadside
- speed reductions immediately downstream of the strips
- material costs
- durability
- installation and removal times
- damage done to the pavement during removal

1.5 Approach

In order to collect the sound, vibration, and roadside noise levels, it was necessary to deploy at least one set of each types of strip being tested. The strips were traversed by three test vehicles over an array of conditions, measuring and cataloguing the measurements for each pass. Vehicle speed data were also collected to compare the effect of each type of strip on vehicle speeds and vehicle speed reduction. During the installation of the test deployments, the times and costs of installation were observed and quantified. The strips were then left in place for the duration of the construction project. Approximately three weeks of speed data were collected at each site. The durability of the strips was observed with respect to their adherence to the pavement and their wear. Removal times and costs were also observed and quantified, and the damage suffered by the strips was examined.

The MOE can be grouped into the following: measures of perceptability (sound and vibration), measures of driver response (speed reductions), and measures of cost (installation and removal). Chapter 3 discusses the measurement, data analysis, and results of the sound, vibration, and roadside noise tests. Chapter 4 discusses the measurement, analysis, and results for the vehicle speeds tests. Chapter 5 discusses the measurement and analysis of the tests necessary for a benefit/cost analysis. The following chapter (Chapter 2) discusses the details of three test installations and the related data collection processes.

CHAPTER 2

TEST INSTALLATIONS

Three types of rumble strips were evaluated: the Rumbler rumble strip from Swarco Industries, Inc., in black (Rumbler); the Removable Rumble Strip from Advance Traffic Markings in orange (Orange); and the KDOT standard asphalt rumble strips (Asphalt).

2.1 Rumble Strip Characteristics

2.1.1 Rumbler

Each Rumbler rumble strip consists of a 1.2 m (4 ft) piece of black rubber with three raised ridges, as shown in Figure 2.1. The strip is applied to the pavement using contact cement (provided by Swarco for this study). The Rumbler is also available in reflective white and reflective yellow, but the black strip was used best conform to the MUTCD guidelines. It is assumed that the brightly colored reflective strips will perform as well as or better than the black strip (potentially better because of their added visual effect).

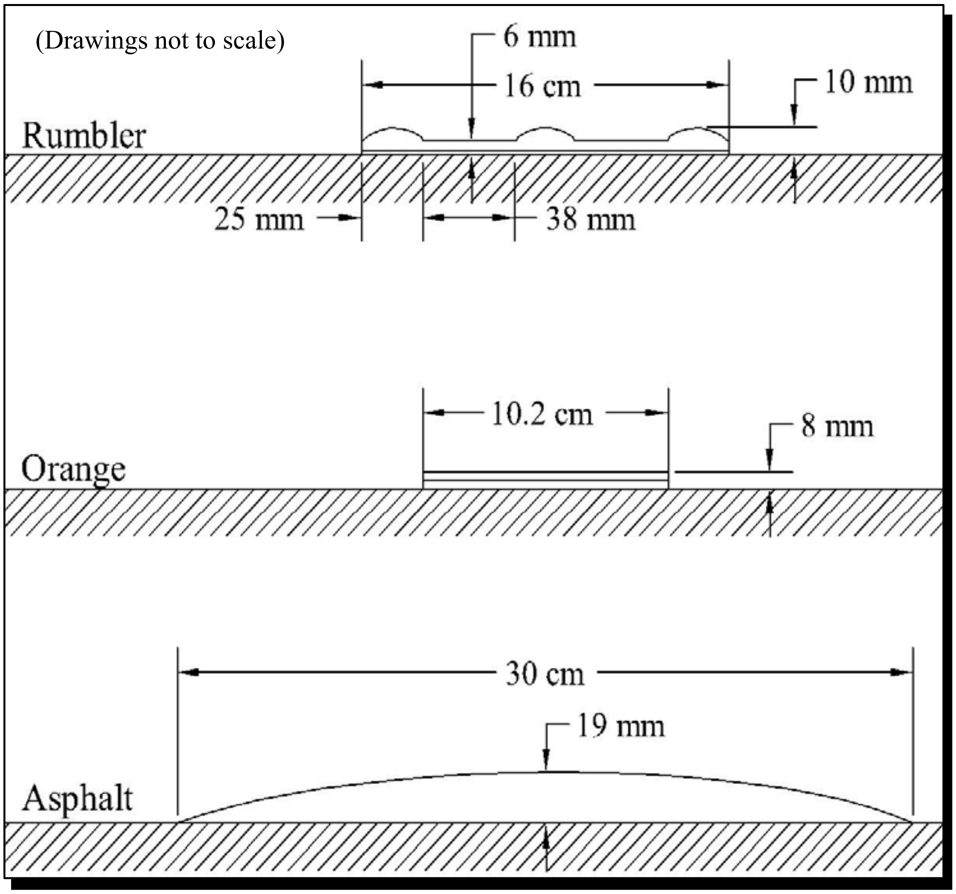


Figure 2.1: Rumble Strip Cross-Sections

2.1.2 Orange Rumble Strips

The orange rumble strips are non-reflective, self-adhesive, and come in 27.4 m (90 ft) rolls. The manufacturer produces strips that are orange, white, black, or customized colors. All are non-reflective. Previous studies using the orange rumble strips with a single thickness had determined that they did affect driver behavior, but that their effectiveness was mostly due to their high visibility. It was suggested that the strips might be more effective if the thickness of the strips were doubled. [7, 15] To consider the value of the orange color and to build on the results of the previous test, orange rumble strips with double thickness were used in this study.

2.1.3 Asphalt Rumble Strips

The asphalt rumble strips consisted of raised strips formed from cold-mix asphalt. The asphalt strips typically have a cross-section that is best described as dome shaped, as shown in Figure 2.1. This type of strip is currently the most commonly used raised rumble strip. [3]

2.2 Installation Methods

2.2.1 Rumbler

For proper installation, the pavement must be clean, dry, and warmer than 10˚ C (50˚ F). The pavement was dry, and its temperature just before installation was 32˚ C (90˚ F). The pavement was swept with a push broom to remove loose debris. Once the pavement was clean, it was marked using masking tape to indicate the proper placement for the strips. Adhesive was then applied to the pavement with a paint roller and allowed to set for approximately 3 minutes. A second coat of adhesive was applied to the pavement and a single coat was applied to the underside of the strip. Both were allowed to set for 3 minutes. The strip was placed and rolled with a 22 kg (48 lb) tamper cart carrying an additional 90 kg (198 lb). The manufacturer recommended the use of a customized tamper cart whose wheel had been shaped to match the profile of the strips. Such tamper carts are available from the manufacturer, who provided one for this test. Figure 2.2 shows the tamper cart being used on the Rumbler rumble strips.

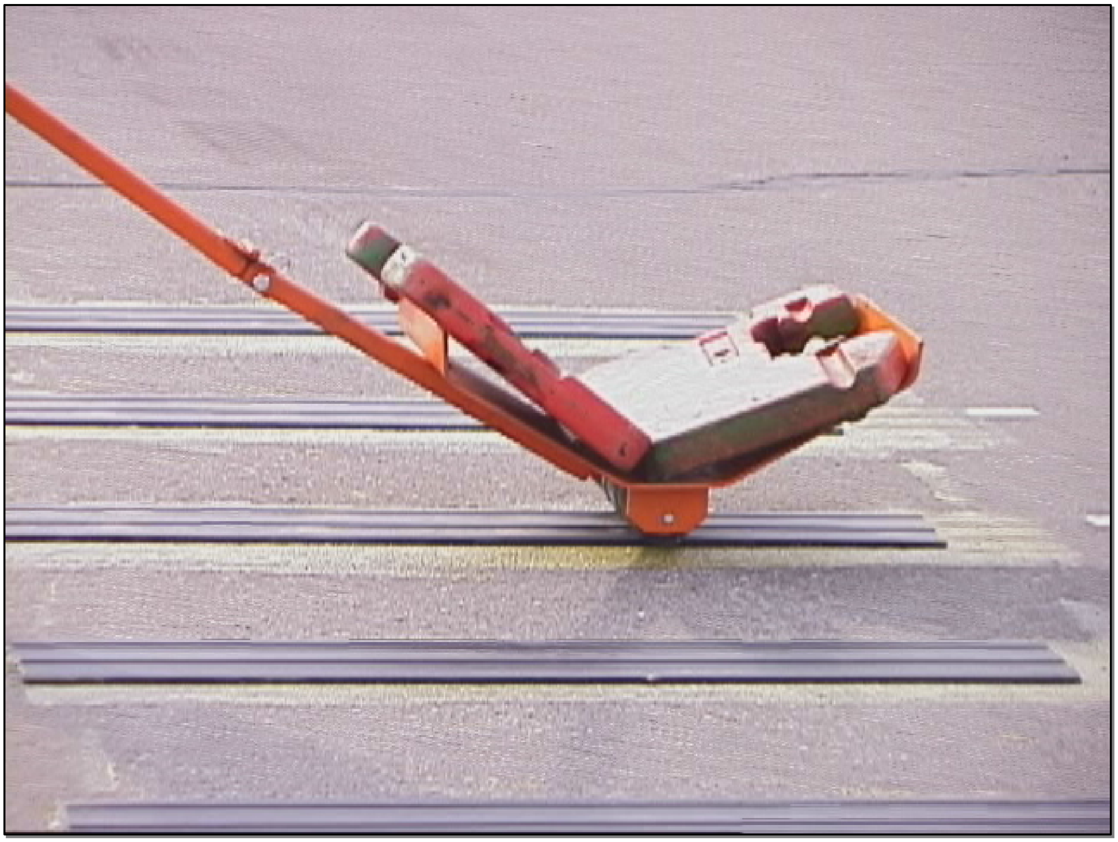


Figure 2.2: Tamper Cart with Custom Wheel Rolling Rumbler Rumble Strips

2.2.2 Orange Rumble Strips

The orange rumble strips were first cut to the appropriate length, 1.2 m (4 ft), using tin snips. The pavement temperature was 45˚ C (113˚ F), and the pavement was completely dry. The pavement surface was swept clear of debris using a push broom. The placement of the rumble strips was measured and marked using a tape measure and masking tape. The adhesive, which was pre-applied to the strip by the manufacturer, was exposed by removing the protective backing. The strip was then positioned on the pavement and rolled with a 22 kg (48 lb) tamper cart carrying an additional 90 kg (198 lb). The tamper cart used to adhere the orange rumble strips to the pavement was similar to the cart used for the Rumbler, except that the wheel had a flat profile. The plastic backing tore on approximately one out of every five pieces, significantly increasing the effort required for installation. This was reported to the manufacturer who affirmed the problem would be addressed. The orange rumble strips are only 3.8 mm (0.150 in) thick, which a previous study had determined to be too thin to produce sufficiently noticeable noise and vibration. [7, 15] To compensate, two pieces were used, one on top of another, in order to double the thickness, effectively doubling the installation time, as well.

2.2.3 Asphalt Rumble Strips

Asphalt rumble strips are usually installed using one of two methods. (1) Asphalt strips often are installed by using wooden forms that consist of seven pieces of 3 cm x 31 cm x 3.7 m (1 in x 12 in x 12 ft) lumber. These boards are placed on the pavement at 0.6 m (2 ft) center-to-center spacing, and the spaces between the boards are filled with asphalt and compacted using a shovel. (2) Asphalt strips are sometimes placed without using forms, in which case the pavement is marked with chalk or paint, and the asphalt is put in place and formed using shovels. The asphalt is then compacted by driving over it with a truck. The asphalt strips used in these tests were installed using the latter of the two methods.

2.3 Rumble Strip Cross-Sections

The cross-section of the rumble strip directly affects the amount of sound and vibration produced. The ridges on the Rumbler may or may not add significantly to the amount of sound and vibration produced by these strips, but the ridges do increase the thickness of the strip, which should increase the sound and vibration levels. Both types of removable rumble strips are less wide and less thick than the asphalt rumble strips. Figure 2.1 shows the dimensions of the cross-sections of all three types of rumble strips. The dimensions for the asphalt strip are typical, although particular strips can vary considerably.

2.4 Test Locations

The two types of removable rumble strips were deployed at two locations. At each site, the removable strips were used for the most upstream set on one approach. The remaining sets were asphalt rumble strips. Sound and vibration measurements were taken for both smooth pavement and for asphalt rumble strips at both locations.

2.4.1 Rumbler

The Rumbler rumble strips were installed on the eastbound approach to a bridge maintenance project on Kansas State Route 93 at Perry Lake, just south of Ozawkie, Kansas. This location had an ADT of 900 on the westbound approach, and 1200 on the eastbound approach during the study period. This location had two 3.7 m (12 ft) lanes and a posted speed of 105 kph (65 mph).

2.4.2 Orange Rumble Strips

The orange rumble strips were installed on the westbound approach to a bridge maintenance project on Kansas State Route 20 west of Horton, Kansas. This location had an ADT of 1350 on the westbound approach during the study period. This location had two 3.4 m (11 ft) lanes, and a posted speed of 89 kph (55 mph).

2.4.3 Asphalt Rumble Strips

Three out of the four sets of rumble strips at each location were asphalt strips. The sound and vibration levels were taken on asphalt strips at both sites. The speed data was collected on the asphalt strips that were located on the approach opposite the Rumbler approach at the Rumbler test site (Perry Lake).

Figure 2.3 through Figure 2.6 are work zone diagrams showing the traffic control at the test locations. The boxes that contain only a three-digit number represent automatic traffic recorders, which were used to measure speeds, volumes, and classifications (the number is the data point ID). Figure 2.3 shows where the speeds were collected on the asphalt strips, Figure 2.4 shows where the speeds were collected on the Rumbler rumble strips, and Figure 2.6 shows where the speeds were collected on the orange rumble strips.

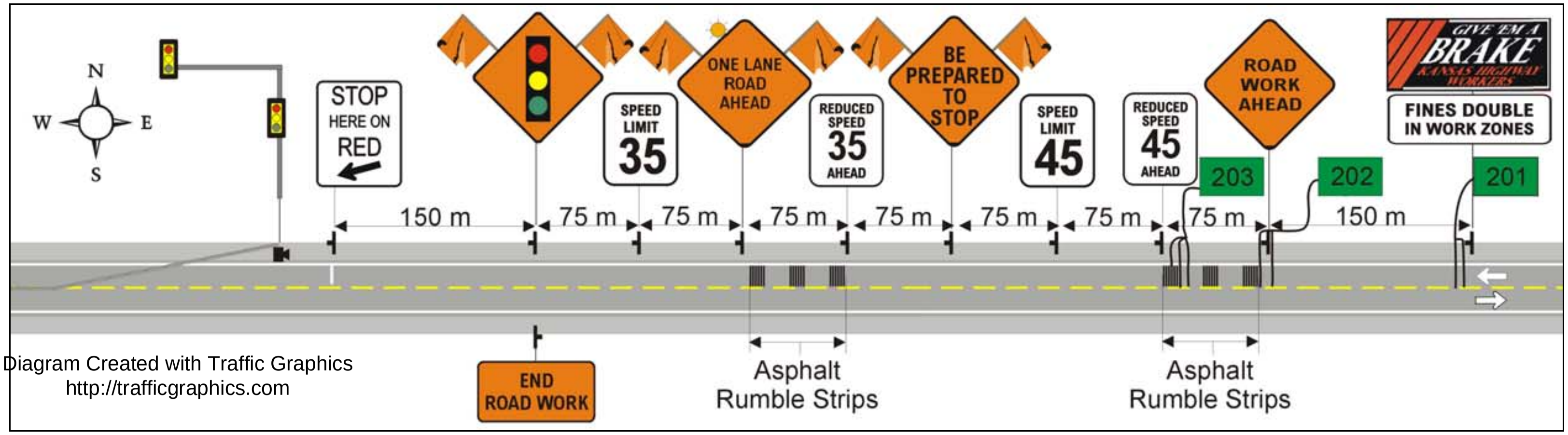


Figure 2.3: Westbound Approach at Rumbler Test Site

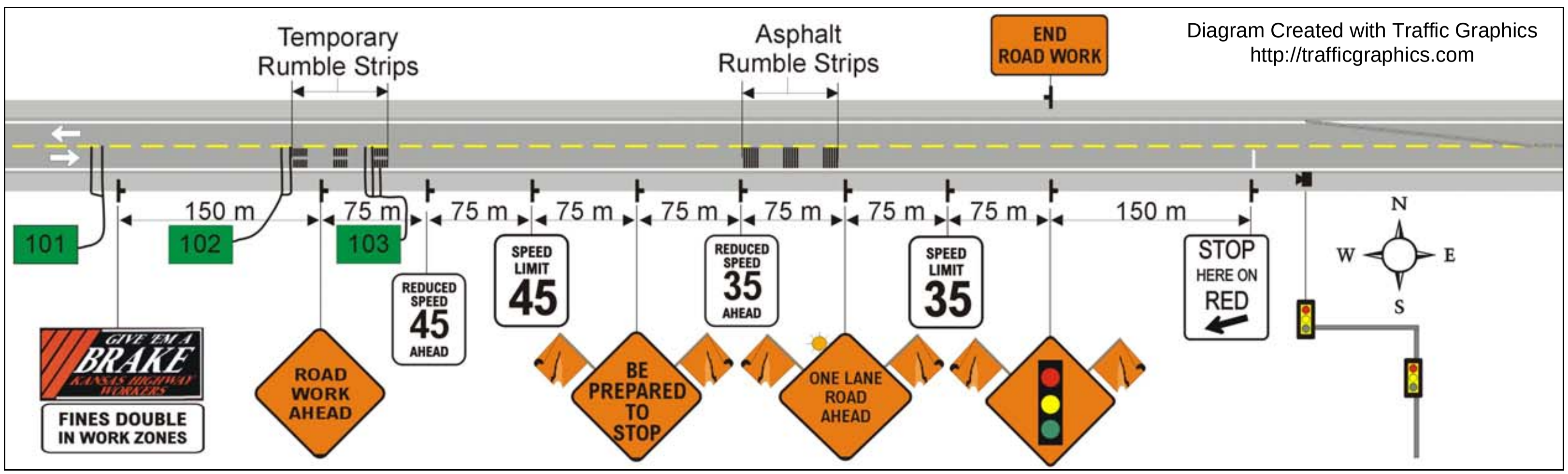


Figure 2.4 - Eastbound Approach at Rumbler Test Site

Deployment Configuration

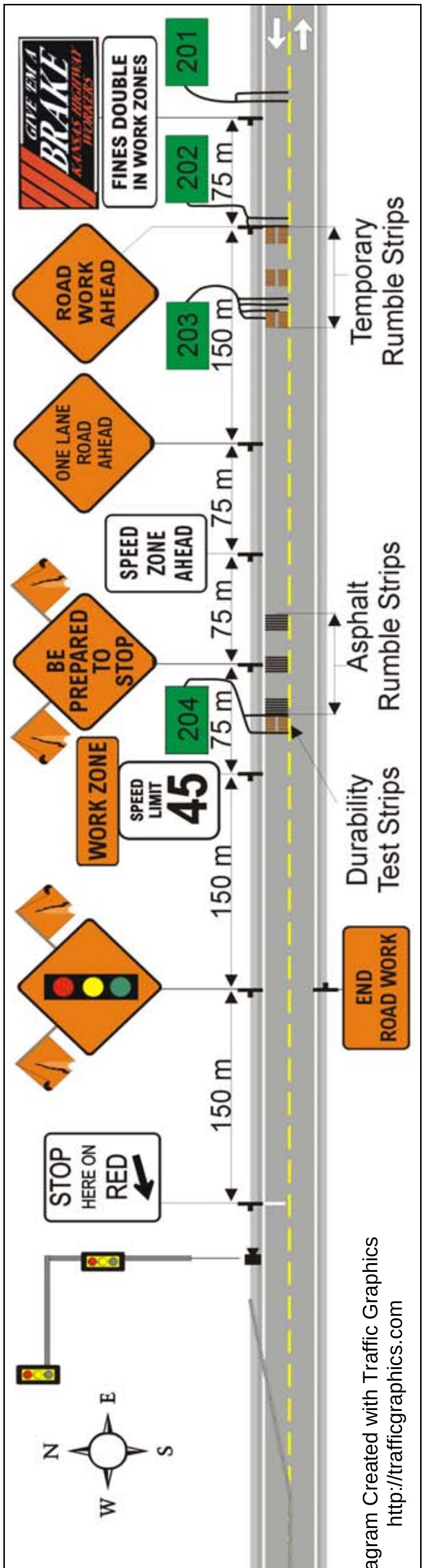


Figure 2.5: Westbound Approach at Orange Rumble Strip Test Site

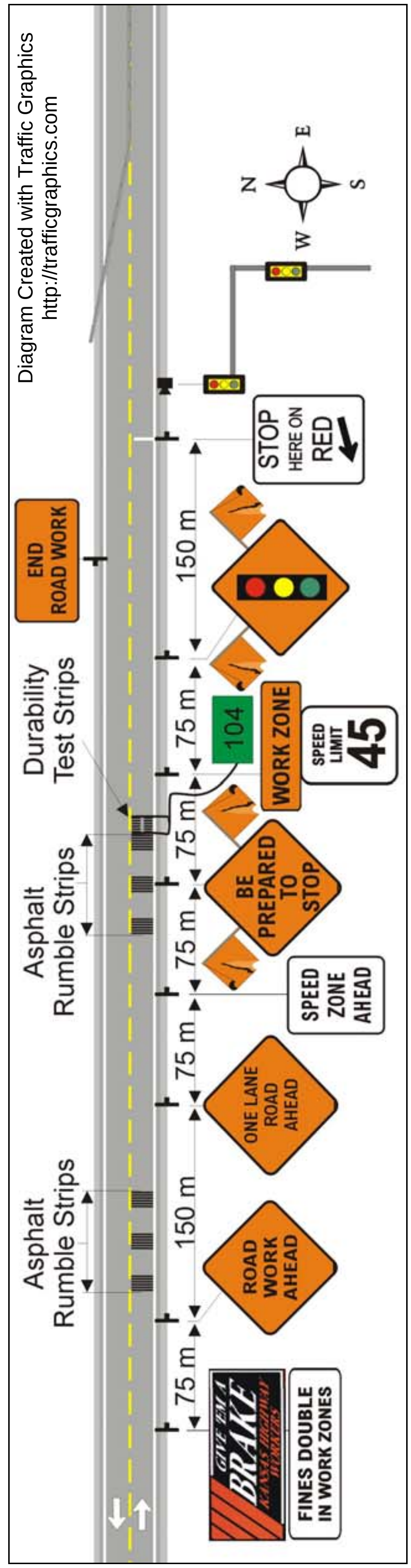


Figure 2.6: Eastbound Approach at Orange Rumble Strip Test Site

The strips are most commonly applied using cold mix asphalt in a configuration comprised of two sets of strips on a given work zone approach. The sets are spaced 152 – 228 m (500 – 750 ft) apart, with the downstream set being 305 m (1000 ft) upstream of the stop bar. Each set contains three groups with 31 m (100 ft) between groups. Each group contains six rumble strips, spaced 0.6 m (2 ft) center to center. These strips often stretch across the entire width of the lane, although a 0.6 to 1.22 m (2 to 4 ft) channel is sometimes left in the center of the strips for motorcycles. In order to compare the two types of removable rumble strips to the asphalt rumble strips, the removable rumble strips were deployed using a similar pattern. A gap was included in the center of the lane, and a 15.2 cm (6 in) space was left beween the edge of the strips and both the edge-line and the centerline. A center gap of 0.9 m (3 ft) was used for the Rumbler location, which had 3.7 m (12 ft) lanes, and a gap of 0.6 m (2 ft) was used for the orange rumble strip test location, which had 3.4 m (11 ft) lanes.

Figure 2.7 shows diagrams of a typical rumble strip deployment for a single approach, a set of rumble strips, and a single group of removable rumble strips.

Sound and vibration data were collected prior to deploying the speed data collection equipment so that the pneumatic hoses would not affect the sound and vibration levels measured. The next chapter discusses the methods used to collect and analyze the sound, vibration, and roadside noise data, and the subsequent chapter discusses the collection and analysis of the vehicle speeds.

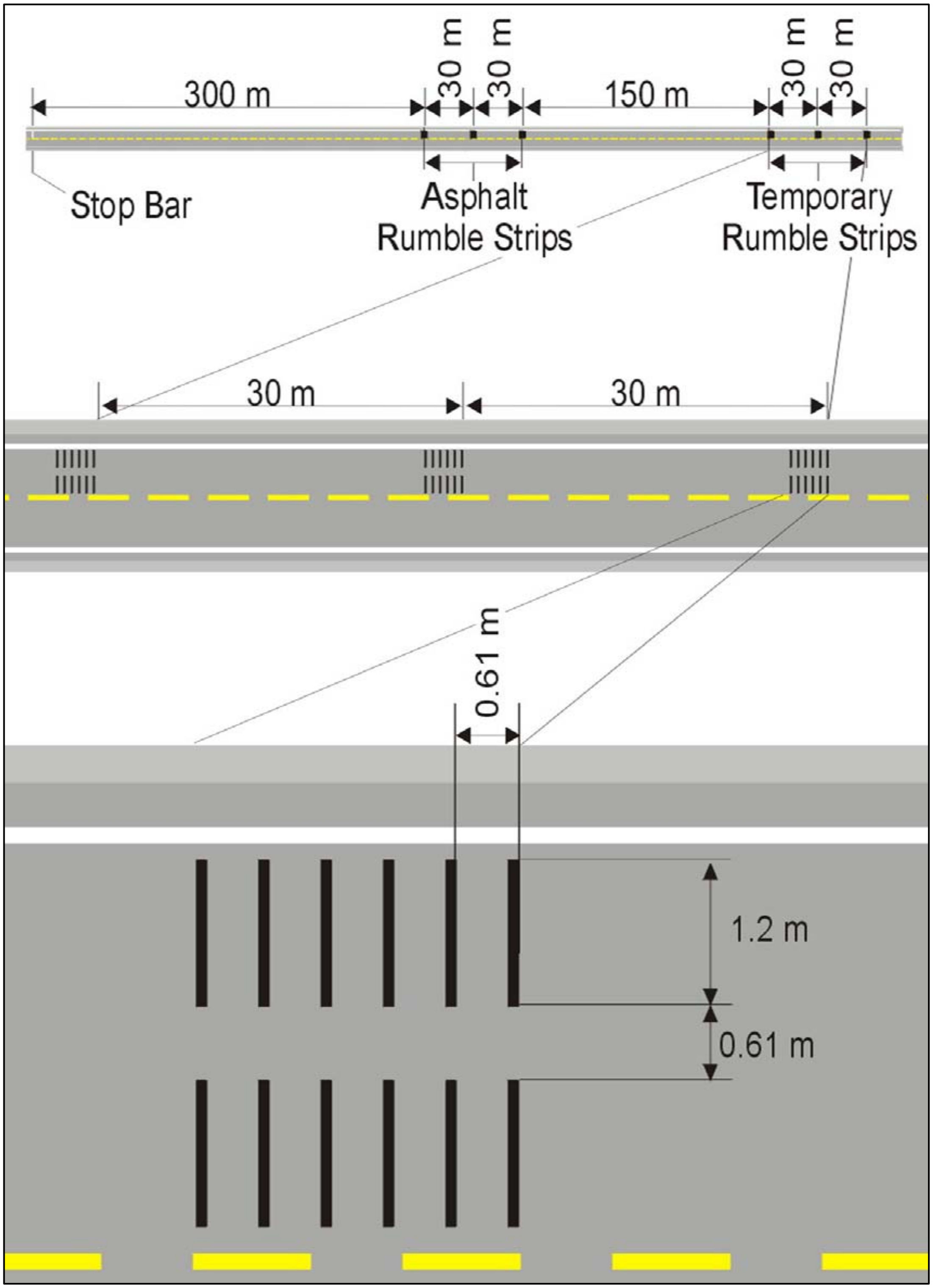


Figure 2.7: Typical Experimental Rumble Strip Deployment

CHAPTER 3

SOUND, VIBRATION, AND ROADSIDE NOISE

The sound and vibration levels produced as a vehicle traverses the strips were used as the principle measures of effectiveness. Roadside noise levels were also measured for the standard configurations of the strips. This chapter outlines the methods used to collect and analyze the data and discusses the results of the analyses.

3.1 Methodology

In-vehicle sound, vehicle body vibration, and roadside noise were measured for the three types of rumble strips using the Kansas Department of Transportation standard configuration and several combinations of speed and vehicle type. Additional tests were conducted using the orange rumble strips to examine the effects of various changes in the configuration of the strips on the sound and vibration levels produced.

3.1.1 Vehicles and Speeds

Three vehicles were used for testing, a typical compact car (1998 Ford Escort SE), a typical midsize passenger car (1992 Honda Accord LX), and a dump truck (Kansas Department of Transportation Maintenance Truck). Table 3.1 shows the characteristics of the test vehicles. Except where noted, the sound and vibration measurements were taken for each vehicle at each of three speeds, 64, 80, and 97 kph (40, 50, and 60 mph), typical approach speeds for highway work zones.

Table 3.1: Test Vehicle Parameters

	Test Vehicle		
Parameter	Compact	Midsize	Truck
Manufacturer	Ford	Honda	Sterling
Model	Escort SE	Accord LX	LT-7501
Year	1998	1992	N/A
Length (in)	174.7	185.2	N/A
Width (in)	67	67.1	96
Height (in)	53.3	54.7	116
Weight (lb)	2468	2857	47000
Wheel base (in)	98.4	107.1	204
Number of Axles	2	2	3
Ground Clearance (in)	N/A	6.3	N/A
Tires	185/65-14	185/70-14	275/80-22
Inner Diameter (in)	14	14	22
Outer Diameter (in)	23.5	24.2	39.3
Width (in)	7.3	7.3	10.8
Pressure (psi)	35	34	95-105
Number of Tires	4	4	10

3.1.2 Measurement Details

To better understand how the driver would perceive each type of rumble strip, sound inside the vehicle and vibration of the vehicle body were measured. Roadside noise levels were also measured because of concerns that the removable rumble strips may create too much roadside noise for use in some areas. Sound and vibration levels were measured as Equivalent Sound Level (Leq) in decibels (dB). Table 3.2 shows sound levels in dB for common sounds. The measurements were recorded using a Norsonic Nor-110 Sound/Vibration Analyzer, shown in Figure 3.1. Leq values were recorded in the time domain using a 3 ms measurement interval. The vibration levels were measured on a linear scale (i.e., no frequency weighting), and the sound levels were measured using an A-Weighting filter. This filter is used to transform the levels collected by a microphone (sound energy scale) into levels that would be perceived by a human (perceptual loudness scale). Humans have difficulty hearing very low or very high frequency sounds. The A-Weighting filter simply accounts for this characteristic of human hearing, and makes adjustments to the Leq based on the frequency of the sound so that the recorded data are more representative of what a typical human would perceive. [13] Figure 3.2 shows the A-Weighting filter.

Table 3.2: Typical Sound Levels for Common Sounds in Decibels (dB)

Soft whisper	30 dB
Refrigerator	40 dB
Normal conversation	50 dB
Television	60 dB
Noisy restaurant	70 dB
Dishwasher	75 dB
Blow dryer	80 dB
Electric razor	85 dB
Lawn mower	90 dB
Roar of crowd	95 dB
Power tools	100 dB
Stereo headset	110 dB
Rock concert	120 dB
.22 caliber rifle	130 dB
Jet take-off	140 dB

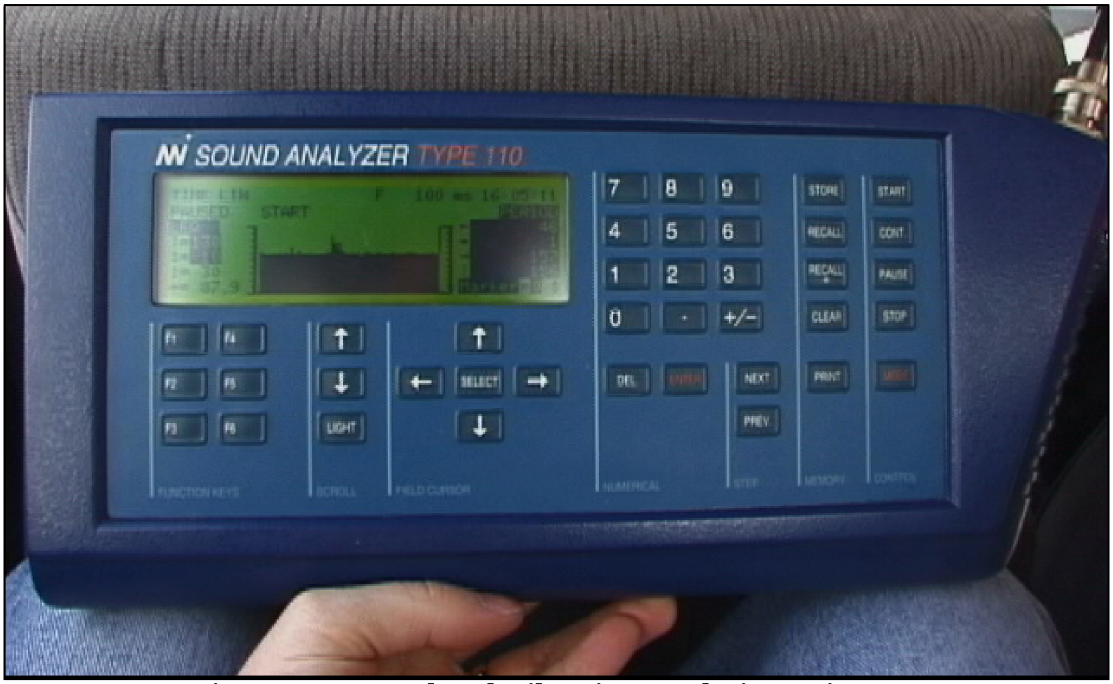


Figure 3.1: Sound and Vibration Analysis Equipment

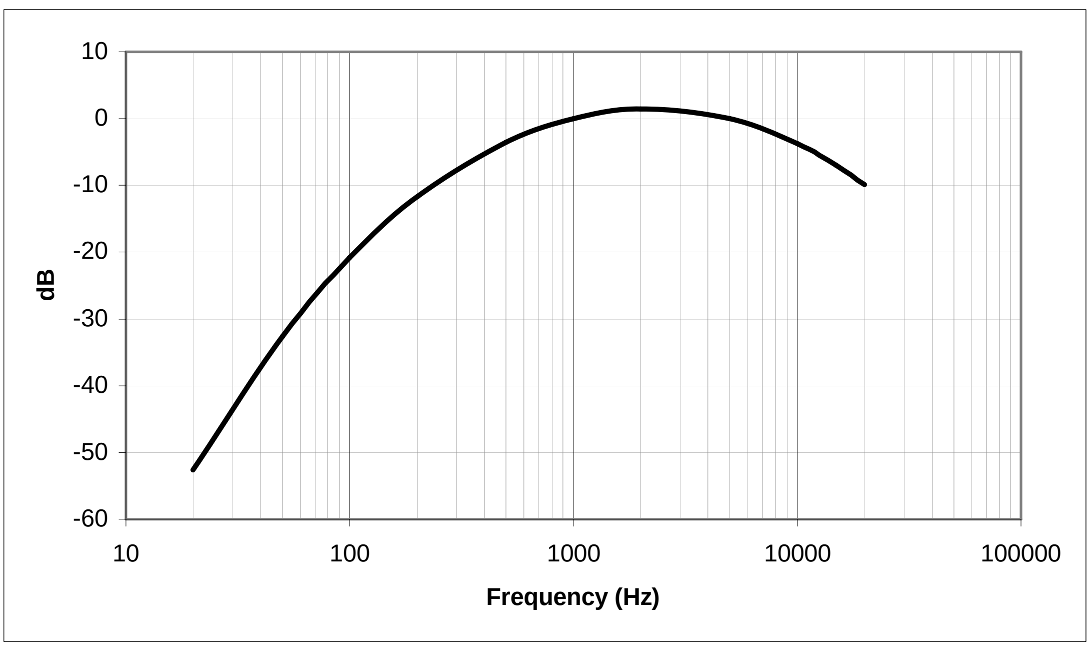


Figure 3.2: A-Weighting Filter

A computer program was developed to help simplify and expedite the data analysis process. The program was used to find the maximum Leqs using certain default parameters and minimal user interaction. The maximum Leqs were then exported to a file with additional data indicating the condition for which the maximum was obtained. Figure 3.3 shows a plot of the data recorded for a typical sound level measurement (one group of strips), and Figure 3.4 shows a screenshot of the data analysis program, depicting date for two sets of strips.

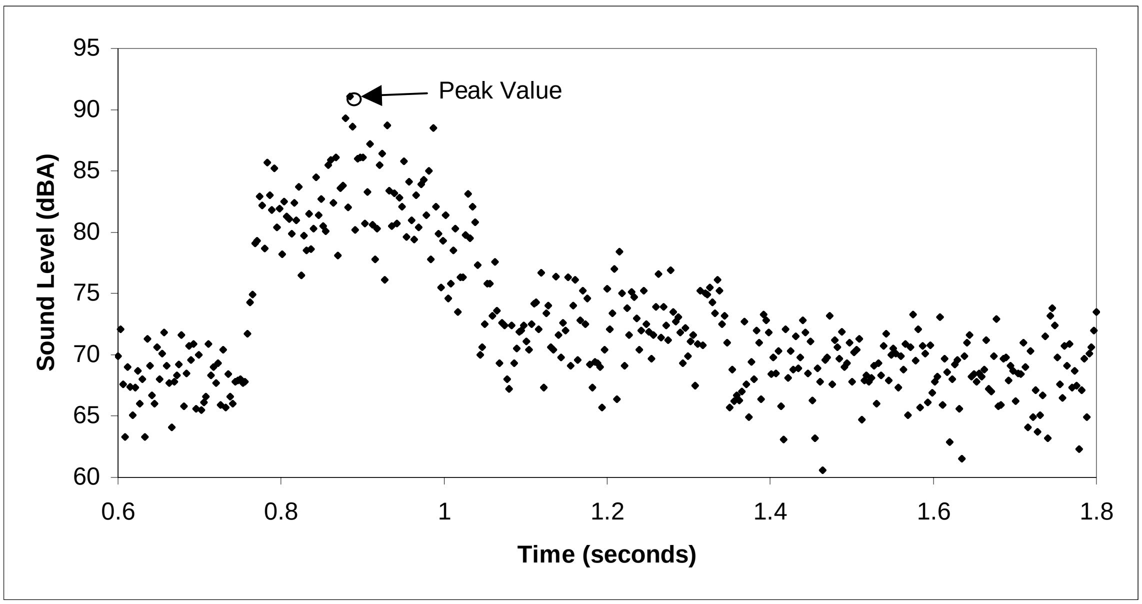


Figure 3.3: Typical Sound Level Measurements

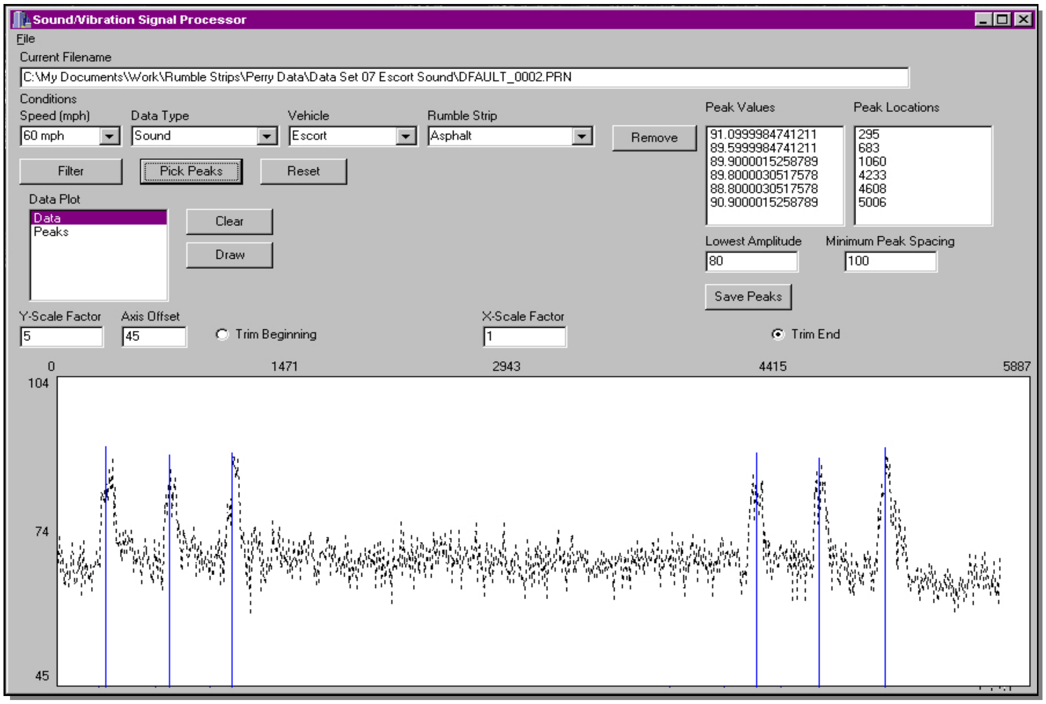


Figure 3.4: Screenshot of Sound and Vibration Data Analysis Program

3.1.3 Instrument Placement

3.1.3.1 In-Vehicle Sound

The in-vehicle sound data were recorded by placing the microphone on a tripod, with the microphone oriented horizontally forward, centered between the driver and passenger seat, 19.1 cm (7.5 in) below the ceiling and even with the joint between the seat back and seat bottom of the driver’s seat. The microphone was placed at this location because it was approximately the same level as the typical driver's ear. Tests were performed to determine in what way and to what extent the radio and air-conditioner noise would affect the in-vehicle sound levels. All other measurements were taken with the windows rolled up and the air-conditioner and stereo turned off. Figure 3.5 shows the measurements collected with the added in-vehicle noise due to the stereo and the air conditioner. The chart shows that the increase in the sound levels caused by the added noise affected the baseline data the strips data by approximately the same amount.

This suggests that moderate noise such as that exemplified by the stereo and air conditioner in these tests will increase the sound levels in the vehicle but will not have a large effect on the magnitude of changes in sound levels relative to a baseline value. On this basis, it is reasonable to assume that the differences determined under the near-ideal conditions of this study are representative of the differences that would be experienced in most situations.

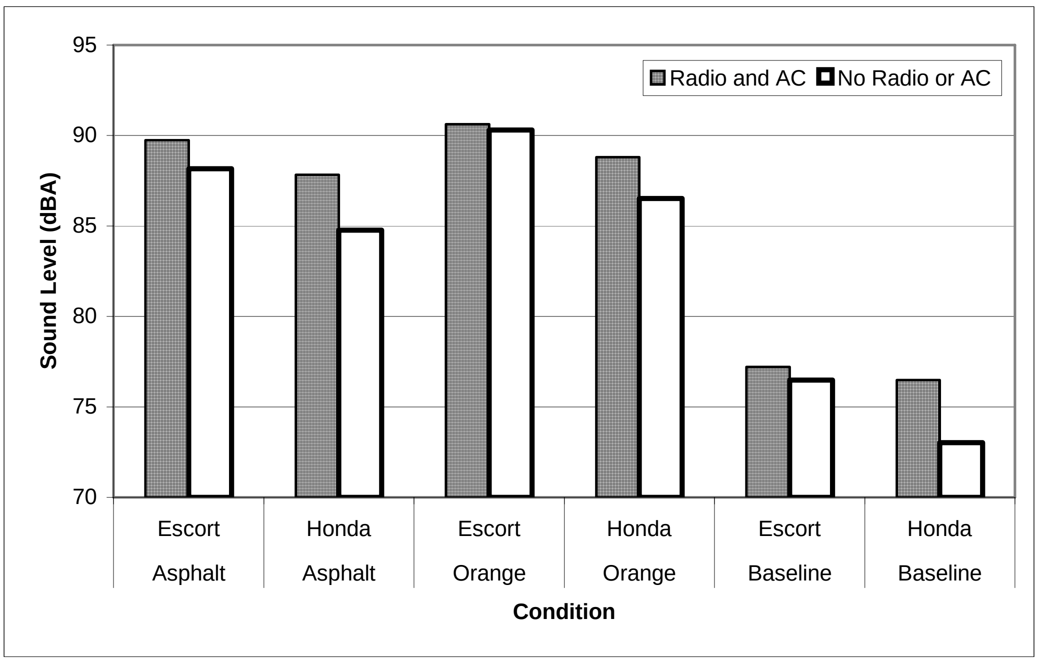


Figure 3.5: Sound Levels with and without the Radio and Air Conditioner

3.1.3.2 Vehicle-Body Vibration

There are several paths through which the vibration caused by the interaction of the tires and the road surface can propagate through the vehicle to the driver's body. The driver could potentially feel vibration through the steering wheel, the seat bottom, the seat back, or the floor of the vehicle. The amount of vibration that would be transferred through each of these means may vary significantly from vehicle to vehicle, depending on the properties of the vehicle, such as the suspension system, the type, quality, and wear of the seat, and any damping mechanism between the steering wheel and the tires. Further, the perception of the vibration by the driver may vary with the type of clothing worn, the build and weight of the driver, the force with which the driver grips the steering wheel, and the position of the driver at the time of the incident vibration. Because of the number of unknowns and the amount of variability, direct measurement of the vibration perceived by the driver is impractical.

To account for the role of vibration using a parameter that can be feasibly measured, it was assumed that the vibration as perceived by the driver relative to a baseline value would be directly related to the relative vibration of the vehicle body. Based on this assumption, comparisons between rumble strips could be made. Thus, the measure of effectiveness related to vibration was designated to be vehicle body vibration, the vibration of the vehicle body measured from the center of the roof. The vehicle body vibration was measured using a unidimensional accelerometer magnetically mounted to the roof of the vehicle, oriented along the vertical axis, and positioned directly above the interior mounting location of the microphone. Figure 3.6 shows the accelerometer mounted to the roof of a test vehicle on the left and the microphone on a tripod inside of a test vehicle on the right.

3.1.3.3 Roadside Noise

The Federal Highway Administration's standards were followed for the roadside noise measurements. The microphone was mounted on a tripod and placed on the shoulder of the road approximately 15.2 m (50 ft) from the center of the lane in which the test vehicle would be driven and 1.5 m (5 ft) above the road surface. [16] The microphone was oriented perpendicular to the roadway and was equipped with a foam windscreen to reduce the effect of wind noise on the data.

Figure 3.6: Accelerometer (Left) and Microphone (Right)

3.1.4 Comparing Measurements

The maximum Leq observed while driving over the rumble strips relative to that observed over smooth pavement was the measure of effectiveness used for both sound and vibration. When multiple observations of the same condition were made, the average of the maximum Leq values was used. By using the difference in maximum Leq relative to smooth pavement, differences between locations such as wind speed, temperature, and atmospheric pressure, can be removed from the data. The relative values measured for the three types of rumble strips can be directly compared.

The relative maximum Leq values were subjected to Analysis of Variance (ANOVA) tests. In this case, the ANOVA tests were used to simply determine whether or not the difference between the means of the two data sets was statistically significant. A confidence level of 95% was used in all of the comparisons. An ANOVA test was performed for each comparison between the three types of strips.

3.1.5 Hearing Limitations

The effectiveness of rumble strips is a function of not only the sound and vibration levels occurring, but also of human perception. Even though direct measurement of driver perceptions is infeasible, perceptibility must be considered in the interpretation of the data. For example, a difference in sound and vibration levels that is detectable by a vibration analyzer may not be detectable by a typical driver, in which case there will be no effect. The difference may be statistically significant, indicating that one strip is indeed louder than another, but if the difference is so small that it would not be perceived by the driver, the difference is not practically significant, meaning that there would be no effect on driver behavior.

The smallest detectable change in sound level is 1 dB, and a change of 3 dB is a slightly noticeable difference for most people. [17] Therefore, if one set of strips were only 1 dB louder than another, to say that it produced more sound would be misleading, because from a human's perspective both types would seem equally loud. Furthermore, a 1 dB difference is only detectable under ideal conditions. 3 dB is a more appropriate threshold for considering a difference to be practically significant in field tests such as those in this study. So, if the sound levels produced by two groups of rumble strips differ by less than 3 dB, then they are considered to perform equally well with respect to the sound produced inside the vehicle or at the roadside.

3.1.6 Vibration Perception

The threshold at which differences in vibration become detectable by humans is not well defined. Most studies involving the perception of vibration are done in order to find the limits at which vibration becomes discomforting or hazardous, but little attention has been given to the human ability to differentiate one vibration from another nearly equal vibration. [18] These studies typically rely on simple harmonic vibrations caused by machines, which are quite different from the vibrations consisting of a wide range of frequencies and amplitudes experienced while driving over rumble strips. Additionally, the measures used are generally subjective, and therefore an objective threshold is difficult to specify. [19, 20] In light of these complicating issues, 3 dB is taken as the threshold of perceptibility of vibration in order to provide symmetry with the sound measurements. Subjective evaluation of this threshold during the study affirmed that 3 dB is a reasonable value.

3.2 Results for Rumble Strip Type Comparisons

3.2.1 In-Vehicle Sound

In most cases, the differences between the three types of strips were neither statistically significant nor noticeable. Table 3.3 shows comparisons of in-vehicle sound levels relative to levels experienced on smooth pavement. There were no in-vehicle sound comparisons that yielded differences that were statistically significant but not noticeable. Comparisons that yielded both statistically significant and noticeable differences are highlighted in Table 3.3. The rumble strip comparisons that show the greatest difference are those involving the orange rumble strips being traversed by the dump truck. When the orange rumble strips were compared to the asphalt rumble strips at the same location, the levels measured in the dump truck were statistically and noticeably lower for the orange rumble strips than for the asphalt strips. This may be because the orange rumble strips are the least thick of the three strips and the dump truck has very large tires. Regardless of the reason or the noticeable amount of difference between the two strips, the orange rumble strips still create in-vehicle sound levels that are noticeably greater than the levels on produced by the smooth pavement, and would therefore be noticeable to the driver of the dump truck. It can also be seen that the asphalt strips at one location produce significantly different sound levels in the Honda Accord than the asphalt rumble strips at the other location. While this is not much of a concern for these sets of strips, since both produce easily noticeable sound levels, it is possible that this difference is an indication that the variation inherent to the cross-sections of asphalt strips can have a significant effect on the levels of sound these strips produce.

Table 3.3: In-Vehicle Sound Comparisons

Vehicle	Compact Car			Midsize Car			Dump Truck		
Speed, kph (mph)	64 (40)	80 (50)	97 (60)	64 (40)	80 (50)	97 (60)	64 (40)	80 (50)	97 (60)
Asphalt (Perry)	+15	+14	+13	+15	+16	+16	+10	+9	+7
Asphalt (Horton)	+14	+12	+12	+12	+12	+13	+12	+10	+8
Rumbler (Perry)	+14	+15	+13	+16	+15	+14	+11	+8	+5
Asphalt (Perry)	+15	+14	+13	+15	+16	+16	+10	+9	+7
Orange (Horton)	+14	+14	+14	+14	+13	+15	+6	+6	+5
Asphalt (Horton)	+14	+12	+12	+12	+12	+13	+12	+10	+8
Rumbler (Perry)	+14	+15	+13	+16	+15	+14	+11	+8	+5
Orange (Horton)	+14	+14	+14	+14	+13	+15	+6	+6	+5

- Values are in dB relative baseline, which are the measurements collected on smooth pavement.
- Highlighted values show statistically significant and noticeable differences.
- Underlined values show statistically significant but not noticeable differences.

3.2.2 Vehicle Body Vibration

The data collected for vehicle body vibration show characteristics similar to those observed in the data collected for in-vehicle sound. Table 3.4 shows the comparisons of vehicle body vibration for the three types of rumble strips. Comparisons that yielded statistically significant and noticeable differences are shaded with gray, and comparisons that yielded differences that were statistically significant but not noticeable are underlined. Overall, differences in vibration Leqs were greater than those observed for the sound measurements. The relative vibrations observed in the dump truck were generally less severe than those observed in the two passenger cars. There were not consistent patterns in variation between the three types of strips. In most cases, the vibration decreased as speed increased. The patterns in the data were not consistent enough to draw any hard conclusions, but this pattern does raise questions about the effectiveness of rumble strips used for purposes of speed reduction. It is important to note that this phenomenon was observed on both the removable rumble strips and the asphalt strips.

Table 3.4: Vehicle Body Vibration Comparisons

Vehicle	Compact Car			Midsize Car			Dump Truck		
Speed, kph (mph)	64 (40)	80 (50)	97 (60)	64 (40)	80 (50)	97 (60)	64 (40)	80 (50)	97 (60)
Asphalt (Perry)	+16	+14	+14	+21	+13	+12	+13	+10	+4
Asphalt (Horton)	+14	+13	+15	+15	+14	+11	+11	+15	+11
Rumbler (Perry)	+16	+10	+9	+13	+14	+13	+15	+8	+3
Asphalt (Perry)	+16	+14	+14	+21	+13	+12	+13	+10	+4
Orange (Horton)	+13	+11	+16	+14	+16	+12	+8	+15	+9
Asphalt (Horton)	+14	+13	+15	+15	+14	+11	+11	+15	+11
Rumbler (Perry)	+16	+10	+9	+13	+14	+13	+15	+8	+3
Orange (Horton)	+13	+11	+16	+14	+16	+12	+8	+15	+9

- Values are in dB relative to baseline, which are the measurements collected on smooth pavement.
- Highlighted values show statistically significant and noticeable differences
- Underlined values show statistically significant, but not noticeable difference.

3.2.3 Roadside Noise

Some rumble strip deployments have met with complaints from neighboring areas about excessive noise levels. Such complaints can necessitate expensive noise exposure studies and potentially noise abatement measures. [21, 22] These types of complaints are more commonly associated with permanent rumble strip deployments, partly because noise in work zones is considered by the public and by officials to be necessary and temporary. Consequently, they are not necessarily subject to the same criticisms voiced for permanent installations. However, when temporary rumble strips are to be in place for an extended period of time (e.g., more than a few weeks), the impact of sound from rumble strips on the neighboring community merits some consideration.

The amount of roadside noise that is acceptable depends on several factors. The noise level and pitch, the frequency of occurrence, the duration of the noise, proximity of dwellings to the roadside, terrain, the propagation of the noise through walls (affects noise levels that would be experienced inside someone's home), and the time of day that the noise occurs are all common factors that are used to determine if a noise level is excessive. In typical noise studies, most of the contributing factors are lumped into a single parameter, L10, which is the noise level exceeded 10 percent of the time. L10 accounts for the noise level and pitch, the frequency of occurrence, and the duration of the noise. L10 maximums are commonly given for day, night, and type of area. [16, 23] Because L10 is as much a function of traffic patterns as it is of strip type, it is very site specific. Because this study is seeking to draw more general conclusions about the applicability of removable rumble strips to work zones, L10 is not an appropriate measure for this study. Instead, roadside noise Leqs were considered. The roadside noise Leqs alone cannot determine whether a type of rumble strip is either acceptable or unacceptable for use, but will provide a means of comparing between strip types. Table 3.5 shows the maximum roadside noise levels generated by the three types of rumble strips.

Table 3.5: Maximum Roadside Noise L_{eq}s

Vehicle	Compact Car			Midsize Car			Dump Truck		
Speed, kph (mph)	64 (40)	80 (50)	97 (60)	64 (40)	80 (50)	97 (60)	64 (40)	80 (50)	97 (60)
Baseline (Perry)	76	77	80	72	76	80	-	-	-
Asphalt (Perry)	+3	+5	+4	+5	+5	+2	-	-	-
Rumbler (Perry)	+11	+11	+9	+13	+12	+7	-	-	-
Baseline (Horton)	78	85	83	80	84	87	82	82	85
Asphalt (Horton)	-	-	-	-	-	-	-	-	-
Orange (Horton)	+4	+2	+4	+2	+2	0	+3	+2	+3

- Baseline values are in dB and others are in dB relative to baseline
- '-' indicates that no measurement is available.
- Most values represent a single measurement, therefore ANOVA tests cannot be used to determine the statistical significance of differences.

Table 3.5 shows that the roadside noise caused by the Rumbler rumble strips was noticeably greater than the noise caused by the orange rumble strips and the asphalt strips. More detailed analysis should be considered before using the Rumbler rumble strip in noise sensitive areas, such as highly developed residential areas. Special care should be given to nighttime conditions, because this is when residential areas are most sensitive to noise. Unlike most construction noise, the noise caused by rumble strips continues throughout the night and varies depending upon the number of vehicles traversing the strips during these hours.

3.3 Methodology for Configuration Tests

In addition to comparing the removable strips with the asphalt strips, this study sought to determine the extent to which strip configuration affected sound and vibration. Data were collected for 15 configurations, as detailed in Table 3.6. The rumble strips used for the configuration tests were the orange rumble strips, which are approximately 4 mm (0.15 in) thick and 10 cm (4 in) wide. Since a single thickness of the rumble strips had been previously determined to be inadequate [7, 15], the strips were applied one on top of another in order to double the thickness. One group of strips was installed using only a single thickness and the standard configuration so that the affect of the thickness on sound and vibration could be quantified.

Table 3.6: Details for Experimental Configurations

Configuration	Height, mm (in)	Number of Strips	Spacing (On Center) cm (in)	Offset cm (in)	Parameter of Interest	Notes (See Below)
Asphalt Std	19.1 (0.75)	6	61 (24)	0	Thickness	
Orange Std	7.6 (0.3)	6	61 (24)	0	Thickness	
1	3.8 (0.15)	6	61 (24)	0	Thickness	
2	7.6 (0.3)	6	31 (12)	0	Spacing	*
3	7.6 (0.3)	8	46 (18)	0	Spacing	
4	7.6 (0.3)	5	76 (30)	0	Spacing	
5	7.6 (0.3)	4	91 (36)	0	Spacing	*
6	7.6 (0.3)	4	122 (48)	0	Spacing	*
7	7.6 (0.3)	8	46 (18)	23 (9)	Offset	
8	7.6 (0.3)	6	61 (24)	31 (12)	Offset	
9	7.6 (0.3)	10	61 (24)	0	Length	
10	7.6 (0.3)	11	31 (12)	0	Length	*
11	7.6 (0.3)	6	23, 262 (9, 104)	0	Multiple	1
12	7.6 (0.3)	6	46, 97 (18, 38)	0	Multiple	2*
13	7.6 (0.3)	12	23, 193 (9, 76)	0	Multiple	3*

Notes:
* - L_{eq} values for these sets are from a single trial for each condition
1 - 2 triplets of strips spaced at 23 cm (9 in), and 2.62 m (104 in) between triplets
2 - 3 pairs of strips spaced at 46 cm (18 in), and 97 cm (38 in) between pairs
3 - 2 triplets of 6 strips spaced at 23 cm (9 in), and 1.93 m (76 in) between triplets

While these tests do not relate directly to any comparisons between the removable strips and the asphalt strips, they do help to determine if a comparison between the asphalt strips and the orange strips using a configuration other than the standard would be more appropriate. If the standard configuration of the orange rumble strips were the configuration that produced the least amount of sound and vibration, then a comparison between the asphalt strips and the orange strips using this configuration would be inconclusive, since the degree to which an improved configuration could compensate for the lesser thickness would be unknown.

Fifteen configurations were tested with both the compact and the midsize passenger cars. Eight of the configurations were also tested with a dump truck. The experimental configurations were deployed for a few hours at the same test site as the standard orange rumble strip configuration, Kansas State Route 20 west of Horton, Kansas. Figure 3.7 is a generalized diagram of a rumble strip configuration with spacing and offset indicated.

Figure 3.8 is a generalized diagram of the rumble strip configurations that had multiple spacings. The standard configuration in Kansas uses six strips with no offset and a spacing of 0.6 m (2 ft). This was used as the baseline configuration. Table 3.6Table shows descriptive parameters for each of the configurations tested. The first twelve configurations listed used uniform spacings. The last three configurations (11, 12, and 13) were based on the results of a test conducted by the New Jersey Department of Transportation. [13] Configurations 11, 12 and 13 used a combination of spacings in an attempt to capitalize on the advantages of both spacings identified in the New Jersey study.

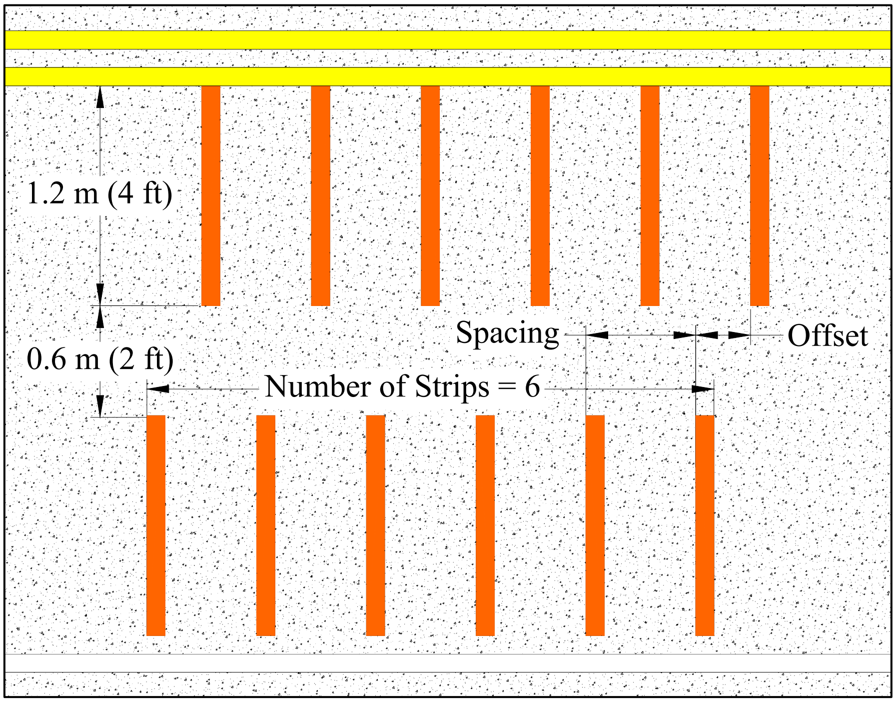


Figure 3.7: Experimental Configuration Diagram

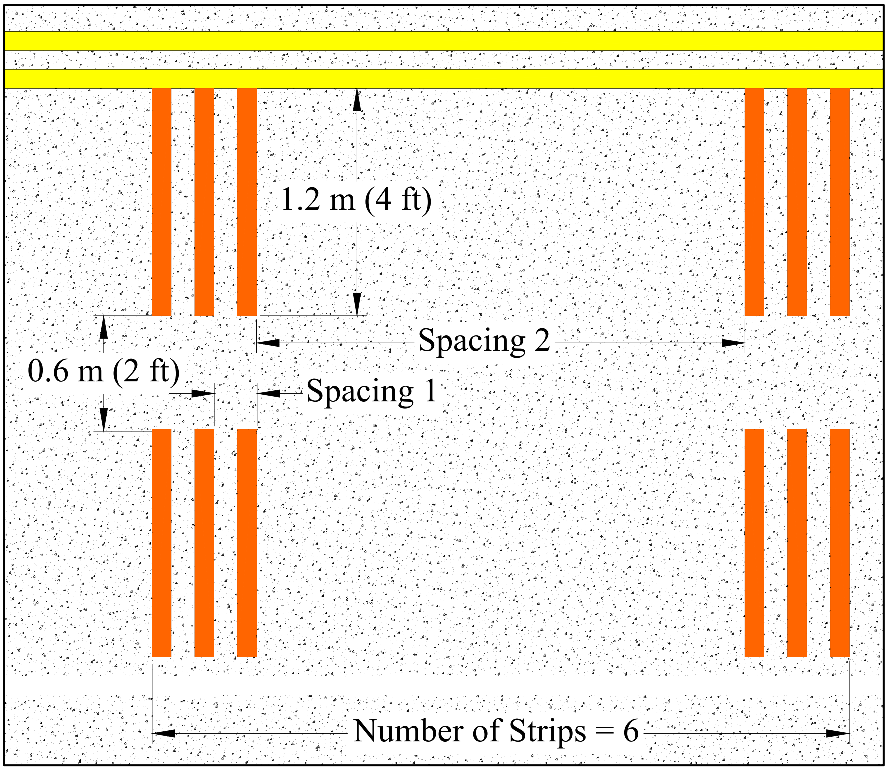


Figure 3.8: Alternate Spacing Configuration Diagram

The sound and vibration data for the configuration tests were collected over a period of two days. At the end of the first day, the data were examined to determine which configurations had performed the best in order to plan more focused testing during the second day. It had also been determined that the variation between subsequent measurements of the same condition was small enough, less than 2 dB in most cases, to allow a single trial per condition to adequately describe the levels produced. This allowed for more combinations to be tested in a limited period of time, but regretfully precluded the application of ANOVA techniques for determining the statistical significance of the differences in the means. In order for the trials with a single measurement to be compared to baseline configurations using the ANOVA test, it was necessary to estimate their standard deviations. This was done using the calculated standard deviations for all similar conditions. The distribution of the calculated standard deviations was analyzed, and the 95th percentile standard deviation was used as the estimate for the tests with only a single measurement. While this method may not be as statistically robust as could be obtained with unlimited time and resources, it is sufficient to provide a reasonable means of comparison, and the results should tend to be conservative.

3.4 Results for Configuration Tests

The results for the configuration tests are split into five categories based on the property of the configuration that was varied for each set of tests. The categories are cross-section, spacing, alternate spacing, offset, and length. The following sections present the results of the sound and vibration data comparisons. Table 3.7 through Table 3.11 display the values of the sound and vibration measurements relative to a given baseline configuration. For the baseline configuration in each case, the actual collected sound and vibration levels in decibels (dB) are shown, indicated with bold type. Highlighted values are noticeable differences that are statistically significant at the 95% level. Underlined values are differences that are statistically significant but not noticeable.

3.4.1 Cross-Sectional Profile

Table 3.7 shows the sound and vibration levels for the tests in which the cross-section was varied. Intuitively, as the height of the strip increases, the sound and vibration should also increase. However, it can be seen from the data that even though the asphalt rumble strip is about three times the height of the orange rumble strips, with all else held constant, the orange rumble strips generally produce greater sound and approximately the same vibration for the passenger cars. The asphalt rumble strips were typically smooth-edged and rounded on top, whereas the orange rumble strips have a rectangular cross-section. The asphalt rumble strips are also approximately 30 cm (12 in) wide, which is three times the width of the orange rumble strips. See Figure 2.1 on page 12 for a comparative profile of the two types of strips.

Table 3.7: Results for Cross-Section Tests

				Sound									Vibration								
				Compact Car			Midsize Car			Dump Truck			Compact Car			Midsize Car			Dump Truck		
Configuration	Height, mm (in)	Shape	Number of Strips	64 (40)	80 (50)	97 (60)	64 (40)	80 (50)	97 (60)	64 (40)	80 (50)	97 (60)	64 (40)	80 (50)	97 (60)	64 (40)	80 (50)	97 (60)	64 (40)	80 (50)	97 (60)
Smooth	0 (0)	Smooth	6	-14	-14	-14	-14	-13	-15	-6	-6	-5	-13	-11	-16	-14	-16	-12	-9	-16	-9
1	3.8 (0.15)	Rectangular	6	-5	-3	-3	-6	-4	-4	-	-	-	-6	-7	-5	-7	-4	-8	-	-	-
Orange Std	**7.6 (0.3)**	**Rectangular**	**6**	**88**	**91**	**93**	**86**	**87**	**90**	**87**	**88**	**89**	**89**	**89**	**93**	**93**	**98**	**97**	**105**	**104**	**98**
Asphalt Std	19.1 (0.75)	Domed	6	0	-2	-3	-2	-2	-2	+6	+4	+3	+1	+2	-1	+1	-2	-1	+3	0	+2

- Values are in dB relative to standard orange rumble strip configuration, which shows the measured values in dB and is indicated using bold type.
- Highlighted values show statistically significant and noticeable differences
- Underlined values show statistically significant but unnoticeable differences

3.4.2 Spacing

In general, the 0.6 m (2 ft) spacing produced the greatest sound and vibration Leqs. However, some dramatic increases in vibration Leqs were seen for the compact car at 64 kph (40 mph) for the 31 cm (12 in) and the 91 cm (36 in). Since the increase was so large, and the two conditions are related, one spacing being a denomination of the other, it is possible that these are caused by some resonance within the vehicle. Such a phenomena would be undesirable, especially since the increase is only at the slower speed. However, the 48 cm (18 in) spacing is also a denomination of 12 and no similar phenomena were observed for this condition. Additionally, these two unusually high Leqs were each taken from a single measurement, and, therefore, their accuracy cannot be verified. In other cases, however, measurements from similar tests were almost always within a few decibels of the average value. In the absence of additional information, the two measurements cannot be used to support any particular conclusion, and must be treated as statistical outliers and discounted. The overall results of the spacing tests indicate that the current 0.6 m (2 ft) spacing standard is appropriate, and will produce the maximum sound and vibration Leqs under the study conditions. Table 3.8 shows the sound and vibration data for the spacing tests.

Table 3.8: Results for Spacing Tests

				Sound									Vibration								
				Compact Car			Midsize Car			Dump Truck			Compact Car			Midsize Car			Dump Truck		
Configuration	Number of Strips	Spacing (On Center) cm (in)	Total Length m (ft)	64 (40)	80 (50)	97 (60)	64 (40)	80 (50)	97 (60)	64 (40)	80 (50)	97 (60)	64 (40)	80 (50)	97 (60)	64 (40)	80 (50)	97 (60)	64 (40)	80 (50)	97 (60)
2	6	31 (12)	1.6 (5.3)	-4	-3	+1	0	-1	-1	-2	-3	-1	+17	0	-1	-4	+5	+4	-	-6	0
3	8	46 (18)	3.3 (10.8)	+1	-1	-3	-2	-1	+1	-	-	-	0	+1	-3	-1	-6	-2	-	-	-
Orange Std	**6**	**61 (24)**	**3.1 (10.3)**	**88**	**91**	**93**	**86**	**87**	**90**	**87**	**88**	**89**	**89**	**89**	**93**	**93**	**98**	**97**	**105**	**104**	**98**
4	5	76 (30)	3.1 (10.3)	0	-2	-1	+1	-2	-5	-	-	-	-2	-3	-4	+2	-8	+6	-	-	-
5	4	91 (36)	2.8 (9.3)	-4	-3	-2	-1	-1	-6	-3	-3	-3	+19	-2	0	-3	-1	-4	-	-5	-3
6	4	122 (48)	3.8 (12.3)	-3	-4	-2	0	-2	-4	-4	-4	-2	-4	-2	-4	-3	-5	0	-	-11	-4

- Values are in dB relative to standard orange rumble strip configuration, which shows the measured values in dB and is indicated using bold type.
- Highlighted values show statistically significant and noticeable differences
- Underlined values show statistically significant but unnoticeable differences

3.4.3 Alternate Spacing

Table 3.9 shows the sound and vibration levels measured in the alternate spacing tests. The two tests conducted using the 23 cm (9 in) center-to-center spacing and 3.2 m (125 in) head-to-head spacing were, as mentioned earlier, motivated by the results of the New Jersey study.

[13] The sound and vibration observed for these configurations did vary from the standard configuration, but they did not vary consistently nor did the variation follow any recognizable pattern. The configuration with two groups of 3 strips showed significant and noticeable increases in both sound and vibration for the passenger cars. Time constraints precluded collecting data in the dump truck for this configuration. The configuration using two groups of 6 strips showed significant and noticeable decreases.

While increases may be possible with this type of configurations, limited data, especially for the truck, and conflicting data obtained on the longer group makes drawing conclusions from these results difficult. These potential increases may warrant further investigation into the use of these patterns, but since the increases were not consistent, their use cannot be recommended based solely on this study.

Table 3.9: Results for Alternate Spacing Tests

					Sound									Vibration								
					Compact Car			Midsize Car			Dump Truck			Compact Car			Midsize Car			Dump Truck		
Configuration	Number of Strips	Spacing1 cm(in)	Spacing2 cm(in)	Diagram	64 (40)	80 (50)	97 (60)	64 (40)	80 (50)	97 (60)	64 (40)	80 (50)	97 (60)	64 (40)	80 (50)	97 (60)	64 (40)	80 (50)	97 (60)	64 (40)	80 (50)	97 (60)
Orange Std	**6**	**61 (24)**	**0**	| | | | | |	**88**	**91**	**93**	**86**	**87**	**90**	**87**	**88**	**89**	**89**	**89**	**93**	**93**	**98**	**97**	**105**	**104**	**98**
11	6	23 (9)	262 (104)	III III	+1	+5	+1	0	+3	0	-	-	-	+1	+3	+1	+8	-1	-3	-	-	-
12	6	46 (18)	97 (38)	|| || ||	+1	-2	-4	0	+1	-4	+1	-5	-3	-1	-3	-2	-1	-6	+6	-	-10	-5
13	12	23 (9)	193 (76)	IIIIII IIIIII	-2	0	0	-1	-2	-2	+1	-2	+1	-3	0	0	+4	-4	-3	-	-8	-5

- Values are in dB relative to standard orange rumble strip configuration, which shows the measured values in dB and is indicated using bold type.
- Highlighted values show statistically significant and noticeable differences
- Underlined values show statistically significant but unnoticeable differences
-

3.4.3 Offset

An offset was added to the rumble strip configuration with the intent of increasing the number of collisions between the tires and the rumble strips, thus potentially generating more sound and vibration with the same amount of material and labor. However, by only having one tire hit the strips at a time, the amount of energy transferred by each collision would be significantly reduced. The net effect observed was no change or a small decrease in sound levels. None of the sound level increases were noticeable, but some of the decreases in sound level were noticeable. Overall, the configurations with no offset performed better than those with an offset. Table 3.10 shows the sound and vibration levels for the offset tests.

3.4.4 Length

Tests were conducted to investigate the effect of increasing the length of the rumble area by adding more strips. Intuitively, adding strips to a configuration already tested would either have no effect or would increase the sound and vibration levels. In the observations made, the sound or vibration Leqs were statistically higher in several cases, and noticeably so in three.

Table 3.11 shows the sound and vibration measurements for the tests that varied the length of the rumble strip groups. The configuration with 6 strips using the 31 cm (12 in) spacing produced some odd results for the compact car at 64 kph (40 mph). This particular measurement is discussed further in the section 3.4.2. The 106 dB baseline measurement is concluded to be a statistical outlier, and 91 dB (106 – 15) measurement is assumed to be the more accurate value.

Table 3.10: Results for Offset Tests

			Sound									Vibration								
			Compact Car			Midsize Car			Dump Truck			Compact Car			Midsize Car			Dump Truck		
Configuration	Offset cm(in)	Spacing (On Center) cm(in)	64 (40)	80 (50)	97 (60)	64 (40)	80 (50)	97 (60)	64 (40)	80 (50)	97 (60)	64 (40)	80 (50)	97 (60)	64 (40)	80 (50)	97 (60)	64 (40)	80 (50)	97 (60)
3	**0**	**46(18)**	**88**	**90**	**90**	**84**	**86**	**92**	**-**	**-**	**-**	**89**	**89**	**90**	**92**	**91**	**95**	**-**	**-**	**-**
7	23(9)	46(18)	+1	+2	+1	+1	+2	-1	-	-	-	-1	0	0	0	-1	-4	-	-	-
Orange Std	**0**	**61(24)**	**88**	**91**	**93**	**86**	**87**	**90**	**87**	**88**	**89**	**89**	**89**	**93**	**93**	**93**	**97**	**105**	**104**	**98**
8	31(12)	61(24)	+1	-4	-1	0	-1	-3	-	-	-	-3	-2	-3	0	0	-3	-	-	-

- Second row values are in dB relative to configuration number 3, which shows the measured values in dB and is indicated using bold type.
- Fourth row values are in dB relative to the standard orange configuration, which shows the measured values in dB and is indicated using bold type.
- Highlighted values show statistically significant and noticeable differences
- Underlined values show statistically significant but unnoticeable differences

Table 3.11: Results for Group Length Tests

				Sound									Vibration								
				Compact Car			Midsize Car			Dump Truck			Compact Car			Midsize Car			Dump Truck		
Configuration	Number of Strips	Spacing (On Center) cm (in)	Total Length m (ft)	64 (40)	80 (50)	97 (60)	64 (40)	80 (50)	97 (60)	64 (40)	80 (50)	97 (60)	64 (40)	80 (50)	97 (60)	64 (40)	80 (50)	97 (60)	64 (40)	80 (50)	97 (60)
Orange Std	**6 strips**	**61 (24)**	**3.1 (10.3)**	**88**	**91**	**93**	**86**	**87**	**90**	**87**	**88**	**89**	**89**	**89**	**93**	**93**	**98**	**97**	**105**	**104**	**98**
9	10 strips	61 (24)	5.6 (18.3)	+1	0	0	0	+1	-1	-	-	-	0	+1	+1	+1	+3	+1	-	-	-
2	**6 strips**	31 (12)	**1.6 (5.3)**	**83**	**88**	**94**	**86**	**85**	**89**	**84**	**85**	**88**	**106**	**88**	**92**	**89**	**103**	**101**	**-**	**98**	**99**
10	11 strips	31 (12)	3.1 (10.3)	+3	+3	-1	+4	+2	-1	0	+1	+1	-15	-1	0	+2	0	0	-	-3	-1

- Second row values are in dB relative to standard orange configuration, which shows the measured values in dB and is indicated using bold type.
- Fourth row values are in dB relative to configuration number 2, which shows the measured values in dB and is indicated using bold type.
- Highlighted values show statistically significant and noticeable differences
- Underlined values show statistically significant but unnoticeable differences

3.4.5 Sound Results

The only parameter that appeared to have an identifiable effect was the height. The greater height produced greater sound Leqs. The tests indicated that the KDOT standard configuration using the 0.6 m (2 ft) center to center spacing produced the greatest sound levels overall.

3.4.6 Vibration Results

The tests indicated that the KDOT standard configuration using the 0.6 m (2 ft) center to center spacing produced the greatest vibration levels overall.

CHAPTER 4

VEHICLE SPEEDS

The primary points of comparison between the removable rumble strips and the asphalt rumble strips were the sound and vibration levels. Speed reductions were used only as a secondary measure of effectiveness, because the effectiveness of rumble strips at reducing speeds is arguable. Whether or not speed reductions are observed, it is important to examine effects of the three types of strips on speeds to verify that driver behavior supports the conclusions about effectiveness drawn from the sound and vibration data.

4.1 Methodology

Observed speeds were filtered to remove the effects of platoons. Freeflow, as suggested by the Highway Capacity Manual, is indicated by a headway greater than or equal to 5 seconds. [24] Vehicles with less than a 5-sec headway were omitted from the statistical analyses. A computer utility was used to identify specific vehicles at each data point on an approach, generating vehicle specific speed profiles for the test segment. Vehicles that could not be identified at one or more data points were excluded from the analysis. This typically resulted in less than 10% of the vehicles being excluded from the analysis, and in no cases were more than 15% of the vehicles excluded.

4.1.1 Hose Placement

The vehicle speed data were collected using pneumatic hoses and automatic traffic recorders. Hoses were deployed on three approaches, one with asphalt strips, one with the Rumbler rumble strips, and one with the orange rumble strips. Hoses were not deployed to measure vehicle speeds on the approach using the asphalt strips at the orange rumble strip test site, because the approach was located on a downgrade that was severe enough to have a significant effect on the data. Figure 4.1 shows a topographic map of the construction site. The construction site is indicated by the shaded rectangle, and the black circle indicates the steep downgrade. Since the vehicle speeds for the asphalt rumble strips at the orange rumble strip test site were not collected, the speeds observed on the orange rumble strips had to be compared to the speeds observed on the asphalt rumble strips at the Rumbler test site. While there were some differences between the two sites that may have affected speeds, the differences were taken into account in the analysis of the data to the extent possible.

Jamar TRAX I traffic counters were used, operating in Raw Data mode. All vehicle identification and classification was completed with the VelocityNT software package, developed at the University of Kansas.

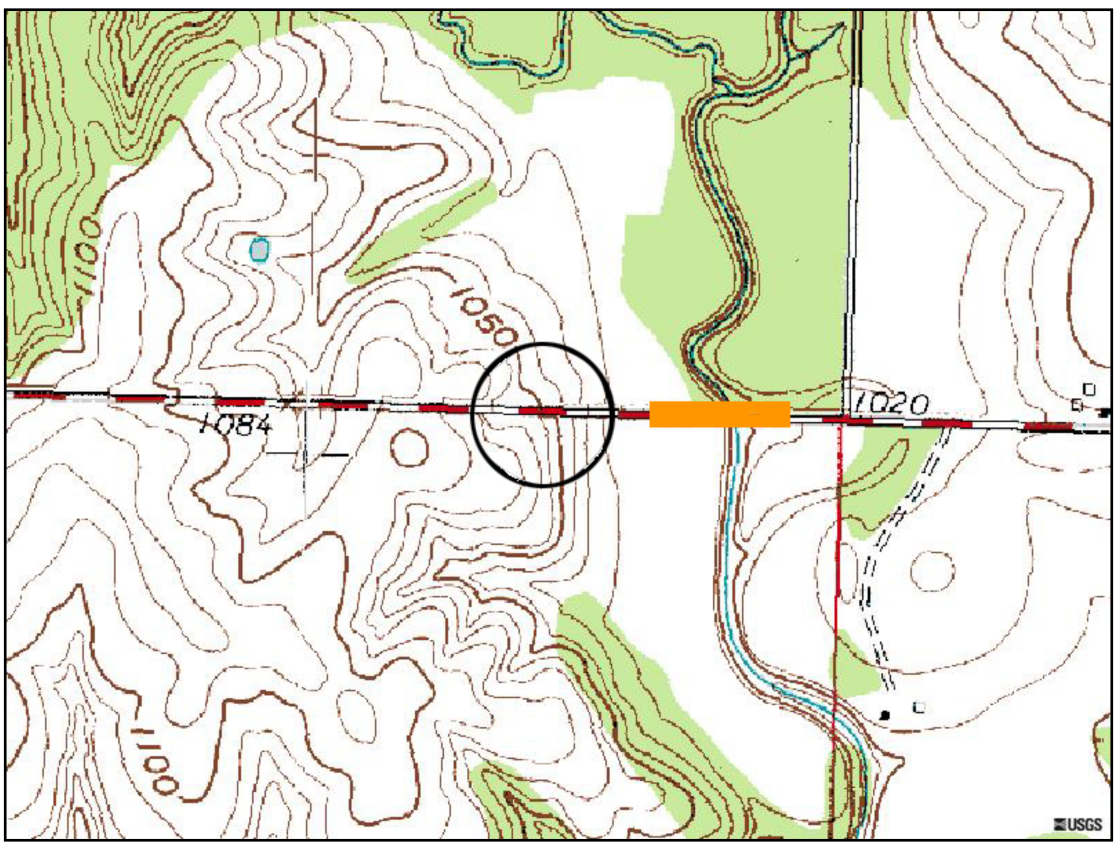


Figure 4.1: Topographic Map of Horton Construction Site [25]

4.1.2 Duration of Study

The hoses were deployed the day after the removable rumble strips were installed in order to allow enough time for the sound and vibration measurements to be taken without the affect of the hoses. The hoses were put in place at the Perry Lake location on March 26, 2001, and removed on April 14, 2001. This allowed data to be collected for 19 days. The hoses near Horton, KS were put in place on June 12, 2001, and removed on July 17, 2001. However, some of the data were not usable due to hose failures. Approximately 21 days worth of usable data were collected. The data from each site were split into daytime and nighttime data sets. For the data collected at the Rumbler test site, daytime was taken as being between 8:30 AM and 7:30 PM. For the data collected at the orange rumble strip test site, daytime was taken as the hours between 7:30 AM and 7:30 PM. Nighttime was taken as the hours between 10:30 PM and 5:30 AM for both sites. The differences are due to the time of the year during which the strips were deployed at each site.

4.2 Results

The speed data collected on each set of rumble strips were analyzed as a whole and by using several data subgroups. The subgroups were created in order to look for differences within a data set. The data subgroups were created based on several factors; vehicle classification (passenger car or truck), day and night, and first and second half of collected data (chronologically). Table 4.1 shows all of the data subgroups for a single set of rumble strips. When differences of practical significance were found between subgroups, both groups are presented and the difference is discussed. When all data sets produced relatively similar results either the overall results or a single representative subgroup are presented.

Table 4.1: Speed Data Analysis Subgroups

Vehicle Type	Time of Day	Collected Data Set	Rumble Strip
Cars	Day	1st	Asphalt
Trucks	Day	1st	Asphalt
All	Day	1st	Asphalt
Cars	Night	1st	Asphalt
Trucks	Night	1st	Asphalt
All	Night	1st	Asphalt
Cars	24 Hour	1st	Asphalt
Trucks	24 Hour	1st	Asphalt
All	24 Hour	1st	Asphalt
Cars	Day	2nd	Asphalt
Trucks	Day	2nd	Asphalt
All	Day	2nd	Asphalt
Cars	Night	2nd	Asphalt
Trucks	Night	2nd	Asphalt
All	Night	2nd	Asphalt
Cars	24 Hour	2nd	Asphalt
Trucks	24 Hour	2nd	Asphalt
All	24 Hour	2nd	Asphalt
Cars	Day	All	Asphalt
Trucks	Day	All	Asphalt
All	Day	All	Asphalt
Cars	Night	All	Asphalt
Trucks	Night	All	Asphalt
All	Night	All	Asphalt
Cars	24 Hour	All	Asphalt
Trucks	24 Hour	All	Asphalt
All	24 Hour	All	Asphalt

4.2.1 Speed Reduction

The actual reductions in speed attributable to the rumble strips might not be fully realized at the data points located on the strips, but more likely occur downstream of the strips. However, the objective was to compare speed reduction patterns between deployments, not assess the maximum reduction at any one site. The data collection points used support the desired comparison, as well as facilitating the identification of vehicles that cross the centerline to avoid the strips, which could not be done if the third data point were moved downstream of the strips. Figure 4.2 and Figure 4.3 show the mean and 85th percentile speeds observed on the three types of rumble strips. Figure 4.4 shows a plot of the speed reductions observed. Statistical descriptions of the collected speed data for all three types of rumble strips are located in Table 4.2 and Table 4.3. The speeds observed on the asphalt strips are a little higher, especially the 85th percentile speeds, than those observed on the Rumbler approach. These high initial speeds may have been due to a downgrade located just upstream of the asphalt rumble strips. The speeds observed on the orange rumble strips are generally lower because the posted speed was 89 kph (55 mph) upstream of the orange rumble strip test location, and 105 kph (65 mph) upstream of the Rumbler and asphalt strips. All three types of rumble strips show speed reductions that are statistically significant at the 99% level. However, it is not possible to determine what portion of the reduction is attributable to which traffic control measures since all measures were in place for the duration of the construction. Similar levels of speed reduction were observed on all three types of rumble strips.

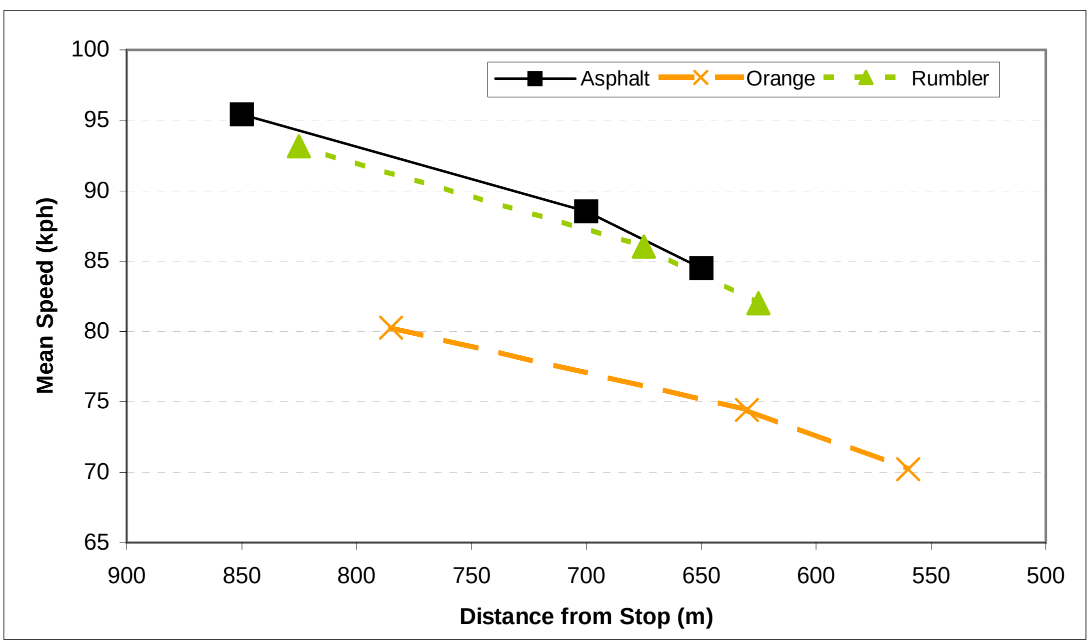


Figure 4.2: Mean Speeds Comparison (Passenger Cars, 24 Hours)

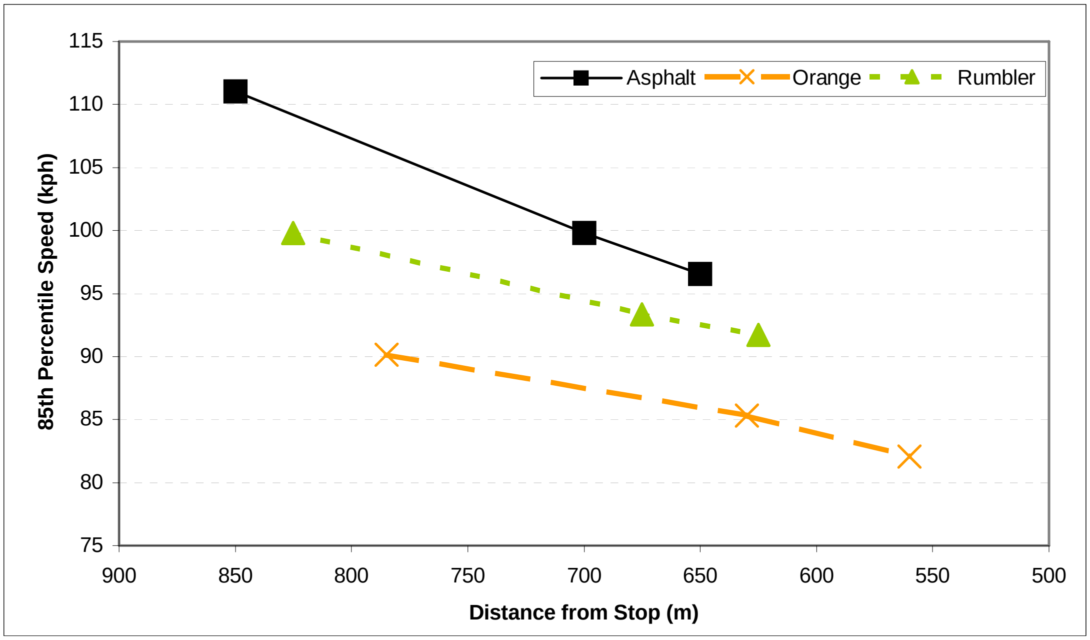


Figure 4.3: 85th Percentile Speed Comparison (Passenger Cars, 24 Hours)

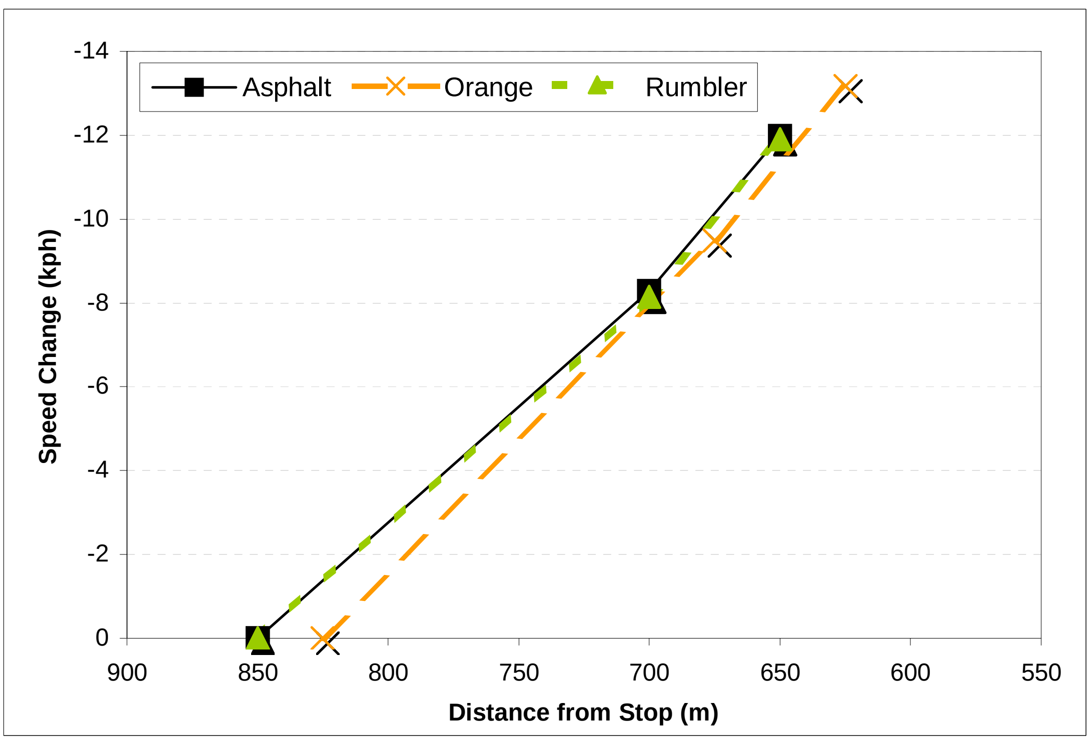


Figure 4.4: Speed Reductions (All Vehicles, 24 Hours)

Table 4.2: Overall Speed Summary for Rumbler and Asphalt Rumble Strips

	Rumbler			Asphalt		
Data Point*	101	102	103	201	202	203
Distance from Stop (m)	825	675	625	850	700	650
	Cars			Cars		
Count	12115	12235	12368	11531	11435	11346
Mean (kph)	93.2	86.0	82.0	95.4	88.5	84.5
85th Percentile (kph)	99.8	93.3	91.7	111.0	99.8	96.6
Pace (kph)	92	87	85	105	93	82
Standard Deviation (kph)	8.8	10.5	12.7	18.6	13.6	13.6
% of Vehicles in Pace	68%	57%	46%	43%	45%	46%
Δ Speed (kph)	0	-8.1	-11.9	0	-8.3	-12.0
	Trucks			Trucks		
Count	1003	997	1008	927	986	968
Mean (kph)	90.8	85.1	81.8	94.1	87.1	82.0
85th Percentile (kph)	96.6	93.3	91.7	109.4	98.2	93.3
Pace (kph)	92	87	85	105	85	80
Standard Deviation (kph)	9.8	11.0	12.6	18.7	14.2	14.1
% of Vehicles in Pace	68%	56%	51%	43%	45%	47%
Δ Speed (kph)	0	-6.2	-12.2	0	-8.5	-12.1

** See Figure and Figure on page 18 for the location of the data points.*

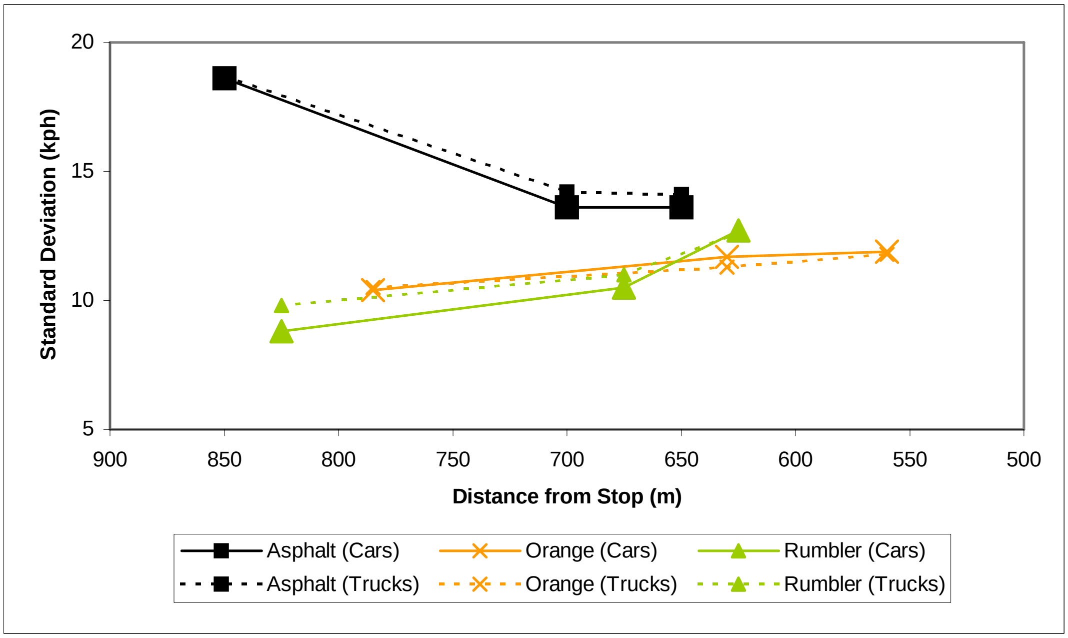
Table 4.3 Overall Speed Summary for Orange Rumble Strips

** See Figure and Figure on page 19 for the location of the data points.*

Data Point*	201	202	203
Distance from Stop (m)	785	630	560
	Passenger Cars		
Count	17276	17055	17158
Mean (kph)	80.3	74.4	70.2
85th Percentile (kph)	90.1	85.3	82.1
Pace (kph)	80.0	76.0	69.0
Standard Deviation (kph)	10.4	11.7	11.9
% of Vehicles in Pace	58%	52%	50%
Δ Speed (kph)	0	-9.5	-13.2
	Trucks		
Count	962	1133	1019
Mean (kph)	79.7	74.0	69.8
85th Percentile (kph)	90.1	85.3	80.5
Pace (kph)	82	76	71
Standard Deviation (kph)	10.5	11.3	11.8
% of Vehicles in Pace	58%	52%	53%
Δ Speed (kph)	0	-9.9	-14.0

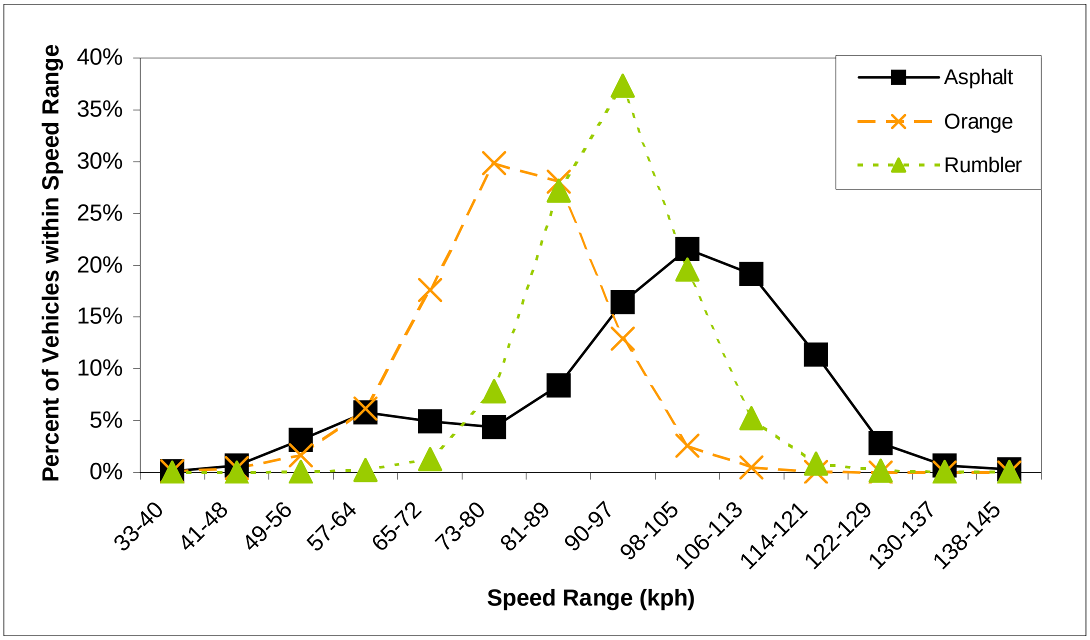
4.2.2 Speed Variation

A common measurement that is used in order to obtain a better understanding of vehicle speed patterns is the variation in speeds. When a large variation exists in the speeds of vehicles traveling the same path, an increase in the frequency of accidents can be expected. [26] The standard deviation of speeds (shown in Table 4.2 and 4.3) is an indication of speed uniformity. For the Rumbler, the standard deviation increased from the baseline point (101) to the most downstream data collection point (103), whereas the standard deviation observed on the asphalt strips decreased. The standard deviation did not vary much from the baseline point to the most downstream point for the orange rumble strips. Figure 4.5 shows the standard deviation of speeds observed on the three types of strips. While the asphalt strips seemed to have a decreasing affect on the speed variability, the standard deviation of the observed speeds was always greater on the asphalt strips. Figure 4.6, 4.7 and 4.8 show the speed distributions observed on the three types of rumble strips for the most upstream data point, the first point on the rumble strips, and the most downstream data point, respectively. The distribution of speeds observed on the rumble strips varies a great deal upstream of the rumble strips, especially for the asphalt strips. This could be due to the downgrade upstream of the asphalt rumble strip approach. As the vehicles traverse the rumble strips, the speed distributions become increasingly similar.



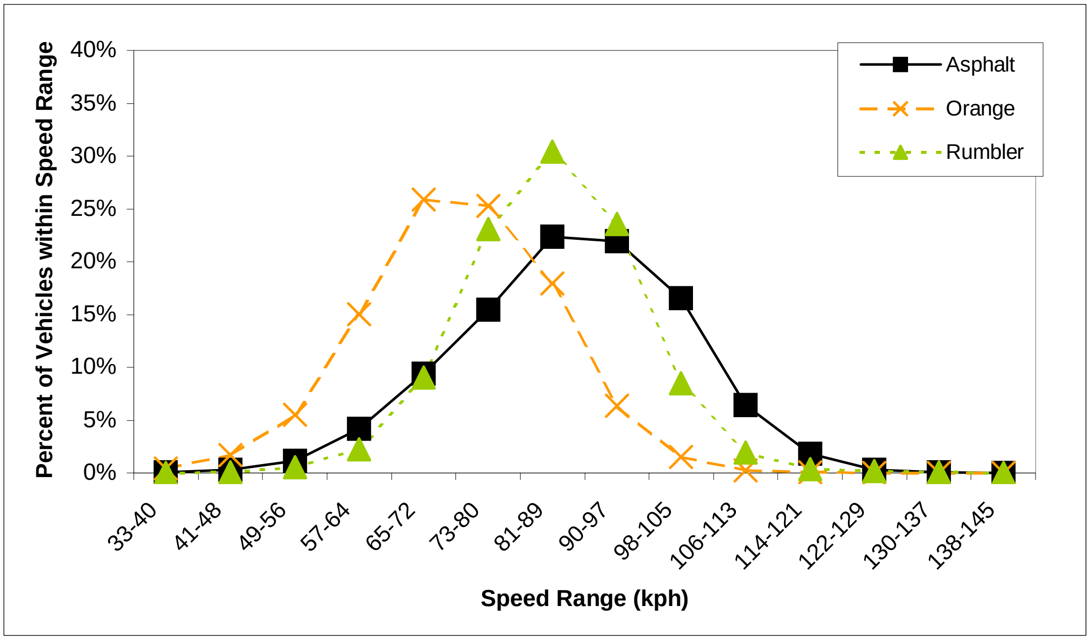
*Standard Deviations for day and night, and first and second data sets.

Figure 4.5: Standard Deviation of Speeds



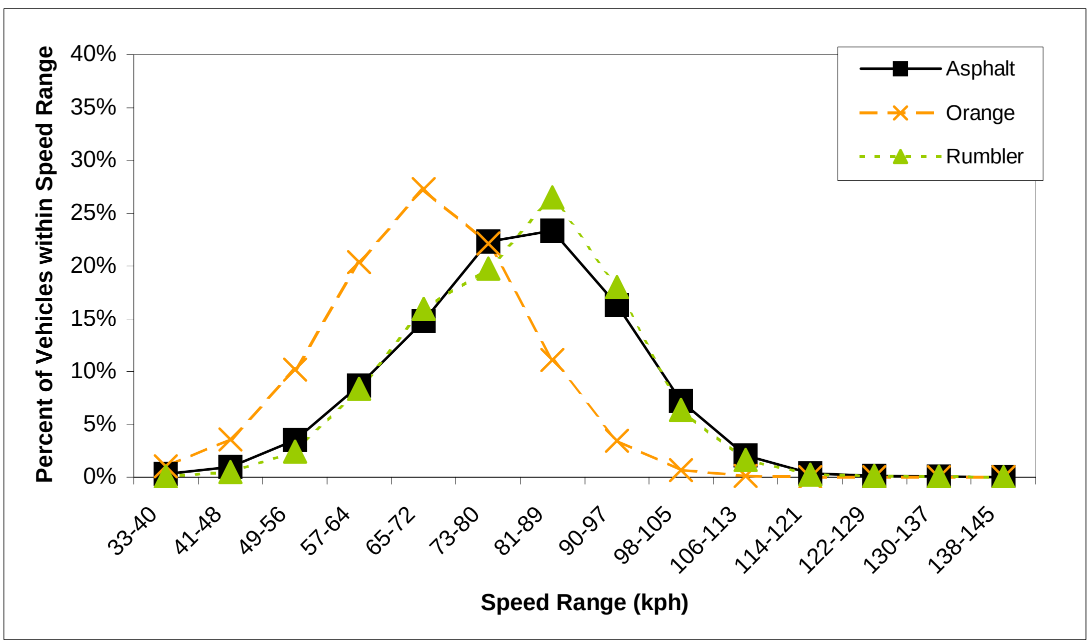
*Distribution for passenger cars, day and night, first and second data sets.

Figure 4.6: Speed Distribution Comparison for First Data Point (Cars)



*Distribution for passenger cars, day and night, first and second data sets.

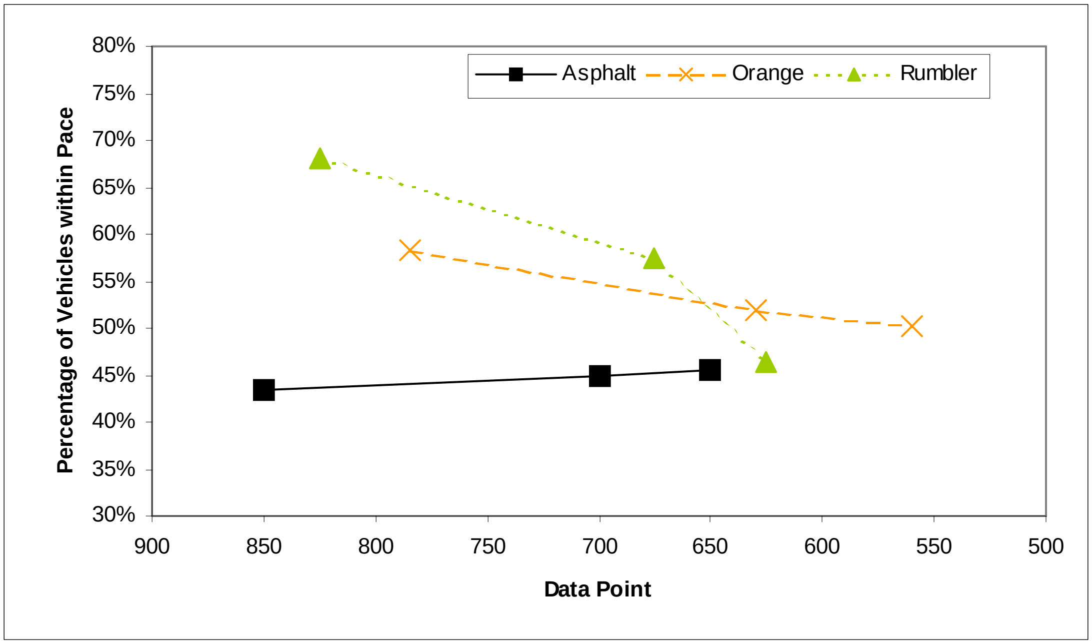
Figure 4.7: Speed Distribution Comparison for Second Data Point (Cars)



*Distribution for passenger cars, day and night, first and second data sets.

Figure 4.8: Speed Distribution Comparison for Third Data Point (Cars)

Another way to gauge speed variation is to look at the percentage of vehicles in the 16 kph (10 mph) pace. The summary data related to the pace are also located in Table 4.2 and 4.3. In all cases, the percentage of vehicles within the 16 kph (10 mph) pace is greater for the removable rumble strips than it is for the asphalt rumble strips. However, the percentage was decreasing on the removable rumble strips and increasing on the asphalt strips. Figure 4.9 shows the percent of passenger cars within the 16 kph (10 mph) pace observed on the three types of rumble strips, a similar pattern was observed for trucks. The decrease observed from point 2 to point 3 on the Rumbler approach was attributed to turning vehicles, as this location was just upstream of a turning lane for a left turn. Turning vehicles were not detected by the counter. However, vehicles with at least 5 seconds of headway between them and a preceding turning vehicle may have been affected by turning vehicles in the adjacent lane, but would still have been counted as being freeflow vehicles, and as such may have caused a decrease in the percent of vehicles in the pace.



*Plotted data includes passenger cars data for day and night, and first and second data sets.

Figure 4.9: Percent of Passenger Cars within the 16 kph (10 mph) Pace

4.2.3 Temporal Change

A common concern regarding traffic control devices intended to reduce speeds is that often much of their effectiveness is due to a novelty effect. Drivers decrease their speed because they see something in the roadway—or feel and hear something, in this case—that they are unfamiliar with. Once the commuters begin to understand and become comfortable with the devices, their speed reducing effect decreases. This did not seem to be the case with these deployments. Both segments used in this study link small neighboring communities. Such routes tend to carry a low proportion of through traffic. Consequently, most drivers are repeat drivers (i.e., commuters) who drive the segment regularly, and temporal changes in traffic speeds will show whether or not the effectiveness of the rumble strips is a novelty effect.

The speed data were collected over a period of 3-4 weeks and split into two data sets. The first data set contained data observed for 8 - 10 days immediately after the deployment. The second data set was collected over a period of 10 – 12 days, 4 weeks after the deployment at the orange rumble strip test site, and 2 weeks at the Rumbler test site. The second half of the speed data gives results almost identical to the first half for the Rumbler rumble strip. The two sets of data for the asphalt strips are also quite similar except that greater baseline speeds were observed upstream of the strips in the latter time period. This indicates that no novelty affect was evident for either of these types of strips. Tables 4.4 and 4.5 show the mean and 85th percentile speeds from the first data set and the second data set for both the Rumbler rumble strip and the asphalt rumble strip.

Table 4.4: Change in Speed Reduction Over Time on Rumbler Rumble Strips

			85th Percentiles			Means		
Rumble Strip	Class.	Data Set	101	102	102	101	102	103
Rumbler	Cars	1st	101	-6	-8	93	-8	-12
Rumbler	Cars	2nd	101	-5	-6	93	-7	-11
Rumbler	Trucks	1st	98	-3	-6	90	-6	-9
Rumbler	Trucks	2nd	98	-3	-5	91	-5	-9

*Speed values for data point 101 are in kph, all others are in kph relative to 101.

Table 4.5: Change in Speed Reduction Over Time on Asphalt Strips

			85th Percentiles			Means		
Rumble Strip	Class.	Data Set	201	202	203	201	202	203
Asphalt	Cars	1st	111	-10	-13	96	-7	-11
Asphalt	Cars	2nd	113	-11	-14	95	-7	-11
Asphalt	Trucks	1st	113	-13	-18	96	-8	-13
Asphalt	Trucks	2nd	109	-10	-14	93	-6	-11

*Speed values for data point 201 are in kph, all others are in kph relative to 201.

The pattern of vehicle speeds observed on the orange rumble strips did change from the first data set to the second. The observed change was mostly a change in where along the approach the vehicles began to decrease their speeds. The first half of the data, which is essentially the speeds measured for the first week after the deployment, indicate that the largest changes in speed occurred between the baseline data point (upstream of the first set of strips) and the second data point (on the first group of orange rumble strips). This is most likely due to the visibility of the strips during daylight hours. The drivers would see bright orange lines on the roadway and decrease their speed before traversing them. The drivers were not used to seeing orange strips on the pavement, and they approached them cautiously, significantly decreasing their speed upstream of the first rumble strip set. This confirms the findings from previous tests. [7, 29] A few weeks later, when the second half of the data was collected, this pattern was no longer observed. The speed decreases were more gradual, and occurred over the entire length of the rumble strip deployment. This suggests that there was a novelty effect for the orange rumble strips, most likely due to their high visibility. However, speed decreases observed in the second data set on the orange strips closely resembled the patterns observed on the other types of strips. This indicates that though the orange rumble strips may cause less speed reduction over time, they begin to affect vehicle speeds more like the asphalt strips once the novelty is gone. Thus the novelty effect is not a disadvantage, but rather an advantage applicable only to short term deployments.

Since the orange rumble strips are not reflective, there is some concern about how visible they are at night. The speed patterns observed during nighttime hours exhibited this same pattern, although to a lesser extent. This suggests that the strips are visible at night, even though they are not reflective. Table 4.6 show the 85th percentile and mean speeds observed on the orange rumble strips for day, night, and overall for both the first and second data sets. Figure 4.10 shows the mean speeds of passenger cars for all three types of strips. The patterns observed for all subgroups were nearly identical to the patterns seen in Figure 4.10 and are therefore not shown individually.

Table 4.6: Change in Speed Reduction Over Time on Orange Rumble Strips

			85th Percentile			Mean		
Time	Class.	Data Set	201	202	203	201	202	203
24 Hour	Cars	1st	90	-8	-11	79	-8	-12
24 Hour	Cars	2nd	90	-3	-6	81	-5	-9
24 Hour	Trucks	1st	89	-10	-13	79	-9	-13
24 Hour	Trucks	2nd	90	-3	-6	80	-4	-8
Day	Cars	1st	90	-6	-10	82	-9	-13
Day	Cars	2nd	92	-3	-8	82	-5	-9
Day	Trucks	1st	90	-10	-13	80	-10	-13
Day	Trucks	2nd	90	-2	-6	81	-4	-8
Night	Cars	1st	82	-3	-8	72	-4	-10
Night	Cars	2nd	87	-3	-6	77	-3	-7
Night	Trucks	1st	82	-3	-13	72	-3	-14
Night	Trucks	2nd	85	-2	-5	76	-3	-7

*Speed values for data point 201 are in kph, all other values are kph relative to data point 201

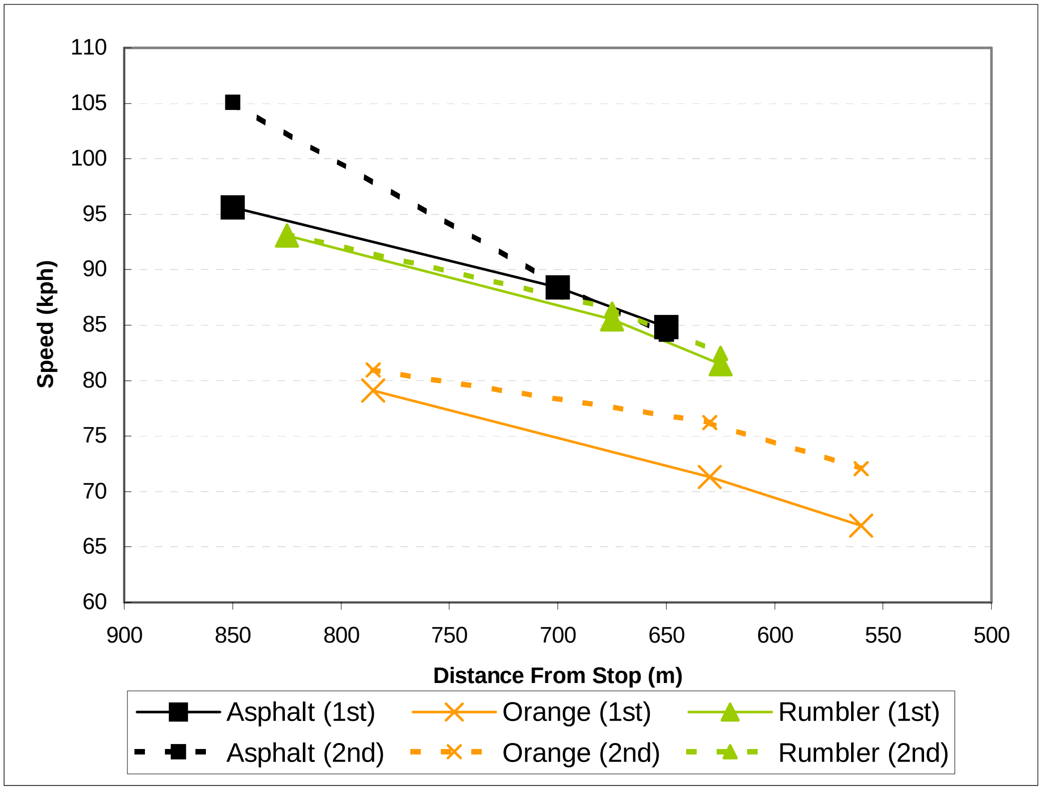


*Chart represents change in mean speeds for passenger cars, from both day and night

Figure 4.10: Change in Speed Reduction Patterns Over Time

CHAPTER 5

COST AND DURABILITY

In order to provide a detailed and thorough comparison between the removable rumble strips and the asphalt rumble strips, a comparison of the costs associated with each of the strips is essential. Life-cycle costs comprise initial material costs, installation and removal costs, and any savings that may be derived from reuse. The damage done to the pavement upon removal was also examined.

5.1 Methodology

The costs associated with rumble strips fall into two basic categories: installation and removal costs, and material costs. To analyze the costs, it was necessary to observe and record data detailing the processes and methods used for the installation and removal of the strips.

5.1.1 Installation

The installation process was similar for both types of removable rumble strips. The locations where the strips were to be placed were determined using a tape measure and marked with masking tape. The dry pavement was swept with a push broom.

5.1.1.1 Rumbler

Installation required two workers plus appropriate traffic control, and took about 30 minutes per group of strips. Figure A.1 in the Appendix shows pictures of the Rumbler rumble strips being installed. The installation process is discussed in more detail on page 13.

5.1.1.2 Orange Rumble Strips

The orange rumble strips came in 27.4 m (90 ft) rolls and had to be cut to length prior to installation. This was done offsite before the deployment and took two workers about 15 minutes per group (6 strips, 24 pieces each 1.2 m (4 ft) long) to complete the task. The need for a double thickness strip effectively doubled the installation time, compared to an installation using a single thickness. The process required three workers plus appropriate traffic control, and took approximately 15 minutes per group of strips. Figure A.3 in the Appendix shows pictures of the installation process. The installation process is discussed in more detail on page 14.

5.1.1.3 Asphalt

The asphalt rumble strips required slightly more time and effort than was required for the removable rumble strips. The installation required three workers plus appropriate traffic control approximately 40 minutes per group. The installation process is discussed in more detail on page 15.

5.1.2 Removal

To remove either type of removable rumble strip, a corner was pried free with a crow bar or other similar tool, and the strips were then pulled by hand until they were entirely removed. For both types, an individual strip could be pulled up by a single worker. All strips came up in one piece. The process required two workers approximately 4 minutes to remove a group of orange rumble strips, and one worker approximately 7 minutes to remove a group to the Rumbler rumble strips.

The removal of the asphalt rumble strips required heavy equipment and more than 5 times the labor required to remove the removable rumble strips. The asphalt rumble strips are typically removed using a Skid Steer Loader or a Loader/Backhoe to scrape the raised asphalt strips off of the pavement. Two additional workers, equipped with shovels and brooms, removed the loose pieces of asphalt and gravel from the roadway. The loaders had to back into the other lane of traffic in order to be able to scrape off the strips starting at the centerline, necessitating that traffic in both directions be temporarily stopped. Removal required approximately 15 minutes per group of strips with 5 workers.

5.1.3 Cost Estimation

The material costs and the installation and removal times were measured directly. However, to determine the total costs for all three types of strips, a few estimations were necessary. The labor rates for those installing the strips and providing traffic control were estimated, as well as the cost of the loaders used to remove the asphalt rumble strips. The cost for the material used to make the asphalt rumble strips was estimated based on the compacted volume. All estimates were derived using R.S. Means Facility Construction Cost Data 2001. [27]

5.1.4 Durability

Determining the durability of the removable rumble strips was done by simply observing the amount of damage the strips had incurred over the length of their deployment. The orange rumble strips were in place for 6 months and traversed by approximately 225,000 vehicles. The Rumbler rumble strips were in place for 2 months and traversed by approximately 75,000 vehicles. A single group of the Rumbler rumble strips was also deployed at the orange rumble strip test site on the opposite approach. These remained in place for a period of 6 months with no damage. The durability of the asphalt strips is generally not a problem, although it is not uncommon for small pieces of the asphalt strip to become detached. The thickness of the asphalt rumble strips decreases over time as well, which could decrease the levels of sound and vibration they produce. An important point to consider is that failures of removable rumble strips are easier to repair than failures of asphalt strips. If a single removable rumble strip is removed or damaged, it can be easily replaced. Asphalt strips are more difficult to repair not only because of the greater labor requirements, but also because of the availability of material, especially at rural sites.

5.1.5 Reusability

Reuse of the Rumbler is neither supported nor discouraged by the manufacturer. In contrast to the orange rumble strips, the Rumbler does not come with pre-applied adhesive, so a used strip should be as effective as a new one, provided of course that the old adhesive could be removed. Since reuse of these strips could significantly decrease their overall cost, tests were conducted to determine if the reuse of the Rumbler were feasible. Several strips that were used at the Rumbler test site were cleaned and reused alongside an equal amount of new rumble strips at the orange rumble strip test site. This was done to determine if the used strips were more likely to be damaged than the new strips and if the contact cement would adhere the used strips to the pavement as well it did the new strips. The strips were placed immediately following the most downstream set of asphalt rumble strips. It was thought that this location would be where the most severe braking would occur, and, hence, where the strips would receive the maximum wear. The reused strips, just like the new strips at the same location, did not incur any significant damage at the second location.

5.1.6 Benefit/Cost Analysis

The primary benefit of rumble strips is their positive effect on safety and the subsequent reduction in accidents and fatalities. It is infeasible to perform a quantitative analysis of the safety benefits of each of the strips due to their limited length of deployment. At least several years of before and after accident data would be needed to facilitate a benefit/cost analysis based on safety effects. Because of the limited data available, only qualitative comparisons of the benefits and quantitative comparisons of the costs of the types of strips are presented.

5.2 Results

While the removable rumble strips may have some advantages over the asphalt rumble strips, they are also more expensive. The largest portion of the removable rumble strip's expense is in the material, or the cost of the rumble strips themselves. While the costs associated with the labor hours and equipment required to install and remove the rumble strips are less for the removable rumble strips, this decrease alone is not sufficient to offset the greater material costs.

5.2.1 Benefits

Based on the observed speed, sound, and vibration data, the removable strips appear to perform similarly to the asphalt strips, and can thus be assumed to have similar safety benefits. They may provide some additional safety benefits because of the decreased installation and removal times, and the high visibility in the case of the orange rumble strips. The removable strips also cause much less damage to the underlying pavement upon their removal than do asphalt strips.

5.2.2 Total Deployment Costs

Table 5.1 shows the cost estimates for labor costs, material costs, and equipment costs. While the cost of asphalt is almost negligible, the cost of the removable rumble strips is not. The material costs for the Rumbler rumble strips include the cost of both the strips and the adhesive, and the material cost for the reused Rumbler rumble strips only includes the cost of the adhesive. The cleaning time for the reused Rumbler rumble strips is included in the Labor Costs category under Removal Time. Life cycle costs were not calculated because the failure rate could not be determined from the data collected. Annualized costs would be a function of the new cost, reused cost, and the failure rate.

Costs associated with the asphalt strips were compared with previous studies [3] and found to be reasonable. No comparison was available for the removable strips, but all costs included in the analysis were directly observed.

It should be noted that KDOT provides the asphalt for the strips and the transport of the asphalt to the site. All other costs pertain to the contractor.

Table 5.1: Deployment Costs

Labor Costs

Type of Strip	Installation Time min/Group	Number of Installation Workers	Removal Time min/Group	Number of Removal Workers	Estimated Labor Cost/hr	Total Labor Cost/Group
Rumbler	30	4	7	2	$16.28	$36.36
Reused	30	4	97	2	$16.28	$85.20
Orange	20	5	4	3	$16.28	$30.39
Asphalt	40	5	15	5	$16.28	$74.62

Material Costs

Type of Strip	Material Cost per meter	(per foot)	Total Length meters	(feet)/Group	Total Material Cost/Group
Rumbler	$15.03	($4.58)	14.6	(48)	$219.84
Reused	$1.41	($0.43)	14.6	(48)	$20.64
Orange	$13.12	($4.00)	29.3	(96)	$384.00
Asphalt	$0.66	($0.20)	21.9	(72)	$14.40

Equipment Costs

Type of Strip	Equipment Cost/hr	Equipment Cost/Group
Rumbler	$0.00	$0.00
Reused	$0.00	$0.00
Orange	$0.00	$0.00
Asphalt	$33.75	$8.44

Total Cost

Type of Strip	**Total Cost/ Group**	**Total Cost/ Approach**
Rumbler	**$256.20**	**$1,537.19**
Reused	**$105.84**	**$635.03**
Orange	**$414.39**	**$2,486.34**
Asphalt	**$97.45**	**$584.73**

5.2.3 Installation

As mentioned previously, the installation of the removable rumble strips was quick and simple. The time estimates for the installation of the removable rumble strips are probably conservative, assuming that a more experienced crew would be more efficient. The installation time decreased from over an hour for the first group to less than 30 minutes for the last group for the Rumbler rumble strip. A similar pattern existed for the orange rumble strips. The time taken to install the final group for each type of strip was used as the estimate for installation time.

5.2.4 Removal

Removal of the removable rumble strips required no special equipment and fewer workers than did their asphalt counterparts. No time estimates were available for the time required to remove asphalt strips without heavy machinery.

5.2.5 Reusability

Since the orange rumble strips are self-adhesive, the damage done to the adhesive backing makes the strips no longer usable with the same adhesive. The orange rumble strips could be reused if they were nailed to pavement or cleaned and then attached using another adhesive. However, there are obvious problems with both of these installation methods, and neither method is recommended by the manufacturer. While it may be possible to reuse the orange rumble strips, it was not attempted in this study.

The Rumbler rumble strips were successfully reused. In order for the strips to be reused, all adhesive that remained on the strips following their removal was cleaned off. The test strips were cleaned using a small metal scraper to remove the adhesive. The amount of time required to clean the strips decreased significantly from the first strip to the last as removal tools were improvised and methods were improved. For example, it was discovered that preheating the old adhesive in the direct sunlight weakened its bond to the strip, making it much easier to remove. The average time required to clean the test strips was about 30 minutes per strip. The experience of cleaning the strips, however, suggested that, assuming the availability of proper tools and experienced workers, 15 minutes was a more appropriate time to use for cost estimation. 15 minutes is still considered to be a conservative estimate. Table 5.1 shows costs estimates for both new and reused Rumbler rumble strip deployments.

5.2.6 Durability

The durability of the rumble strips depends on several factors, such as the number and type of vehicles that will traverse them, the duration of the deployment, and the quality of the initial installation. Under the test conditions, both types of removable rumble strips performed well, showing little wear over the 6 months of service.

5.2.6.1 Rumbler Rumble Strips

The Rumbler rumble strips did suffer some damage. 2 out of 36 strips deployed at the Rumble test site had a piece of significant size—about 1/2 of the strip—torn off. However, the strips that were torn were torn in the same place, and other strips had deep cuts in the same line of travel, indicating that some unusual circumstance may have caused the damage, such as a vehicle dragging something. Pictures of the damaged strips are located in the Appendix. Two additional strips became completely detached from the pavement in the same path as the two strips that were torn. Both of these strips came from the same group, which was the group that had been applied using the least amount of adhesive. This suggests that it was not a problem with the strip or the adhesive, but a problem with the installation and the amount of adhesive used. Since these strips were in the same path as the torn strips, the removal of the strips could have also been due to whatever unusual circumstances caused the damage to the other strips. The Rumbler rumble strips that were deployed for six months at the orange rumble strip test site, half of which were reused strips from the initial test, suffered no damage.

5.2.6.2 Orange Rumble Strips

The orange rumble strips had no durability problems throughout the duration of their deployment. A few strips were slightly chipped, but none of the strips had large pieces missing nor were there any strips detached from the pavement.

5.2.6.3 Asphalt Rumble Strips

The asphalt rumble strips incurred minor damage as well. None of the strips were entirely removed from the pavement, but many had pieces of significant size removed from the strips. Pictures of the damaged strips can be found in the Appendix.

Tests of the same types of removable rumble strips have found similar results. A test recently conducted in Florida using the Rumbler rumble strips had no durability problems throughout the four-week deployment. [28] Several tests have also been conducted using the orange rumble strips. Some tests indicated no durability problems, and others indicated that strips had torn. Tests performed as part of the Midwest Smart Work Zone Deployment Initiative (MwSWZDI) all found that the orange rumble strips, if installed correctly, would stay attached to the pavement and not suffer excessive damage due to traffic. However, improper installation can lead to total failure of the adhesive and the deployment. A deployment that was made on wet pavement and rolled using a truck instead of a tamping cart had most of the strips become detached from the pavement in a single day. Another test that was also part of the MwSWZDI had several strips become detached. The pavement was not swept prior to installation, and the strips that were detached had a large amount of debris and gravel stuck to the adhesive. The un-swept pavement was believed to be the cause of the failures. All other strips remained attached for the duration of the project. [15]

5.2.7 Pavement Condition

Part of the motivation to use removable rumble strips is that they cause less damage to the pavement than asphalt rumble strips upon removal. Although small bits of gravel remained on the back of the rumble strips, and some of the adhesive remained on the pavement, the pavement was not significantly damaged by removing the removable rumble strips. The remaining adhesive only slightly discolored the pavement, and it quickly wore away under normal traffic and weather conditions. The removal of the asphalt strips damaged the pavement more than the removal of the removable rumble strips. Pictures of the pavement after removal of the strips can be seen in the Appendix. Both locations had asphalt pavement. Results on concrete pavement may differ.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The data collected and the analyses performed in this study showed that removable rumble strips are durable and are as effective as asphalt strips, even though their vertical profile is as little as one third that of asphalt strips.

6.1.1 Rumbler

In general, the Rumbler rumble strips performed comparably to the asphalt rumble strips with respect to sound and vibration generated and speeds observed. Slightly higher sound levels were observed at the roadside. The roadside noise is not likely to be problematic unless the strips are used on a longer-term application that is located in a residential area on a segment with substantial nighttime traffic.

The Rumbler strips were much quicker and easier to install and remove than asphalt rumble strips. The reduced exposure for workers and reduced disruption to traffic are very difficult benefits to quantify in terms of reduced accidents or injuries, but are nonetheless significant and should be considered.

The Rumbler strips were more expensive than asphalt strips for a single application, but could prove to be of similar or even less expense if the strips are reused.

The strips adhered well to the pavement and demonstrated long-term durability. When removed, damage to the pavement was nominal.

6.1.2 Orange Rumble Strips

The ATM Removable Rumble Strips also performed comparably to the asphalt rumble strips with respect to sound and vibration generated and speeds observed. The orange color appeared to increase the speed reductions, but that additional reduction was short lived. For very short applications, the color may be an added benefit, but for longer applications it does not appear to be so (or at least the magnitude of the benefit decreases over time). It should be noted that while the added effect of the color may dissipate over time, it does not become a detriment. The effectiveness of the strips does not decrease over time, but only the additional effect of the orange color.

The strips were very easy to install, and even easier to remove. Very little damage was done to the pavement. The only complaint about the installation process was that the backing tore frequently, increasing the effort necessary to lay down each strip. The vendor attributed this to the manufacturing process (specifically, the blades that cut the strips at the time our samples were produced must have become dull and needed to be replaced). The factory was contacted to ensure that it was rectified immediately. In the field, a device for cutting the strips to length with a single motion would be very helpful, perhaps something akin to a paper cutter. For one installation (four sets of strips), perhaps as much as an hour or more could be saved by a more efficient means of cutting the strips to length.

The data confirmed the earlier findings that a single thickness of the orange rumble strips was insufficient. A double thickness, however, performed similarly to the asphalt strips, even though it was considerably thinner.

The cost of the strips is substantially greater than that of asphalt strips. They do not appear to be easily reusable. They proved to be quite durable. No strips became detached during the 6-month evaluation. Very little scarring was apparent upon removal.

Table 6.1 shows a qualitative comparison of four types of deployments of the removable rumble strips relative to the asphalt rumble strips.

Table 6.1: Rumble Strip Qualitative Comparison Table

	Orange (Single Thickness)	Orange (Double Thickness)	Rumbler (New)	Rumbler (Reused)
In-vehicle Sound	— —	=	=	=
Vibration	— —	=	=	=
Roadside Noise	NA	=	—	—
Speed Control	—	=	=	=
Durability	=	=	=	=
Cost	—	— —	—	=
Installation Time	+ +	+	+	+
Removal Time	+	+	+	+

- All strips are being compared to the KDOT standard asphalt strips
- Much Better (+ +), Much Poorer (- -): difference of substantial practical significance
- Slightly Better (+), Slightly Poorer (-): definite difference, but practical significance is small
- Similar (=): the same or nearly the same, including real differences that are unlikely to be of any practical significance
- Not Available (NA): data needed for judgment was not collected or was inconclusive

6.2 Summary

The results show that these removable rumble strips are quite comparable to the standard asphalt strips, with each type of strip having their own advantages and disadvantages. Table 6.2 outlines some of these advantages and disadvantages.

Table 6.2: Rumble Strip Type Summary

	Asphalt Rumble Strips	Orange Rumble Strips	Rumbler Rumble Strips
	▪ The cheapest option ▪ More familiar to workers and drivers ▪ No need to order and pay shipping for expensive materials ▪ Can be formed to any size or shape desired	▪ Quick and easy and installation and removal (complete installation can be transported in a pickup truck) ▪ Easy repair of broken or removed strips ▪ Orange color increases effectiveness (short-term) ▪ Consistent size and shape ▪ Does little damage to pavement	▪ Quick and easy installation and removal (complete installation can be transported in a pickup truck) ▪ Easy repair of broken or removed strips ▪ Strips come in 1.2 m (4 ft) pieces, no cutting required ▪ Reusable ▪ Consistent size and shape ▪ Little or no damage to pavement
Disadvantages	▪ Removal typically damages the pavement ▪ Time consuming installation and removal ▪ Inconsistent size and shape ▪ Thickness of strips decrease over time ▪ Not reusable ▪ Material and transport provided by KDOT	▪ Leaves adhesive on pavement ▪ Most expensive of the three strips ▪ Double thickness requires double installation time and double cost ▪ Unfamiliar to workers and drivers ▪ Strips require cutting to size prior to installation ▪ Not reusable	▪ Leaves adhesive on pavement ▪ New strips are more expensive than asphalt ▪ Produces higher roadside noise levels than asphalt strips ▪ Requires tamping cart with a custom wheel ▪ Unfamiliar to workers and drivers

6.3 Recommendations

While removable rumble strips are not a wholesale replacement for asphalt strips, they do offer advantages in some circumstances—such as work zone approaches—that make them an attractive alternative. Given due consideration and used with discretion, removable rumble strips may have the potential to improve the safety of both drivers and construction workers, while saving time for construction crews. Based on the results of this study[2], the following are recommended.

The Rumbler rumble strip, by Swarco, and the Orange Rumble Strip, by ATM, should be allowed as substitutes for asphalt rumble strips on work zone approaches. For the Rumbler, special consideration should be given to the issue of roadside noise for applications longer than 30 days in residential areas on segments with significant nighttime traffic.

Other removable strips should be allowed provided they meet the following conditions:

- Applied thickness of at least 8 mm (300 mil) and not more than 19 mm (750 mil)[3], preferably 13 mm (500 mil) or less;
- Width (along direction of vehicle travel) of between 10 cm (4 in) and 15 cm (6 in);
- Flexible strip material[4] and adhesives[5] must be used for asphalt applications;
- Applied as per manufacturer-approved procedures and materials;

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[2] Some recommendations are based on a test of a rumble strip manufactured by Davidson-Plastics. The data analysis is not complete at the time of this writing and will be documented in a subsequent report. However, some of the observations from that test are germane to these recommendations and have been incorporated to the extent justifiable without the complete results from the data analysis.

[3] The strips made by Davidson-Plastics (see Footnote 2 on Pg 75) had a thickness of 19 mm (750 mil), and sound and vibration levels were not found to be egregiously severe based on subjective evaluation. However, given that only two profiles were investigated, any strips thicker than 13 mm (500 mil) should be subjectively tested prior to installation to verify the combined thickness and profile will not generate overly severe sound and vibration.

[4] Based on a test of a Davidson-Plastics rumble strip (see Footnote 2 on Pg 75). The strips were comprised of a rigid plastic, which began to fail under light traffic in less than 1 week.

[5] Based on a test of a Davidson-Plastics rumble strip (see Footnote 2 on Pg 75). A two-part epoxy was used, which created a rigid bond between the strip and the pavement. The strip pulled large pieces of asphalt out of the pavement, leaving holes as deep as 2.5 cm (1 in).

- Color conforms to MUTCD guidelines (e.g., black or orange); and
- Configuration conforms as closely as possible to KDOT standard configuration.

Reuse should be considered. They appear to be rugged enough to endure multiple applications, and the improvement to life cycle costs is substantial. If contact cement such as used in this study is employed, the strips should be warmed before cleaning the strips for reuse. Simply allowing them to sit in direct sunlight for a few minutes significantly expedites the cleaning process. Cleaning the ATM strips for reuse was not attempted, but may be worth investigating.

Use of orange strips should be permitted. Both orange and black are in conformance with the MUTCD, and orange may have some additional safety benefit, especially for short-term applications.

Configurations should conform to the KDOT standard configuration: 2 sets per approach, 3 groups per set, 6 strips per group, no greater than 0.9 m (3 ft) gap in the center of the lane, 0.6 m (2 ft) center to center spacing.

The following installation guidelines should be observed in the application of any removable strips:

- Pavement must be dry at the time of application.
- Pavement should be swept clean of dust and debris prior to application. In most circumstances, sweeping with a hand broom is sufficient.
- Pavement temperatures must conform to the recommendations provided by both the strip manufacturer and the adhesive manufacturer.

Tar-based adhesives should be used with caution. Ambient temperatures of 32°C (90°F) in direct sunlight can result in pavement temperatures of 49°C (120°F) or higher. Tar-based adhesives may suffice for rumble strips with relatively low profiles (e.g., ≤ 10 mm (400 mil)), but the higher the profile, the greater the lateral forces that will be incurred. Depending on the height, cross-section, temperatures, and specific adhesive used, the lateral forces may cause the strip to slide along the pavement, eventually detaching completely.

A truck tire should *not* be used in lieu of a tamper cart. A tamper cart will produce a better bond between the strip and the pavement, thus reducing the detach rate.

Any strip that is misplaced during installation and has to be pulled up may need to be discarded, particularly if it has already been rolled with the tamper cart. If significant debris has become imbedded in the underside of the adhesive, it may not be able to fully bond with the pavement if reapplied. If a reusable strip is being used, the adhesive may be removed from the strip and reapplied.

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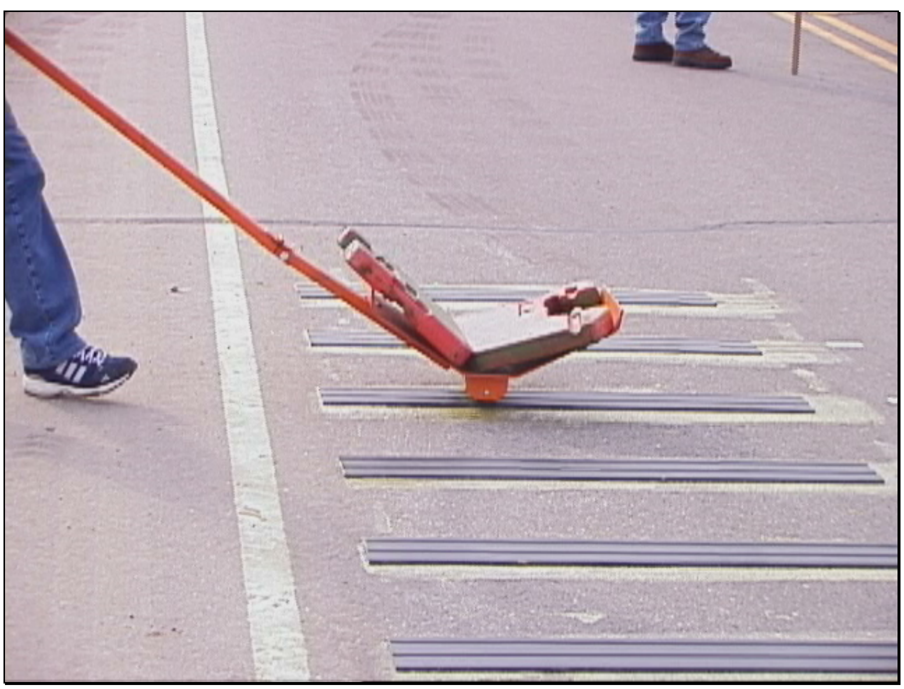
APPENDIX

Table A.1: Maximum L_{eq} Values in Decibels (dB)

Sound									
Vehicle	Compact Car			Midsize Car			Dump Truck		
Speed, kph (mph)	64 (40)	80 (50)	97 (60)	64 (40)	80 (50)	97 (60)	64 (40)	80 (50)	97 (60)
Baseline (Perry)	73	73	77	73	74	77	79	81	86
Asphalt (Perry)	88	87	90	88	90	93	89	90	93
Rumbler (Perry)	86	88	90	89	89	91	89	89	91
Baseline (Horton)	73	76	78	72	73	75	80	82	84
Asphalt (Horton)	87	88	90	84	85	88	93	92	92
Orange (Horton)	88	91	93	86	87	90	87	88	89
Vibration									
Vehicle	Compact Car			Midsize Car			Dump Truck		
Speed, kph (mph)	64 (40)	80 (50)	97 (60)	64 (40)	80 (50)	97 (60)	64 (40)	80 (50)	97 (60)
Baseline (Perry)	73	77	79	77	80	81	76	78	82
Asphalt (Perry)	89	92	93	98	93	93	89	88	86
Rumbler (Perry)	89	88	88	90	94	94	92	86	86
Baseline (Horton)	76	77	77	79	82	85	96	88	89
Asphalt (Horton)	90	90	92	94	96	96	107	103	101
Orange (Horton)	89	89	93	93	98	97	105	104	98
Roadside Noise									
Vehicle	Compact Car			Midsize Car			Dump Truck		
Speed, kph (mph)	64 (40)	80 (50)	97 (60)	64 (40)	80 (50)	97 (60)	64 (40)	80 (50)	97 (60)
Baseline (Perry)	76	77	80	72	76	80	X	X	X
Asphalt (Perry)	79	82	84	78	81	81	X	X	X
Rumbler (Perry)	87	88	89	85	88	87	X	X	X
Baseline (Horton)	78	85	83	80	84	87	82	82	85
Asphalt (Horton)	X	X	X	X	X	X	X	X	X
Orange (Horton)	82	87	86	83	87	87	85	84	88

Applying adhesive with paint roller



Rolling the strips with the tamper cart

Figure A.1: Installation of Rumbler Rumble Strips

Prying corner of strip off of the pavement with a crow bar

Peeling strip off of the pavement by hand

Figure A.2: Removing the Rumbler Rumble Strips

Peeling the plastic backing from the strip

Rolling the strips with a tamper cart

Figure A.3: Installation of the Orange Rumble Strips

Condition of pavement upon removal

Pavement close-up

Figure A.4: Pavement After Removal of the Rumbler Rumble Strips

Removal of asphalt strips with Loader/Backhoe

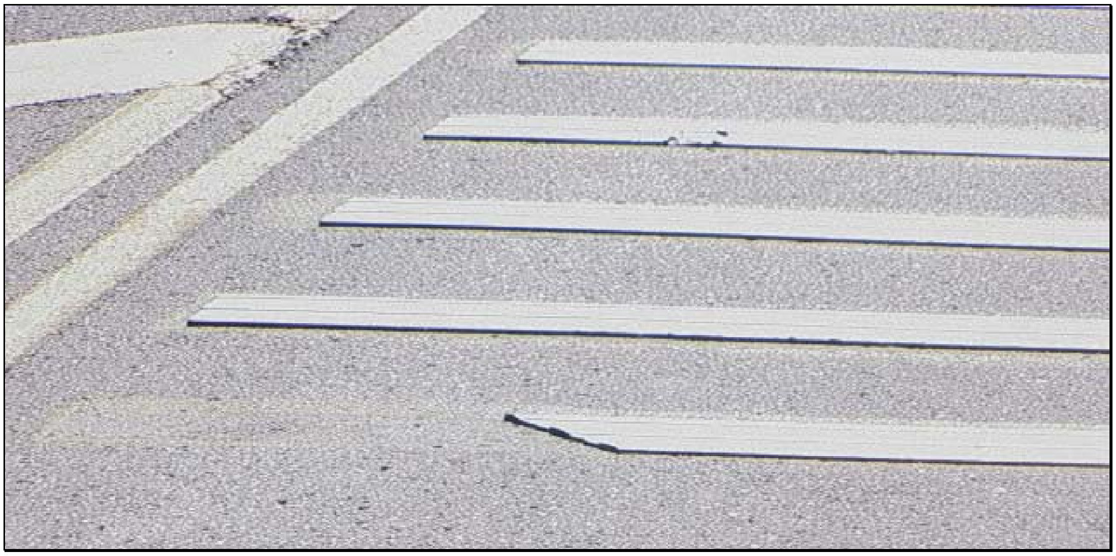
Bucket scraping up the asphalt strips

Figure A.5: Removal of the Asphalt Strips

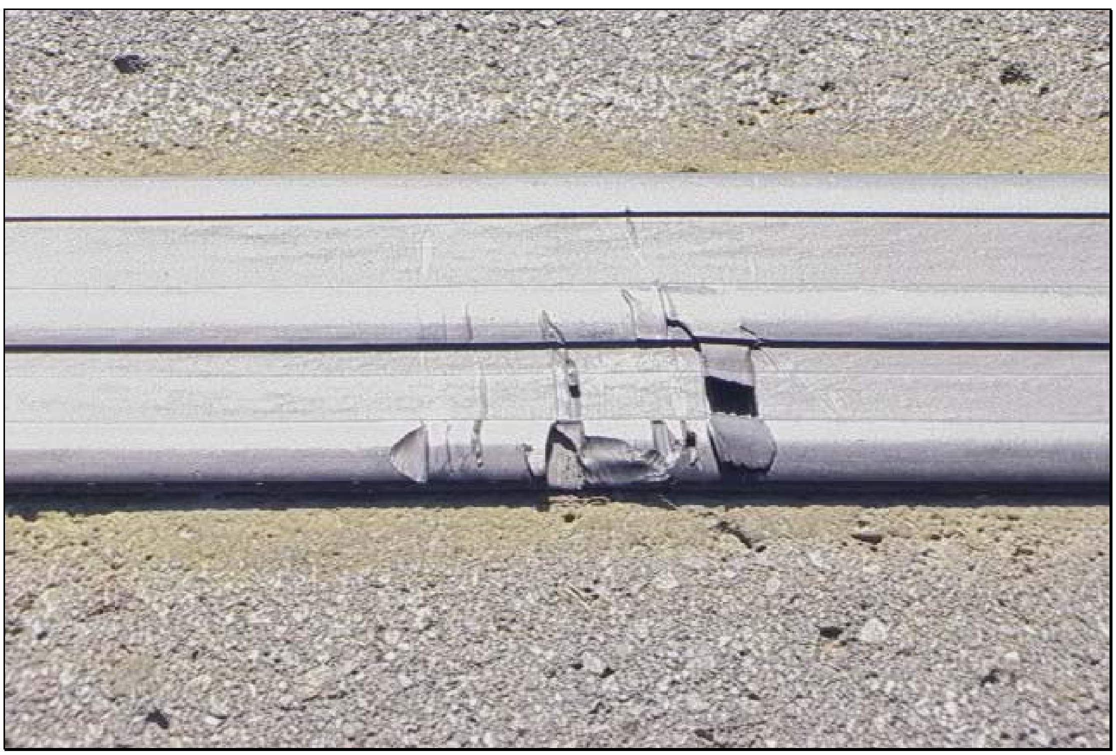
Damaged asphalt strips

Close-up of damage

Figure A.6: Damaged Asphalt Rumble Strips

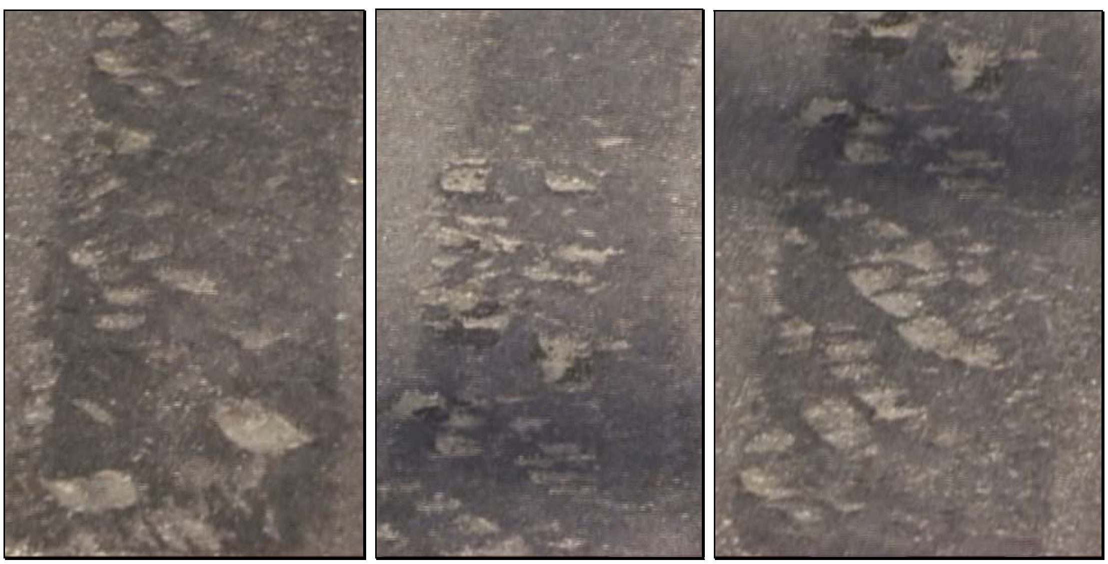


Damaged Rumbler rumble strips



Close-up of damage (fourth strip back in above picture)
Figure A.7: Damaged Rumbler Rumble Strips

Overview



Close-ups

Figure A.8: Pavement Damage from Asphalt Strips

Underside of Rumbler rumble strips

Underside of orange test strips

Figure A.9: Removable Strips After Removal

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