MIDWEST SMART WORK ZONE DEPLOYMENT INITIATIVE

MwSWZDI

FHWA POOLED FUND STUDY

Report Title	Report Date: 2002

Preformed Rumble Strips

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Supplemental Notes

Abstract

The Swarco Rumble device was compared directly with asphalt rumble strips (Kansas DOT standard) for effectiveness in garnering driver attention. Three measures of effectiveness were used: vehicle speed reduction, sound levels inside the vehicle, and vibration of the vehicle body. Additionally, sound levels at the roadside were examined. A cost comparison was performed based solely on installation and removal time plus life cycle costs. Safety benefits were not quantified. The Rumbler strips performed similarly to the asphalt strips with respect to sound and vibration inside the vehicle, and with respect to speed reduction. Sound levels at the roadside were higher for the Rumbler. For a single application, the Rumbler is approximately three times as expensive as asphalt strips (roughly $1,500 per approach for the standard KDOT configuration), but if the Rumbler units are reused the costs are very similar. It was demonstrated that the rumbler could be reused without significant loss of performance. The rumblers proved to be very secure, remaining affixed to the pavement for six weeks with the only failures occurring when a couple of the strips were improperly installed (i.e., too little adhesive was used) and when something tore off pieces of the strips (likely farm equipment inappropriately dragging a metal blade). It was recommended that the strips be allowed on KDOT construction projects, and KDOT has since approved their use.

Comparison of Rumbler and Asphalt Rumble Strips

by

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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 9 on page 14 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 A-weighting filter, used for sound measurements

L_{eq} ⇨ equivalent sound level (dB)

L_{10} ⇨ sound level exceeded 10 percent of the time (dB)

Reference pressure ⇨ 20 micropascals (μPa) for sound

Technology

In Kansas, the Department of Transportation (KDOT) 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. In this evaluation, the Rumbler rumble strip from Swarco Industries Inc. in black (Rumbler) was compared with the KDOT standard asphalt rumble strips (Asphalt). The Rumbler rumble strip is manufactured by

Swarco Industries
PO Box 86
Columbia, TN 38402
931-388-5900
931-388-4039 (fax)
www.swarco.com

Rumblers are available in black, yellow, and white. The cost for a package of ten 4-ft strips ranges from $166.00 (1-4 packages) down to $140.50 (21 or more packages). Strips are also available in reflective yellow or white for about 12% more. A 5-gallon pail of contact cement is $95, also available from Swarco. Black strips were used in this evaluation.

Layout

Rumble strip patterns range from a single continuous section of textured roadway to single strips placed at varying spacings. The most common rumble strip layout patterns consist of a few sets with each set containing a few small 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 30.5 m (100 ft) apart. Each of the six groups consists of six strips with 0.6 m (2 ft) center-to-center spacing. [1] Rumble strips at an approach to an intersection consist of a single group containing 25, 10 cm (4 in) grooves with 0.3 m (1 ft) center-to-center spacing. [2]

Each Rumbler rumble strip consists of a 1.2 m (4 ft) long piece of black rubber with three raised ridges that is applied to the pavement using contact cement. While the Rumbler is also available in reflective white and reflective yellow, the black strip was used to obtain the lower bound for the performance of these strips. It is assumed that the brightly colored reflective strips will perform as well as or better than the black strip because of their added visual effect.

The asphalt rumble strips consist of a raised strip formed from cold-mix asphalt. The asphalt strips typically have a cross-section that is best described as dome shaped. This type of strip is currently the most commonly used type of raised rumble strip. [2]

Installation

For proper installation of the Rumbler strips, the pavement must be clean, dry, and warmer than 10˚ C (50˚ F). During both installations involved in this study, 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 profile of the strips is best accommodated with a tamper cart using a wheel with a customized shape, provided by the manufacturer. Figure 1 shows the tamper cart being used on the Rumbler rumble strips.

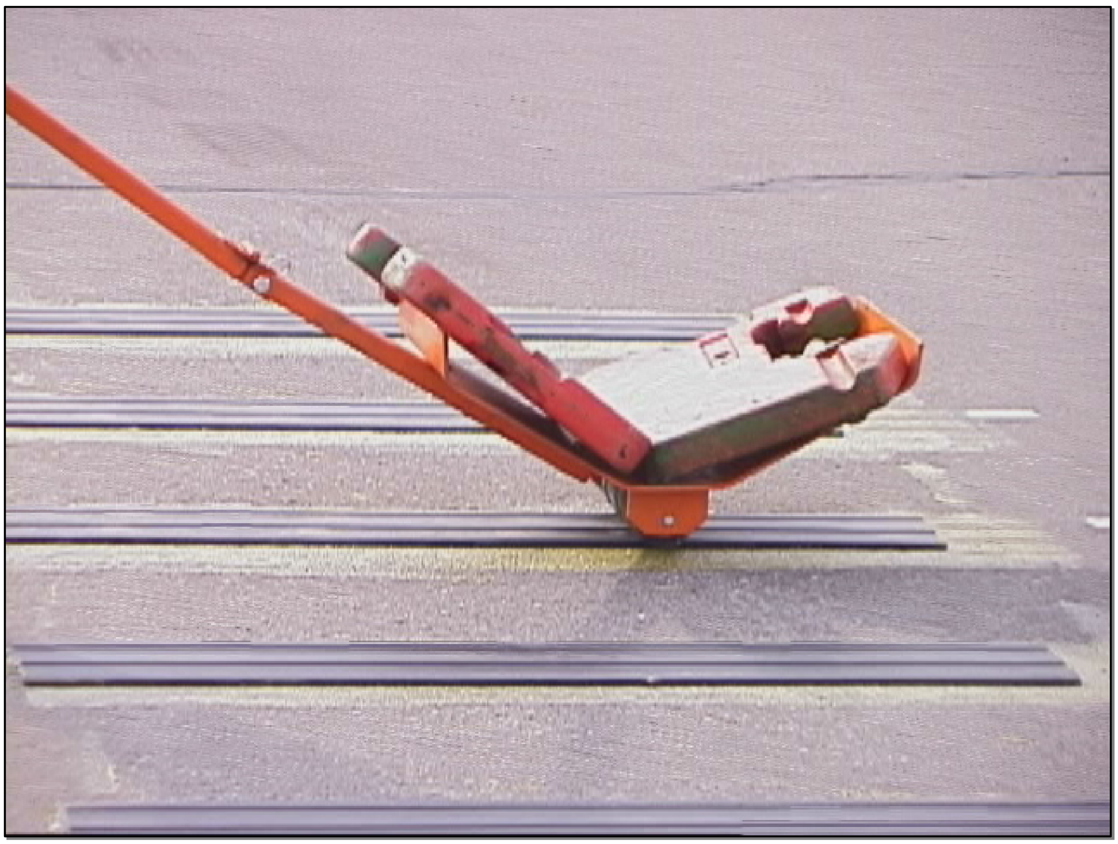


Figure 1 - Tamper Cart with Custom Wheel Rolling Rumbler Rumble Strips

Asphalt rumble strips are usually installed using one of two methods. Sometimes asphalt strips 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. Asphalt strips are sometimes placed without using the forms. Instead, 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 later method.

Cross-sections

The cross-section of the rumble strip directly affects the amount of sound and vibration that each type of strip will produce. 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. They are both less wide and less thick than the asphalt rumble strips. Figure 2 shows detailed drawings and dimensions of the cross-sections of both types of rumble strips. The dimensions for the asphalt strip are approximations as the cross-section can vary.

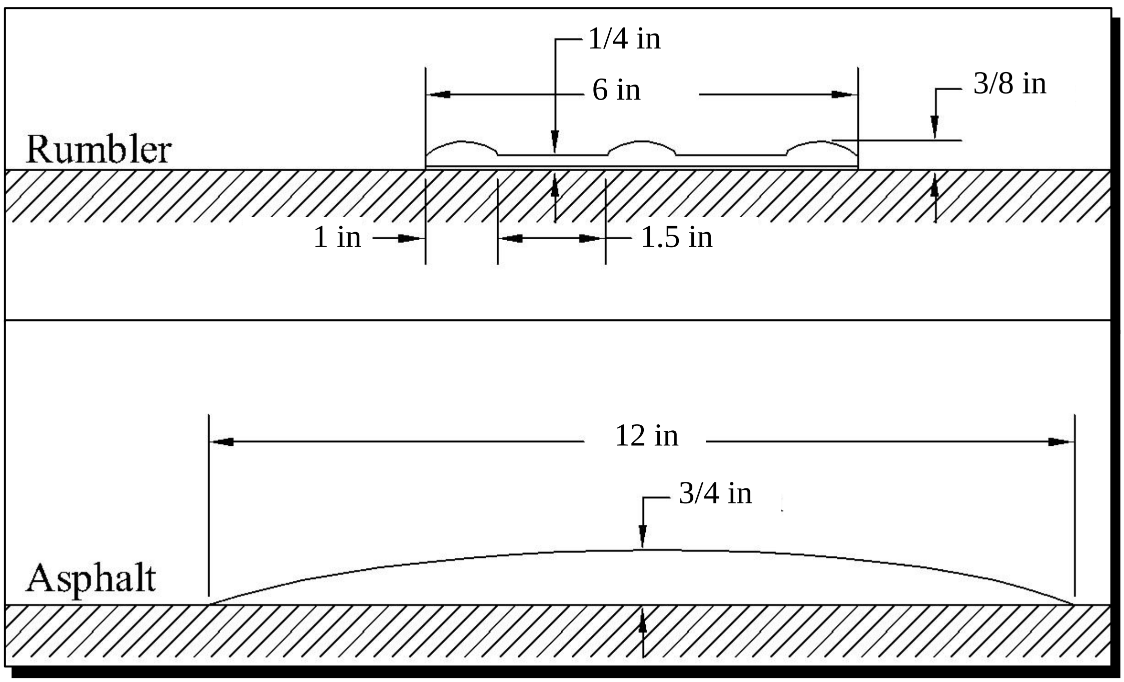


Figure 2 - Rumble Strip Cross-Sections

Study Sites

Data were collected at two work zones. The removable strips were used for the most upstream set on one approach at each site. The remaining sets were asphalt rumble strips. Sound and vibration measurements were taken for both smooth pavement and asphalt rumble strips at both locations.

Perry Lake Test Site

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 vpd on the westbound approach and 1200 vpd 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).

Horton Test Site

The second test site was 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).

Layout

Sound and vibration levels were taken on asphalt strips at both sites. Speed data was collected on the asphalt strips that were located on the approach opposite the Rumbler approach at the Perry Lake test site.

Figure 3 through Figure 6 are work zone diagrams of the test sites. The boxes that contain only a three-digit number represent automatic traffic recorders, which were used to monitor speeds, volumes, and vehicle classifications. Figure 3 shows where the speeds were collected on the asphalt strips, Figure 4 shows where the speeds were collected on the Rumbler rumble strips, and Figure 5 shows where the speeds were collected for a different removable product that was associated with a different study.

In Kansas, work zone rumble strips are most commonly applied using cold mix asphalt in a configuration comprised of two sets of strips. The sets are spaced 152 – 228 m (500 ft - 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 sometimes a 0.6 to 1.2 m (2 to 4 ft) channel is left in the center of the strips for motorcycles. In order to compare the two types of temporary rumble strips to the asphalt rumble strips, the temporary rumble strips were deployed using the same pattern, although, a gap was included in the center of the lane and 15 cm (6 in) between the edge of the strips and the edgeline and 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 Horton location, which had 3.4 m (11 ft) lanes. Figure 7 shows diagrams of a typical rumble strip deployment for a single approach, a set of rumble strips, and a single group of temporary rumble strips.

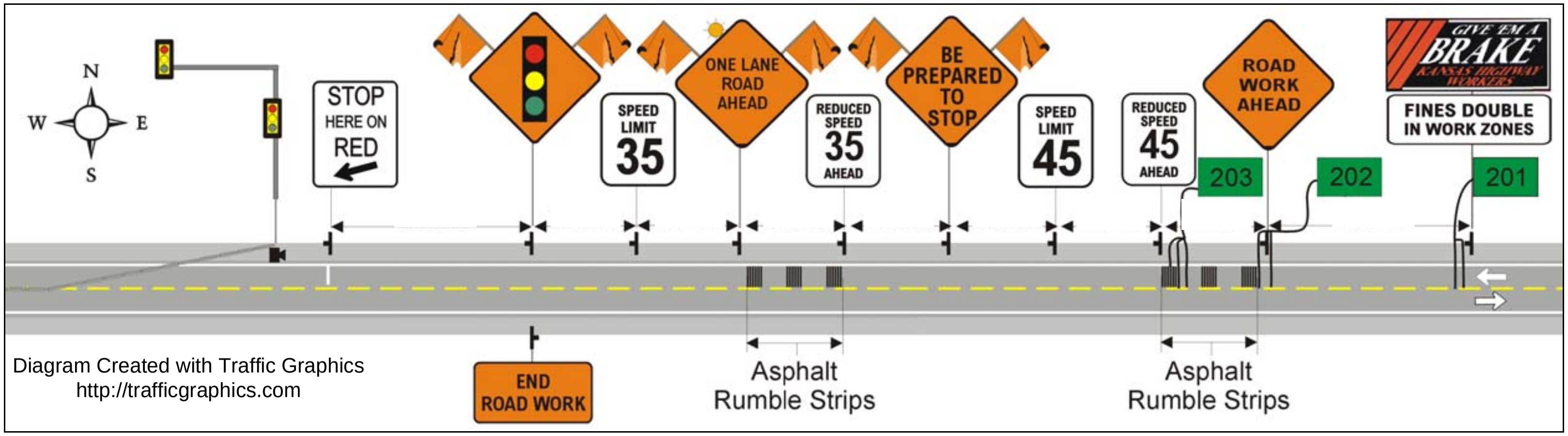


Figure 3 - Westbound Approach at Perry Lake Test Site

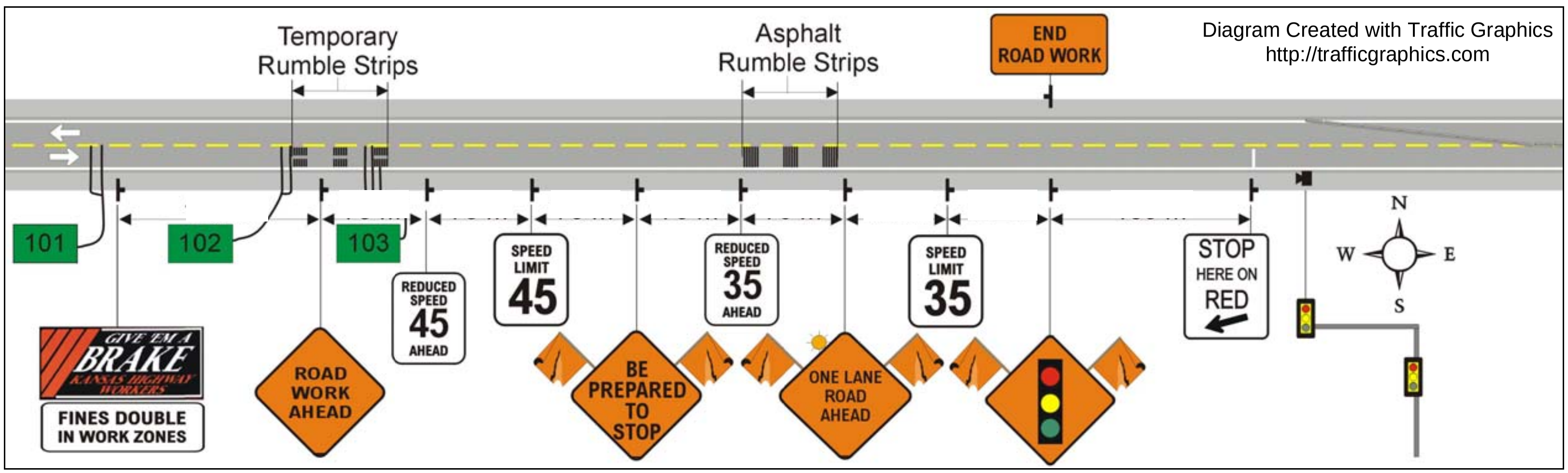


Figure 4 - Eastbound Approach at Perry Lake Test Site

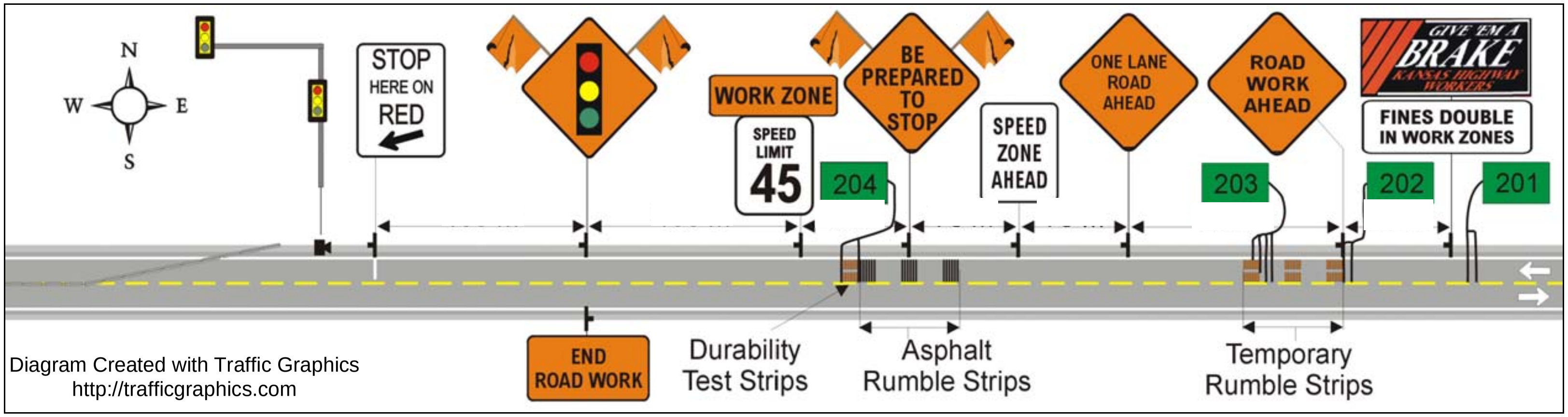


Figure 5 - Westbound Approach at Horton Test Site

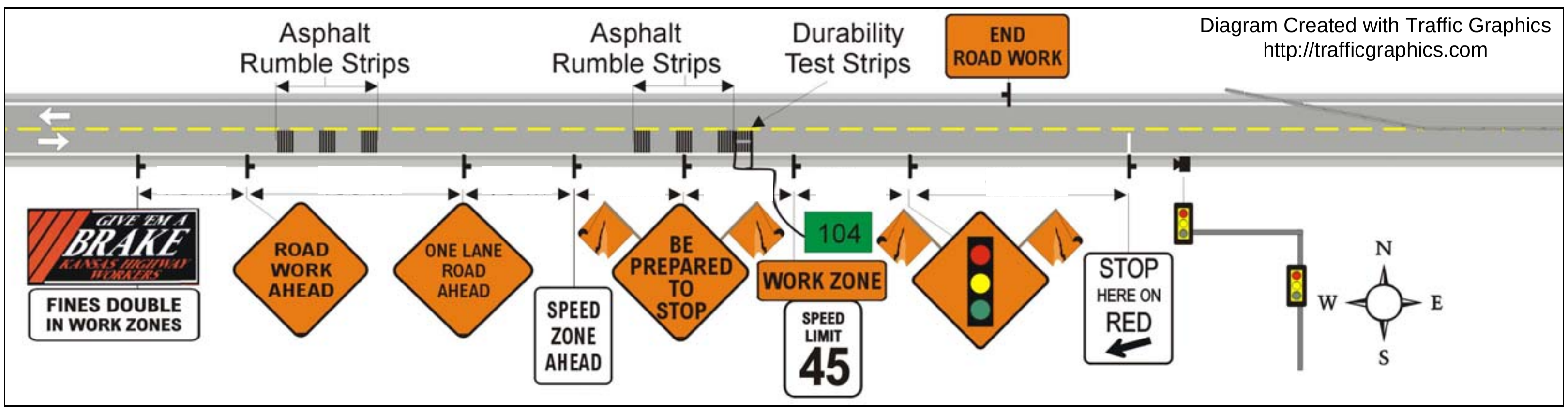


Figure 6 - Eastbound Approach at Horton Test Site

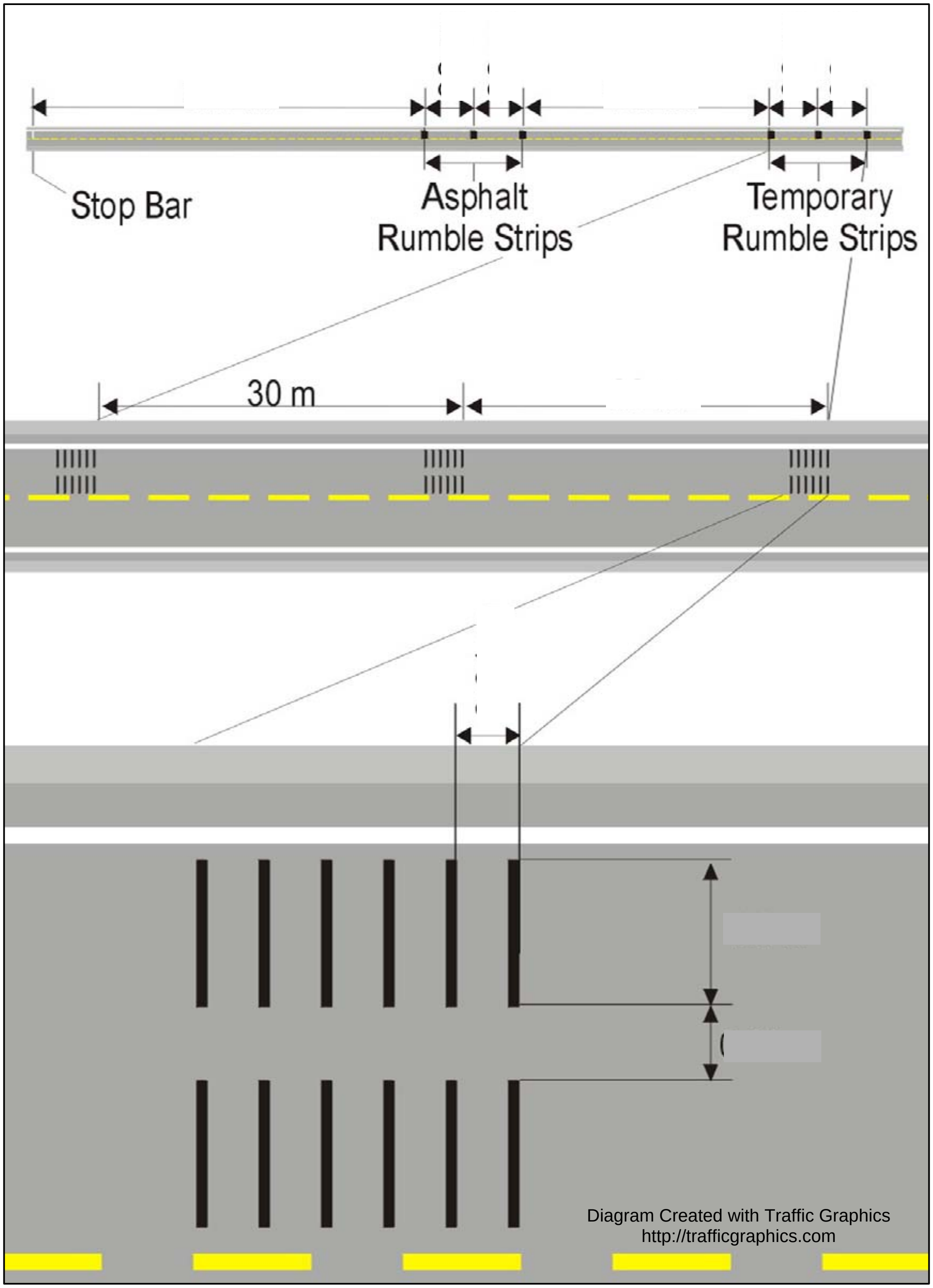


Figure 7 - Typical Experimental Rumble Strip Deployment

Data Collection—Sound and Vibration

Rumble strips work by producing sound and vibration intended to alert the driver. While there are undoubtedly many other factors involved, the ability of rumble strips to get the driver's attention is directly related to the magnitude of the sound and vibration generated. With that in mind, the sound and vibration levels generated by the strips are very important points of comparison between different types of strips. In additional to measuring the sound in the vehicle and the vibration of the vehicle body, roadside noise levels were also measured for the KDOT standard configuration.

In order to collect the sound, vibration, and roadside noise levels, it was necessary to deploy a set of each of the types of the strips that were to be tested. These strips were then traversed repeatedly with three test vehicles at three different speeds until all of the data necessary for the comparisons had been collected. Vehicle speed data was collected in order to compare the rumble strips effect on vehicle speeds and speed reductions. Through the process of installing these model deployments, the times and costs of the installation were observed and quantified. The strips were then left in place for the duration of the respective construction projects in order to allow for the collection of speed data and to test the durability of the strips for use in long-term deployments. When the strips were removed, the removal times and costs were recorded. The amount of damage suffered by the strips was observed in order to get a better understanding of the durability of the different types of strips.

For measuring sound and vibration, three vehicles were used: 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). The measurements were taken for each vehicle at each of three different speeds: 64, 80, and 97 kph (40, 50, and 60 mph). These speeds were chosen in order to obtain measurement ranges that would be typical for approaches to highway work zones. Table 1 shows the characteristics of the test vehicles.

Sound and vibration levels were measured as Equivalent Sound Level (L_{eq}) in decibels (dB). Table 2 shows sound levels in dB for common sounds. The measurements were recorded using a Norsonic Nor-110 Sound/Vibration Analyzer, shown in Figure 8. L_{eq} values were recorded using a 3 ms measurement interval. The vibration levels were measured with no frequency weighting (sometimes referred to as flat or linear), and the sound levels were measured using the 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, and makes adjustments to the L_{eq} based on the frequency of the sound, so that the recorded data are more representative of what an average human would perceive. [3] Figure 9 shows a graph of the function comprising the A-Weighting filter.

Table 1 - Test Vehicle Parameters

Parameter	Test Vehicle 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

Table 2 - Typical Sound Levels for Common Sounds in Decibels (dB) [3]

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
Subway train screech	115 dB
Rock concert	120 dB
.22 caliber rifle	130 dB
Jet take-off	140 dB

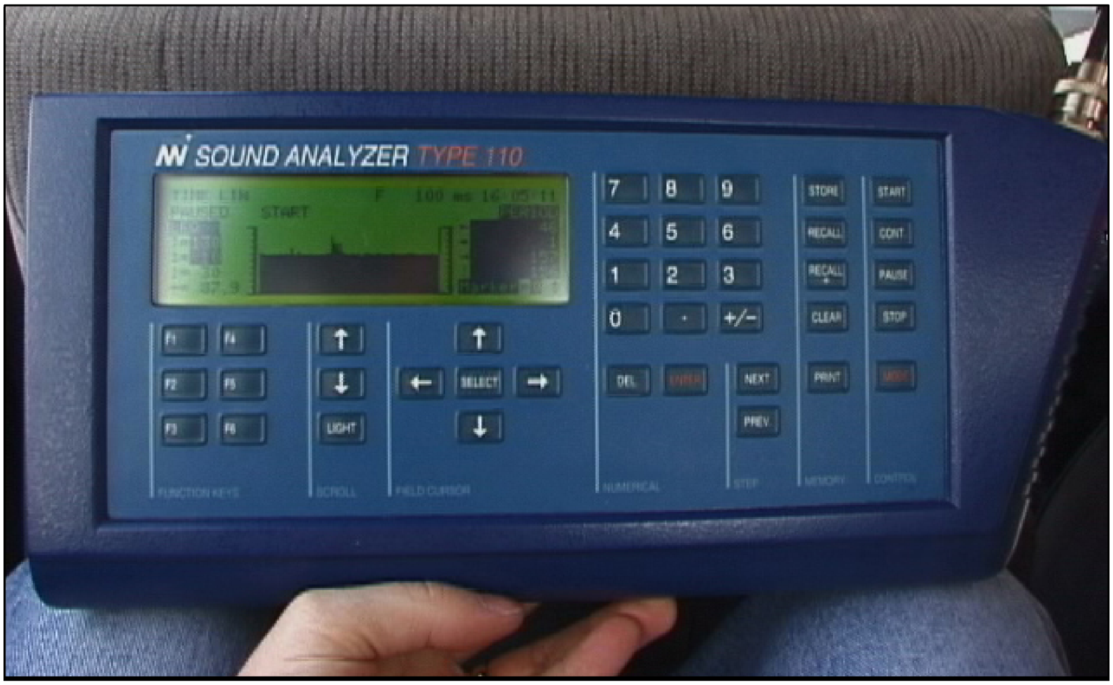


Figure 8 - Sound and Vibration Analysis Equipment

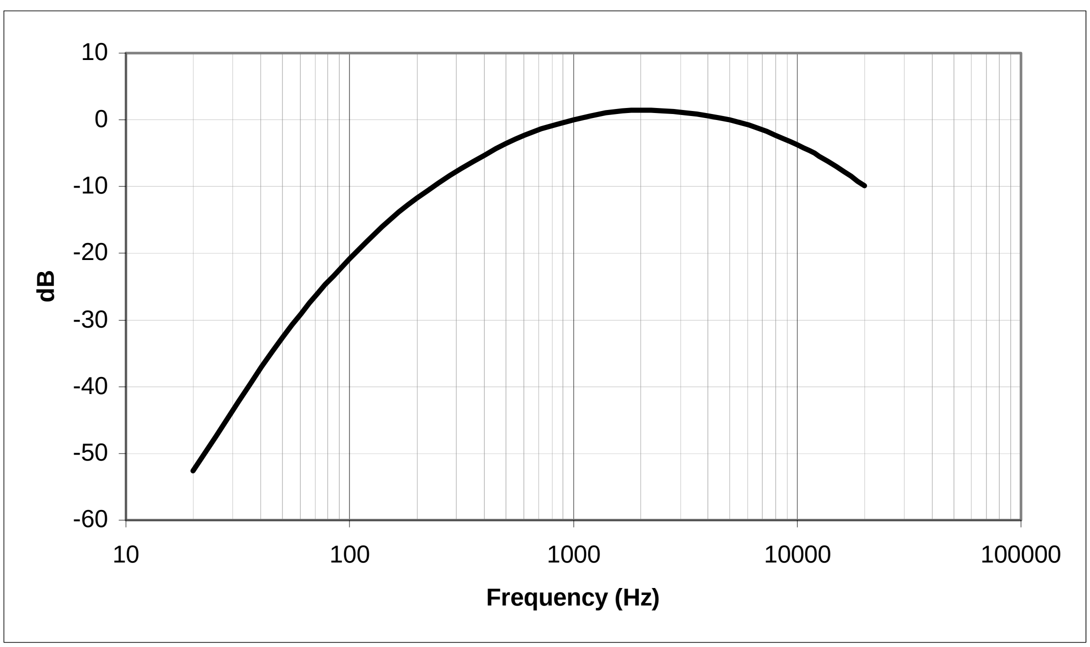


Figure 9 - A-Weighting Filter

Instrument Placement

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 seats, 19 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 location was intended to approximate the position of the ear of a typical driver. All measurements used in the analysis were taken with the windows rolled up and the air-conditioner and stereo turned off. Measurements were also taken to compare the sound generated by the rumble strips with the sound generated by the radio (at a moderate volume setting) and the air-conditioner (on the highest fan setting). Figure 10 shows a comparison of the measurements collected with and without the radio and air conditioner. The chart shows that the increase in the sound levels caused by the added noise affected the sound levels on both the baseline data point and on the strips by approximately the same amount. This indicates that while the stereo and air conditioner do affect the sound levels, they do not affect the difference between the baseline levels and the levels produced by the strips. Since the differences in sound levels observed without the radio and the air conditioner are quite similar to the differences in the sound levels that would be experienced with the radio and air conditioner, it is reasonable to assume that the differences determined under these ideal conditions are representative of the differences that would be experienced in more realistic situations.

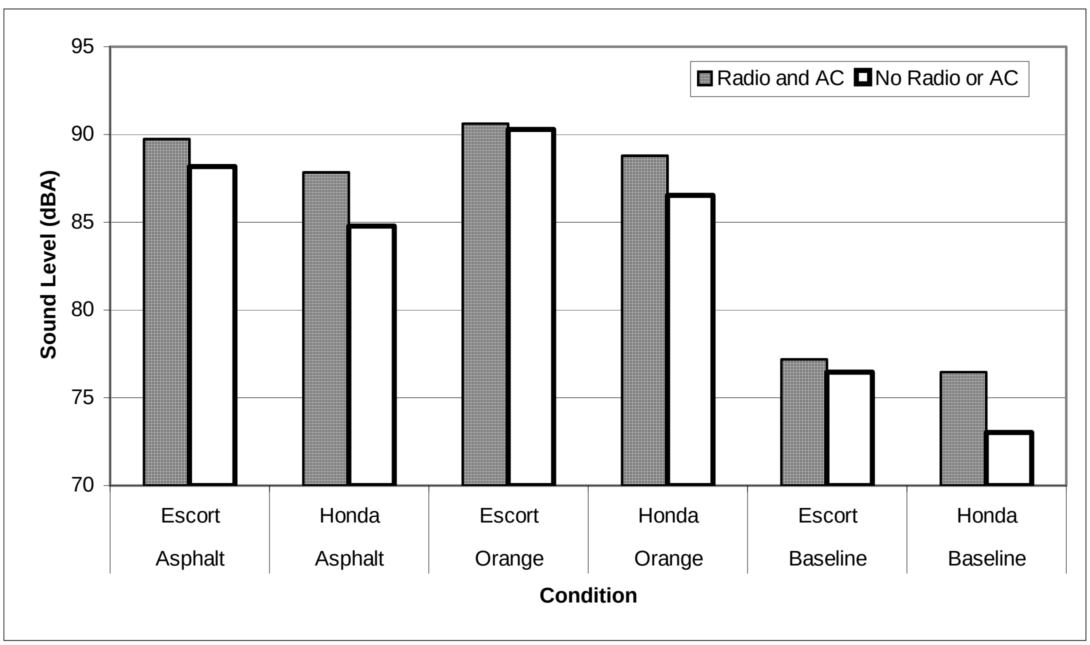


Figure 10 - Sound Levels with and without the Radio and Air Conditioner

Vehicle-Body Vibration

There are several ways in 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 can feel vibration through the steering wheel, the seat, and the floor of the vehicle. The amount of vibration that would be transferred through each of these means varies tremendously from vehicle to vehicle, depending on vehicle characteristics such as the suspension system, the type of and quality of the seat, and any damping mechanism between the steering wheel and the tires. To accurately measure the precise vibratory sensations caused by a set of rumble strips would require measuring the vibratory energy transmitted to the driver through each of these mechanisms. Additionally, the method and extent of the transmission of vibratory energy would also be a function of the driver's body. The weight of the driver, the length of the driver's arms and legs, and the thickness and fat content of the skin will all effect what levels of vibration will be perceived through each of the possible mechanisms.

Because this study is a comparison between a new device and a typical device, it is only necessary that a measurement be taken whose relative magnitude varies similarly to driver-perceived vibration. Toward this end, *vehicle body vibration* was use as the comparative measure. The implied assumption is that as vehicle body vibration increases, the vibratory energy propagating through the vehicle to the driver would be increased for every propagation mechanism. The vehicle body vibration was measured using an accelerometer that was magnetically mounted to the roof of the vehicle, directly above the mounting location of the microphone. Figure 11 shows the accelerometer mounted to the roof of a test vehicle (left) and the microphone on a tripod inside of a test vehicle (right).

Roadside Noise

The Federal Highway Administration's standards were followed for the roadside noise measurements. The microphone was mounted on a tripod and placed at the roadside 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. [4] The microphone was oriented perpendicular to the road and was covered with a foam windscreen in order to reduce the effect of wind noise on the data.

Figure 11 - Accelerometer (Left) and Microphone (Right)

Data Analysis—Sound and Vibration

Comparisons of both sound and vibration were based on the maximum of the Leq values measured over 3 ms intervals while crossing the rumble strips. When multiple observations of the same condition were made, the average was used. The measure used to compare data from different sites was the difference between the maximum L_{eq} values observed while traversing the rumble strips and the maximum L_{eq} observed while traversing smooth pavement under the same conditions. By using the difference in maximum L_{eq} relative to smooth pavement, differences between locations such as wind speed, temperature, and atmospheric pressure can be removed from the data, assuming these factors remained constant during the data collection. The relative values measured for the different types of rumble strips can be directly compared.

The relative maximum L_{eq} 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 interval of 95% was used in all of the comparisons.

To help simplify and expedite the data analysis process, a computer program was developed. The program was used to find the maximum L_{eq} values using certain default parameters and limited user interaction. The maximum L_{eq} values were then exported to a file with additional data indicating the condition for which the maximum was obtained. Figure 12 shows a plot of the data recorded for a typical sound level measurement, and Figure 13 shows a screenshot of the data analysis program.

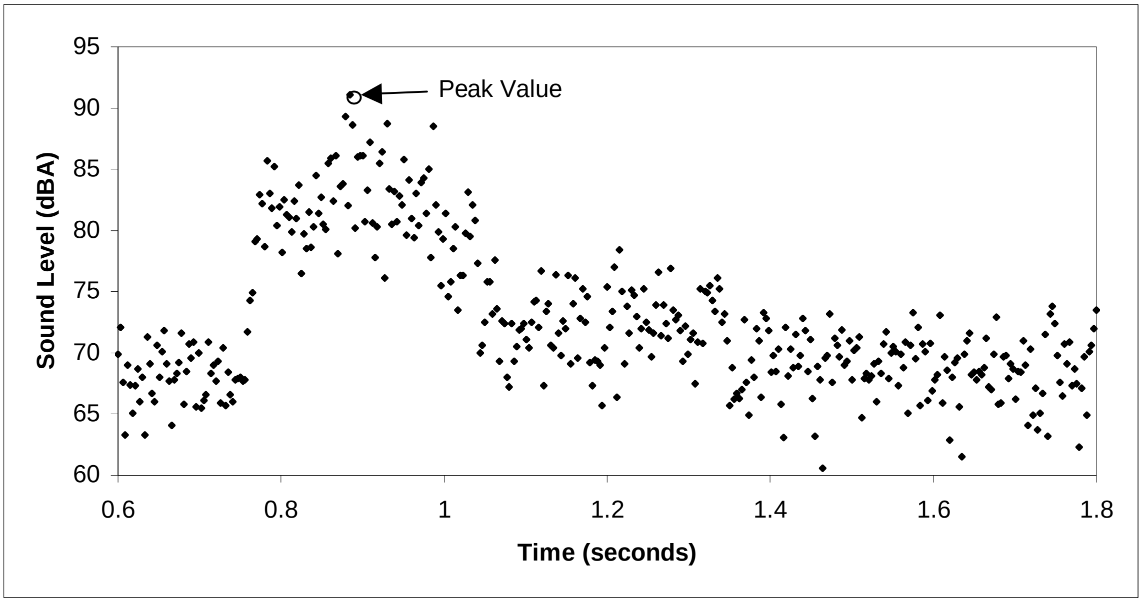


Figure 12 - Typical Sound Level Measurements

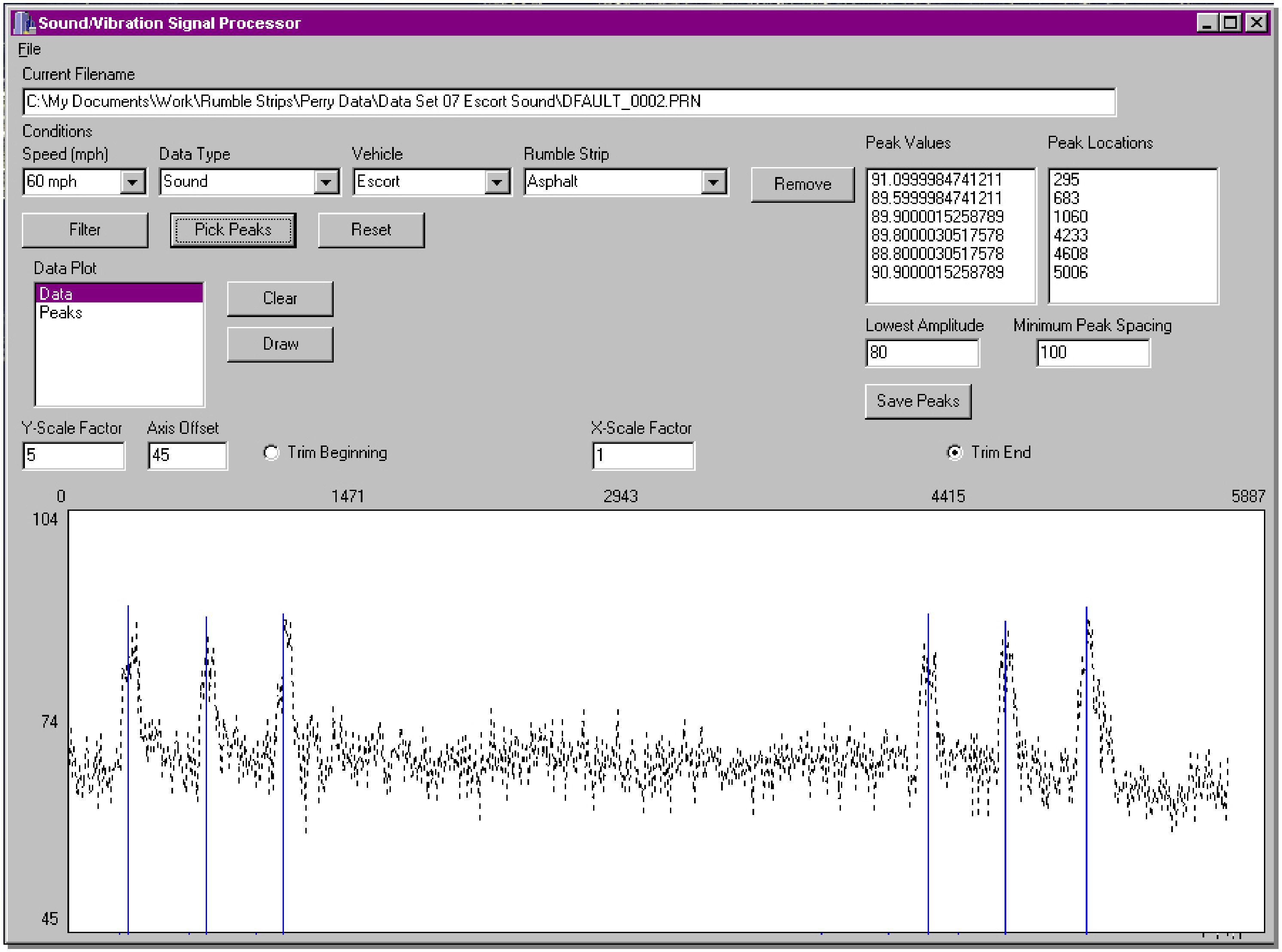


Figure 13 - Screenshot of Sound and Vibration Data Analysis Program

Hearing Limitations

How the sound and vibration produced by the rumble strips are perceived by the driver is not only a function of the sound and vibration levels but is also a function of human perception. Therefore, the perceptibility of the differences in sound and vibration must be considered in addition to the statistical significance. Humans cannot detect very small changes in sound levels. The smallest detectable change in sound level is 1 dB, and a change of 3 dB is a slightly noticeable difference for most people. [5] Therefore, if one set of strips were only 1 dB louder than the other, to say that it produced more sound would be misleading, because a human would perceive them to be equally loud. 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. Therefore, 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.

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. [6] These studies typically rely on simple harmonic vibrations caused by machines, which are quite different than vibrations comprised of a wide range of frequencies and amplitudes, such as those experienced while driving over rumble strips. Additionally, the measures used are generally subjective, making the identification of an objective threshold very difficult. [7, 8] 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. The subjective assessment based on the experience of those who collected the vibration data was that using 3 dB as the threshold of perceptibility was reasonable.

Results—Sound and Vibration

In-Vehicle Sound

In most cases the temporary rumble strips did not differ by an amount that was statistically significant and noticeable. Table 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, nor were there any comparisons that had noticeable but not statistically significant differences. Comparisons that yielded both statistically significant and noticeable differences are highlighted in Table 3. 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 does show 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 - 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

- 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 imperceptible differences.

Vehicle Body Vibration

The data collected for the vehicle body vibration were similar to the data collected for in-vehicle sound. Table 4 shows the comparisons of vehicle body vibration for the two types of rumble strips. Comparisons that yielded statistically significant and perceptible differences are highlighted in gray, and comparisons that yielded differences that were statistically significant but imperceptible are underlined. Overall, differences in vibration L_{eq} values were greater than those observed for the sound measurements. However, no pattern of differences is readily apparent. The one pattern that is common among the measurements is that the vibration experienced by the dump truck is typically less than the vibration of the passenger cars, each relative to smooth pavement. For some cases, as the speed decreased the vibration caused by the rumble strips increased. This is an undesirable effect. The rumble strips are mostly used in areas where drivers need to decrease their speed. If the vibratory sensation increases as the speed decreases, then drivers might be encouraged to maintain higher speeds in order to limit the somewhat unpleasant vibratory sensation. However, as mentioned earlier, this is only the case for a few conditions. This happens with the Rumbler rumble strip for the compact car and the dump truck. It also happens with the asphalt rumble strips deployed in Perry for the dump truck and the midsize car, and with the asphalt rumble strips deployed in Horton for the midsize car. It is important to note that this phenomenon was observed on both the temporary rumble strips and the asphalt strips.

Table 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

- 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.

Roadside Noise

Some rumble strip deployments have met with complaints from nearby residents about excessive noise levels. The complaints often result in expensive studies being performed and sometimes even more expensive noise abatement measures being installed. [9, 10] While these types of complaints normally result from permanent rumble strip deployments, noise could potentially be an issue for temporary rumble strips deployments that are in place for an extended period of time (e.g., more than a few weeks). 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 factors that are used to determine if a noise level is excessive. Most of these factors are lumped into a single factor, the L_{10}, which is the noise level exceeded 10 percent of the time. The L_{10} accounts for the noise level and pitch, the frequency of occurrence, and the duration of the noise. Different L_{10} maximums are set for day, night, and type of area. [4, 11] Another factor that complicates the problem is that there are different criteria for noise levels in work zones, which is where temporary rumble strips would be used most frequently, at least in Kansas. Noise in work zones is considered by the public and officials to be necessary and only temporary. The L_{10} is as much a function of traffic patterns as it is of strip type, and is consequently very site-specific. Thus L_{10} is not an appropriate measure for this study and only roadside noise L_{eq} values were considered. The roadside noise L_{eq}s 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 5 shows the maximum roadside noise levels generated by the rumble strips.

Table 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)	-	-	-	-	-	-	-	-	-

- 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 any differences.

Table 5 shows that the roadside noise caused by the Rumbler rumble strips is noticeably greater than the noise caused by 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.

Data Collection—Vehicle Speeds

Vehicle speeds were monitored to compare driver response to the temporary rumble strips with driver response to the asphalt rumble strips in terms of speed reduction. Only the speeds of vehicles that were considered to be freeflowing (i.e., headway greater than or equal to 5 seconds [12]) were considered. A computer utility was used to identify specific vehicles at each data point on an approach in order to generate vehicle specific speed profiles. Vehicles that could not be identified at one or more data points were excluded from the analysis. At all sites, at least 85% of the vehicles were identified at all data points.

The vehicle speed data were collected using pneumatic hoses and automatic traffic recorders. The hoses were placed in sets of two in order to determine vehicle speeds at three points on each approach. Hoses were deployed on both approaches at the Perry Lake site. At the Horton test site, hoses were not deployed on the approach using the asphalt strips, because the approach was located on a downgrade that was severe enough to have a significant effect on the data. Figure 14 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.

The hoses were deployed the day after the temporary rumble strips were installed so that sound and vibration measurements could be completed first. 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, Kansas, 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. Daytime and nighttime data were analyzed separately. For the data collected at the Perry Lake site, daytime was defined as the hours between 8:30 AM and 7:30 PM. For the data collected at the Horton test site, daytime was defined 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 the strips were deployed.

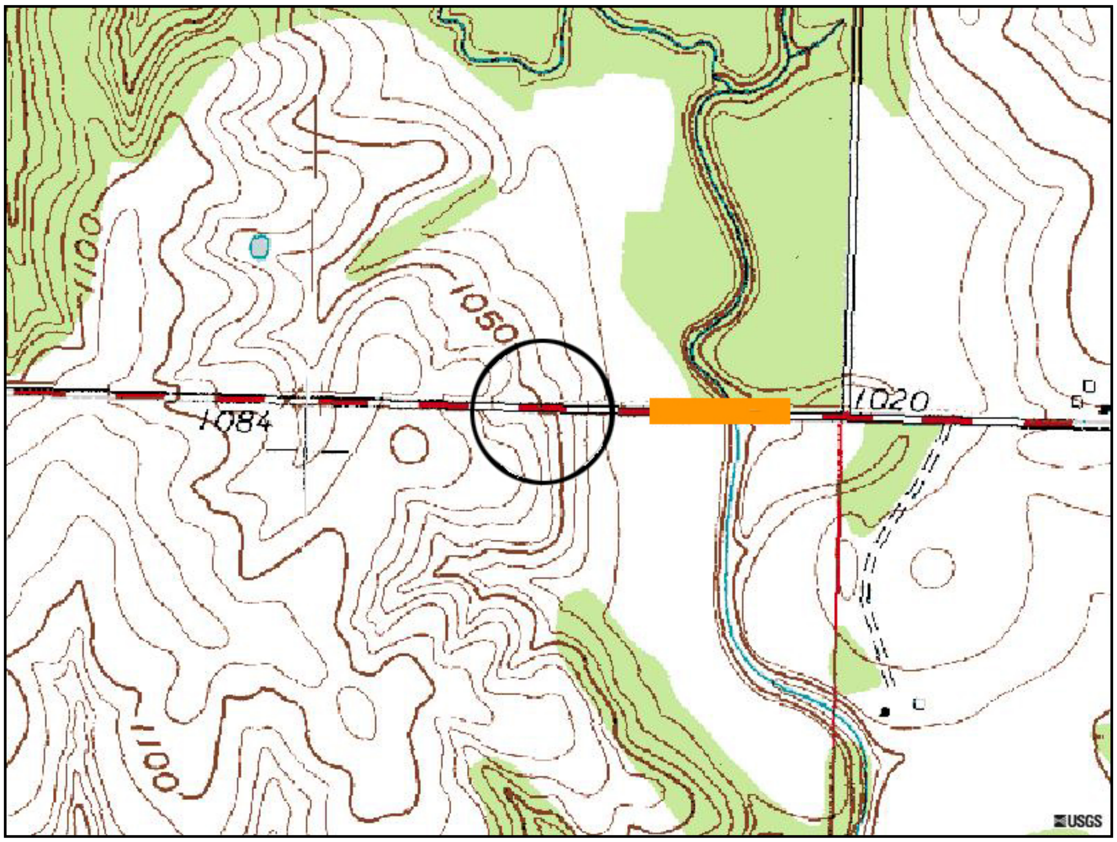


Figure 14 - Topographic Map of Horton Construction Site [13]

Data Analysis—Vehicle Speeds

The speed data collected on each set of rumble strips were analyzed as a whole, by vehicle type (passenger cars and trucks), by time of day (daytime and nighttime), and by time relative to rumble strip installation (first and second half of collected data, chronologically). Table 6 shows all of the data subgroups for a single set of rumble strips. Where 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.

Speeds were examined relative to the baseline speed measured 150 m (500 ft) upstream of the strips. Variation among vehicles is represented by the standard deviation of speeds at each location, the 85th percentile speeds, and by the percentage of vehicles within the 16-kph (10-mph) pace.

Table 6 - 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

Results—Vehicle Speeds

All speed-related variables showed predictable patterns, and the patterns were very similar between the two approaches.

Speed Reduction

Figure 15 and Figure 16 show plots of the mean and 85th percentile speeds, respectively. Figure 17 shows a plot of the speed reductions. Statistical descriptions of the collected speed data for the rumble strips are located in Table 7. 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. Both types of rumble strips show a speed reduction that is 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 both types of rumble strips.

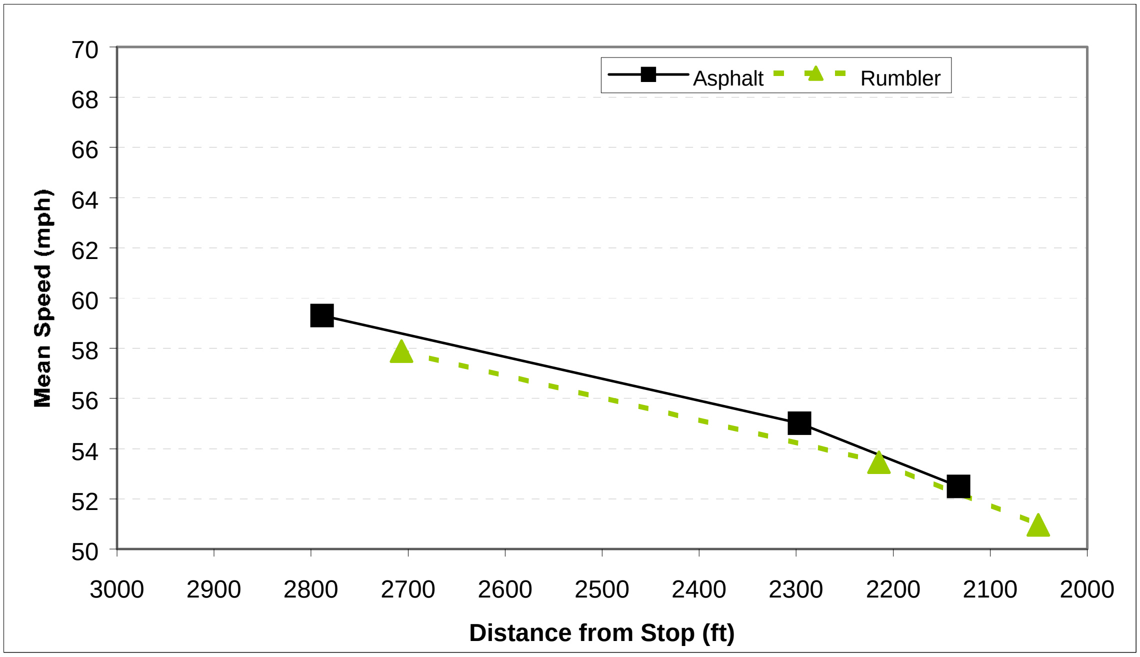


Figure 15 - Mean Speeds Comparison (Passenger Cars, 24 Hours)

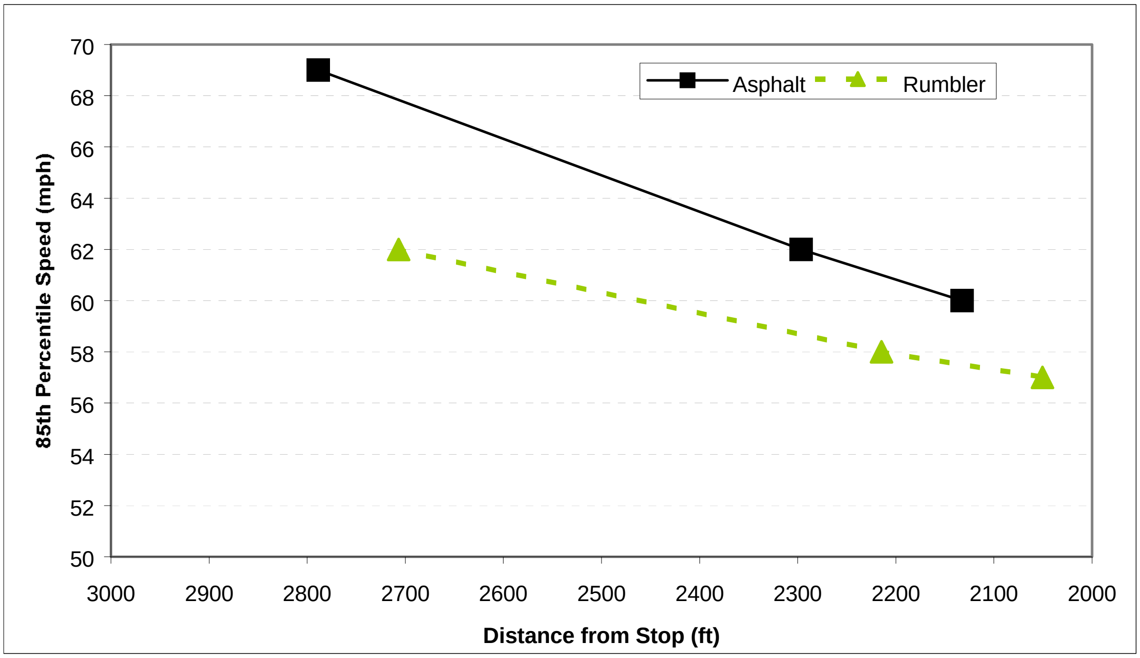


Figure 16 - 85th Percentile Speed Comparison (Passenger Cars, 24 Hours)

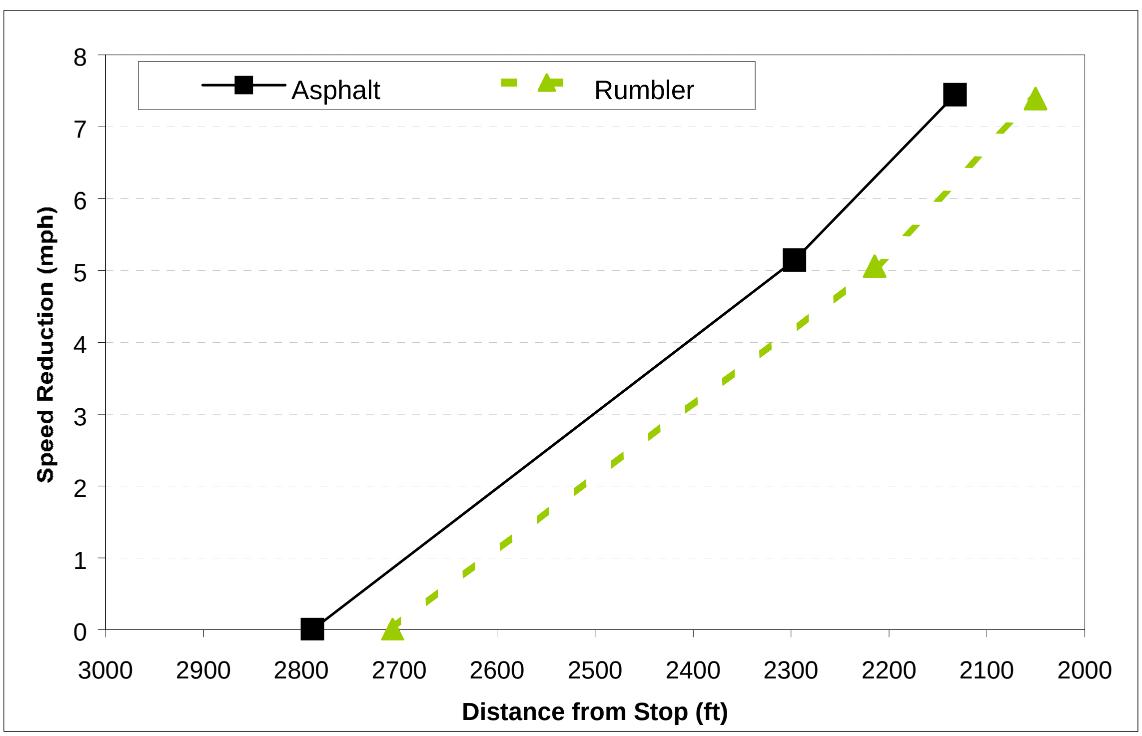


Figure 17 - Speed Reductions (All Vehicles, 24 Hours)

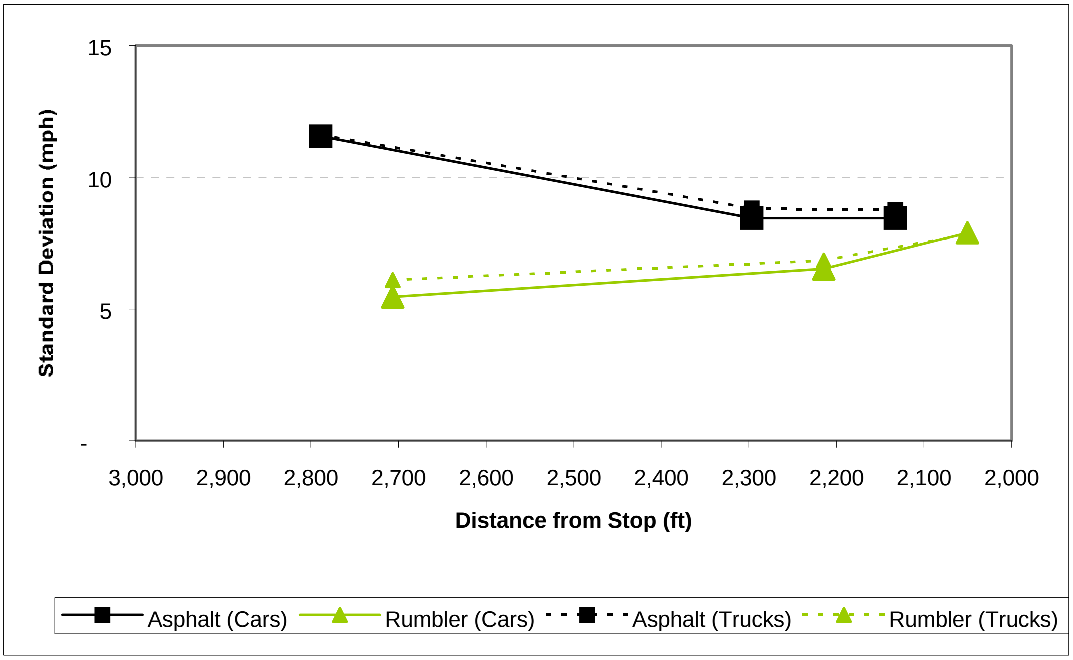
Table 7 – Overall Speed Summary for Rumbler and Asphalt Rumble Strips

	Rumbler			Asphalt		
Data Point*	101	102	103	201	202	203
Distance from Stop (ft)	2707	2215	2051	2789	2297	2133
		Cars			Cars	
Count	12115	12235	12368	11531	11435	11346
Mean (mph)	57.9	53.5	51.0	59.3	55.0	52.5
85th Percentile (mph)	62	58	57	69	62	60
Pace (mph)	57	54	53	65	58	51
Std Deviation (mph)	5.5	6.6	7.9	11.5	8.5	8.4
% of Vehicles in Pace	68%	57%	46%	43%	45%	46%
Δ Speed (mph)	0.0	-5.1	-7.4	0.0	-5.1	-7.4
		Trucks			Trucks	
Count	1003	997	1008	927	986	968
Mean (mph)	56.4	52.9	50.8	58.5	54.1	51.0
85th Percentile (mph)	60	58	57	68	61	58
Pace (mph)	57	54	53	65	53	50
Std Deviation (mph)	6.1	6.8	7.8	11.6	8.8	8.8
% of Vehicles in Pace	68%	56%	51%	43%	45%	47%
Δ Speed (mph)	0.0	-3.8	-7.6	0.0	-5.3	-7.5

** See Figure 3 and Figure 4 on page 9 for the location of the data points.*

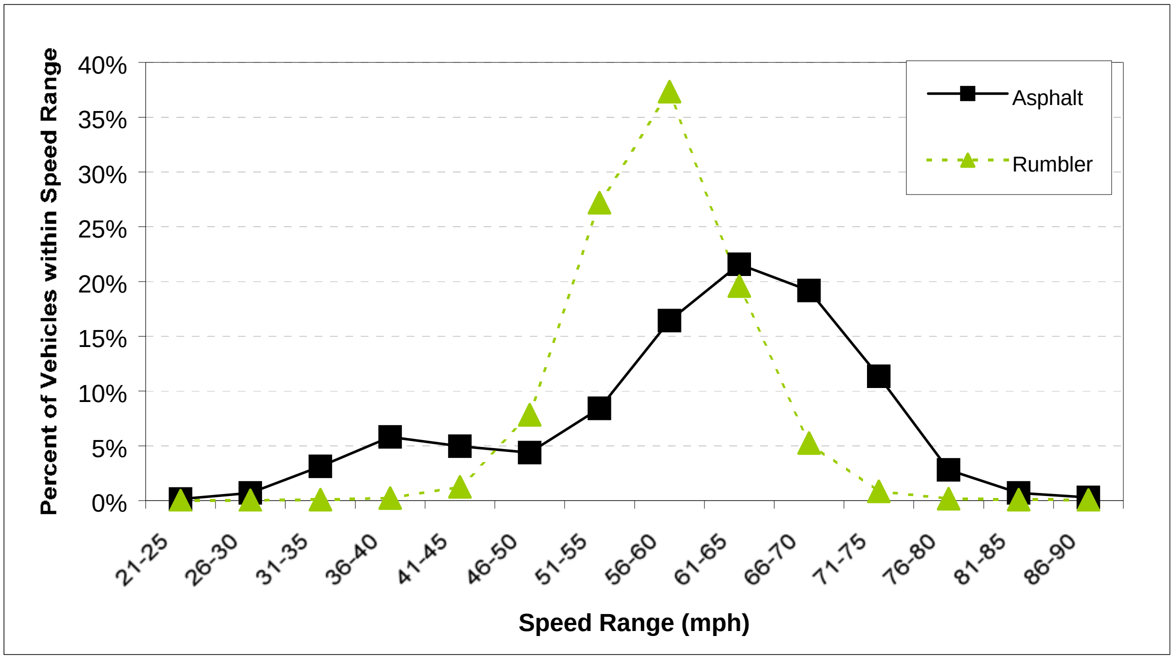
Speed Variation

When a large variation in the speeds of vehicles traveling the same path exists, an increase in the frequency of accidents can be expected. [14] The standard deviation of speeds found in Table 7 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. Figure 18 shows the standard deviation of speeds observed on the two types of strips. While the asphalt strips seemed to cause a decrease in the speed variation, the standard deviation of the observed speeds was always greater on the asphalt strips. Figure 19, Figure 20, and Figure 21 show the speed distributions observed on the rumble strips for the most upstream data point, the first point on the rumble strips, and the most downstream data point, respectively. The higher standard deviations on the asphalt strips may be attributable to the downgrade upstream of the asphalt rumble strip approach. At each successive data point, the speed distributions become increasingly similar.



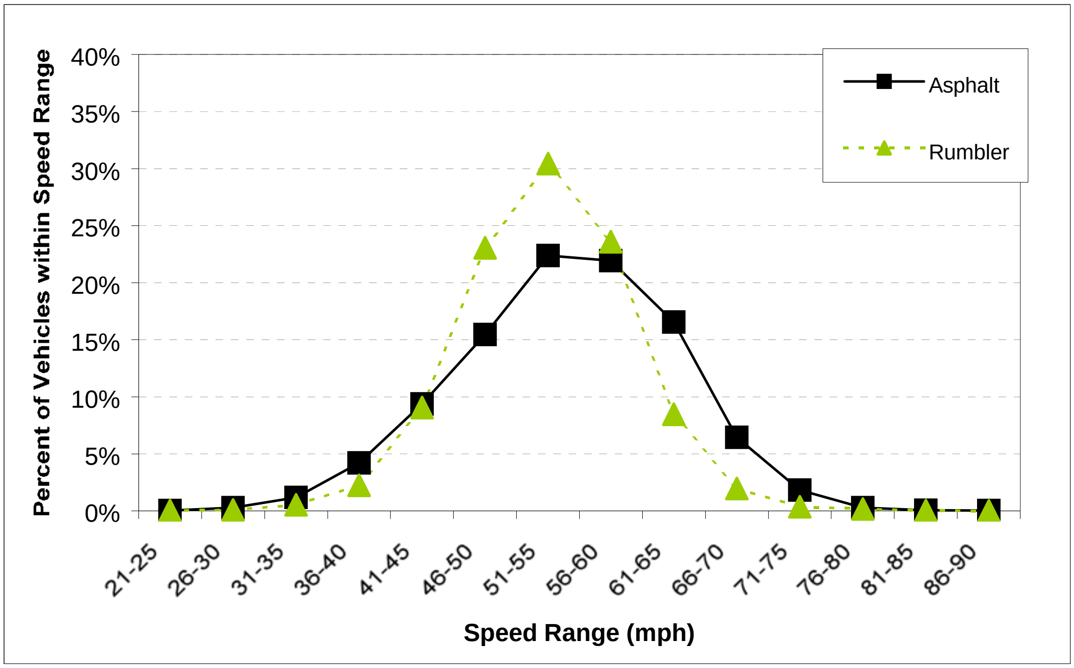
**Standard Deviations for day and night, and first and second data sets.*

Figure 18 - Standard Deviation of Speeds



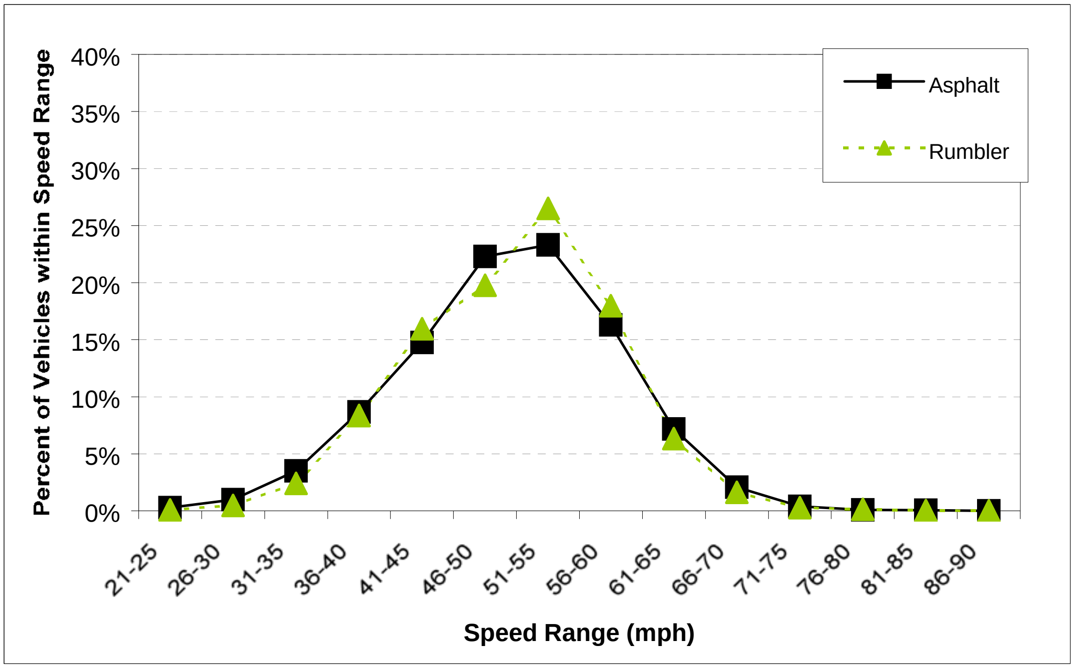
**Distribution for passenger cars, day and night, first and second data sets.*

Figure 19 - Speed Distribution Comparison for First Data Point (Cars)



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

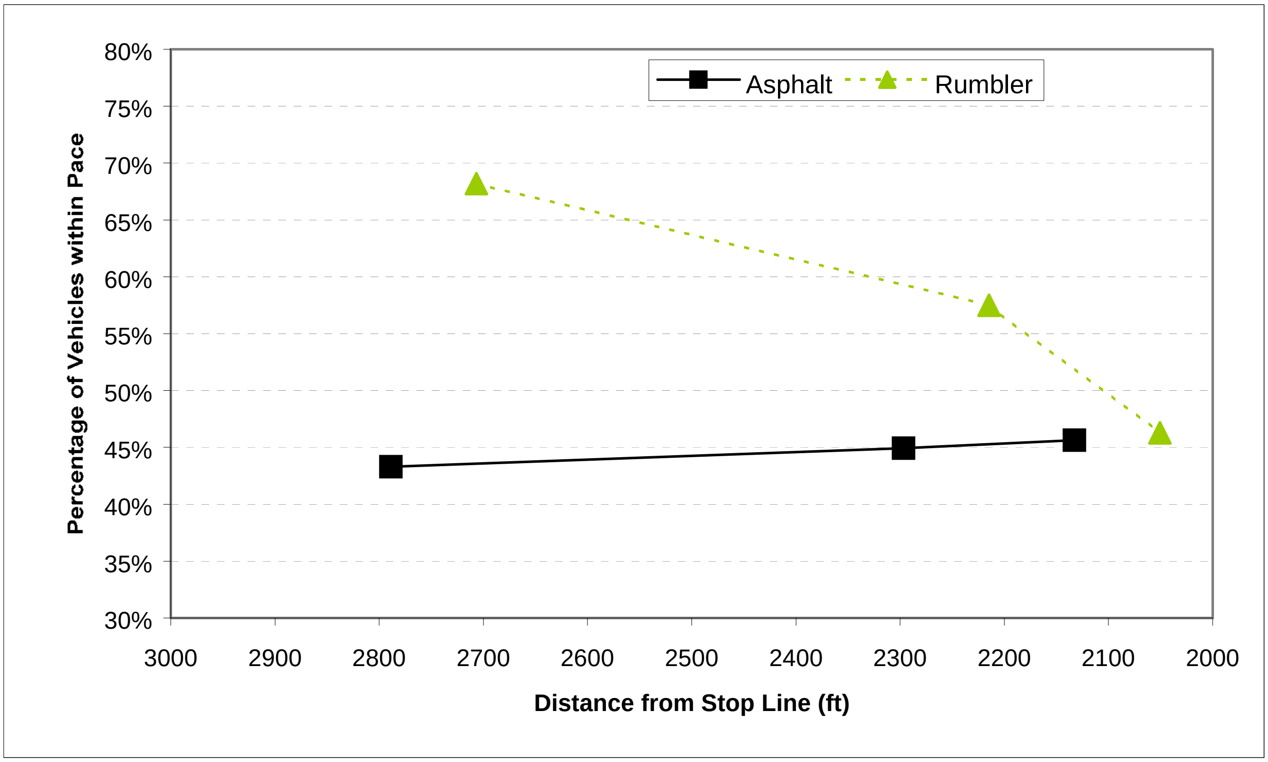
Figure 20 - Speed Distribution Comparison for Second Data Point (Cars)



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

Figure 21 - Speed Distribution Comparison for Third Data Point (Cars)

The 16-kph (10-mph) pace at each data point is shown in Table 7. In all cases, the percentage of vehicles within the pace was greater for the temporary rumble strips than for the asphalt rumble strips. However, the percentage was decreasing on the temporary rumble strips and increasing on the asphalt strips. Figure 22 shows the percent of passenger cars within the pace. A similar pattern was observed for trucks. The decrease observed from point 2 to point 3 on the Rumbler approach may be attributable to turning vehicles, as this location was just upstream of a turning lane for an intersection with a county road. Because the intersection was downstream of the last counter, there was no way of identifying which were turning vehicles and which were through vehicles. A similar pattern was observed for trucks.



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

Figure 22 - Percent of Passenger Cars within the 16 kph (10 mph) Pace

Temporal Effects

One objective of this study was to assess the temporal change in the effectiveness of the strips, that is, to determine the extent to which the effectiveness may be due to a *novelty effect*. If a novelty effect is present, speeds immediately after installation of the strips will be lower than those observed several weeks later, after drivers have come to expect the strips. This did not seem to be the case with these deployments. The segment used for the test simply links small neighboring communities, and is not major through route. Consequently, most of the traffic is repeat traffic, local travelers who traverse the segment frequently.

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, at least 2 weeks after the initial deployment. 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. Table 8 and Table 9 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 8 - 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	63	-4	-5	58	-5	-7
Rumbler	Cars	2nd	63	-3	-4	58	-4	-7
Rumbler	Trucks	1st	61	-2	-4	56	-4	-6
Rumbler	Trucks	2nd	61	-2	-3	57	-3	-5

**Speed values for Data Point 101 are in mph, all others are in mph relative to Data Point 101.*

Table 9 - 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	69	-6	-8	59	-4	-7
Asphalt	Cars	2nd	70	-7	-9	59	-4	-7
Asphalt	Trucks	1st	70	-8	-11	59	-5	-8
Asphalt	Trucks	2nd	68	-6	-9	58	-4	-7

**Speed values for Data Point 201 are in mph, all others are in mph relative to Data Point 201.*

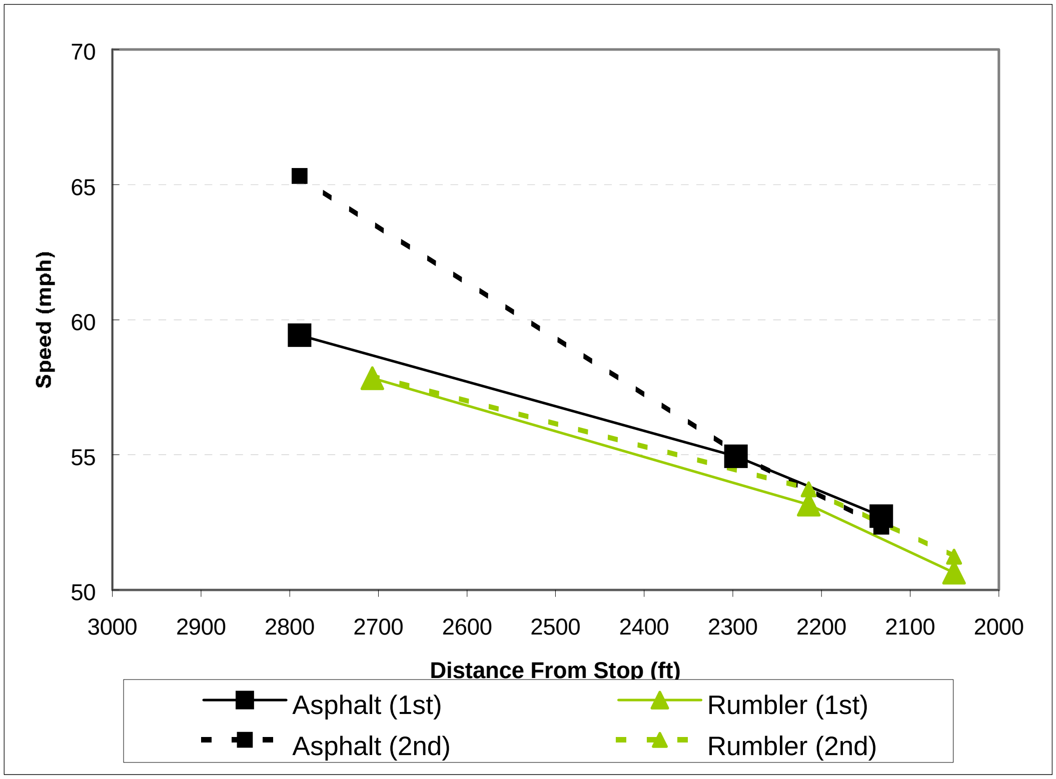


**Chart represents change in mean speeds for passenger cars, from both day and night*

Figure 23 - Change in Speed Reduction Patterns Over Time

Data Collection—Cost and Durability

The cost of the rumble strips is directly related to their durability. If the strips need to be replaced every few weeks, then they will have higher life-cycle cost. If they never need to be replaced, and they can be reused indefinitely, then their life-cycle cost will be much less. Durability is also important for reasons other than its effect on cost. Strips that are likely to fail require more attention and frequent fixing. If individual strips become damaged, torn, or detached from the pavement, the effectiveness of the overall deployment of strips may decrease. In order to provide a detailed and thorough comparison between the temporary rumble strips and the asphalt rumble strips, a comparison of the cost/benefit ratio associated with each of the strips is essential. Comparisons of the installation and removal times, the durability, the reusability, and the amount of damage done to the pavement were also examined.

Data Analysis—Cost and Durability

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.

Installation

The process required two workers plus appropriate traffic control, and took about 30 minutes per group of strips. Application time could be cut considerably with experience. A more detailed description of the installation process is provided on 6. Figure 24 on page 45 in the Appendix shows pictures of the Rumbler rumble strips being installed.

The asphalt rumble strips required slightly more time and effort to install than did the temporary rumble strips. The installation required three workers plus appropriate traffic control and took approximately 40 minutes per group to complete.

Removal

To remove the temporary rumble strip, a corner was pried free with a crow bar or other similar tool, and the strips were pulled by hand until they were entirely removed. The process proceeded quickly with one or two individuals plus appropriate traffic control. Since the removal of each strip took less than a minute, when vehicles were seen approaching, workers could step onto the shoulder, allow the vehicles to pass, and then resume removing the strips. This allowed the strips to be removed with little or no disruption of traffic. All strips came up in one piece. The process required two workers approximately 7 minutes to remove a group to the Rumbler rumble strips.

The removal of the asphalt rumble strips required more than 5 times the labor required to remove the temporary rumble strips, and it required heavy equipment. The asphalt rumble strips were 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 center of the lane, requiring that traffic in both directions be temporarily stopped. Removal required approximately 15 minutes per group of strips with 5 workers.

Cost Estimation

The installation and removal times, and the material costs for the temporary rumble strips were all 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. [15]

Durability

The durability of the rumble strips was compared by simply observing the amount of damage the strips had incurred over the length of their deployment. 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 another test site exclusively to test the durability. These remained in place for a period of 6 months (225,000 vehicles) 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 temporary rumble strips are easier to repair than failures of asphalt strips. If a single temporary rumble strip is removed or damaged, it can be easily replaced. Asphalt strips are more difficult to repair.

Reusability

Reuse of the Rumbler is neither supported nor discouraged by the manufacturer. Since reuse of these strips could significantly decrease their overall cost, tests were conducted to determine if reuse of the Rumbler strips were feasible. A few strips that were used at the Perry Lake test site were cleaned and reused alongside an equal amount of new rumble strips at the Horton 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 with 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. Neither the new strips nor the reused strips incurred any significant damage at the second location.

Benefit/Cost Analysis

The primary benefit of rumble strips is their positive effect on safety and the subsequent reduction in accidents and fatalities. It was not possible to quantify the safety benefits because the length of deployment was minimal. Several years of before and after accident data would be needed to provide a reasonable quantitative benefit/cost analysis. Consequently, the safety benefits can only be examined indirectly using sound and vibration levels and installation and removal times.

Results—Cost and Durability

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

Benefits

Because the asphalt strips and the removable strips were similar with respect to the sound and vibration generated, any resulting safety benefits would also be similar. The temporary rumble strips might, however, have increased benefits in terms of safety because of the decreased installation and removal times. Additionally, the differences in the amount of damage done to the pavement by the removal of the strips is notable, but assigning an actual monetary value to this benefit is also quite difficult since there are so many other factors involved, such as the type and age of the pavement, the quality installation, the duration of the deployment, and the method used to remove the strips.

Total Deployment Costs

Table 10 shows estimates for labor costs, material costs, equipment costs, and total costs. The largest portion of the total costs associated with the temporary rumble strips was the material costs. While the cost of asphalt is almost negligible, the cost of the temporary rumble strips is not. The material costs for the Rumbler rumble strips include the costs of both the strips and the adhesive, and the material cost for the reused Rumbler rumble strips includes only the cost of the adhesive. The cleaning time for the reused Rumbler rumble strips is included in the *Labor Costs* category under *Removal Time*.

Costs associated with the asphalt strips were compared with previous studies [2] and found to be reasonable. No comparison was available for the temporary strips, but all costs were observed costs, and as such are considered to be reliable.

Table 10 - 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
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
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
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**
Asphalt	**$97.45**	**$584.73**

Installation

As mentioned previously the installation of the temporary rumble strips was simple and expeditious. The time estimates for the installation of the temporary rumble strips may be 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 of Rumbler rumble strip. The time taken to install the final group was used as the estimate for installation time.

Removal

The time required to remove all types of rumble strips was much less than the time required to install them. The temporary rumble strips required no special equipment and fewer workers to remove them than their asphalt counterparts. No time estimates were available for the time required to remove asphalt strips without heavy machinery, although it is probable that significantly more time would be required.

Reusability

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. A small metal scraper was used 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 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 conservative estimate. Table 10 shows costs estimates for both new and reused Rumbler rumble strip deployments.

Durability

Although the durability of the rumble strips depends on many factors, such as the number and type of vehicles that will traverse them, the duration of deployment, and the quality of the initial installation, the temporary rumble strips were found to be quite durable.

The Rumbler rumble strips did suffer some damage. 2 out of 36 strips deployed at the Lake Perry 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 on page 49. 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 indicates 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 Horton test site, half of which were reused, suffered no damage.

The asphalt rumble strips were damaged 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 on page 48.

Tests of the same types of temporary rumble strips have found similar results. A test recently conducted in Florida using the Rumbler rumble strips had no durability problems throughout their four-week deployment. [16]

Pavement Condition

Part of the motivation to use temporary 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 temporary 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 temporary rumble strips. Pictures of the pavement after removal of the strips can be seen in the Appendix on pages 50 and 51. Both locations had asphalt pavement. Results on concrete pavement may differ.

Conclusions

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 a long-term durability. When removed, damage to the pavement was nominal.

Table 11 shows a qualitative comparison of Rumbler relative to asphalt rumble strips. Specific advantages and disadvantages are listed in Table 12.

Table 11 - Rumble Strip Qualitative Comparison Table

	Rumbler (New)	Rumbler (Reused)
In-vehicle Sound	=	=
Vibration	=	=
Roadside Noise	—	—
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

Table 12 - Rumble Strip Type Summary

	Asphalt Rumble Strips	Rumbler Rumble Strips
Advantages	▪ 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 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, ready to apply. ▪ Reusable ▪ Consistent size and shape ▪ Does little damage to pavement
Disadvantages	▪ Removal typically damages the pavement ▪ Time consuming installation and removal ▪ Inconsistent size and shape ▪ Thickness of strips decreases over time ▪ Not reusable	▪ Leaves adhesive on pavement ▪ New strips are expensive ▪ Unfamiliar to workers and drivers ▪ Produces excessive roadside noise levels ▪ Requires tamping cart with a custom wheel

Recommendations

Rumble strips have been demonstrated to be an effective means of alerting drivers and enhancing safety. New materials and manufacturing techniques have opened the door to temporary rumble strips, which are intended to replace asphalt rumble strips for temporary deployments. While these 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.

Based on the results of this study, it is recommended that the Rumbler rumble strip be allowed as a substitute for asphalt rumble strips on work zone approaches. 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. The pavement must be dry and swept clean before applying the strips. Minimum pavement temperatures depend on the adhesive and related manufacturer recommendations should be observed.

Reuse of the strips 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.

The Swarco Rumbler rumble strip demonstrated itself to be durable, effective, and easy to use. It is highly recommended as an alternative to asphalt rumble strips for work zone applications.

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APPENDIX

Table 13 - Maximum Leq Values in Decibels (dB)

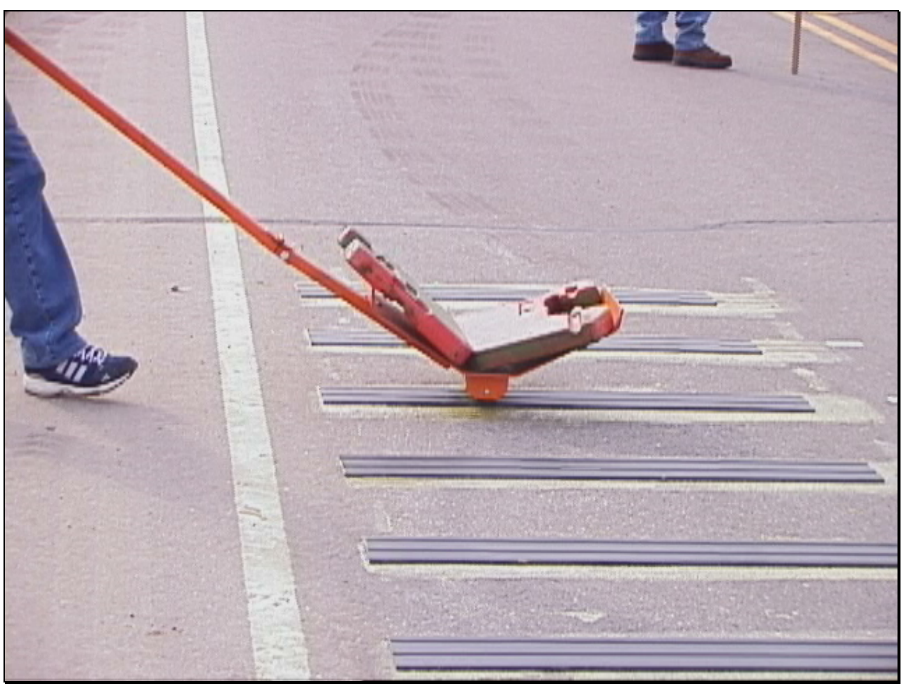
Sound									
Vehicle	Compact Car			Midsize Car			Dump Truck		
Speed, kph (mph)	64 (40)	80 (50)	97 (60)	64 (40)	80 (50)	97 (60)	64 (40)	80 (50)	97 (60)
Baseline (Perry)	73	73	77	73	74	77	79	81	86
Asphalt (Perry)	88	87	90	88	90	93	89	90	93
Rumbler (Perry)	86	88	90	89	89	91	89	89	91

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

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

Figure 24 - Installation of Rumbler Rumble Strips

Applying adhesive with paint roller



Rolling the strips with the tamper cart

Figure 25 - Removing the Rumbler Rumble Strips

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

Peeling strip off of the pavement by hand

Figure 26 - Removal of the Asphalt Strips

Removal of asphalt strips with Loader/Backhoe

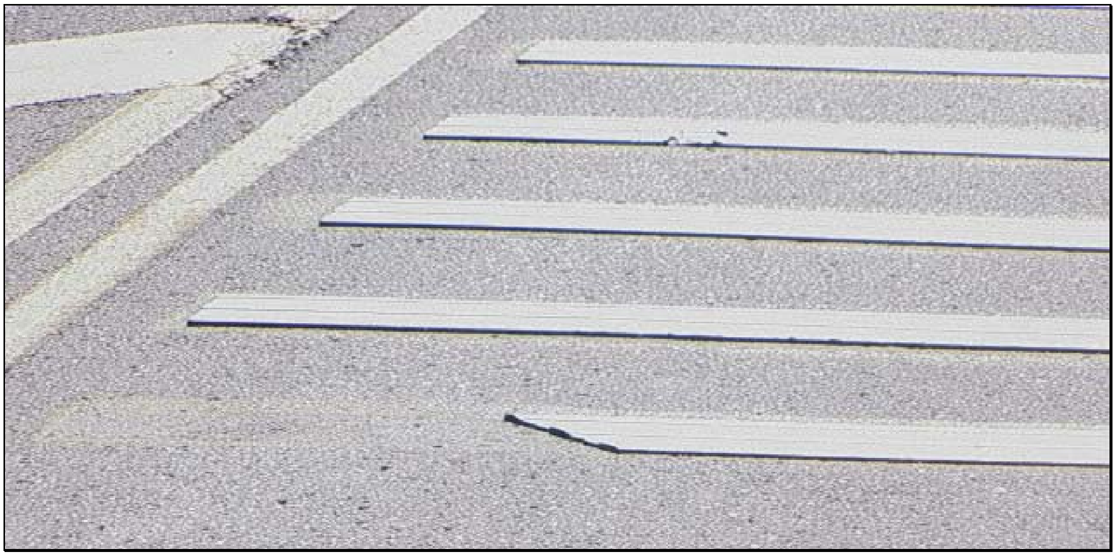
Bucket scraping up the asphalt strips

Figure 27 - Damaged Asphalt Rumble Strips

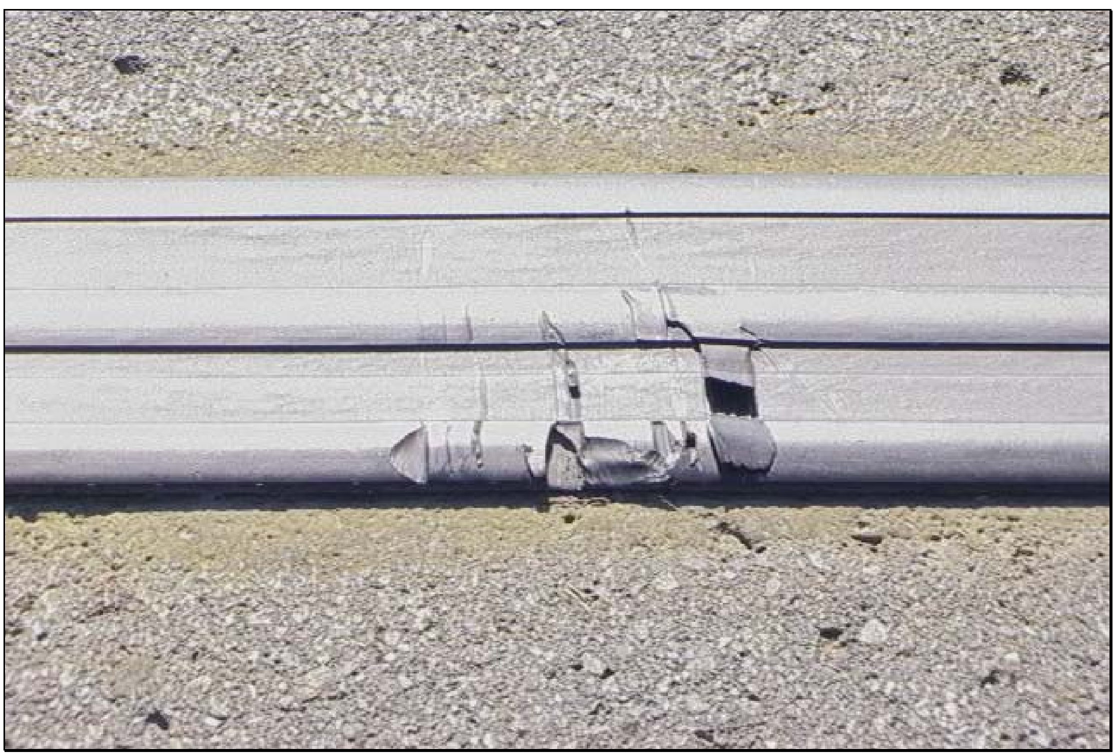
Damaged asphalt strips

Close-up of damage

Figure 28 - Damaged Rumbler Rumble Strips



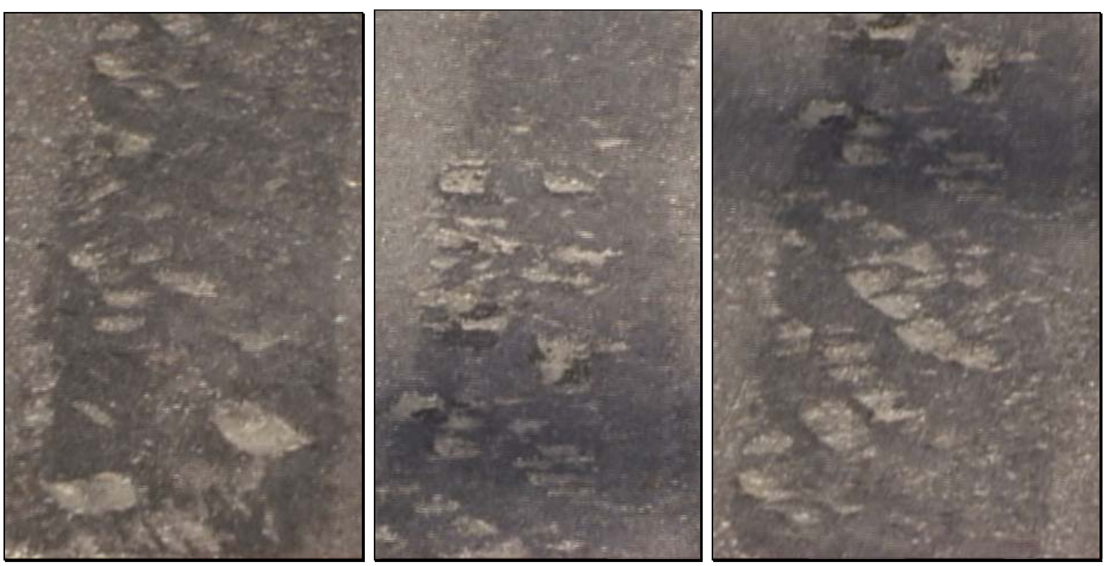
Damaged Rumbler rumble strips



Close-up of damage (fourth strip back in above picture)

Figure 29 - Pavement Damage from Asphalt Strips

Overview



Close-ups

Figure 30 – Pavement Following Removal of Rumbler Strips

Condition of pavement upon removal

Pavement close-up

Figure 31 - Temporary Strips After Removal

Underside of Rumbler rumble strips