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Closed Course Testing of Portable Rumble Strips to Improve Truck Safety at Work Zones

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16. Abstract
The purpose of this research was to compare the attention-getting characteristics, movements and vertical displacements of several portable, reusable rumble strips. The attention-getting characteristics and displacement were measured after passes of a fully loaded heavy truck and a passenger vehicle.

Sound and vibration tests revealed that the portable plastic rumble strips were more effective on cars than trucks for generating in-vehicle vibration and increasing in-vehicle sound levels. Further, they were generally better able to match the characteristics of the tested permanent rumble strip compared to the adhesive rumble strips, and that this was also true for the configurations that contained less than six portable plastic rumble strips. The configurations with four plastic rumble strips were found to be sufficient enough to generate similar vibration and sound levels for either heavy trucks or passenger cars. If the vibration generated by the permanent strips is considered as the standard performance, these configurations could be implemented in short-term work zones and provide similar results to permanent rumble strips. The movement and vertical displacement test results revealed that the earlier generations of plastic rumble strips did not perform as well as the fourth generation especially at 60 mph (96.6 km/hr). The steel rumble strips also hold some promise; however, the structural integrity of the steel rumble strips is an issue that needs to be addressed.

17. Key Words
Rumble strips, closed course, short term work zone, sound, vibration, movement and vertical displacement

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Chapter 1 Introduction

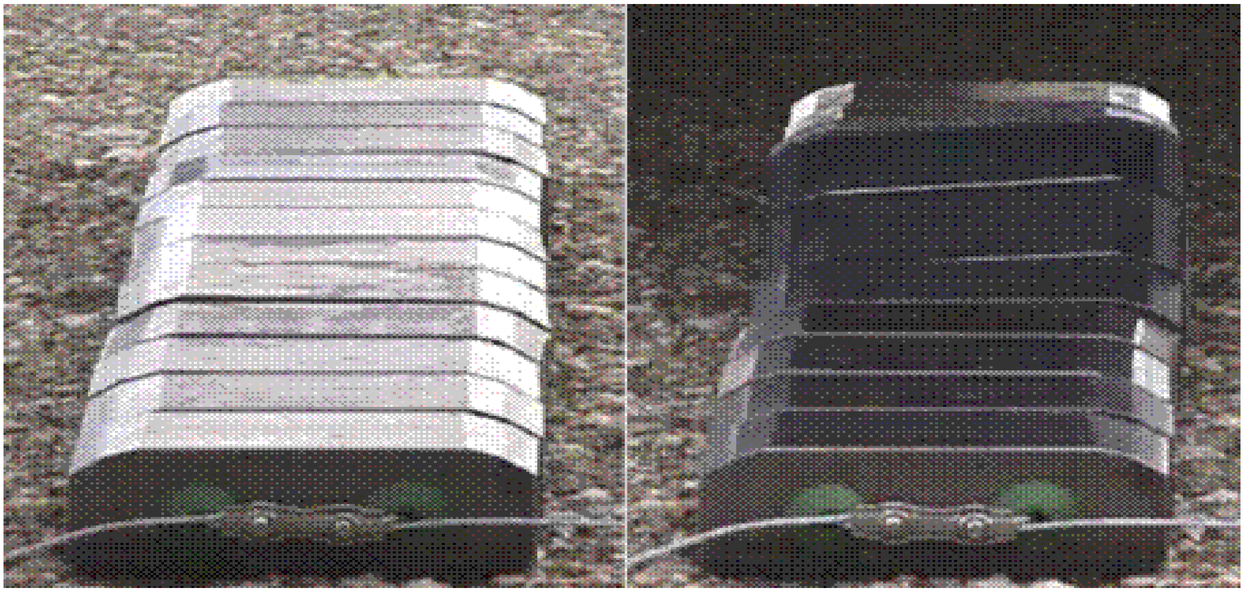
Work zone safety is of paramount importance for both drivers and workers. Driver distraction and speeding are two of the major contributors of crashes in construction and maintenance work zones. Many traffic control devices, such as static signing, barrels, and portable message signs have been used to indicate to drivers they are approaching a work zone. Rumble strips can be an effective device and have been used in some states to alert drivers to reduce speed in advance of an alteration in the driving situation, such as at intersections. Previous research has examined the potential of using temporary rumble strips in advance of work zones. Due to the time required to install typical adhesive rumble strips, these devices have tended to only be used in long-term work zones. For short-term work zones, especially for flagger controlled projects, the application of rumble strips has been limited. However, in the aforementioned projects there can be an increased potential for an unobservant driver to strike the back of a queue, which could result in a severe crash.

To enhance short-term work zone safety, departments of transportation have been looking for innovative portable devices that can be easily implemented to increase driver alertness as they approach work zones. The purpose of the closed course testing was to compare the attention-getting characteristics, sound and vibration, of different types of portable rumble strips with permanent rumble strips and measure the movements and vertical displacements of several portable reusable rumble strips. The attention-getting characteristics and movements of rumble strips were measured after passes of a fully loaded heavy truck and a passenger vehicle. To evaluate sound and vibration, the devices tested were of two basic types: plastic rumble strips and adhesive rubberized polymer rumble strips. Both were tested for their ability to generate steering wheel vibrations and in-vehicle sound; then the results were compared with a set of permanent cut in-place (CIP) rumble strips. The movements and vertical displacements were tested on four generations of plastic rumble strips and reusable temporary rumble strips made out of steel with a rubber bottom. Examples of the tested devices are shown in figures 1.1 and 1.2.

(a) Adhesive rumble strips

(b) Plastic rumble strips

Fig. 1.1 Tested temporary rumble strip technologies for vibration and sound tests.



(a) Steel Rumble Strips

(b) Plastic rumble strips

Fig. 1.2 Tested Temporary Rumble Strip Technologies for Movement and Vertical Displacement Tests.

1.1 Research Objective

This research was conducted with the objective of determining how best to incorporate portable rumble strips into traffic control plans for short-term and moving or mobile work zones. The goals of closed course testing are listed below.

- To determine whether portable plastic rumble strips and adhesive rumble strips can generate vibration and sound significantly different than the background vibration and noise from the roadway and from permanent in-pavement rumble strips.
- To ascertain the vibration and sound differences of various configurations of portable plastic rumble strips and develop a standard application of adhesive rumble strips at different traveling speeds.
- To determine whether the portable plastic rumble strips and reusable temporary rumble strips can withstand repeated impact by vehicles as it concerns movement and vertical displacement.
- To designate movement and vertical displacements of various configurations of the plastic rumble strips and reusable temporary rumble strips at different traveling speeds.

1.2 Work Plan

This research was divided in two phases. Phase I (Task 1-2) involved an examination of the state of the literature and preparation of the items required for the closed course test. Phase II (Task 3-5) involved field data collection, reduction and analysis of results from the tests and report writing. The work plan consisted of the following five tasks: a review of pertinent literature, preparation of temporary rumble strip test requirements, field data collection and reduction, analysis of results, and report preparation.

The literature review is presented in Chapter 2, the examination and preparation for the tests and the methodology are presented in Chapter 3, the analysis is presented in Chapters 4 and 5, and findings are presented in Chapter 6.

Chapter 2 Literature Review

There are several sources in the literature review that address similar types of tests performed using either the same or different types of rumble strips.

2.1 Sound and Vibration

Several types of portable rumble strips available on the market have been used and tested in some construction projects. The test results showed effectiveness of such rumble strips were varied, with respect to speed reduction and warning proficiency. A review of this previous research is provided in this section.

2.1.1 Adhesive Rumble Strips

Typical adhesive rumble strips are 0.25 in. (6 mm) thick, self-adhesive, and removable (*1*). The strips are available in 50 ft (15.2-m) rolls and can be cut to the desired length. The adhesive rumble strips have a pre-applied adhesive backing that creates a secure bond to the road surface. Manufacturers indicate that these strips are reusable by applying supplementary adhesive.

Several tests have been performed on adhesive rumble strips and found that 0.25 in. (6 mm) strips were effective in providing sound and rumbling sensation to passenger cars and pickup trucks but did not provide adequate sensation for drivers of commercial trucks (*2*). They can be an effective warning device when compared to a strip composed of raised asphalt bumps (*3*). However, as a warning device, they were nearly as effective as a cut in-pavement rumble strip when traversed at 55 mph (88.5 km/hr), but were ineffective when traversed at 40 mph (64.4 km/hr) (*4*).

A study by Walton and Meyer tested the resulting vibration and sound of adhesive rumble strips 0.15 in. (4 mm) high (*5*). Fifteen different configurations were created to analyze the effects of thickness, spacing, and offset. A compact car, a midsize car, and a dump truck, driven at 40, 50, and 60 mph, (64.4, 80.5, and 96.6 km/hr) were used during the project. Sound and vibration levels were measured as Equivalent Sound Level (Leq) in decibels (dB). The average increase in sound was 10 dB and 4 dB for the cars and dump truck, respectively. From the results it was found that an increase in rumble strip height, achieved by installing two layers of adhesive rumble strips on top of each other, increased the sound and vibration. The 24 in. (0.61 m) spacing appeared to be optimal, and offsetting rumble strips reduced the sound and vibration.

The primary costs of the adhesive rumble strips include the material, several hours of labor for installation and removal, and any additional traffic delay or hazard caused by the temporary lane closures required for installation and removal (*6*).

A second type of adhesive rumble strip has been evaluated, specifically designed to be placed in the wheel paths of a traffic lane rather than across the entire lane. This rumble strip was six in. (0.151 m) wide, four to six ft. (1.22 to 1.83 m) long, and between 0.15 and 0.25 in. (4 to 6 mm) high (*7*). This system is glued to the pavement in a set of lines such that a vehicle's tires would hit several strips within a short time interval. It is advertised to produce an 80 dB interior warning at speeds between 30 and 55 mph.

A test of this type of rumble strip in Wisconsin revealed that it was designed to be more permanent and was somewhat more difficult to install (*3*). The researchers concluded that it was much quieter than a conventional CIP rumble strip, and produced considerably less vibrations in the test automobile. Although the system's sound was reported to be qualitatively different and louder than road sound, it did not elicit a large behavioral response from drivers.

In another test of this system using 0.75 in. (19 mm) high application, the researchers found that these strips performed comparably to the permanent asphalt rumble strips with respect to sound and vibration inside the vehicles (*10*). Slightly higher sound levels were observed at the roadside. It was demonstrated that the system could be reused without significant loss of performance, and the strips proved to be secure, remaining affixed to the pavement for six weeks with the only failures occurring when strips were improperly installed.

A similar study in Wisconsin also measured the vibration and sound generated, and found peak sound levels averaged 77.3 dB and averaged 85.0 dB for the permanent rumble strips (*8*). Sounds from the tested rumble strips were noticeably above the road sound for about 0.7 sec whereas the conventional rumble strips were audible for about 0.5 sec.

2.1.2 Recycled Tire Rubber Rumble Strips

These rumble strips (*9*) are 0.75 in. (19 mm) thick, 6 in. (0.15 m) wide and 5 ft (1.52 m) in length, with a 45 degree bevel on all sides. They are made of recycled tire rubber and several installation options are available, including various types of adhesive.

A closed course test in Wisconsin concluded the recycled tire rubber strips were effective warning devices for vehicle speeds between 10 and 40 mph (16.1 and 64.4 km/hr) (3). However, it was found in a test in Kansas that the recycled tire rubber strips alone are not heavy enough to remain in place without adhesive under traffic traveling at highway speeds (*10*). The test also recommended that the adhesive provided was not suitable for very short-term applications. This is either because of the damage likely to be done to the pavement upon removal or the set time for the adhesive is too long to be practical for portable rumble strip applications.

2.1.3 Steel Rumble Strips

The prototype steel rumble strip is comprised of a set of steel elements, in which each element is 2 in. (51 mm) wide and 1.25 in. (32 mm) high. These elements are strung together with steel cable passing through the two drilled holes located about one in. (25 mm) from the end of each element. Each strip has 24 elements strung together, comprising a nominal unit length of four ft (1.22 m). Movement and uplift studies have been conducted on this system but they never moved beyond the prototype. Thereby, the low number of units available for use precluded its inclusion in this study (*11*).

2.1.4 Portable Plastic Rumble Strips

The portable plastic rumble strip is 11 ft (3.35 m) long one ft (0.30 m) wide and 0.83 in. (21 mm) thick with non-slip textured surface (*12*). The plastic rumble strips do not use adhesives or other fasteners, relying instead on their weight (105 pounds (47.6 kg) each) to remain in place. It is made from engineered polymer materials with a steel core. This system is designed for quick installation and removal, and is intended for repeated use. While several anecdotal tests have been conducted (*12*), there was no evidence in the literature of a controlled experiment examining sound and vibration levels.

2.1.5 Comparison between different rumble strips

Horowitz and Nothbohm also measured the sound and vibration level generated by 0.25 in. (6 mm) adhesive and 0.75 in. (19 mm) recycled tire rubber rumble strips in comparison with permanent CIP rumble strips (*3*). The average sound level for both the standard CIP strips at 40 and 55 mph (64.4 and 88.5 km/hr) was found to be 75.2 and 75.8 dB, respectively. For adhesive rumble strips the average sound level was 70.9 and 76.8 dB at 40 and 55 mph (64.4 and 88.5 km/hr). Peak sound levels within the 0.3-sec time interval were also obtained for all strips. For the standard CIP strips at 40 mph (64.4 km/hr), these levels were 6.5 dB above its average, and 7.5 dB above its average at 55 mph (88.5 km/hr). The peak sound levels for adhesive strips were 7.9 dB above its average at 55 mph (88.5 km/hr), and 9.0 dB above its average at 40 mph (64.4 km/hr).

Based on previous research, vibration and sound are affected by the thickness, spacing and material of rumble strips as well as the traveling speeds. As the height of a rumble strip increases, vibration and sound are augmented provided that a tire is still permitted to obtain maximum displacement. To ensure the latter, the spacing between strips must be far enough apart to allow for maximum displacement. However, increasing the space beyond the distance required to allow for maximum tire displacement will decrease vibration and sound because the frequency of the tire displacement decreases.

2.2 Movement and Vertical Displacement

Temporary rumble strips that require adhesive to affix to the roadway have been tested over the last 15 years. Meyer evaluated the effectiveness of adhesive, removable orange rumble strips manufactured by Advanced Traffic Markings (ATM) on a rural, two-way, 65 mph (104.6 km/hr) highway with a reduced work zone speed limit of 30 mph (48.3 km/hr) (*2*). Meyer concluded that these rumble strips significantly reduced mean speeds downstream of its location for both passenger cars and heavy trucks by 2.2 - 2.3 mph (3.5 - 3.7 km/hr). Additionally, he reported that the optimal thickness and spacing of the strips needed to be determined as well as a method for overcoming the detachment problem. A similar set of orange rumble strips with supplemental adhesive were also tested by Meyer for their ability to resist vertical loading and repeated installation and removal (*13*). He concluded that supplemental adhesive was easy to apply and made the strips more difficult to remove, but not to the extent of preventing a single person from detaching them. He also noted that these strips could be reused by reapplying supplemental adhesive.

Fontaine et al. also evaluated the effectiveness of adhesive, temporary orange rumble strips on two-lane, 70 mph (112.7 km/hr) highways and rural roads (*14*). The rumble strips were installed by removing the protective backing, placing the strip on the road surface, and using a weighted roller to firmly adhere the strip to the pavement. They found that the rumble strips achieved a greater speed reduction on heavy trucks than passenger cars—reducing the average heavy truck speed by 3 - 4 mph (4.8 - 6.4 km/hr). Passenger cars experienced mean speed reductions of less than 2 mph (3.2 km/hr). Although the rumble strips could be peeled off the road surface, if the road was not clean or was composed of loose pavement, debris could be attached to the back of the rumble strip and render the strips unusable. Two types of removable rumble strips, manufactured by 3M and Swarco, were tested by Zech (*15*). The 3M rumble strip applications were installed in a four-lane, divided rural freeway with a 65 mph (104.6 km/hr) speed limit that reduced to a 45 mph (72.4 km/hr) work zone speed limit. The results showed that the 3M rumble strips were effective in reducing passenger car speeds by approximately 2.4 mph (3.9 km/hr). The Swarco rumble strips were installed on a six-lane, divided urban expressway with a speed limit of 55 mph (88.5 km/hr) and a work zone speed limit of 45 mph (72.4 km/hr). Adhesive glue was used to install the rumble strips to concrete pavement. Two rumble strip sets were placed 300 ft (91.4 m) apart. The results showed that the Swarco rumble strips were not effective in reducing vehicle speeds in either lane.

This literature search established that the only commercially available temporary rumble strips that have been studied were attached to the roadway using adhesive. Reusable temporary rumble strips that used adhesive were not always salvageable if debris remained attached to the strip after removal. Meyer experimented with a reusable, temporary rumble strip prototype that did not use adhesive but this system has not been developed beyond this initial stage (*13*).

Chapter 3 Methodology

3.1 Vibration and Sound Testing

Tests of the portable rumble strips were conducted on a private asphalt service road surrounding the Kansas Speedway in Kansas City, Kansas. Two test stations with a nominal separation of 1000 ft (305 m) were set to implement different configuration sets of rumble strips. The test was performed on May 20, 2009, in dry weather and daylight conditions. The rumble strips were tested using a passenger car (shown in fig. 3.1) and a WB-50 heavy truck (nominal truck weight: 53,000 lb (24,040 kg) (shown in fig. 3.2) traveling at 45, 53 and 60 mph (72.4, 85.3, 96.6 km/hr). A total of six configurations of plastic rumble strips with different numbers of strips and spacing among strips were used in order to determine if altering the placement had an effect on the resulting vibration and sound generated. The adhesive rumble strips were installed in a single application of six strips spaced at 24 in (0.61 m) on-center per the recommendations made by Walton and Meyer (*5*).

Additionally, baseline sound and vibration measurements for the permanent CIP rumble strips were taken on US-56 in Douglas County, Kansas. The permanent asphalt rumble strips were CIP rumble strips with 25 grooves set on 1.5 ft (0.46 m) centers, with a 5.25 in (133 mm) width and 0.15 in. (4 mm) depth. Three measures of effectiveness were collected: in-vehicle vibration measured in acceleration rate (m/s^2) at the steering wheel (as shown in fig. 3.3); in-vehicle sound level measured in decibels (dB) from the area between the driver and passenger seats at nominal shoulder height (as shown in fig. 3.4); and roadside sound measured in decibels (dB) from the roadside (as shown in fig. 3.5).

Fig. 3.1 Passenger Car used for Testing Rumble Strips

Fig. 3.2 WB-50 Heavy Truck used for Testing Rumble Strips

Fig. 3.3 Arrangement of Accelerometer Meter inside the Vehicle

Fig. 3.4 Arrangement of Sound Level Meter inside the Vehicle

Fig. 3.5 Arrangement of Sound Level Meter outside the Vehicle

The in-vehicle vibration was measured using a tri-axial accelerometer. The peak value of the vibration and sound level data as the test vehicles traversed the rumble strips was used for analysis. All sound measurements used in the analysis were recorded with the vehicles' windows closed and with the air conditioner and radio deactivated.

3.1.1 Test Configurations

As the plastic rumble strips were new to the market, there was no standard configuration for its implementation in work zones. Several different test configurations were developed to determine if small alterations in the configuration of the rumble strips within a group made a significant difference in the vibration and sound generated. A total of six different configurations with variations in the number of strips and spacing were tested using plastic rumble strips, and are shown as Configurations 1 through 6 in table 3.1. One set of adhesive rumble strips were tested and are shown as Configuration 7, whereas the permanent in-pavement rumble strips are referred to as Configuration 8.

The background vibration and sound generated by the test vehicles was collected on both the closed course facility (shown as Configuration 9) and US-56 (shown as Configuration 10) in areas without rumble strips. For each configuration, at least seven passes were conducted for each vehicle type traveling at each speed level.

Table 3.1 Rumble Strips Test Configuration

Configuration Number	Number of Strips	Spacing (in.)	Rumble Strip Type
1	4	24	Portable Plastic (4-24)
2	4	36	Portable Plastic (4-36)
3	5	24	Portable Plastic (5-24)
4	5	36	Portable Plastic (5-36)
5	6	24	Portable Plastic (6-24)
6	6	36	Portable Plastic (6-36)
7	6	24	Adhesive
8	25	18	Permanent Cut in-Pavement
9	Baseline vibration readings for the closed course facility (e.g., no rumble strips were present)		
10	Baseline vibration readings for US-56 in the vicinity of the CIP rumble strips (e.g., no rumble strips were present)		

3.2 Movement and Vertical Displacement Testing

The testing of the portable rumble strips was conducted on a private asphalt service road surrounding the Kansas Speedway in Kansas City, Kansas. Three test stations with about 1320 ft (402 m) gap were set to implement different configuration sets of rumble strips as shown in figure 3.6. The closed course test was performed on May 18-19, 2009, in dry weather and daylight conditions. The rumble strips were tested using a passenger car and a WB-50 heavy truck (nominal weight: 53,000 lb (24,040 kg)) traveling at 45, 53 and 60 mph (72.4, 85.3, 96.6 km/hr). Two types of reusable temporary rumble strips made out of steel with a rubber bottom, each 1.25 in. (32 mm) tall and four ft (1.22 m) long were tested One of the prototypes was 4 in. (102 mm) wide and the other was 6 in. (152 mm) wide. Also tested were four generations of plastic rumble strips. Each generation was of the same dimensions with the main difference being the formulation of plastic used in the construction of the strip. Examples of each kind of rumble strip are shown in figure 1.2.

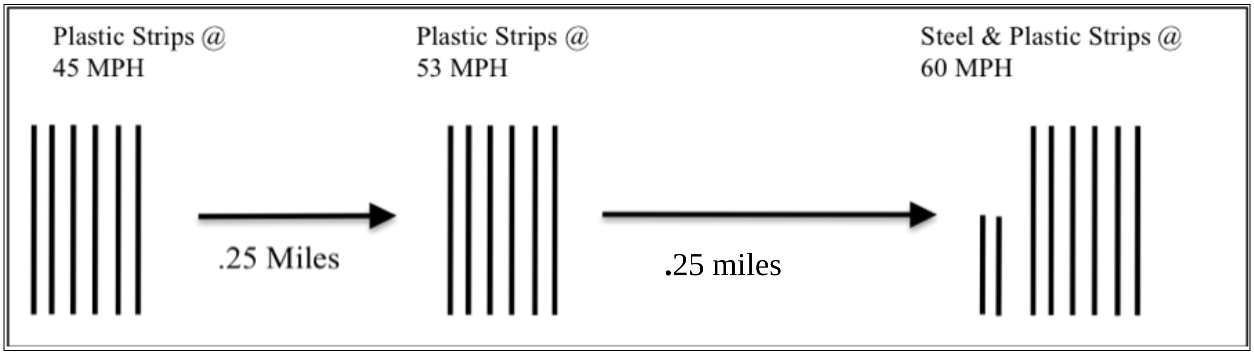


Fig. 3.6 Tested Configuration of the Reusable Rumble Strips (Not to scale)

The steel strips were set at 60 mph (96.6 km/hr) in order to test the most extreme conditions used in this study. This value was established because there was only one of each type of steel strip available for testing. Each of the rumble strips were tested by repeated passes of the heavy truck and Ford Fusion passenger car. Table 3.1 presents the configuration of the rumble strips.

Two measures of effectiveness were collected: the degree of movement for the rumble strips after a number of passes made by a heavy truck and passenger car (shown in fig. 3.7 through 3.10), and the vertical displacement of the rumble strips during selected passes made by the aforementioned vehicles.

Each set of rumble strips was traversed 30 times by the heavy truck and measurements were taken after each pass. With the passenger car, measurements were taken after each of the first 30 passes and after the 50^{th}, 75^{th}, 100^{th}, and 150^{th} passes. During these simulations the placement of the strips within each set was as follows. One strip from the first generation of portable rumble strips was placed first, and then two strips from the second generation were

Fig. 3.7 Position of Portable Plastic Rumble Strips before Vehicle Passes

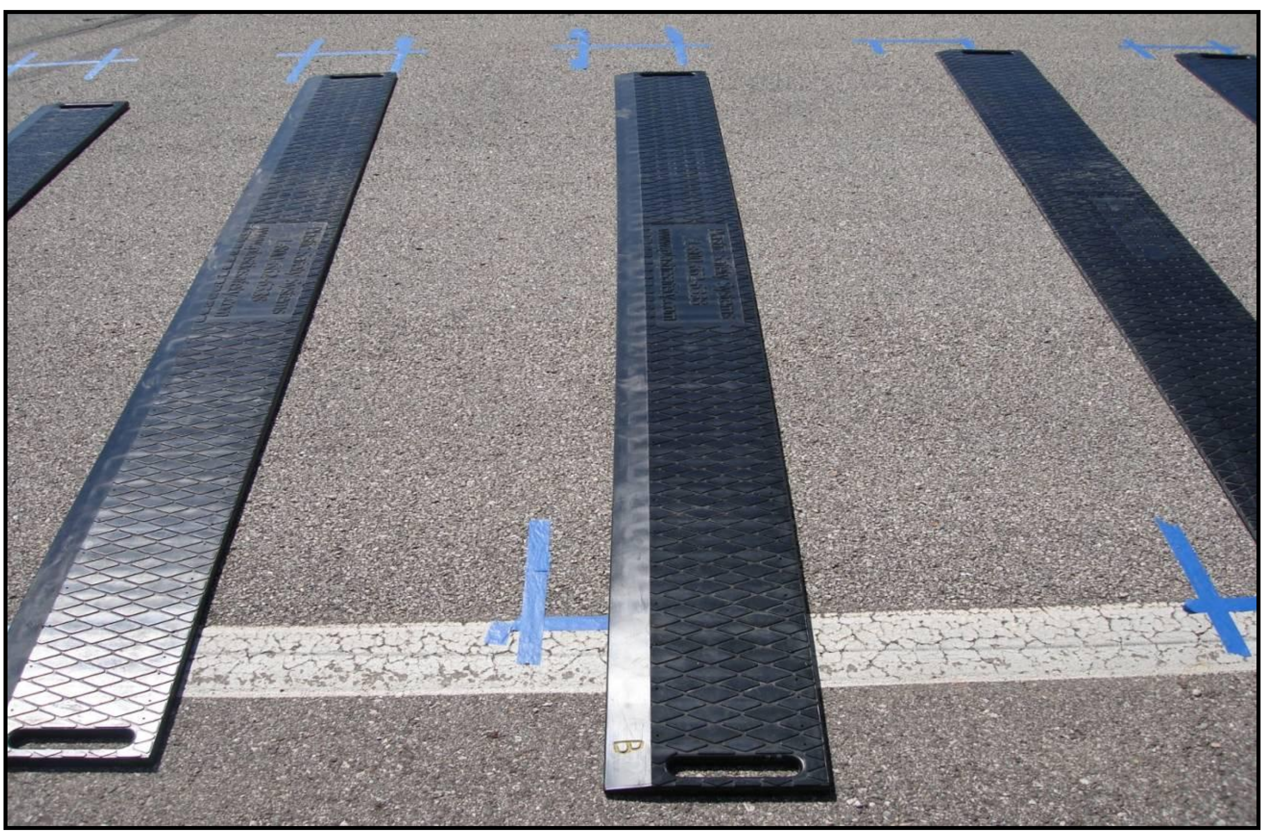


Fig. 3.8 Example of Portable Plastic Rumble Strips after Vehicle Passes

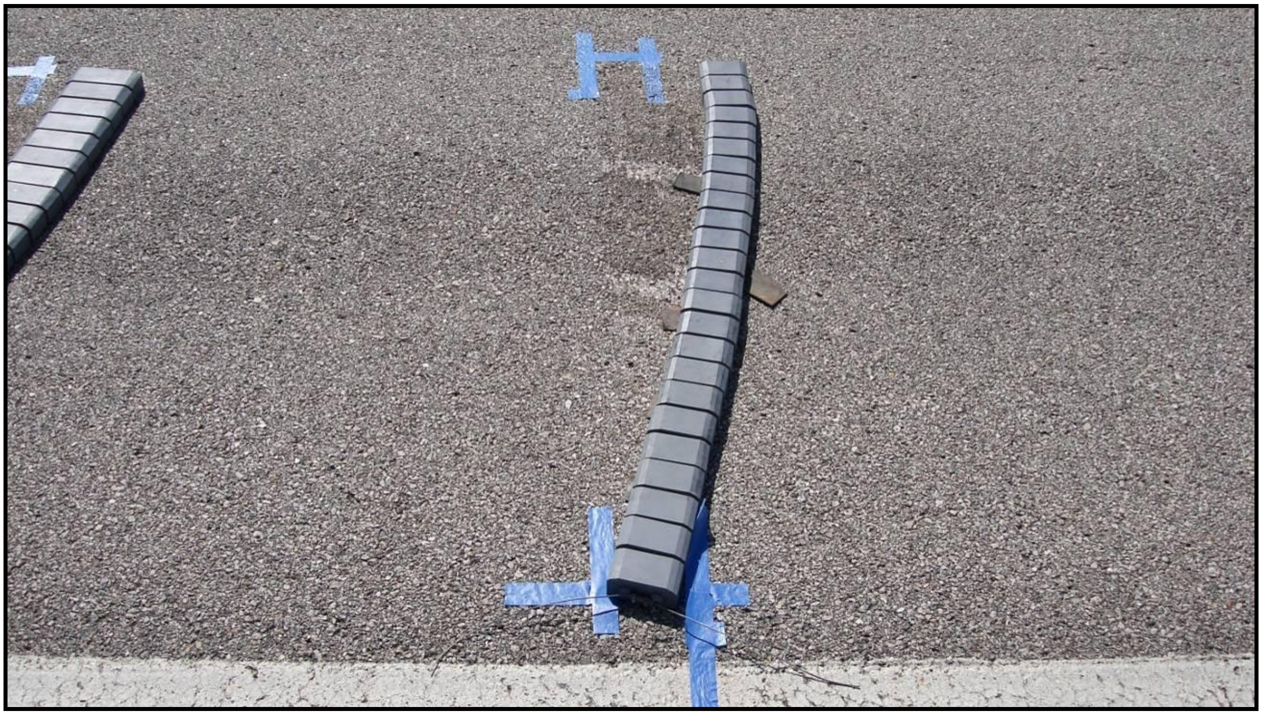


Fig. 3.9 Example of Narrow Reusable Temporary Rumble Strips after Vehicle Passes

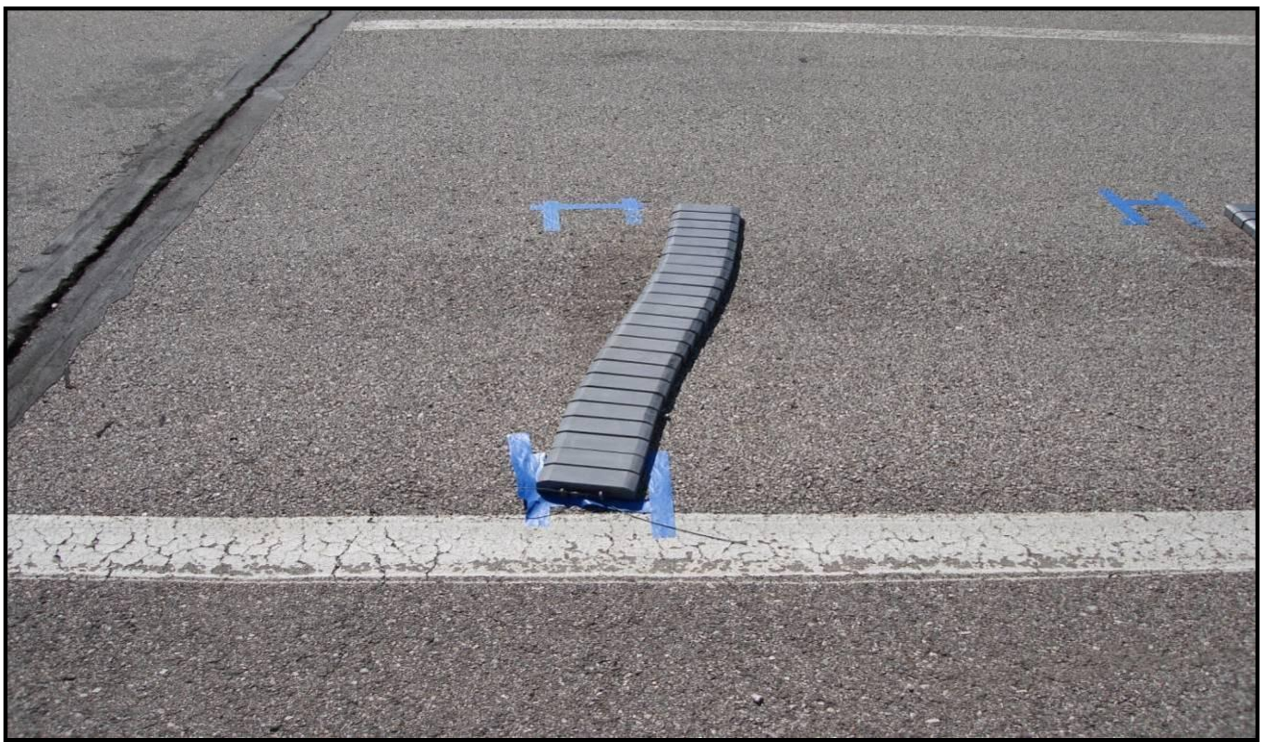


Fig. 3.10 Example of Wide Reusable Steel Rumble Strips after Vehicle Passes

placed next. These strips were followed by one rumble strip from the third generation and then two strips from the fourth generation. Each of these strips was measured separately to show the effectiveness of the newer versus the older generations.

Each rumble strip was marked at the original position and a measurement was taken after each pass to determine movement. A high-speed camera was used to calculate the vertical displacement of the rumble strips at all three speeds. The second, third and fourth generations of plastic rumble strips were used and two types of steel rumble strips were measured at 60 mph (96.6 km/hr) with the WB-50 heavy truck only.

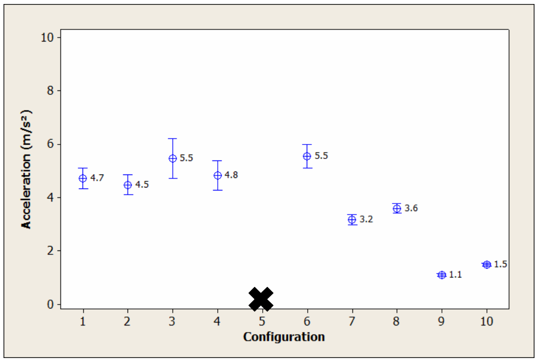
Chapter 4 Analysis for Vibration and Sounds Tests

The data analysis was conducted with the following considerations. (1) The vibration and sound generated by the permanent CIP rumble strips were regarded as the desired performance for the portable rumble strips. Any configuration that generated a similar vibration or sound would be deemed a comparable configuration. (2) A configuration which generated the highest vibration or sound, especially much higher than the permanent rumble strips, could be considered an unacceptable configuration. Namely, too much vibration or sound could make drivers uncomfortable, distracted, or promote overreaction or evasive maneuvers to avoid the rumble strips. (3) The increase of the vibration or sound relative to the base roadway condition (e.g., no rumble strips present) was the other performance measure evaluated in this study. Since the portable plastic and adhesive rumble strips were tested under different base conditions from the CIP permanent rumble strips, the *relative* changes in vibration and sound were believed to better reflect actual effects of the rumble strip configurations.

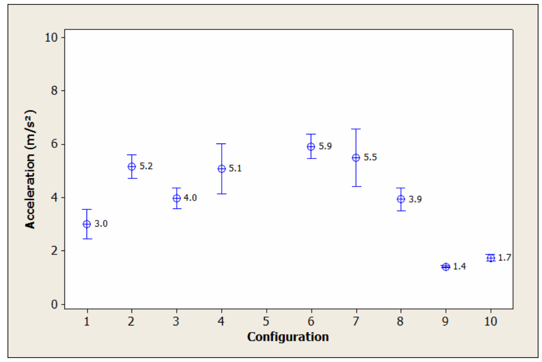
4.1 In-Vehicle Vibration

Figures 4.1 and 4.2 show 95% confidence intervals for in-vehicle vibration at different speeds in all rumble strip configurations for both the heavy truck and the passenger car. Generally, in the base condition without any rumble strips, the vibration inside the truck was greater than that of the car. When the rumble strips were implemented, the vibration inside the car was higher than that of the truck in most of the configurations at 45 mph (72.4 km/hr) and 53 mph (85.3 km/hr). This information indicates that the rumble strips are more effective for cars than trucks in generating vibration at these speeds.

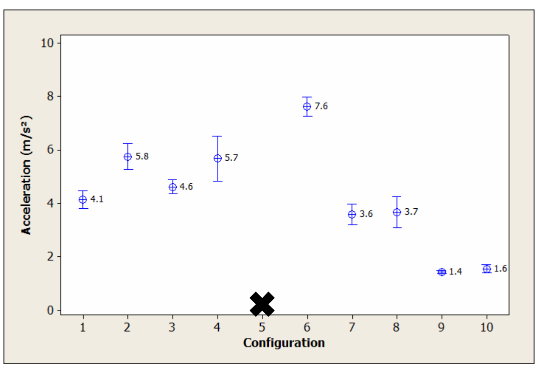
Table 4.1 summarizes the relative difference for in-vehicle vibration. Vibration increases were observed compared to the base condition for all rumble strip configurations. The vibration



(a) Truck Inside Vibration 45mph



(b) Truck Inside Vibration 53mph

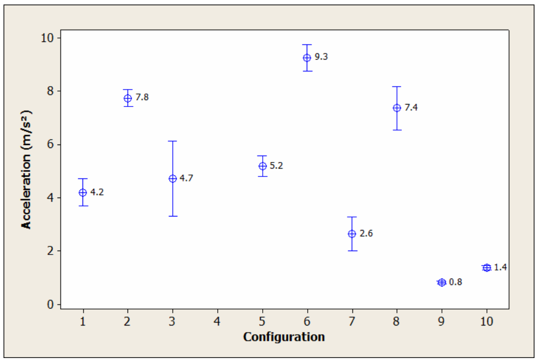


(c) Truck Inside Vibration 60mph

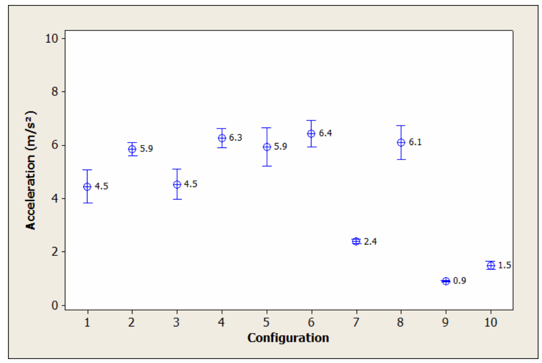
Configuration Number	Rumble Strip Type
1	4 at 24"
2	4 at 36"
3	5 at 24"
4	5 at 36"
5	6 at 24"
6	6 at 36"
7	Adhesive
8	Permanent
9	Closed Course Baseline
10	US56 Baseline

✖ :Data not Available

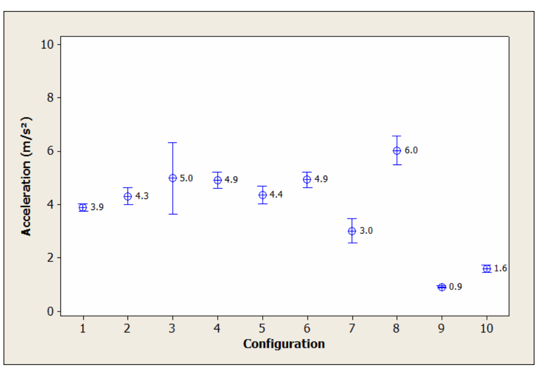
Fig. 4.1 Truck In-Vehicle Vibrations at all Speeds



(a) Car Inside Vibration 45mph



(b) Car Inside Vibration 53mph



(c) Car Inside Vibration 60mph

Configuration Number	Rumble Strip Type
1	4 at 24"
2	4 at 36"
3	5 at 24"
4	5 at 36"
5	6 at 24"
6	6 at 36"
7	Adhesive
8	Permanent
9	Closed Course Baseline
10	US56 Baseline

✖ :Data not Available

Fig. 4.2 Car In-Vehicle Vibrations at all Speeds

Table 4.1 Statistic and Grouping Results of Change for In-Vehicle Vibration

	Configuration	45 mph Ave accel. (m/s^2)	45 mph Dif. from Base Acc.	45 mph Group	45 mph No. of Runs	53mph Ave accel. (m/s^2)	53mph Dif. from Base Acc.	53mph Group	53mph No. of Runs	60 mph Ave accel. (m/s^2)	60 mph Dif. from Base Acc.	60 mph Group	60 mph No. of Runs
Truck													
On Speedway	9 (Base)	1.1		D	12	1.4		E	12	1.4		F	12
	1	4.7	3.6	B	7	3.0	1.6	D	7	4.1	2.7	D	7
	2	4.5	3.4	B	10	5.1	3.7	B	10	5.7	4.3	B	10
	3	5.5	4.4	A	7	4.0	2.6	C	7	4.6	3.2	C	7
	4	4.9	3.8	B	7	5.1	3.7	B	7	5.7	4.3	B	7
	5	**	**	**	**	**	**	**	**	**	**	**	**
	6	5.5	4.4	A	10	5.9	4.5	A	10	7.6	6.2	A	10
	7	3.2	2.1	C	6*	5.5	4.1	BA	7	3.6	2.2	E	6*
On US56	10 (Base)	1.5		D	12	1.7		E	12	1.6		F	10
	8	3.6	2.1	C	7	3.9	2.2	C	7	3.7	2.1	ED	5*
Passenger Car													
On Speedway	9 (Base)	0.8		F	12	0.9		F	12	0.9		F	12
	1	4.2	3.4	D	2*	4.5	3.6	C	7	3.9	3.0	C	6*
	2	7.8	7.0	B	10	5.9	5.0	B	10	4.3	3.4	C	10
	3	4.7	3.9	DC	6*	4.5	3.6	C	7	5.0	4.1	B	6*
	4	**	**	**	**	6.3	5.4	BA	7	4.9	4.0	B	6*
	5	5.2	4.4	C	10	5.9	5.0	BA	9	4.4	3.5	C	10
	6	9.3	8.5	A	10	6.4	5.5	A	9	4.9	4.0	B	10
	7	2.6	1.8	E	7	2.4	1.5	D	7	3.0	2.1	D	7
On US56	10 (Base)	1.4		F	12	1.5		E	12	1.6		E	12
	8	7.4	6.0	B	10	6.1	4.6	BA	10	6.0	4.4	A	10

** No data available

* Limited sample size

groupings were based on the LSD test with a 95% confidence level. Groups denoted by the same letter were not significantly different in terms of average relative differences in vibrations generated. The average relative vibration differences decrease as the alphabet sequence increases. For example, vibrations in group a are significantly higher vibrations than group b.

4.1.1 The Effect on Heavy Trucks

For the heavy truck, Configurations 1 through 6 (portable plastic rumble strips) increased in vibration, ranging from 1.6 to 6.2 m/s^2 compared to the base condition. The increase in vibration depended on the configurations and traveling speeds. Configuration 7 (adhesive rumble strips) increased 4.4 to 6.2 m/s^2 at different speeds compared to the base condition. Configuration 8 (permanent CIP rumble strips) increased 2.1 to 4.1 m/s^2.

At 60 mph (96.6 km/hr), the average change in truck vibration generated by Configurations 1 and 7 were not significantly different from the vibration generated by Configuration 8 (permanent CIP rumble strips). At 53 mph (85.3 km/hr), Configuration 3 was not significantly different from Configuration 8. At 45 mph (72.4 km/hr) Configuration 7 was not significantly different from Configuration 8.

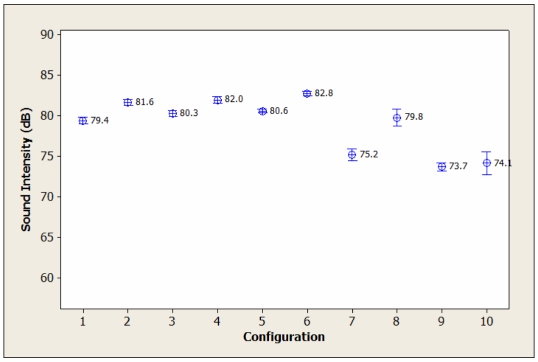
4.1.2 The Effect on Cars

For the passenger car, Configurations 1 through 6 increased in vibration ranging from 3.0 to 8.5 m/s^2 compared to the base condition. Configuration 7 increased the vibration ranging from 1.5 to 2.1 m/s^2. Configuration 8 increased in vibration from 4.4 to 6.0 m/s^2.

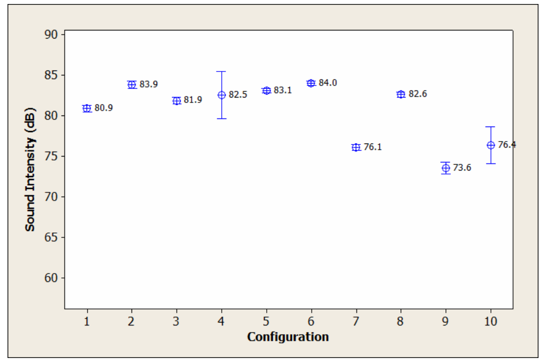
At 60 mph (96.6 km/hr), the increases in vibration generated by Configurations 1 through 7 were significantly lower than the increase in vibration generated by Configuration 8. At 53 mph (85.3 km/hr), Configurations 2, 4, and 5 resulted in relative vibration increases similar to Configuration 8. Configuration 2 was not significantly different from Configuration 8 at 45 mph (72.4 km/hr).

4.2 In-Vehicle Sound Level

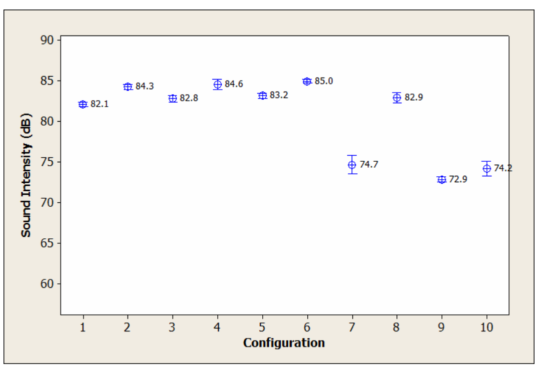
The in-vehicle sound generated by all types of rumble strips and configurations is shown in figures 4.3 and 4.4. In general, the sound inside the heavy truck was greater than the sound inside the passenger car in the base conditions without any rumble strips present (Conditions 9 and 10). Configurations 1 through 6 and Configuration 8 tended to produce similar in-vehicle sound level ranging from 79.4 to 85.0 dB for the truck and from 75.7 to 85.7 dB for the



(a) Truck Inside Sound 45mph



(b) Truck Inside Sound 53mph

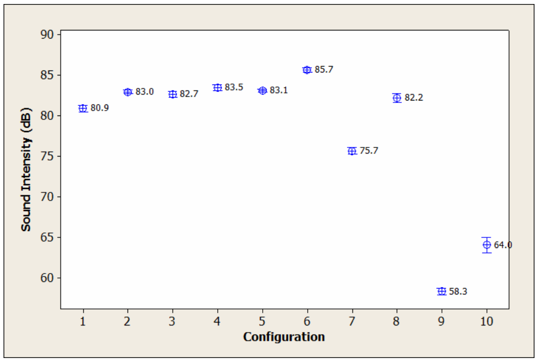


(c) Truck Inside Sound 60mph

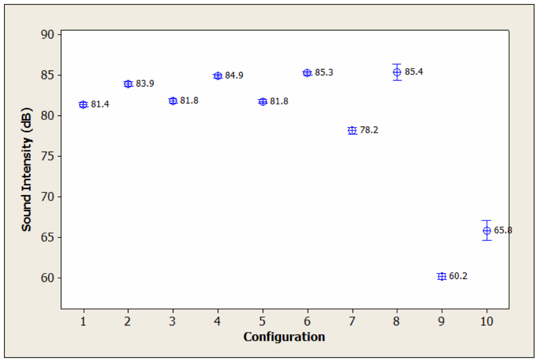
Configuration Number	Rumble Strip Type
1	4 at 24"
2	4 at 36"
3	5 at 24"
4	5 at 36"
5	6 at 24"
6	6 at 36"
7	Adhesive
8	Permanent
9	Closed Course Baseline
10	US56 Baseline

✖ :Data not Available

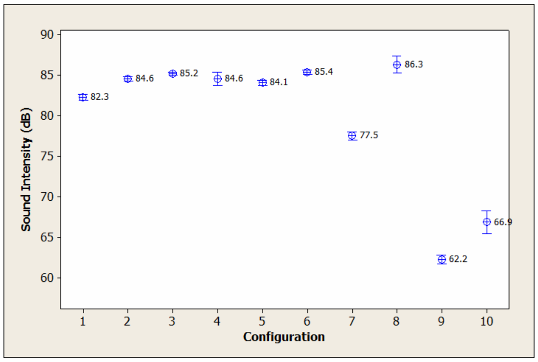
Fig. 4.3 Truck In-Vehicle Sound at all Speeds



(a) Car Inside Sound 45mph



(b) Car Inside Sound 53mph



(c) Car Inside Sound 60mph

Configuration Number	Rumble Strip Type
1	4 at 24"
2	4 at 36"
3	5 at 24"
4	5 at 36"
5	6 at 24"
6	6 at 36"
7	Adhesive
8	Permanent
9	Closed Course Baseline
10	US56 Baseline

✖ :Data not Available

Fig. 4.4 Car In-Vehicle Sound at all Speeds passenger car. However, the relative increase in sound level resulting from Configurations 1 through 6 increased more for the passenger car than for the heavy truck. Configuration 7 generated the lowest in-vehicle sound for either the passenger car or the heavy truck.

As the speed increased, the sound inside the heavy truck was increased for Configurations 1 through 6. For the sound inside the car, this trend was only observed in Configurations 1 and 2.

Table 4.2 summarizes the average in-vehicle sound level, sound increase compared to the base condition and the grouping result for all configurations. The sound groupings are based on the LSD test with 95% confidence level. A configuration denoted by a letter earlier in the alphabet is significantly louder than other groups.

4.2.1 The Effect on Trucks

Configurations 1 through 6 increased the inside-truck sound level and ranged from 5.7 to 12.1 dB. Configuration 8 created 5.7 to 8.7 dB more sound inside the truck. Configuration 7 increased the least with the inside-truck sound level ranging from 1.5 to 2.5 dB. At all tested speeds, Configuration 6 generated the greatest sound level inside the trucks: 85.0 dB at 60mph (96.6 km/hr), 84.0 dB at 53mph (85.3 km/hr) and 82.8 dB at 45 mph (72.4 km/hr), respectively.

At 60 mph (96.6 km/hr), Configurations 3 and 5 were not significantly different from Configuration 8. At 53 mph (85.3 km/hr), Configurations 2 through 6 were not significantly different from Configuration 8. At 45 mph (72.4 km/hr), Configurations 1, 3, and 5 were not significantly different from Configuration 8.

Table 4.2 Average In-Vehicle Sound, Increase Sound and Grouping Results

Test Field	Configuration	45 mph				53mph				60 mph			
		Avg. Peak Sound Level (dB)	Dif. from Base Sound	Group	No. of Runs	Avg. Peak Sound Level (dB)	Dif. from Base Sound	Group	No. of Runs	Avg. Peak Sound Level (dB)	Dif. from Base Sound	Group	No. of Runs
Truck													
On Speedway	9 (Base)	73.7		F	12	73.6		F	12	72.9		F	12
	1	79.4	5.7	D	7	80.9	7.3	D	7	82.1	9.2	D	7
	2	81.6	7.9	B	10	83.9	10.3	BA	10	84.3	11.4	B	10
	3	80.3	6.6	DC	7	81.9	8.3	DC	7	82.8	9.9	C	7
	4	82.0	8.3	BA	7	82.5	8.9	BC	7	84.6	11.7	BA	7
	5	80.6	6.9	C	10	83.1	9.5	BAC	10	83.2	10.3	C	10
	6	82.8	9.1	A	10	84.0	10.4	A	10	85.0	12.1	A	10
	7	75.2	1.5	E	7	76.1	2.5	E	7	74.7	1.8	E	7
On US56	10 (Base)	74.1		F	11	76.4		E	10	74.2		E	8
	8	79.8	5.7	DC	10	82.6	6.2	BAC	10	82.9	8.7	C	10
Passenger Car													
On Speedway	9 (Base)	58.3		H	12	60.2		F	12	62.2		G	12
	1	80.9	22.6	E	6*	81.4	21.2	C	7	82.3	20.1	D	7
	2	83.0	24.7	CB	10	83.9	23.7	B	9	84.6	22.4	BC	10
	3	82.7	24.4	CD	7	81.8	21.6	C	7	85.2	23.0	B	7
	4	83.5	25.2	B	7	84.9	24.7	A	7	84.6	22.4	BC	7
	5	83.1	24.8	CB	10	81.8	21.6	C	9	84.1	21.9	C	10
	6	85.7	27.4	A	10	85.3	25.1	A	8	85.4	23.2	BA	10
	7	75.7	17.4	F	7	78.2	18.0	D	7	77.5	15.3	E	7
On US56	10 (Base)	64.0		G	12	65.8			12	66.9		F	12
	8	82.2	18.2	D	10	85.4	19.6	A	10	86.3	19.4	A	10

* Limited sample size

4.2.2 The Effect on Cars

Configurations 1 through 6 increased the inside-car sound level with figures ranging from 20.1 to 27.4 dB. Configuration 8 increased sound inside the passenger car and results ranged from 18.2 to 19.6 dB. Configuration 7 increased the least: ranging from 15.3 to 18.0 dB. At all speed ranges, Configuration 6 generated the largest sound level inside the passenger car.

At 60 mph (96.6 km/hr), only Configuration 6 generated sound intensity that was not significantly different from Configuration 8 at 53 mph (85.3 km/hr), Configurations 4 and 6 were not significantly different from Configuration 8. At 45 mph (72.4 km/hr), Configuration 3 was not significantly different from Configuration 8.

Chapter 5 Analysis for Movement and Vertical Displacement Tests

5.1 Rumble Strip Movement

Movement was measured at each edge of the rumble strips. In figure 5.1, A and C measure the movement downstream (positive) or upstream (negative), and B and D measure movement right (positive) or left (negative) with respect to the vehicle. The results for each generation of rumble strips follow.

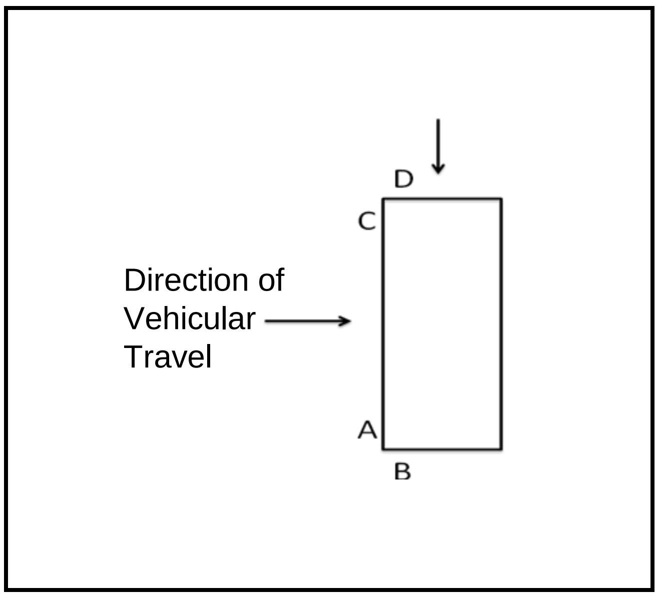


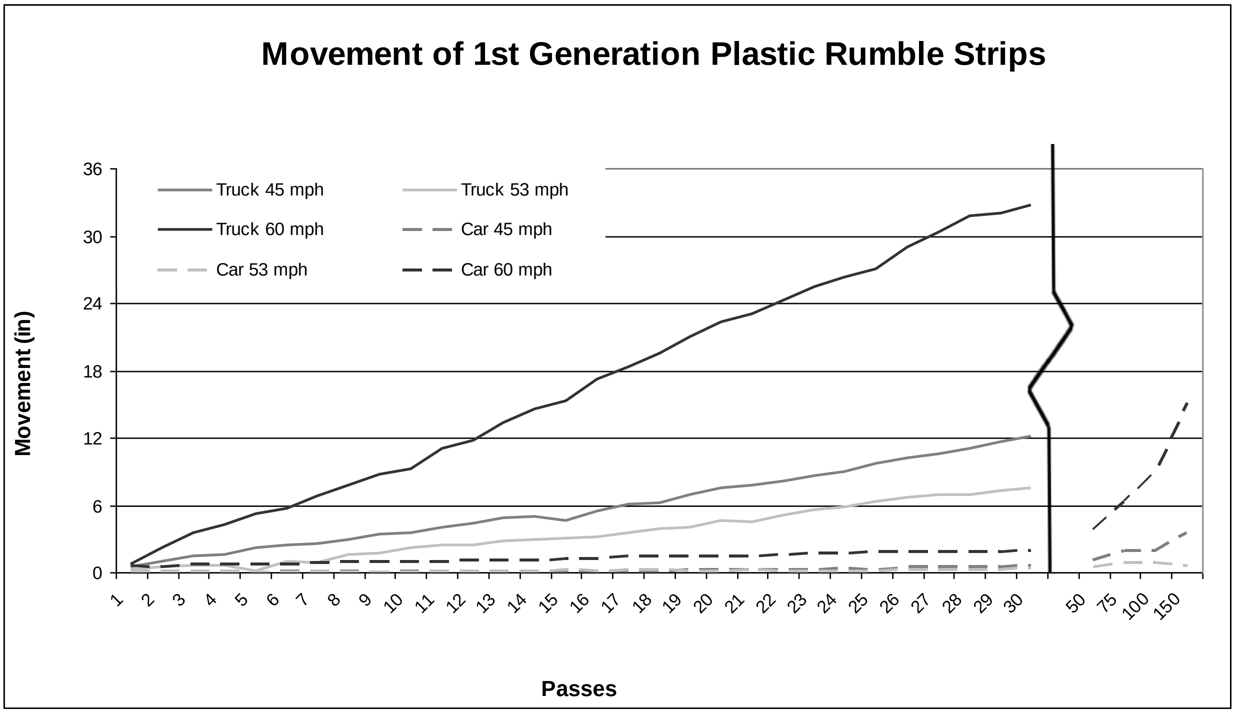
Fig. 5.1 Rumble Strip Movement Orientation

5.1.1 First Generation Plastic Rumble Strips

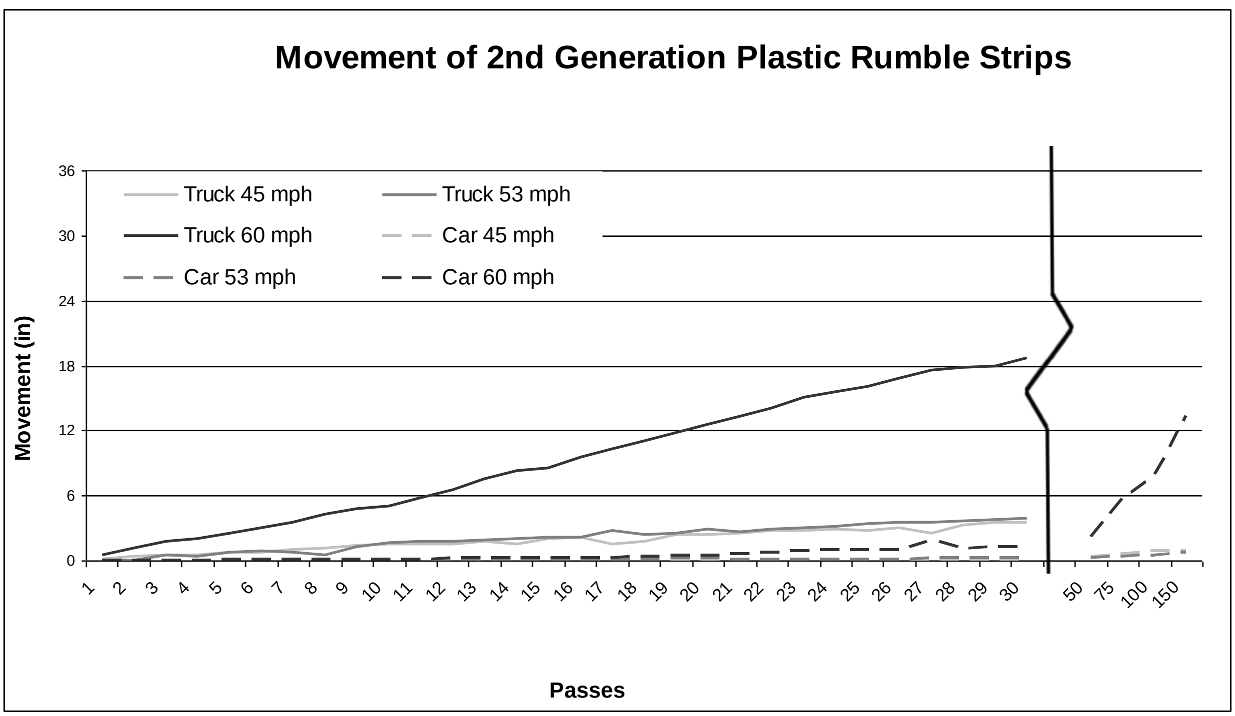
The first generation was placed at the beginning of each set and performed the worst. The results for this generation follow and are shown in figure 5.2(a).

The heavy truck after 30 passes:

- 45 mph (72.4 km/hr): Point B moved the most with a 12.25 in. (311 mm) shift to the right while point A moved 7.19 in. (183 mm) upstream.



(a)



(b)

Fig. 5.2 Lateral Movement for 1st and 2nd Generation Plastic Rumble Strips

- 53 mph (85.3 km/hr): The largest movement was at point C and moved 7.75 in. (197 mm) upstream and point D moved 7.5 in. (191 mm) to the right.
- 60 mph (96.6 km/hr): The largest movement was at point D and moved 32.75 in. (832 mm) to the right and point C moved 16 in. (406 mm) downstream.

The passenger car after 150 passes:

- 45 mph (72.4 km/hr): The largest movement was at point B and moved 3.5 in. (89 mm) to the right while points A and C moved 1.38 in. (35 mm) upstream.
- 53 mph (85.3 km/hr): The largest movement was at point A and moved 1.75 in. (44 mm) upstream and point B moved 0.63 in. (16 mm) to the right.
- 60 mph (96.6 km/hr): The largest movement was at point B and moved 15 in. (381 mm) to the right and point A moved 10.5 in. (267 mm) downstream.

This generation of rumble strips moved such a large amount that it would not be ideal for use at a work zone of any kind, especially one with higher speeds and heavy truck traffic. As figure 18(a) demonstrates, the strips had more movement during the 45 and 60 mph (72.4 and 96.6 km/hr) passes and surprisingly less at the 53 mph (85.3 km/hr).

5.1.2 Second Generation Plastic Rumble Strips

Two rumble strips from the second generation were placed second and third in each group of six. The results of this type of strip are shown in figure 5.2 (b).

The heavy truck after 30 passes:

- 45 mph (72.4 km/hr): The most movement from the first strip was 13.16 in. (334 mm) upstream from point C and 3.5 in. (89 mm) to the right from point D. The most movement on the second was 10.75 in. (273 mm) upstream at point C and 2 in. (51 mm) to the right from point D.

- 53 mph (85.3 km/hr): The largest movement from the first strip was at point C and moved 7.87 in. (200 mm) upstream and point D moved 3.88 in. (99 mm) to the right. The most movement from the second was at point C and moved 8.63 in. (219 mm) upstream and point D moved 2 in. (51 mm) to the right.
- 60 mph (96.6 km/hr): The largest movement on the first strip was at point B by 19 in. (483 mm) to the right and points A and C moved 4.75 in. (121 mm) downstream. For the second strip, point D moved 24 in. (610 mm) to the right, making it the largest variation, and point C moved 8 in. (203 mm) downstream.

The passenger car after 150 passes:

- 45 mph (72.4 km/hr): The first strip moved in a counter-clockwise motion with point A moving 0.38 in. (10 mm) downstream and point C moving 1.63 in. (41 mm) upstream. The whole strip also moved 1.13 in. (29 mm) to the right. The largest movement from the second strip was at point B and was 0.63 in. (16 mm) downstream. This shift meant that it ended up in the same spot from which it started for lateral movement after the 150th pass.
- 53 mph (85.3 km/hr): The first strip moved the most at point C, shifting 0.38 in. (10 mm) downstream, and point B shifted 0.75 in. (19 mm) to the right. The next strip moved the most at point C and moved 0.75 in. (19 mm) upstream and point B moved 0.38 in. (10 mm) to the right.
- 60 mph (96.6 km/hr): The largest movement on the first strip was at points B and D and both moved 5 in. (127 mm) to the right while point A moved 3.75 in. (95 mm) downstream. The second strip moved the most at point D, which was 13.25 in. (337 mm) to the right, and point A was 10.25 in. (260 mm) downstream.

With the passenger car, there was little movement at the 45 and 53 mph (72.4 and 85.3 km/hr) ranges. However, there was a larger amount of movement at 60 mph (96.6 km/hr). Consequently, this generation of plastic rumble strips might be reasonable for work zones with high volumes of cars at lower speeds.

5.1.3 Third Generation Plastic Rumble Strips

A third generation rumble strip was placed fourth in the line of rumble strips. The results from this generation follow and are shown in figure 5.3 (a):

The heavy truck after 30 passes:

- 45 mph (72.4 km/hr): The most movement was 5.69 in. (145 mm) upstream from point A and 3.5 in. (89 mm) to the right from point B.
- 53 mph (85.3 km/hr): The largest movement was at point A and was 3.06 in. (78 mm) upstream while point B moved 3 in. (77 mm) to the right.
- 60 mph (96.6 km/hr): The largest movement was at point B and moved 10.5 in. (267 mm) to the right and point C moved 10 in. (254 mm) downstream.

The passenger car after 150 passes:

- 45 mph (72.4 km/hr): The largest movement was at point C and moved 2.13 in. (54 mm) downstream and point B moved 0.88 in. (22 mm) to the right.
- 53 mph (85.3 km/hr): The largest movement was at point C and moved 1.25 in. (32 mm) downstream and point B moved 1.25 in. (32 mm) to the right.
- 60 mph (96.6 km/hr): The largest movement was at point C and moved 2.25 in. (57 mm) downstream and point B moved 0.75 in. (19 mm) to the right.

This generation of portable rumble strips would be reasonable in work zones that have a low number of heavy trucks at all speeds. At higher speeds there was more movement, which calls into question the effectiveness of the strip at higher speeds over a day with many passes.

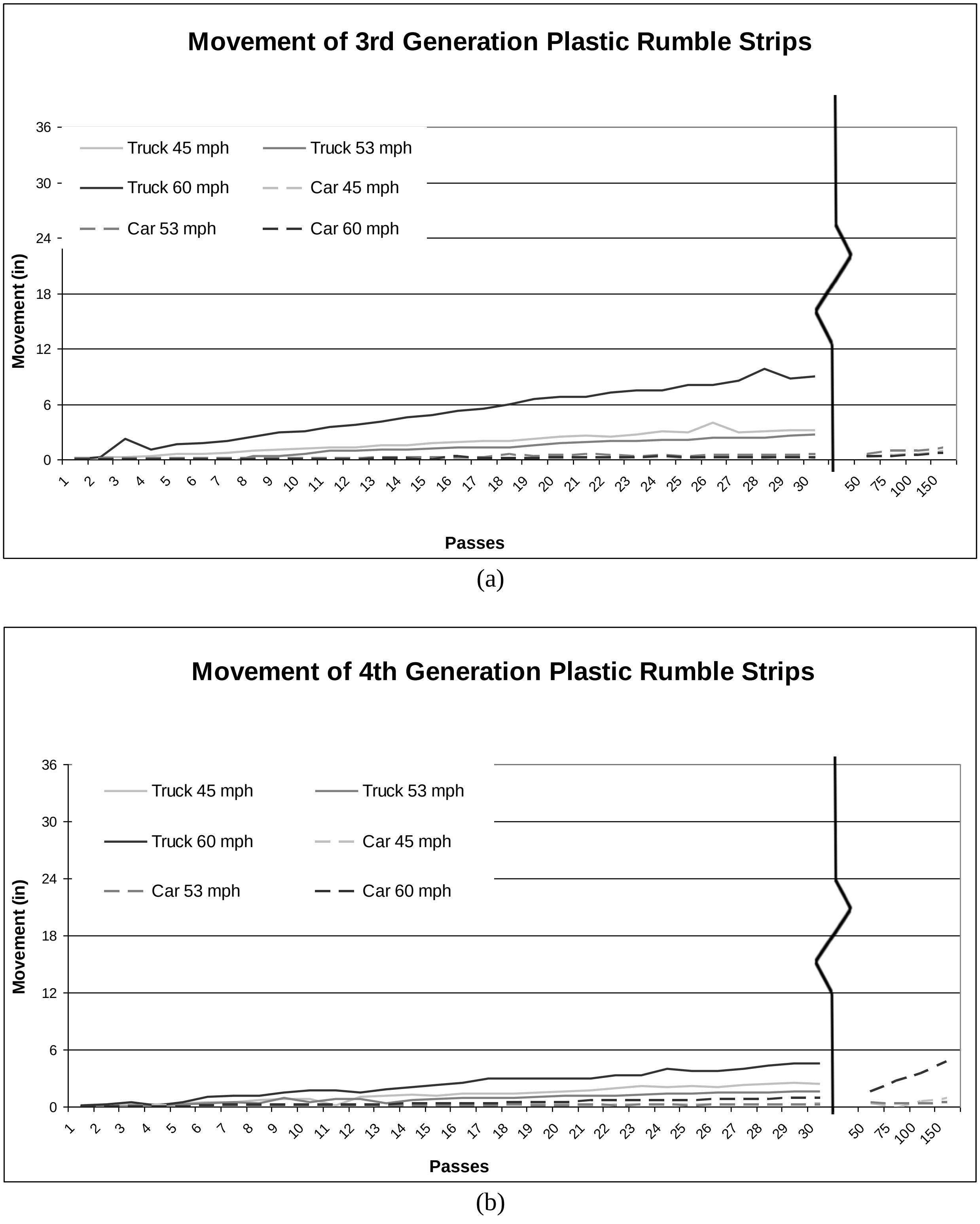


Fig. 5.3 Lateral Movement for Third and Fourth Generation Rumble Strips

5.1.4 Fourth Generation Plastic Rumble Strips

The last two strips on each set were from this generation and moved the least. The results from this generation follow and are shown in figure 5.3(b):

The heavy truck after 30 passes:

- 45 mph (72.4 km/hr): The most movement from the first strip was 6.63 in. (168 mm) upstream from point C and 2.38 in. (60 mm) to the right from point D. The largest movement from the second strip was 5.88 in. (149 mm) upstream from point C and 2.38 in. (60 mm) to the right from point B.
- 53 mph (85.3 km/hr): The largest movements from the first strip were at point C which moved 3.94 in. (100 mm) upstream and point D moved 1.5 in. (38 mm) to the right. The most movement at the second strip occurred at point A and moved 4.06 in. (103 mm) upstream and point D moved 1.63 in. (41 mm) to the right.
- 60 mph (96.6 km/hr): The largest movements from the first strip were at points B and D which moved 9.5 in. (241 mm) downstream and point C moved 5 in. (127 mm) to the right. The largest movement from the second strip was at points B and D and moved 4.5 in. (114 mm) to the right and point C moved 2 in. (51 mm) downstream.

The passenger car after 150 passes:

- 45 mph (72.4 km/hr): The first strip moved in a clockwise motion. Point A moved 0.38 in. (10 mm) downstream, point C moved 0.16 in. (4 mm) upstream and point B moved 0.88 in. (22 mm) to the right. On the second strip, point C moved 0.25 in. (6 mm) downstream and point B moved 0.38 in. (10 mm) to the right.
- 53 mph (85.3 km/hr): On the first strip, point A moved 0.38 in. (10 mm) upstream and points B and D moved 0.5 in. (13 mm) to the right. The second strip moved in a clockwise

motion with point A moving 0.16 in. (4 mm) upstream, point C moving 2 in. (51 mm) downstream and point B moved 0.25 in. (6 mm) to the right.

- 60 mph (96.6 km/hr): The largest movement from the first strip was at point B and moved 4.75 in. (121 mm) to the right while point A moved 3.25 in. (83 mm) downstream. The largest movement for the second strip was at point B, which moved 1.88 in. (48 mm) to the right, and at point A, which moved 1.38 in. (35 mm) downstream.

This generation of portable strips would be the most reasonable choice in all situations because it moved the least. The only movement that would require more investigation would be implementation in work zones at 60 mph (96.6 km/hr).

5.2 Steel Rumble Strips

The two steel rumble strips were placed right before the last set of plastic rumble strips at 60 mph (96.6 km/hr) and measured with the heavy truck. At the end of the heavy truck evaluation, the steel rumbles strips became unraveled, and so were no longer usable for testing, so testing them at other speeds during this evaluation was not possible.

5.2.1 Narrow Steel Strip

After 30 passes from the heavy truck:

- 60 mph (96.6 km/hr): The largest movement was at point C and point D, which moved 0.38 in. (10 mm) downstream and 0.31 in. (8 mm) to the right, respectively.

5.2.2 Wide Steel Strip

After 30 passes from the heavy truck:

- 60 mph (96.6 km/hr): The largest movement was at point D and point C, which moved 0.63 in. (16 mm) to the right and 0.19 in. (5 mm) downstream, respectively.

These rumble strips were only tested where the most movement occurred, and was altogether minimal. However, since the steel rumble strips broke after the heavy truck testing there is a need to further develop the fasteners of the steel strips to improve durability.

5.3 Rumble Strip Movement Comparison

The average movement from each side was measured from each type and generation of rumble strip. Apart from the fourth generation, the movement from point A was upstream when the heavy truck was going 45 and 53 mph (72.4 and 85.4 km/hr) and downstream at 60 mph (96.6 km/hr). The average results from the 30 passes of the heavy truck revealed that the rumble strips moved upstream. The average results of the 150 passes of the passenger car revealed that the rumble strips moved downstream. Table 5.1 details the results for points A - D.

The movement for point B shows that at 53 mph (85.3 km/hr) the lateral movement was less than the other two speeds in all but three categories. This clearly shows that the portable rumble strips are more efficient at this speed. Point C also demonstrates the upstream and downstream movement at different speeds and with different generations. However, all but one of the averages moved in the downstream direction. Every rumble strip, on average, moved in a clockwise motion except the strip from the second generation. Figure 5.4 demonstrates the average movement, from the heavy truck, of each generation of rumble strip.

5.4 Rumble Strip Vertical Displacement

Vertical displacement was measured at the edge and middle of each strip with a high-speed camera on the two types of the steel rumble strips and second-fourth generations of the plastic rumble strips. With every measured pass on each type of steel rumble strip, the maximum vertical displacement always occurred in the middle. Figure 5.5(a) and (b) show each type of steel rumble strip, the wide one on the left and the narrow one on the right. Figure 5.5(c) and (d)

Table 5.1 Average Displacement from Each Measuring Point (in Inches)

Measuring Point A	Heavy Truck				Passenger Car			
	45 mph	***53 mph***	***60 mph***	***Avg.***	***45 mph***	***53 mph***	***60 mph***	***Avg.***
1st Generation	-3.58	-2.17	3.57	-0.73	-0.21	-0.33	1.73	0.40
2nd Generation	-1.63	-1.80	3.08	-0.11	2.03	1.66	3.06	2.25
3rd Generation	-3.11	-1.77	2.81	-0.69	-0.04	-0.05	0.09	0.00
4th Generation	-1.18	-1.29	-0.23	-0.90	0.01	-0.22	0.26	0.01
Measuring Point B	**Heavy Truck**				**Passenger Car**			
	45 mph	***53 mph***	***60 mph***	***Avg.***	***45 mph***	***53 mph***	***60 mph***	***Avg.***
1st Generation	5.64	3.31	16.82	8.59	0.42	0.20	2.13	0.92
2nd Generation	1.04	1.47	10.56	4.36	0.09	0.13	0.98	0.40
3rd Generation	2.03	1.56	5.30	2.97	0.17	0.37	0.16	0.23
4th Generation	1.12	0.81	3.49	1.80	0.15	0.11	0.44	0.24
Measuring Point C	**Heavy Truck**				**Passenger Car**			
	45 mph	***53 mph***	***60 mph***	***Avg.***	***45 mph***	***53 mph***	***60 mph***	***Avg.***
1st Generation	-3.18	-3.40	9.20	0.87	-0.30	0.19	0.16	0.02
2nd Generation	-6.81	-5.19	2.34	-3.22	0.04	0.00	0.36	0.13
3rd Generation	-2.67	-0.87	5.00	0.49	0.25	0.04	0.29	0.19
4th Generation	1.98	1.22	0.95	1.39	-0.04	0.15	0.17	0.09
Measuring Point D	**Heavy Truck**				**Passenger Car**			
	45 mph	***53 mph***	***60 mph***	***Avg.***	***45 mph***	***53 mph***	***60 mph***	***Avg.***
1st Generation	5.83	3.48	16.67	8.65	0.11	-0.05	1.57	0.54
2nd Generation	1.40	1.69	10.47	4.52	-0.07	0.07	0.93	0.31
3rd Generation	1.79	1.15	4.96	2.63	0.03	0.12	0.02	0.06
4th Generation	1.13	0.74	3.22	1.69	-0.08	0.07	0.29	0.09

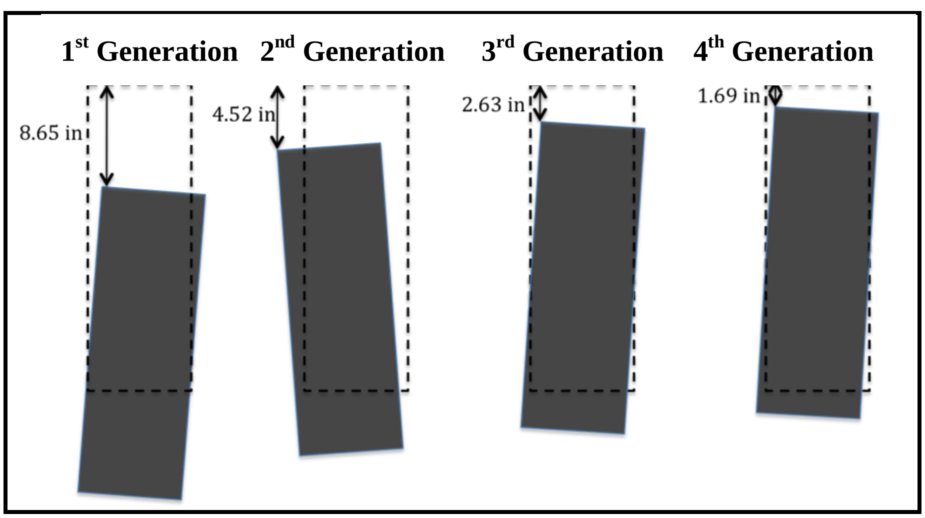


Fig. 5.4 The Average Movement of each Generation of the Plastic Rumble Strips

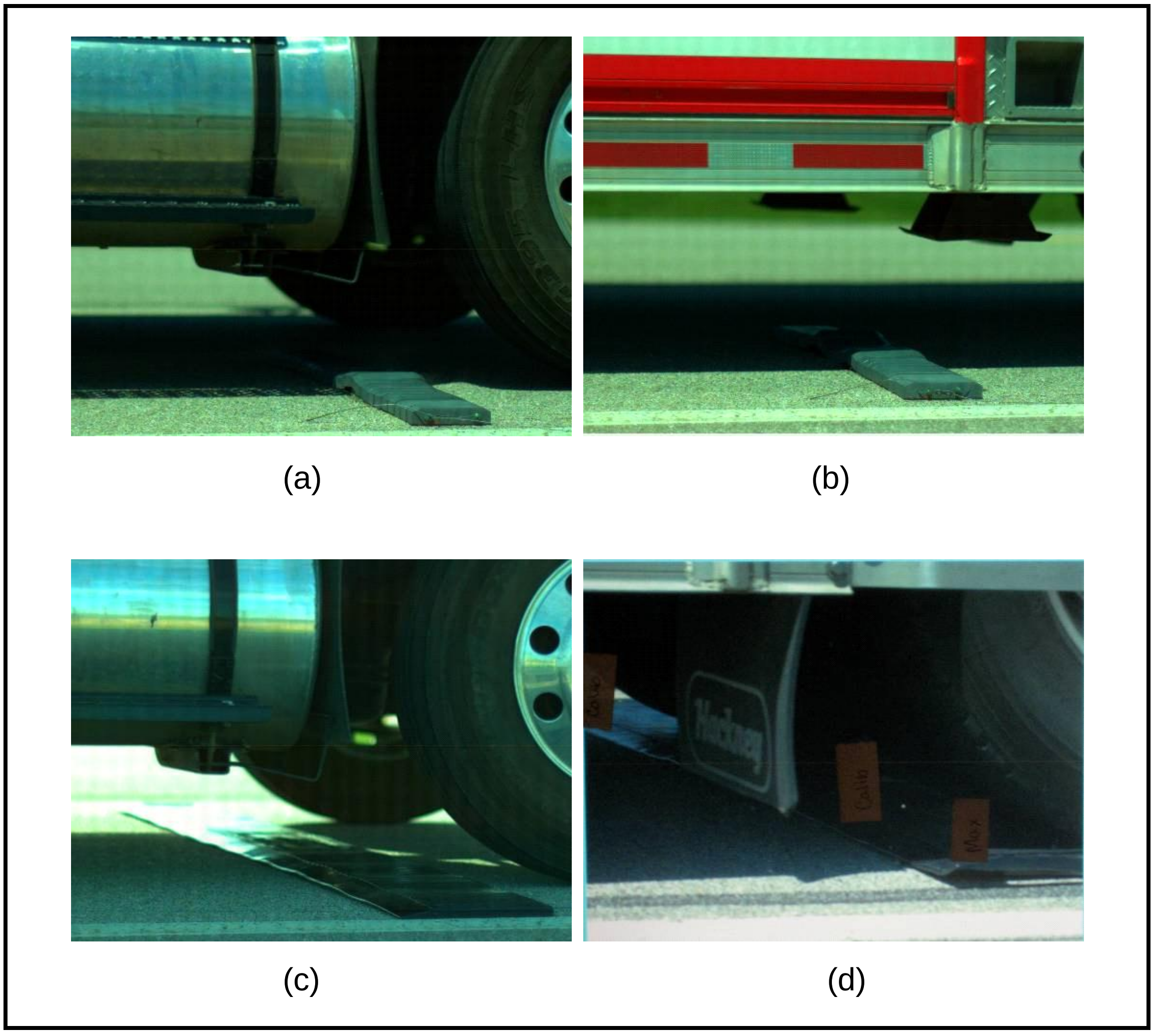


Fig. 5.5 Pictures of Vertical Displacement on the Edge and in the Middle

show examples of vertical displacement on the edge and in the middle of the plastic rumble strips. The results for the vertical displacement follow.

5.4.1 Second Generation Plastic Rumble Strip

The heavy truck

- 53 mph (85.3 km/hr): There were four measured passes at 53mph (85.3 km/hr) and the maximum vertical displacement occurred all four times at the edge. The highest displacement was 0.8 in. (20 mm) and the lowest was 0.3 in. (8 mm).

- 60 mph (96.6 km/hr): There were eight measured passes and the maximum vertical displacement occurred five times on the edge and three times in the middle. When the maximum vertical displacement was at the edge, the highest displacement was 1.4 in. (36 mm) and the lowest was 1.2 in. (30 mm). When the maximum vertical displacement was in the middle, the highest displacement was 1.2 in. (30 mm) and the lowest was 1.0 in. (25 mm).

The passenger car

- 45 mph (72.4 km/hr): There were eight measured passes and the maximum vertical displacement occurred in the middle of the strip all eight times. The highest displacement was 0.2 in. (5 mm) and the lowest was 0.1 in. (3 mm).
- 53 mph (85.3 km/hr): There were eight measured passes and the maximum vertical displacement occurred in the middle every time. The highest displacement was 0.2 in. (5 mm) and the lowest was 0.1 in. (3 mm).
- 60 mph (96.6 km/hr): There were eight measured passes and the maximum vertical displacement occurred six times at the edge, one time in the middle, and one time at both the edge and middle. When the maximum vertical displacement occurred at the edge, the highest displacement was 0.7 in. (18 mm) and the lowest was 0.3 in. (8 mm). When the maximum vertical displacement was in the middle, the vertical displacement was 0.3 in. (8 mm). When the maximum vertical displacement occurred at the middle and edge equally, the displacement was also 0.3 in. (8 mm).

Over one inch (25 mm) of vertical displacement occurred on all 60 mph (96.6 km/hr) heavy truck passes. This vertical displacement may explain the large amount of movement in this generation of rumble strip.

5.4.2 Third Generation Plastic Rumble Strip

The heavy truck

- 45 mph (72.4 km/hr): There were eight measured passes and the maximum vertical displacement occurred on the edge four times, in the middle three times, and at both locations one time. When it occurred at the edge, the highest displacement was 0.8 in. (20 mm) and the lowest was 0.5 in. (13 mm). When it occurred in the middle, the highest displacement was 0.6 in. (15 mm) and the lowest was 0.4 in. (10 mm). When the maximum vertical displacement occurred both at the middle and edge, the displacement was 0.6 in. (15 mm).
- 53 mph (85.3 km/hr): There were five measured passes and the maximum vertical displacement occurred at the edge four times and once at both the middle and edge. When the maximum vertical displacement was at the edge, the highest displacement was 1.1 in. (28 mm) and the lowest was 1.0 in. (25 mm). When it was at both, the vertical displacement was 0.9 in. (23 mm).
- 60 mph (96.6 km/hr): There were six measured passes and the maximum vertical displacement occurred five times at the edge and once at both the edge and middle. At the edge, the highest displacement was 1.1 in. (28 mm) and the lowest was 0.9 in. (23 mm). When it occurred at both the middle and edge, the displacement was 0.8 in. (20 mm).

The passenger car

- 45 mph (72.4 km/hr): There was one measured pass and the maximum vertical displacement occurred in the middle and was 0.2 in. (5 mm).
- 60 mph (96.6 km/hr): There were seven measured passes and the maximum vertical displacement occurred in the middle with the highest displacement at 0.2 in. (5 mm) and the lowest at 0.1 in. (3 mm).

With this generation of portable rumble strips there was movement every pass and with the heavy truck traveling at 53 and 60 mph (85.3 and 96.6 km/hr) there was almost 1 in. (25 mm) of vertical displacement. This rumble strip had similar or greater vertical displacement than the second generation but did not move as much as the second generation.

5.4.3 Fourth Generation Plastic Rumble Strip

The heavy truck

- 53 mph (85.3 km/hr): With eight measured passes, the maximum vertical displacement occurred six times on the edge and twice in the middle of the strip. The highest displacement on the edge at this speed was 0.6 in. (15 mm) and the highest in the middle was 0.3 in. (8 mm). The minimum displacement in the middle was 0.2 in. (5 mm) and the minimum at the edge of the strip was 0.3 in. (8 mm).
- 60 mph (96.6 km/hr): There were eight measured passes and the maximum vertical displacement occurred four times in the middle and four times on the edge. When the maximum vertical displacement was on the edge, the highest displacement was 1.1 in. (28 mm) and the lowest was 0.4 in. (10 mm). When the maximum vertical displacement was in the middle, the highest displacement was 0.6 in. (15 mm) and the lowest was 0.2 in. (5 mm).

The passenger car

- 45 mph (72.4 km/hr): There were eight measured passes at this speed and the maximum vertical displacement occurred in the middle all eight times. The maximum displacement was 0.2 in. (5 mm) and the minimum was 0.1 in. (3 mm).
- 53 mph (85.3 km/hr): The maximum vertical displacement occurred in the middle of the rumble strip for all eight measured passes. The maximum displacement was 0.3 in. (8 mm) and the minimum was 0.2 in. (5 mm).

- 60 mph (96.6 km/hr): The maximum vertical displacement occurred in the middle of the rumble strip on all eight measured passes. The maximum displacement was 0.2 in. (5 mm) and the minimum was 0.1 in. (3 mm).

With this generation of portable rumble strips, there was little movement every pass and with the heavy truck traveling at 53 and 60 mph (85.3 and 96.6 km/hr) there was much less vertical displacement than the other generations. The smaller vertical displacement could be one of the main factors causing the observed lateral displacement to be less than the other generations of plastic rumble strips.

5.4.4 Narrow Steel Rumble Strip

The heavy truck

- 45 mph (72.4 km/hr): There were five measured passes and the maximum displacement was 0.4 in. (10 mm) and the minimum was 0.3 in. (8 mm).
- 53 mph (85.3 km/hr): There were four measured passes and the maximum displacement was 0.5 in. (13 mm) and the lowest was 0.1 in. (3 mm).
- 60 mph (96.6 km/hr): There were four measured passes and the maximum displacement was 0.8 in. (20 mm) and the lowest was 0.6 in. (15 mm).

The passenger car

- 45 mph (72.4 km/hr): There were two measured passes and the maximum vertical displacement was 0.2 in. (5 mm) and the minimum was 0 in. (0 mm).
- 53 mph (85.3 km/hr): There were five measured passes and the maximum displacement was 0.4 in. (10 mm) and the minimum was 0 in. (0 mm).
- 60 mph (96.6 km/hr): There were eight measured passes and the maximum displacement was 0.4 in. (10 mm) and the minimum was 0 in. (0 mm).

There was more vertical displacement with the heavy truck than there was with the passenger car. In fact, vertical displacement was present in every pass with the heavy truck. On the other hand, even with the passenger car going 60 mph (96.6 km/hr), at times there was no measurable vertical displacement. The steel rumble strips' lack of vertical displacement could be one of the main factors why the lateral movement was so small.

5.4.5 Wide Steel Rumble Strip

The heavy truck

- 45 mph (72.4 km/hr): There were eight measured passes and the maximum displacement was 0.7 in. (18 mm) and the lowest was 0.4 in. (10 mm).
- 53 mph (85.3 km/hr): There were eight measured passes and the maximum displacement was 1.0 in. (25 mm) and the minimum was 0.6 in. (15 mm).
- 60 mph (96.6 km/hr): There were six measured passes. The maximum vertical displacement was 1.1 in. (28 mm) and the lowest was 0.6 in. (15 mm).

The passenger car

- 45 mph (72.4 km/hr): There were three measured passes and the maximum displacement was 0.2 in. (5 mm) and the minimum was 0 in. (0 mm).
- 53 mph (85.3 km/hr): There was one measured pass and the vertical displacement was 0.3 in. (8 mm). More passes could not be completed due to failure of the steel rumble strip.

The wide steel strip moved more than the narrow strip, but there was still little vertical displacement with the passenger car. It appears, from the amount of vertical displacement from the wide strip, that the narrow strip would perform better.

Chapter 6 Findings and Discussion of Future Research

6.1 Conclusions from Vibration and Sound Tests

Vibration is one key method of attention-getting that rumble strips can provide. While all of the tested rumble strip applications increased the steering wheel vibrations compared to the baseline pavement vibrations, it was clear that the portable plastic rumble strips were capable of generating more vibration than the adhesive rumble strips. From this research it appears that the portable plastic rumble strips tested have the potential to provide improved attention-getting to drivers. It was also apparent that the amounts of vibration generated generally match that of a permanent CIP rumble strip, and in many applications it provided results that were not statistically different. The adhesive rumble strips were able to provide similar results as the permanent CIP rumble strips in only two instances and these were both with the truck.

The second method of attention-getting by a set of rumble strips is sound generated. Again, the portable plastic rumble strips were able to generally provide similar sound levels as the tested CIP rumble strips, and in many instances there were no statistically significant differences in sound levels. In all instances, the adhesive rumble strip configuration provided significantly less sound than any of the other configurations.

The results show that the use of portable plastic rumble strips can provide improved vibration and sound performance relative to the tested adhesive rumble strip configuration, and even compares well with the tested permanent CIP rumble strip. Further, it appears that configurations with four or five portable plastic rumble strips may be just as capable as configurations with six strips in generating a comparable level of vibration and sound as the CIP rumble strips. This potential reduction in strips could result in a lower cost of materials as well as reduced installation and removal times—factors that could make their use in short-term work zones more feasible.

6.2 The Conclusions from the Movement and Vertical Displacement Tests

The first generation plastic rumble strip moved such a large amount that it would not be ideal for use at a work zone of any kind, especially one with higher speeds and heavy truck traffic. The second generation plastic rumble strip moved less than the first generation, however, there was a larger amount of movement at 60 mph (96.6 km/hr). Consequently, this generation would only be reasonable for work zones with a high proportion of passenger cars at lower speeds. The third generation of plastic rumble strips would be reasonable in work zones that have a low number of heavy tractor-trailers at all speeds. At higher speeds there was more movement, which calls into question the effectiveness of the strip over the period of a day with higher speeds and many vehicular passes. The fourth generation of portable strips would be the most reasonable choice in all situations because it moved the least. The only movement that would require more investigation would be the implementation of this strip in work zones at 60 mph (96.6 km/hr). Steel rumble strips were only tested where the most movement occurred and did not move a significant amount. Since the steel rumble strips broke after the heavy truck testing, there is a need to further improve the design of the steel rumble strips.

Vertical displacement was measured at the edge and middle of each strip with a high-speed camera on the two types of steel strips as well as the second through the fourth generation plastic strips. The second generation of plastic rumble strips had vertical displacement on every pass and over 1 in. (25 mm) of displacement on all 60 mph (96.6 km/hr) heavy truck passes. This kind of vertical displacement explains the large amount of movement in this generation of rumble strip. In the third generation of plastic rumble strips, there was movement every pass and with the heavy truck traveling 53 and 60 mph (85.3 km/hr and 96.6 km/hr) there was almost 1 in. (25 mm) of vertical displacement. This rumble strip had similar or greater vertical displacement than the second generation, however, it did not move as much as the second generation. The fourth generation of plastic rumble strips had little movement every pass and with the heavy truck at 53 and 60 mph (85.3 km/hr and 96.6 km/hr) there was much less vertical displacement than the other generations. The lack of vertical displacement could be one of the main factors why the movement was so small. There was more vertical displacement with the heavy truck than there was with the passenger car and, with the former, it occurred in every pass over the narrow steel strips. Even with the passenger car moving at 60 mph (96.6 km/hr), at times there was no vertical displacement. The steel rumble strips lack of vertical displacement could be one of the main factors why the movement was so small. The wide steel strip had more vertical displacement than the narrow strip, but there was still little vertical displacement with the passenger car. It appears—in comparing the wide steel rumble strip to the narrow—that the narrow strip would perform better.

The best solution for most work zones would be the fourth generation of plastic rumbles strips. The earlier generations did not perform as well as the fourth generation especially at 60 mph (96.6 km/hr). The steel rumble strips also hold promise; however, the structural integrity of the steel rumble strips is an issue that needs to be addressed.

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