Development of a Decision Matrix and Specifications for Portable Temporary Rumble Strips

By

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ABSTRACT

The objective of this thesis was to develop specifications for portable, reusable temporary rumble strips for their applications in different work zone settings in Kansas. A detailed literature review and a closed-course test was performed regarding temporary rumble strips. Additionally, data from permanent cast-in-place (CIP) rumble strips at six locations in Kansas were collected. All commercially available portable, reusable temporary rumble strips were tested in a closed-course setting using a standard dump truck and a full size car. The rumble strips' rotational movement, linear movement, sound and vibration produced by a traversing vehicle were chosen as parameters in developing the decision matrix. Measurements of the strips' linear and angular movements, sound, and vibration generated due to the test vehicles passing over the rumble strips were collected for a total of 40 passes each at speeds of 22.5, 37.5, 57.5 and 67.5mph. A matrix and a classification table were created with class intervals defining the classes based on the performance of temporary rumble strips at each of the speeds.

Threshold limits for movement, rotation, and sound generation of the temporary rumble strips at each of the speeds were calculated for developing classification tables. Annual Average Daily Traffic (AADT) and Average Daily Truck Traffic (ADTT) were used in calculating threshold limits for movement and rotation. Sound threshold limits were based on CIP strips' sound data. Following the results of the closed course test and an additional vibration test conducted at the University of Kansas, vibration was not included as a parameter in the final decision matrix. Unlike other parameters such as movement, rotation, and sound generation the vibration generated by the rumble strips were found not to be statistically different at different test speeds. A decision matrix consisting of parameters – movement (lateral and longitudinal), rotation, and sound – was developed. This matrix consisted of all the classes, including various work zone conditions ranging from low-speed, low-volume to high-speed, high-volume work zone conditions. This matrix in combination with the classification table provides a basis for a recommended method for any vendor or a research team with information regarding the performance of a temporary rumble strip, the type of class it belongs to and its applicability in various work zone conditions.

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CHAPTER 1 INTRODUCTION

Work zone safety is of paramount importance for both drivers and workers. Work zones are classified as long-term, intermediate, short-term and mobile. Intermediate and long-term work zones have work periods extending from more than one day to several days, while short-term and mobile work zones have their working periods ranging from less than an hour to a full day. Mobile work zones are those which continuously or intermittently move. One of the innovative traffic safety devices used at short-term work zones are portable temporary rumble strips. Temporary rumble strips have the potential to be an effective traffic safety device in work zones by warning drivers about changing road conditions ahead of them. Portable temporary rumble strips are usually reusable strips made out of polymer or modular plastic that provide both audible and tactile warning to alert motorists as the vehicle tires traverse the strips. These strips differ from older technologies such as asphalt temporary rumble strips and adhesive-backed temporary stick-down type rumble strips.

Development of specifications for these portable reusable temporary rumble strips can help vendors in assessing the performance and applicability of their new product. In addition, at the time of this research the Kansas Department of Transportation (KDOT) was interested in developing specifications based on performance characteristics rather than simply on material type, size, and weight. A matrix with necessary classifications regarding speed and applicability of temporary rumble strips at various work zone conditions should be able to meet KDOT's criteria.

1.1. Research Objective

This research was conducted with the objective of developing specifications for portable reusable temporary rumble strips that can be used in work zone applications. Variables such as movement, rotation, sound and vibration generation of the temporary rumble strips were studied. As a part of it, all commercially-available portable reusable temporary rumble strips were tested in a closed-course setting for developing a matrix and a classification table to better match the characteristics of current and future temporary rumble strips to the roadway conditions that occur on various Kansas roadways. The goals of this study were to:

- Determine the threshold values for movement and rotation of temporary rumble strips at various speeds that would be suitable for determining acceptable field performance;
- Determine threshold limits for generated sound and vibration at various speeds when compared to permanent cast-in-place (CIP) strips; and
- Create a matrix and a classification table by incorporating all the available variables in such a way that performance specifications can be developed for use in aiding KDOT to determine which temporary rumble strips are suitable in different work zone conditions.

Ultimately, the objectives of this research were meant to provide recommendations on the development of a classification matrix to help determine if current and future portable reusable rumble strips are suitable for various combinations of roadway volumes and approach speeds.

1.2. Thesis Organization

This research was divided into a work plan consisting of seven different tasks: a summary of previous research studies with detailed literature review, a methodology which describes the types of equipment used in the study, the parameters considered for the study and the calculation of threshold values, data collection and reduction procedures followed for a closed course study and for CIP strips, analysis of the reduced data, additional vibration evaluation test, development of decision matrix with determined parameters, and conclusions and discussion.

Chapter 1, Introduction, discusses the work zone safety and the effectiveness of portable temporary rumble strips as a traffic control device. Chapter 2, Literature review, reviews the previous studies conducted evaluating and comparing different types of temporary rumble strips. Chapter 3, Methodology, discusses the types of rumble strips used for this study, the RoadQuake 2F and TrafFix Alert rumble strips, and the different parameters considered in this research. The Chapter also illustrates the test conditions, and the statistical procedure to be followed in chapter 5 and 6. Chapter 4 presents the data collection and reduction procedures followed for this study. Chapter 5, Analysis, presents the statistical analysis comparing performance of the strips with selected parameters. Chapter 6, Additional Vibration Test, explains the vibration testing conducted to evaluate vibration as a parameter, and to determine if it should be included in the decision matrix in Chapter 7. Chapter 7 discusses the finalized decision matrix, the parameters included in the matrix and the classification tables. Chapter 8 summarizes the research effort and presents the conclusions and recommendations for this study, and also the scope for future research.

CHAPTER 2 LITERATURE REVIEW

Temporary rumble strips have been studied in different forms ranging from adhesive backed strips, steel rumble strips, polymer, recycled rubber or molded plastic rumble strips. The understanding of how different rumble strips were evaluated in previous studies helped in developing the specifications and testing the rumble strips in the closed-course test in a more effective way. This literature review summarizes the previous evaluations and testing of different types of temporary portable rumble devices in both the United States and internationally.

2.1 Temporary Adhesive Rumble Strips

A study in Kansas by Meyer (2000) evaluated the effectiveness of removable orange rumble strips manufactured by Advanced Traffic Markings (ATM) *(1)*. The orange rumble strips used for the test were manufactured as 73ft. rolls with a thickness of 0.125in. The strips contained an adhesive backing which could be installed by peeling off the protective back and pressing them against the surface of the pavement. The removable strips were installed on site in addition to all other standard traffic control devices which included the asphalt rumble strips. A set of orange rumble strips with three groups each consisting of six strips were installed (so 18 strips in total) upstream of the standard asphalt rumble strips, with each strip placed at a distance of one ft. apart. Vehicles with less than five seconds of headway were discarded to eliminate the effects of platooning. Statistical analysis at the 95 percent confidence level for the data collected showed significant speed reduction in the mean and 85th percentile speeds downstream of the strips for both the cars and trucks. But the study observed that the thickness of the strips of 0.125 in. seemed insufficient to provide any audible or tactile warning to the drivers of heavy vehicles. The orange color of the strips, which gave the advantage of visible warning was considered to be important by the KDOT Bureau of Traffic Engineering. To improve their effectiveness recommendations were made to increase the thickness of the strips or use a double layer.

Fontaine et al. (2000) also evaluated the effectiveness of adhesive orange rumble strips made by ATM *(2)*. The research team increased the thickness of the strips by adhering one strip to the face of another. Two sets each consisting of six strips were tested at spacing of 18 in. parallel to each other and perpendicular to the road. Lidar guns and traffic counters were used in recording data. The rumble strips were found to be more effective in reducing truck speeds by

3-5 mph compared to its negligible impact on passenger cars. The double-thick strip application required 30 minutes for four workers to apply, which was considered a negative aspect of the system.

Horowitz and Notbohm (2002) evaluated the Rumbler, a series of portable adhesive rumble strips made by Swarco which were 4-6 ft. long, 6 in. wide and about 0.15-0.25 in. in thickness *(3)*. These were attached to the pavement by the adhesive backing and pressing against the surface of the pavement. The Rumbler was installed on the State Trunk Highway 26 in Dodge County, Wisconsin. The strips were installed in six lines with two strips per line and seven ft. spacing between the lines. After the strips were installed, seven weeks of data were collected regarding vehicular speeds, interior noise levels and vibrations. The research team used Lidar guns for speed detection, a hand-held sound level meter to collect noise levels in decibels and a single accelerometer mounted on a test vehicle to identify vibration. Descriptive statistics and t-tests were performed to evaluate the significance of the speed change. For noise and vibration levels, amplitude vs. time and amplitude vs. frequency graphs were compared to that of a conventional rumble strip. The results showed that the Rumbler was not able to produce statistically significant speed reductions at a 95 percent confidence level but it generated distinctly different sounds and were more visible compared to conventional rumble strips.

Manjunath et al. (2002) also evaluated the effectiveness of the Rumbler *(4)*. The study was conducted during 2001 on a work zone section of US 65 in Springfield, Missouri. They evaluated the device effectiveness on three criteria: its ability in reducing the mean speed and speed variance of vehicles, the ease of installation of the device, and their durability. Speed data were collected in the north and southbound directions on US 65, which had two-lanes in each direction. Three sets of rumble strips with each set containing six rows of two strips each were installed. Speed detectors with pneumatic hoses were installed to collect data. The before and after speed data of the vehicles were collected, with data collection made in 15-minute intervals for a span of 48 hours. A two-tailed t-test was conducted at the 0.05 level of significance to determine any significant difference in the mean speeds and a statistical F-test was conducted at a 0.05 level of significance to determine any speed variance differences. The rumble strips were found to be in good condition after four weeks of installation with no noticeable wear and tear. The data collected did not reveal any significant reductions in the mean speeds.

Morgan (2003) conducted a study evaluating the effectiveness and use of temporary rumble strips as part of work zone intrusion countermeasures *(5)*. The study also focused on examining the effectiveness of New York State Department of Transportation's (NYSDOT) current standards for rumble strips spacing, thickness and to recommend any changes if required. Temporary adhesive rumble strips and a rumble strip made of recycled tire treads were evaluated. These tire tread rumble strips came in the lengths of 1.0, 1.3, 1.65 and 2.0 m, widths of 100 or 150 mm, and were 10 to 12 mm high. Both rumble strips were installed using an adhesive which was applied on the strips back and pressed on to the ground. The Rumbler was installed at five work zone sites and the tire tread rumble strips were installed at one site. A 1988 Chevy Suburban and a 1991 GMC Sonoma pick-up truck were used as test vehicles. The driver drove each of the test vehicles a minimum of three times at the posted speed limit over the strips to observe for adhesion effectiveness. The study identified problems related to tearing, shoving, missing short sections and adhesion problems during moist and low temperature situations. But overall, the research concluded that the use of temporary rumble strips at work zones was effective in alerting drivers and should be continued.

A study conducted by Zech et al. (2005) evaluated the effectiveness of rumble strips and police presence in combination with rumble strips *(6)*. Two types of temporary rumble strips - 3M and Swarco - were tested in this study. Both of these rumble strips were temporary adhesive type of strips. The strips were tested on two interstate highways. The 3M rumble strips were tested on Interstate 86 and the Swarco rumble strips were tested on Interstate 990. The 3M rumble strips were 6 in. wide and 0.4 in. thick. Two sets of rumble strips were installed with each set comprising of 6 strips spaced 10 ft. apart. The two sets of strips were separated by a distance of 1050 ft. The Swarco strips were also installed in two sets with each set containing six strips spaced 10ft on center. A police patrol car was present upstream at all times during the study at the site location of the Swarco rumble strips. Jamar traffic counters and pneumatic road tubes were used for data collection. Vehicle speeds were measured before and after installation of the speed control devices. The raw data files were analyzed by categorizing them according to date, lane and vehicle class. A z-test was carried out for a before and after analysis, evaluating the effectiveness of the strips. Another z-test with separate hypothesis was used in evaluating the significance of police presence. The study concluded that the 3M rumble strips were effective in reducing the speeds of passenger cars by approximately 2.4 mph, depending on the lane closure setup. The Swarco rumble strips, on the other hand, displayed no significant difference in the vehicle speeds, whereas the police presence in combination with the Swarco rumble strips proved to be the more effective speed control with observed speed reductions between 4.0 to 6.0 mph.

Miles and Finley (2007) conducted a study focusing on the impact of vehicle speed, vehicle type, pavement type and rumble strip design on the level of sound change that motorists perceived when they traverse rumble strips *(7)*. The study was conducted on a broad range of different types of rumble strips which included transverse rumble strips (TRS) and longitudinal rumble strips. The longitudinal strips were installed along the center line (CRS), lane line (LRS), edge line (ERS), and shoulders (SRS). The rumble strips' characteristics considered in this study were width, length and spacing. More than 400 test runs with three test vehicles - a sedan, ½-ton truck and a commercial vehicle - were conducted with speeds ranging from 45 to 70 mph. A sound-level meter installed inside the test vehicles was used in obtaining the sound readings. The sound readings were measured as a change in the sound levels before and after placement of the rumble strips. For this study the researchers considered a 4dB increase in sound level to be adequate enough in getting a driver's attention. The results showed that the rumble strip dimensions and applications greatly affected the sound-level changes. The research team concluded that the sound is generated when a portion of the kinetic energy from tires is converted as tires displace from the normal road surface when contacting the rumble strips. As the width and length of the rumble strips increased to a point where the tires could completely drop to the bottom of the rumble strip, the sound generated increased in magnitude. They also concluded that the spacing between the strips should be far enough for allowing maximum tire displacement to increase the magnitude of the sound generated.

El-Rayes et al. (2013) conducted a study to develop recommendations for minimizing work zone related crashes in Illinois *(8)*. As part of this study, they evaluated the practicality and effectiveness of temporary rumble strips. The researchers conducted field experiments where they analyzed their efficiency and evaluated the performance of rumble strips. They evaluated three types of rumble strips: ATM; Rumbler; and RoadQuake by Plastic Safety Systems - a reusable temporary portable type of rumble strip. The test results of the ATM and Rumbler are discussed in this section and the testing of RoadQuake rumble strips are discussed in the portable temporary rumble strips section (see Section 2.5). The field experiments were conducted on a taxiway of an airport in Illinois. Four test vehicles were used in this testing which consisted of a motorcycle, a sedan, a cargo van, and a 26-ft truck. The motorcycle was used mainly to evaluate the general concern about that vehicle type's safety and stability while passing over the rumble strips. Due to the loud engine noise of the motorcycle interfering with data collection, the sound measurements were limited to the other three test vehicles. The rumble strips were aligned according to a pre-designed plan which included different configurations with varying number of strips per set and spacing between them. Figure 1 shows all the different configurations of alignment of rumble strips at the test facility.

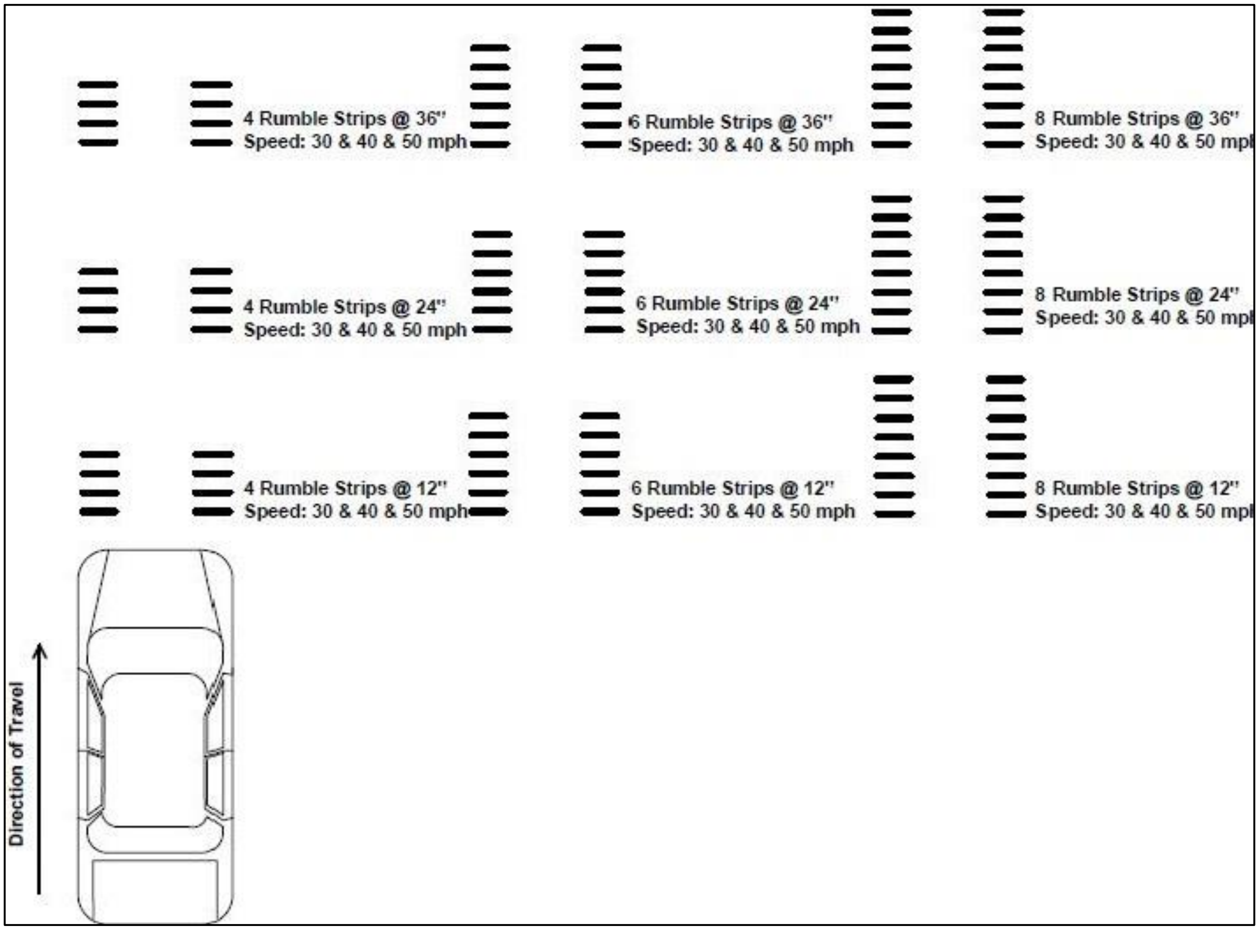

Figure 1. Configurations of Rumble Strip Installations *(8)*

The test vehicles were driven at speeds of 30, 40 and 50 mph along the test patterns of rumble strips. A digital sound noise-level meter with an accuracy of ±1.4 dB was used for recordings. The meter was attached in the center of the vehicle cabin. A total of 351 sound measurements encompassing all configurations were made. A Pearson chi-square test was performed to obtain factors which were correlated with sound readings which included: the spacing of rumble strip, the type of rumble strip, type of vehicle, and vehicle speed. The results showed that larger spacings such as 24 and 36 in., generated greater sound-level changes than spacing of 12 in. The Rumbler rumble strips generated higher sound-levels compared to the ATM rumble strips with the exception of 26-ft truck traveling at speeds below 40 mph. The researchers found that the sound level changes were 9 dB or above for all strips except for the ATM rumble strips when traversed with truck at speeds above 30 mph. The sound generated from the sedan and the van ranged from between 9 and 23 dB, while those of the 26-ft truck ranged from between 7 and 28 dB. They also observed that the sound levels generated at 30 mph were higher than at speeds of 40 and 50 mph.

2.2 Comparison Studies

Horowitz and Notbohm (2005) conducted evaluation tests on existing temporary rumble strips to identify the optimal strip for work zones *(9)*. The team tested the Recycled Technology, Inc. (RTI) rectangular rumble strips which could be installed on the pavement without the use of an adhesive and ATM rumble strips which used an adhesive backing to be installed on the pavement surface. The ATM strips were installed at a work zone in Wisconsin on a two-lane highway, with each strip set containing five strips spaced seven ft. apart. The RTI strips of 0.75 in. thickness were installed in a parking lot, with six pairs used for the test. Sound levels were measured with a handheld sound-level meter for both strips and a single piezoelectric accelerometer was used for measuring vibrations. Vehicles traversed the strips at speeds ranging from 10 to 55 mph and vibrations were collected for eight measurements. Peak sound levels within 0.3-second intervals were collected for all strips. The peak sound levels for standard CIP strips were 6.5dB above its average at 40 mph, 7.5dB above its average at 55mph and for adhesive strips these values were 7.9dB above average at 40mph, and 9.0dB above its average at 55mph. Both the RTI and ATM strips showed no major deterioration, but the RTI strips displaced a little when speeds began exceeding 47mph. The researchers concluded that the ATM strips were effective as a warning device when traversed at speeds more than 55mph but were ineffective at speeds lower than 40mph. The RTI strips were found to be effective in acting as a warning device for speeds ranging from 10 to 40mph but they began to be displaced from their installed locations at higher speeds.

2.3 Multi-Rope Temporary Rumble Strips

Tests were conducted in Saskatchewan, Canada to evaluate the effectiveness of the multi-rope rumble strips at work zones (Wyatt 1998) *(10)*. The device used for this study consisted of a series of rumble ropes about 1.25 in. in diameter which acted as a rumbling agent, tether ropes used to fasten the equipment firmly in their position, a neoprene mat for maintaining spacing and tension within the ropes, and anchor stakes driven into the ground at the side of road which held the ropes with help of steel rings. Two work zones at Gravelbourg and St. Louis were chosen by the research team to perform the study. Preliminary and advanced assessments were done, with each site tested for 40 hours, where the preliminary test location was characterized by stationary construction and the advanced assessment location with relatively mobile construction and maintenance activities. Data were collected using radar units which collected the approaching vehicle speeds before and after it passed the rumble strips. Statistical analysis at the 95 percent confidence interval was used with the limit of acceptable error in the mean speed estimate restricted to ±2.5 km/hr. The preliminary assessment showed a 21.7 percent decrease in the mean speed of vehicles entering the work zone and the advanced assessment indicated a 25.7 percent decrease in the mean speed entering the work zone. The weight of the unit required two people to install and remove the device, and they encountered difficulties during relocation which were some of the negative aspects of this device.

2.4 Steel Rumble Strips

Schrock et al. (2010) evaluated steel rumble strips with a rubber bottom, which relied on their weight to remain in contact with the road without any adhesives *(11)*. Two different types, a narrow reusable temporary rumble strip and a wide reusable rumble strip were tested. These strips were formed by combining a set of steel elements, each 2 in. wide and 1.25 in. high strung together by steel cables passing through two drilled holes of each element. It should be noted that the strips tested were originally developed by Meyer et al. (2006) *(12)* as prototypes and were reused by Schrock et al. for this research. The narrow rumble strips were 4 ft. long, four in. wide and 1.25 in. in thickness, while the wide rumble strips were 6 in. in width. The steel strips were tested on a closed-course setting at 60 mph both with a passenger car and a heavy truck. The movement and the vertical displacement of the strips were recorded using high-speed cameras. The results indicated narrow rumble strips performed better compared to the wider strips, with the maximum vertical displacement of the narrow strips of 0.8 in. to that of 1.1 in. for the wide rumble strips. This limitation in vertical displacement resulted in less lateral movement of the narrow strip compared to the wider rumble strips. However, during the testing both the rumble strips unraveled and were unable to continue for further testing; it was unclear at the time of the research if the prototypes failed due to insufficient design or simply due to deterioration due to their age. This study indicated a further need for the design consideration and fasteners used in these rumble strips, and the importance of any rumble strip system to remain together as an integral unit.

2.5 Portable Plastic Rumble Strips

Schrock et al. (2010) conducted a comparative evaluation of four generations of early RoadQuake rumble strips in a closed-course setting *(11)*. As the rumble strips were relatively new to the market at the time of the test, various configurations with changes in spacing (three to six feet) and number of strips (from three to six per set) were tested. The test was conducted on a closed-course setting in Kansas. A passenger car and a heavy truck were used during the test, driven at speeds 45, 53 and 60 mph. The in-vehicle vibration was measured with a triaxial accelerometer. The collected data included vehicle vibrations and sound generated by the vehicles. A least significance difference (LSD) test was conducted at a 0.05 level of significance which showed that the variations in vibrations inside the car were more significant than those inside the truck, with car vibrations ranging from 9.8 to 27.9 ft/s^2 and truck vibrations from 5.2 to 20.3 ft/s^2. The in-vehicle sound levels for the trucks were recorded between 79.4 to 85.0 dB while for the cars the values are in the ranged 75.7 to 85.7 dB. However, the relative increase in the sound levels for the passenger cars were more than that of the trucks with values of 20.1-27.4 dB increase for cars compared to 5.7-12.1 dB inside trucks. This research indicated that the RoadQuake system was effective in providing similar sound levels and vibrations relative to CIP rumble strips.

The research team also tested the four generations of RoadQuakes to determine their displacement from the point of installation on a closed-course. The horizontal movements were measured from their deviation from the marked points when traversed at different speeds, while the vertical displacements (e.g., how much the strip ‘bounced’ after being traversed) were measured with the help of high-speed cameras. The study identified that the first generation were not suitable for work zones of any kind due to their higher horizontal movements and vertical displacements. The second generation strips were relatively better than the previous ones, but were not suitable for heavy trucks at higher speeds of 60 mph. The third generation rumble strips were more stable in their movement and vertical displacement, which the research team identified as better suited for work zones with low-volumes of heavy trucks at all speeds. The fourth generation rumble strips were found to be the most stable of all with least movement, which can be attributed to its low vertical displacement when the trucks passed over them. Therefore the research team identified the fourth generation to be the most reasonable choice to install. It was also most likely a reflection of the improvements that Plastic Safety Systems had made among the generations of the RoadQuake.

Sun et al. (2011) investigated the effectiveness of non-adhesive portable rumble strips in improving safety in highway work zones *(13)*. The research team tested RoadQuake, an all-weather portable temporary rumble strip which was 11 ft. long, 1 ft. wide and 13/16 in. thick. The study was conducted on a one-lane two-way operation work zone in Missouri. Rumble strips were deployed both perpendicular to the road and at a 60° angle in two pairs of two strips. Two video cameras and a radar gun were used in collecting data and a total of 24 hours of data were collected over two days. Video data were analyzed to check for the application of brake lights, any partial or complete centerline crossovers. Comparing the configurations of angled and perpendicular rumble strips, the results showed that there were no major differences in the percentage of drivers who braked. But it should be noted that these values were considerably higher when compared with scenario where rumble strips were not present. Overall the rumble strips were effective in increasing the percentage of braking vehicles by an average of 10.5 percent, increase in speed compliance by 2.9 percent and also an increase in centerline crossovers by 8.8 percent.

RoadQuake rumble strips were found to be effective on a closed-course setting; their effectiveness in an actual work zone was tested in a follow-up study by Wang et al. (2011) *(14)*. They evaluated these devices at short-term work zones in Kansas. Three chosen sites near Oskaloosa, Kansas were used for data collection. Two set of RoadQuakes were placed at each study location perpendicular to the road at a spacing of 36 in. on center. Tube counters and video cameras were used in data collection, which collected around ten hours of data. An LSD test was conducted for mean speeds comparison and grouping at 0.05 level of significance was used for the values obtained at each counter. The study showed that the rumble strips were effective in significantly reducing the speeds of cars by 4.6 to 11.4 mph, and for trucks 5.0 to 11.7mph (except for one test site with non-significant results). The research team proposed two sets of four rumble strips at 36-in. spacing to be used at short-term work zones in addition to other standard traffic control devices. The study identified about five percent of drivers swerving around the rumble strips, which led researchers to recommend additional driver information and appropriate signage alerting drivers to the presence of the rumble strips.

El Rayes et al. (2013) conducted an evaluation of RoadQuake series of rumble strips *(8).* The rumble strips were tested on a taxiway of an airport in Illinois. As discussed in Section 2.1, four test vehicles were used in this testing which consisted of a motorcycle, a sedan, a cargo van and a 26-ft truck. The RoadQuake rumble strip was tested and a comparative analysis consisting of two other strips ATM and Rumbler rumble strips were performed. The procedure of the testing was discussed in section 2.1. The results showed that with sedan test vehicle the RoadQuake strips generated higher sound level changes than the remaining two types of strips. A sound level change of 22 dB was observed for RoadQuake strips compared to 9 dB change for the two other types of strips. With 26-ft truck as the test vehicle, the RoadQuake strips generated a 28 dB sound level change compared to 23 dB and 14 dB sound level change of Rumbler and ATM strips, respectively. The study concluded that all the three rumble strips were effective in alerting inattentive drivers with auditory stimulus exceeding permanent rumble strips by 4 dB. The study also reported that usage of RoadQuake strips at speeds slower than 40 mph could cause excessive sound decibel levels for trucks.

Summary of the Literature Review:

- Wang et al. (2011) *(14)* showed that about 5 percent of drivers swerved around the installed rumble strips at work zones in Kansas. The study highlighted the requirement for additional signage when the rumble strips were installed in workzones.
- Sun et al. (2011) *(13)* evaluated RoadQuake rumble strips, experimenting with their installation on the road at different angles to the direction of travel. No considerable difference was found with the change in the angle of installation. But the study showed that irrespective of the angle of installation, the rumble strips were effective in increasing the percentage of braking vehicles by an average of 10.5 percent, increase in speed compliance by 2.9 percent and also an increase in centerline crossovers by 8.8 percent.

- El Rayes et al. (2013) *(8)* showed that the auditory stimulus generated inside the cabin of a truck were less effective compared to that of a sedan or a van. The study suggested that temporary rumble strips at the edges of work zones are capable of improving and reducing crashes with similar benefits achieved when permanent rumble strips are used on roadways. The RoadQuake was found to be more effective in generating higher sound level changes compared to temporary adhesive rumble strips such as the ATM and Rumbler rumble strips.
- Schrock et al. (2010) *(11)* found that the RoadQuake rumble strips were effective in generating similar sound levels compared to CIP strips. The four generations of RoadQuake rumble strips which were tested showed that the newer (fourth) generation strips generated lower vertical displacement, which attributed to minimal horizontal displacement even at truck speeds exceeding 60 mph.

This research focusses on portable temporary rumble strips. The evaluation procedures followed for different types of rumble strips and their performance characteristics reported in this literature were useful in developing the test procedure for this study. The information from the literature review reported herein was useful in developing the threshold limits for the development of decision matrix presented in Chapter 3.

CHAPTER 3 METHODOLOGY

This chapter is divided into 3 sections. The first section discusses the types of rumble strips that were used for this study. The second section discusses the parameters considered for this research and the development of the threshold values. The third section discusses the test conditions required and the statistical analysis considered for analyzing the data.

3.1 Rumble Strips

The researcher identified all commercially-available portable reusable temporary rumble strips in order to conduct this research. A total of two types of rumble strips, the RoadQuake 2F from Plastic Safety Systems and the TrafFix Alert rumble strips from TrafFix Devices were identified at the time of this research. The vendors of each of the products were contacted and both provided a set of their rumble strips for use in this research during the closed-course evaluation.

The RoadQuake 2F rumble strip from Plastic Safety Systems was a folding type, one-piece design as shown in Figure 2. The strips relied on their weight and friction to stay intact in their place of installation. Each of the rumble strips was 11 ft. long, 13 in. wide, 0.75 in. thick and weighed 110 lbs.

The TrafFix Alert rumble strip from TrafFix Devices was made up of three individual strips which were joined together to form one individual rumble strip of 11 ft. length which weighed about 72 lbs. The three individual strips were 46.5 in. long, 12 in. wide, 1 in. thick and were connected through a jigsaw connection, as shown in Figure 3.

Figure 2. RoadQuake 2F Rumble Strips

Figure 3. TrafFix Alert Rumble Strips

3.2 Speeds

The speeds chosen for this study were 22.5, 37.5, 57.5, and 67.5 mph. This research focused on developing performance based specifications for portable temporary rumble strips. In order to develop specifications and categorize the rumble strips into different classes (see Figure 30), the strips must be tested at different speeds. These speeds acted as interval limits for a particular class. The specifications developed were related to work zones and the speeds considered also reflected the work zone conditions. Maps containing speeds of the Kansas roads were observed in determining the test speeds. The test speeds 22.5, 37.5, 57.5, and 67.5 mph were not equally spaced in magnitude; these particular speeds were considered after consultation with KDOT officials. A test speed of 67.5 mph acts as an upper interval for a class. If a rumble strip tested at 67.5 mph achieves the necessary performance criteria, then the rumble strip can be installed at work zones with speeds equal to or lower than 67.5 mph. In similar way, if a rumble strips is unable to achieve the necessary performance criteria at 67.5 mph, but achieves the necessary performance criteria at 57.5 mph, then the rumble strip is good enough for installing at work zones with speeds 57.5 mph or lower.

3.3 Thresholds

Variables considered in this test included: movement, rotation, sound and vibration generated. These were evaluated by comparing the test results with calculated threshold values (for relative movement and rotation), sound and vibration (for the sound and vibration measurements) for the strips at each of the tested speeds. The threshold values for movement and rotation of strips were based on the ADTT while the sound and vibration thresholds were calculated based on the results from CIP data. The volumes of different roads in Kansas, ranging from low speed low-volume rural roads and city streets to high-speed high-volume state highways and interstate freeways, were examined from state volume maps (KDOT, 2014) *(15)*. Studies conducted by Schrock et al. (2010) *(11)* and Wang et al. (2011) *(14)* showed that the impact of trucks on the strips linear and angular displacements were much higher than that of cars. So, the developed threshold values for movement and rotation were based on truck traffic.

3.3.1 Rotational Movement Threshold

The portable temporary rumble strips rely wholly on their weight and friction between them and the road surface to stay intact in their initial place of installation. But previous studies (Sun et al. 2011 *(13)*, Schrock et al. 2010 *(11)*) showed that due to vehicular passage, these strips tend to rotate from their position. On a two-lane two-way road, their movement may reach such a position that the oncoming drivers might not recognize the strips as a traffic control device but rather as some debris on the road and try to avoid passing over them. If they swerve around the strips and cross into oncoming traffic this may result in a situation worse than if no strips had been present. In order to avoid such a potential safety issue, a numerical threshold limit for rotational movement was developed.

A preliminary testing was conducted at the West Park & Ride lot at the University of Kansas on July 20, 2014. Three temporary rumble strips of TrafFix Alert were used for the test, spaced at six ft. from each other. A standard pickup truck was used as a test vehicle and test runs were carried out at speeds of 20, 35 and 40 mph. The rumble strips were rotated 5° counterclockwise after each pass at each different speed until 20° and were rotated each degree afterwards for each pass. Three team members participated in the test by driving the vehicle at different speeds and were asked about the appearance of rumble strips from a distance of 50 ft. By consensus of the team members, the researcher came up with the rotational value of 26°, above which team members found the rumble strips to be appearing 'too skewed' and no longer properly placed. Therefore, 26° was chosen as rotational threshold value, which will be useful in evaluating the rotational movement of temporary rumble strips in Chapter 5.

The calculations were carried out with the assumptions that a normal short-term work zone consists of one full day (9 hours) with inspections carried out every four hours after the rumble strips were installed and would be limited to daylight hours. So, the following assumptions were used for later calculations:

- Rotational threshold: no more than 26° over any four hours of the working day.
- Typical work zone lasts 9 hrs.

3.3.1.1 Rotational Threshold for 67.5 mph

From examination of the state traffic count maps (KDOT, 2014) *(15)* the ADTT volumes at roads with speeds above 60 mph were found to be predominantly interstate freeways and major US and Kansas state highways. These roadways have heavy vehicle volumes which are typically in the range of 2,000 – 4,000 trucks per day. Heavy vehicle volumes of 3,000 trucks per day were chosen for calculating threshold limits for both movement and rotation at 67.5 mph passes. The calculations for acceptable rotation were determined as follows:

- Assumed ADTT volume = 3,000 vpd;
- Assumed 50 percent of total traffic of the day observed during work zone hours;
- Truck volume (during work zone hours) = 1,500;
- Maximum threshold for rotation = 26°;
- If inspection were to be carried out every 4 hours, then the rumble strips were allowed to rotate up to a maximum of 26° within those 4 hours;
- Assuming a linear trend in volumes, truck volume for 4 hours = 670;
- For a total of 670 truck passes, the rumble strips can rotate for up to 26°; and

- During a closed-course test, for 40 truck passes the strips should not rotate more than 1.5°.

3.3.1.2 Rotational Threshold for 57.5 mph

Heavy vehicle volumes on roads with speed limits between 35 and 55 mph were examined from the state traffic count maps (KDOT, 2014) *(15)*. These roads ranged from urban arterials, county highways to state highways. Two basic types of roadway-volume combinations were observed: the first was on higher speed facilities with truck volumes ranging from 500-1,000 trucks per day and total volumes ranging from between 500-5,000. The second type were more commonly urban arterials with total volumes ranging from 5,000-30,000 with low truck volumes. Passenger cars appeared to be the major contributors for these high volumes on urban arterials. In order to take these car volumes into account, a truck volume of 2,000 was chosen for calculating threshold limits for a speed of 57.5 mph. The calculations for acceptable rotation were determined as follows:

- ADTT = 2,000 vpd;
- Assuming 50 percent of total traffic of the day observed during work zone hours;
- Truck volume (work zone hours) = 1,000 ;
- Maximum threshold for rotation = 26°;
- If inspection were to be carried out every 4 hours, then the rumble strips were allowed to rotate up to a maximum of 26° within those 4 hours;
- Assuming a linear trend in volumes, truck volume for 4 hours = 450;
- For a total of 450 passes of trucks, the rumble strips can rotate for up to 26°; and
- During a closed-course test, for 40 truck passes the strips should not rotate more than 2.5°.

3.3.1.3 Rotational Threshold for 37.5 mph

Truck volumes on roads with speed limits between 20 and 35 mph were examined from the state traffic count maps (KDOT, 2014) *(15)*. Urban arterials, collector streets and low-speed urban roads were observed to be mainly the types of roadways that would have lower speed limits in the 35 mph range. Rural roads were found to have higher percentages of truck traffic compared to overall volume, whereas collector streets in urban areas experienced similar high car volumes such as arterials. In order to consider the effect of high passenger car volumes on urban streets, the threshold limit for 37.5 mph speed was also calculated for the same truck volume of 2,000. The calculations for acceptable rotation were determined as follows:

- ADTT = 2,000 vpd;
- Assuming 50 percent of total traffic of the day observed during work zone hours;
- Truck volume (work zone hours) = 1,000;
- Maximum threshold for rotation = 26°;
- If inspection were to be carried out every 4 hours, then the rumble strips were allowed to rotate upto a maximum of 26° within those 4 hours;
- Assuming a linear trend in volumes, truck volume for 4 hours = 450;
- For a total of 450 passes of trucks, the rumble strips can rotate for up to 26°; and
- During a closed-course test, for 40 truck passes the strips should not rotate more than 2.5°.

3.3.1.4 Rotational Threshold for 22.5 mph

Truck volumes on roads with speed limits below 25 mph were examined on the state traffic count maps (KDOT, 2014) *(15)*. Low-volume rural roads and city streets volumes were considered for determining the threshold limits. The volumes on these roads ranged from 0-3,000 and the truck traffic ranged between 0-500. Because of the wide variety of local and urban streets that comprise this category, a more conservative and higher truck volume of 1,000 was considered for determining the threshold limits. The calculations for acceptable rotation were determined as follows:

- ADTT = 1,000 vpd;
- Assuming 50 percent of total traffic of the day observed during work zone hours;
- Truck volume (work zone hours) = 500;
- Maximum threshold for rotation = 26°;
- If inspection were to be carried out every 4 hours, then the rumble strips were allowed to rotate upto a maximum of 26° within that 4 hours;
- Assuming a linear trend in volumes, truck volume for 4 hours = 230;
- For a total of 230 passes of trucks, the rumble strips can rotate for up to 26°; and
- During a closed-course test, for 40 truck passes the strips should not rotate more than 5°.

Table 1 Rotation Threshold Values

Speed (mph)	Rotation
67.5	1.5°
57.5	2.5°
37.5	2.5°
22.5	5°

3.3.2 Linear Movement Threshold

The movement thresholds were again divided into lateral movement and longitudinal movement thresholds. Longitudinal movement is the movement of strips observed in the direction of travel whereas lateral movement is the movement observed perpendicular to the direction of travel.

3.3.2.1 Lateral Movement Threshold

The lateral movement threshold is the same irrespective of speeds. The rumble strips are restricted to the edges of the lane and should not creep onto shoulder lane or onto the adjoining lane.

3.3.2.2 Relative Displacement

The longitudinal movement thresholds were based on the relative displacement. Relative displacement is the change in the movement observed between two strips from their initial position after 40 passes at each speed. From Figure 4, it can be observed that the strips were spaced 10 ft. from each other before the test. After the test when measured with respect to the direction of travel the left, middle and right parts of the strips moved X, Y and Z distances, respectively. Relative displacement was calculated by the difference of X, Y and Z distances with the initial 10 ft. spacing between them. By determining relative displacement rather than total displacement, there would be no measured change if all of the strips move equal distances.

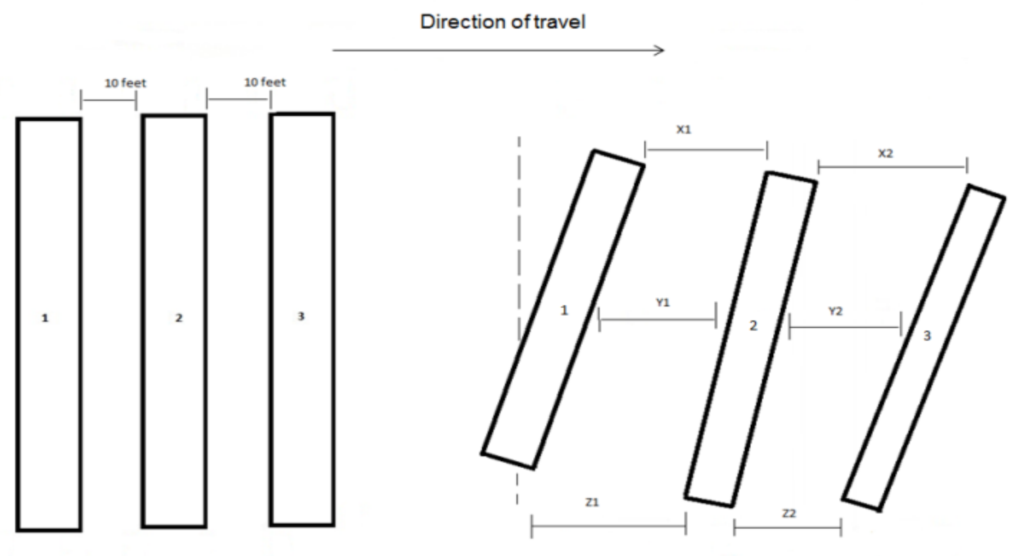

Figure 4. Relative Displacement

3.3.2.3 Longitudinal Movement Threshold

The longitudinal movement thresholds were determined taking into account the inspection procedure followed by the work zone crew of adjusting the rumble strips position every four hours. The threshold for longitudinal movement was determined from previous studies conducted on these rumble strips, survey results (see Appendix A) and practices followed by other states regarding maximum movement thresholds. The average longitudinal movement for each strip relative to other was determined not to be more than 8 in. between two inspections.

3.3.2.4 Calculations

The maximum longitudinal threshold value for the rumble strips was 8 in. at a normal work zone between two inspection periods. Using this basic threshold value, the maximum limit for longitudinal movements were calculated for all speeds for 40 passes. In the closed-course test, for 40 passes, the threshold limits were determined for all speeds using the maximum limit of 8 in. and volume calculations identical to the rotation calculations from Section 3.3.1.

Longitudinal Movement Threshold for 67.5 mph

For 670 truck passes, the strips could move up to a maximum of 8 in. So for 40 truck passes, the strips were limited to move no more than 0.5 in.

Longitudinal Movement Threshold for 57.5 mph

For 450 truck passes, the strips could move up to a maximum of 8 in. So for 40 truck passes, the strips were limited to move no more than 1 in.

Longitudinal Movement Threshold for 37.5 mph

For 450 truck passes, the strips could move up to a maximum of 8 in. So for 40 truck passes, the strips were limited to move no more than 1 in.

Longitudinal Movement Threshold for 22.5 mph

For 230 truck passes, the strips could move up to a maximum of 8 in. So for 40 truck passes, the strips were limited to move no more than 1.5 in.

Table 2 Longitudinal Movement Threshold Values

Speed (mph)	Movement (inches)
67.5	0.5
57.5	1.5
37.5	1.5
22.5	2

3.4 Test Conditions

The closed course study site required a long straight road section, which provides enough distance for the heavy vehicle to accelerate to the fastest test speed, traverse the strips at that speed and decelerate. The Heartland Park Topeka racetrack was chosen as the test facility for the study. The racetrack had a straight section approximately 0.8 miles in length, providing safe distance for the test vehicles to pass through at 67.5 mph.

In order to standardize the test, the baseline sound and vibration measurements from permanent CIP rumble strips were collected from six locations as shown in Table 1. These locations were all in Douglas County, Kansas. The width, depth and length of these strips varied from one location to another gave a diverse set of data for this research.

Table 3. Data Collection Sites for CIP Strips in Douglas County, Kansas

CIP Rumble Strip Data Collection Sites	
1	K-32 and US-24/US-40
2	N1150 Rd and E1000 Rd
3	Southbound E 1250 Rd near U.S.56
4	Northbound E 1250 Rd near U.S.56
5	Northbound 1061 at US-56
6	Southbound 1061 at US-56

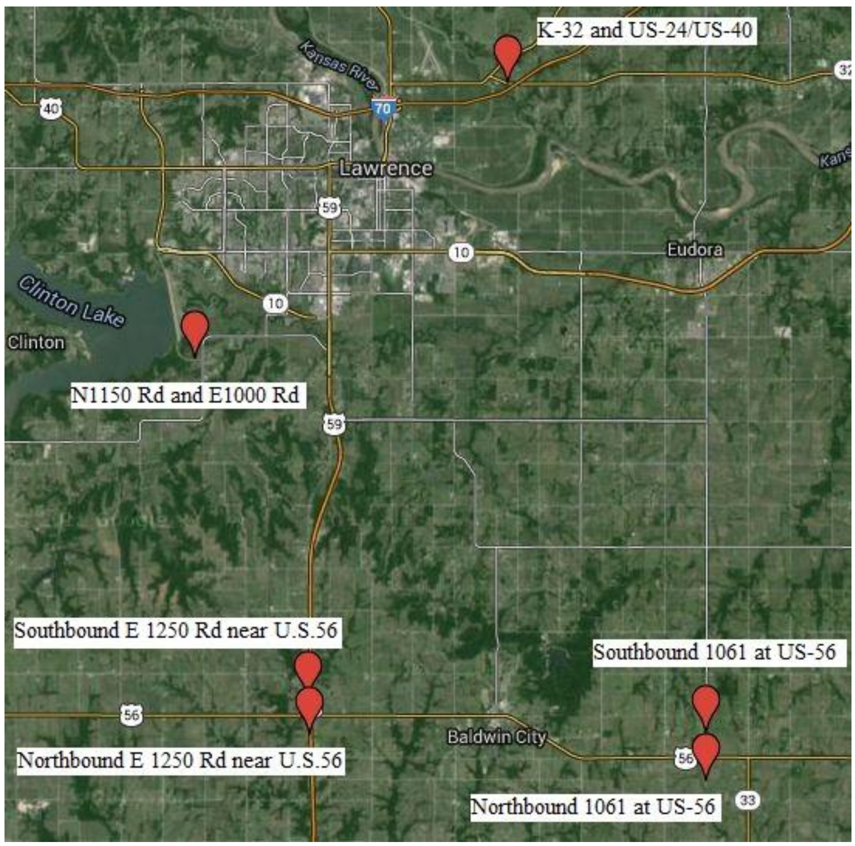

Figure 5. CIP strips Locations in Douglas County, KS.

3.5 Statistical Method

The statistical analysis included one-way ANOVA tests, where by the mean levels of sound and vibration generated by the temporary rumble strips were compared between the test speeds. The ANOVA test is used to determine whether there are any significant differences between the means of the test speeds. If the differences in the means were found to be statistically significant, then Tukey's test was conducted. While ANOVA test can tell the researcher whether the speeds differ from one another, the Tukey’s test provides the information as which speeds differ with significant difference.

CHAPTER 4 DATA COLLECTION AND REDUCTION

The RoadQuake 2F and TrafFix Alert rumble strips were selected for testing in a closed course setting. The rumble strips were tested for movement, rotation, sound and vibration as discussed in chapter 3.This chapter presents the data collection procedure followed for the closed course study, and CIP strips and the data reduction process.

4.1 Data Collection

4.1.1 Closed Course Study

A closed-course test was conducted on an asphalt test track at the Heartland Park Racetrack in Topeka, Kansas. Two test vehicles were used in this study: a standard full-size passenger car shown in Figure 6 and the other a standard tandem-axle dump truck as shown in Figure 7. The dump truck was rated with front and rear axle loads of 18,000 and 20,000 lbs., respectively, but was empty during the test. The test was carried out on October 30-31, 2014 with one test vehicle used each day. The vehicles travelled at speeds of 22.5 mph, 37.5 mph, 57.5 mph and 67.5 mph in order to create class intervals (see Figure 30) for developing specifications. The race track section provided a length of 4200 ft. which was adequate for the dump truck test vehicle to reach the maximum test speed and decelerate after it traversed the rumble strips.

Figure 6. Standard Full-Size Car

Figure 7. Standard Tandem-Axle Truck Used for the Test

The portable rumble strips available on the market were tested at the same time in order to minimize the climatic, vehicular, and driver variations. The configuration used for this test was derived from the KDOT standard of using three rumble strips per set at the manufacturers' recommended spacing. The two types of rumble strips (RoadQuake 2F and TrafFix Alert) were tested with each type consisting of a set of three rumble strips spaced 10 ft. from each other, as shown in Figures 8 and 9. The two different types of rumble strips were spaced 25 ft. apart to provide separation of the sound and vibration recordings and to ensure that any movement of one type could not interact with the other. The strips installed were aligned with each other in the center of the lane, equal lengths from the lane edges for measuring the linear and angular displacements. Figure 10 shows the overview of the setup at Hartland park, Topeka. The vehicles traversed the strips 40 times at each speed for measuring movement and rotational variations from the strips' initial positions of installation. After each set of 40 passes the movement was recorded, photos were taken of the strips, and the strips were reset to their original locations for the next set of 40 passes.

(a) Rumble strip layout - longitudinally

(b) Rumble strip layout – laterally

(c) Rumble strip

Figure 8. Layout of RoadQuake 2F Rumble Strips

(a) Rumble strips layout – longitudinally

(b) Rumble strip

Figure 9. Layout of TrafFix Alert Rumble Strips

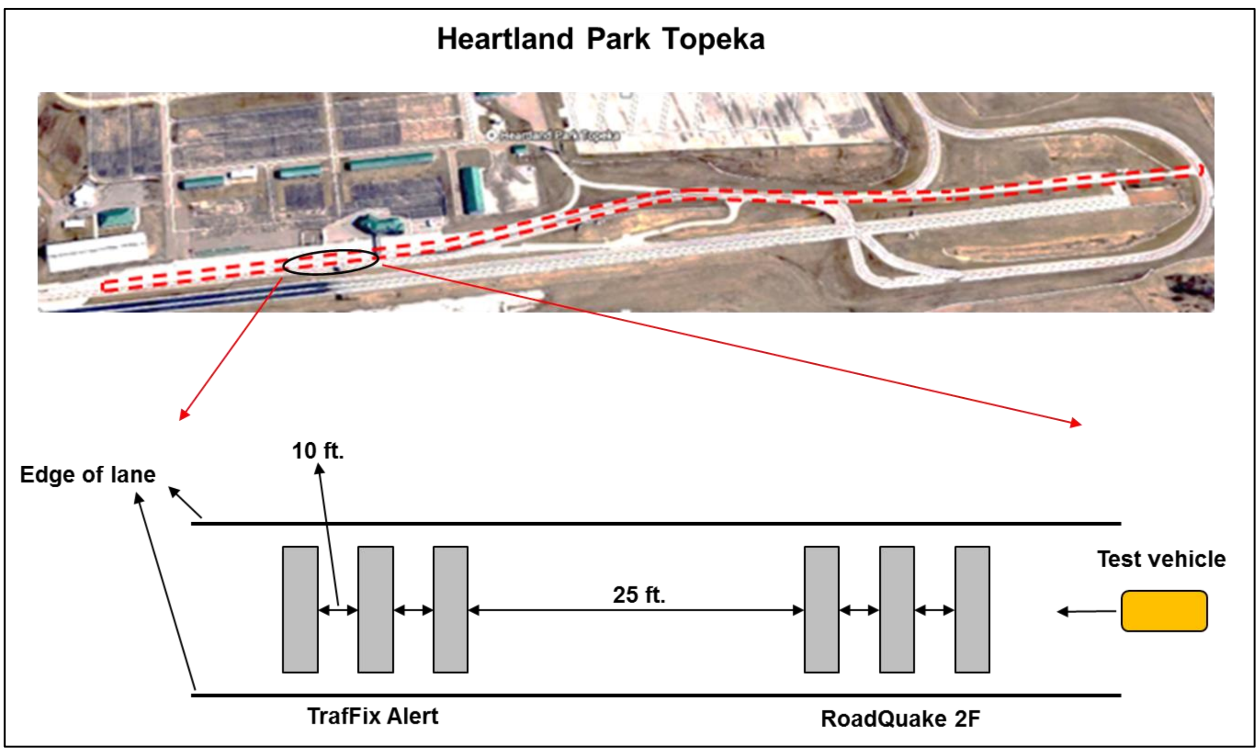

Figure 10 Overview of the closed course study setup

A sound-level meter was used to measure sound generated by vehicles passing over the rumble strips as shown in Figures 11. The sound level meter measured frequency-weighted sound pressure levels giving the output in dB (decibels)-SPL (sound pressure level). A Brüel and Kjær type 2270 hand-held analyzer was used for this study. The meter had a range of 16.6 dB to 140 dB, with an accuracy of ±0.1 dB. Previous studies attached the sound-level meter inside the vehicle cabin collecting the sound measurements produced within the vehicle cabin when traversing the strips (El Rayes et al. *(8)*, Miles and Finley *(7)*). But the design of the car and the insulating materials used for the construction of cars increase the variability in sound produced inside cars' cabins among various car models. It should be noted that even though this test specified the test vehicle as a standard full-size car, the sound generated might vary with different car models within the full size category. To diminish this variability, the sound data were collected outside the car when the car passed over the rumble strips. A sample of ten measurements were collected for each type of rumble strip at each of the speeds. The sound meter was positioned six ft. away from the edge of lane facing the middle strip of the three rumble strips of each type as shown in Figure 12.

Figure 11. Brüel and Kjær type 2270 hand-held analyzer, Sound Meter set up near CIP Rumble Strips

Figure 12. Arrangement of Sound Meter at Closed-Course Facility

A tri-axial shock recorder was used in measuring the vibration produced by the test vehicles when traversing the rumble strips. The shock recorder used was 0.75 in. X 2.5 in. X 4.25 in. It is powered by a 9 volt battery. Although the researcher conducted the vibration testing using this shock recorder, the same test can be performed by a number of shock recorders and tri-axial accelerometers available on the market. The device collected the vibrations experienced by the driver at steering wheel level in three axes while traversing the strips. The shock recorder was installed on the steering wheel of the test vehicle which then was connected to a laptop for observing the readings as shown in figure 14. To accurately operate the shock recorder, an assistant was present in the vehicle during the data collection process. Similar to the sound recordings, a sample of 10 measurements were collected for each speed for both types of rumble strips.

Figure 13. One of the test vehicles traversing the temporary rumble strips during testing

Figure 14. Shock Recorder installed on steering wheel of the vehicle

4.1.2 Movement

Movement was measured at each edge and midpoint of the rumble strips on the side facing the oncoming vehicle. The initial measurement of each edge point was taken as (0, 0) before the test. After 40 passes, longitudinal measurements were taken at the edge and midpoints and movement of the strips were noted as positive or negative as shown in Figure 15. The movement was recorded as positive if the strips moved downstream in the direction of travel and negative if they moved upstream with respect to the direction of travel. The lateral movement was recorded only at the both edge points. The lateral measurements were recorded positive if they moved left with respective edge points and negative if the strips moved right with respective to the strips initial edge position. The difference of longitudinal movements between the two strips was calculated to obtain relative displacements. From Figure 16, X_1 is the relative displacement value obtained from the difference of longitudinal movements of strips 1 and 2 on the left edge. Similarly the remaining relative displacements were calculated. The average of relative displacements observed on the left edge was considered to be the overall relative displacement for the set of strips on the left edge. For example from Figure 16, the average movement *'X_a'* observed in the set of strips to the left side is

Equation 1. Average Relative Displacement

$$X_{\mathrm{a}} = \left|\frac{(X_1 - 10) + (X_2 - 10)}{2}\right|$$

Similarly, the averages of the right edge and midpoint relative displacements were regarded as respective overall relative displacements observed for that particular set of strips.

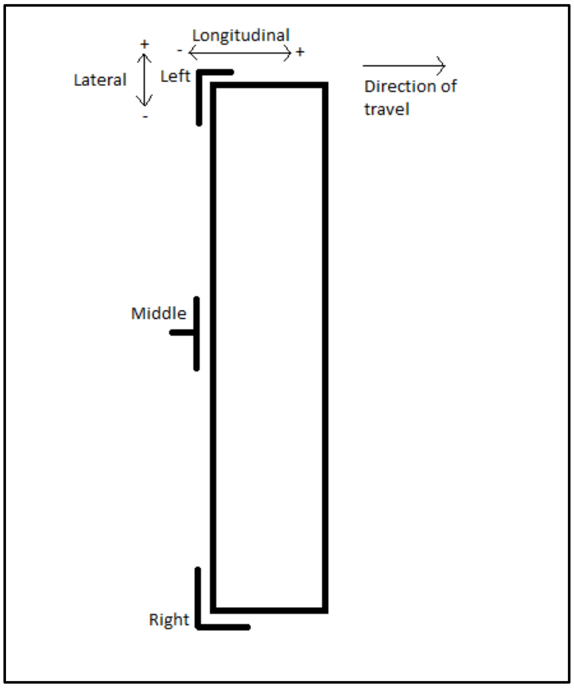

Figure 15. Rumble strip movement measurement

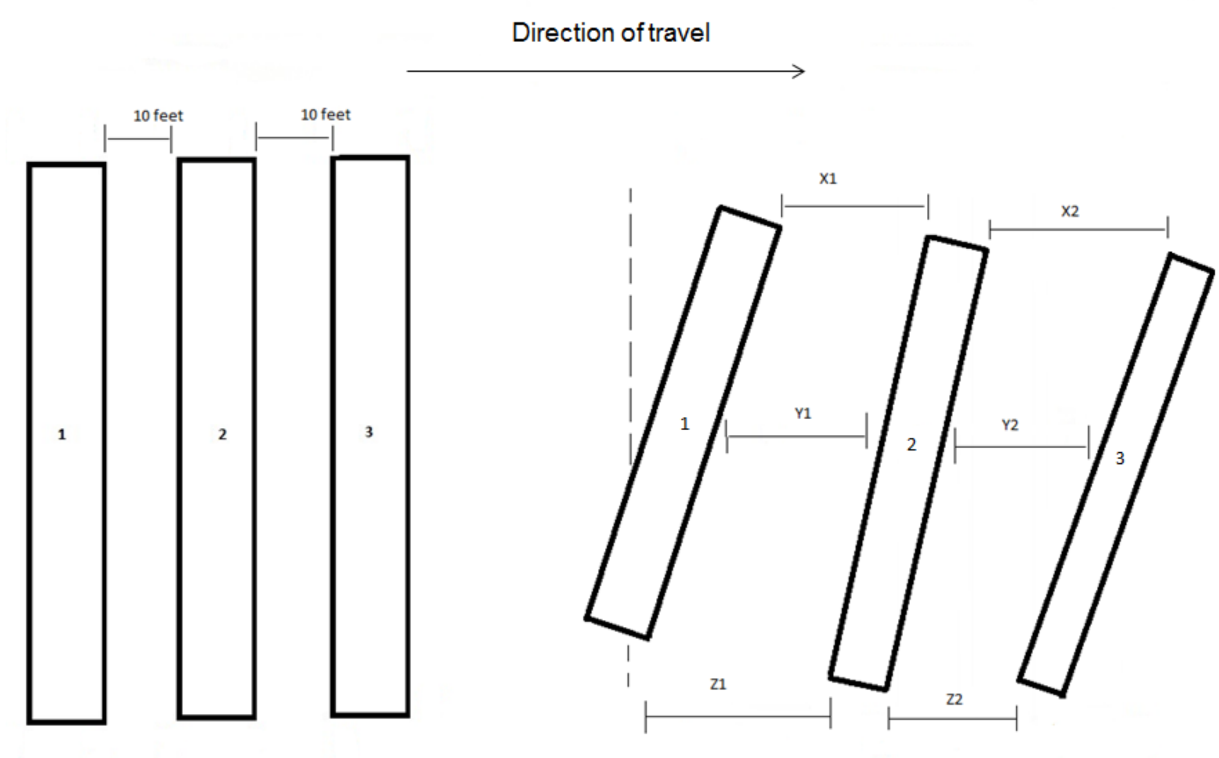

Figure 16. Relative Displacement

4.1.3 Rotation

Rotation of the rumble strips was calculated with respect to left edge using trigonometry. The length of the rumble strips and the longitudinal movements observed were used in calculating the angle which the rumble strips rotated from their initial position. Strips rotated in the counterclockwise were measured as positive and rotation in the clockwise direction was denoted as negative. The average rotation of the three strips of each manufacturer was taken as the overall rotation for a set of strips at a particular speed.

4.1.4 Sound

Sound measurements were recorded when the vehicle passed over the rumble strips. At each of speeds 22.5, 37.5, 57.5 and 67.5 mph, ten measurements were recorded for each set of rumble strips. An operator was present near the sound meter and measurements were taken whenever the vehicle passed over the strips. Sound readings were stored in an SD-card within the device which then later was transferred though data logger software on to a laptop for analyzing. Figure 17 shows a sound level sample depicting the peaks where the vehicle passed over the different rumble strips.

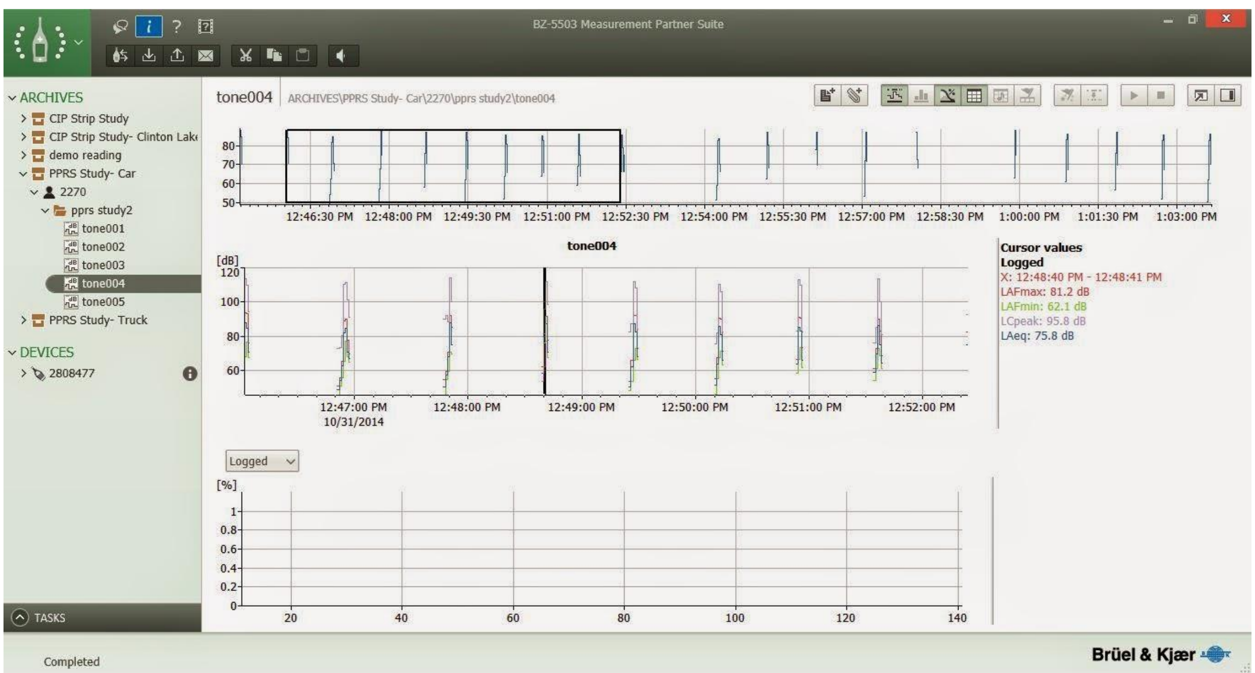

Figure 17. Sound level meter data logger interface

Test vehicles were also made to run at the designated speeds without the rumble strips present and sound data were collected for those passes which were used as base sound readings for analysis. This was done to understand the change in sound level due to presence of rumble strips. The above procedure was carried out with similar setups while collecting sound data for CIP strips.

4.1.5 CIP strips

The baseline sound and vibration measurements from permanent CIP rumble strips were collected from six locations as shown in Table 1 Rotation Threshold Values. The sound and vibration measuring devices were placed identically as in the case of the closed course study for measuring the readings. At each of the locations, three passes were made with passenger car at speeds of 22.5, 37.5, 57.5 and 67.5 mph. Sound data were also collected regarding cars noise generation when passing on a normal section without rumble strips to get the difference of sound in decibels due to the presence of rumble strips.

4.2 Data Reduction

4.2.1 Movement

The relative movement results of the car and truck passes that were conducted for both types of portable reusable rumble strips are shown in Tables 2 - 9. The negative sign indicates that the strips moved closer to each other after the passes.

Table 4. Movement Due to Truck Passes at 22.5 mph

Rumble Strip	Speed: 22.5mph	Right (in.)	Middle (in.)	Left (in.)
Roadquake 2F	Average Relative Displacement (in.)	-0.06	0.38	0.44
TrafFix Alert	Average Relative Displacement (in.)	-0.25	0.75	1.00

Table 5. Movement Due to Truck Passes at 37.5 mph

Rumble strip	Speed: 37.5mph	Right (in.)	Middle (in.)	Left (in.)
Roadquake 2F	Average Relative Displacement (in.)	-0.75	-0.13	0.56
TrafFix Alert	Average Relative Displacement (in.)	-1.38	-1.06	-0.25

Table 6. Movement Due to Truck Passes at 57.5 mph

Rumble Strip	Speed: 57.5mph	Right (in.)	Middle (in.)	Left (in.)
Roadquake 2F	Average Relative Displacement (in.)	-0.88	-0.25	-0.06
TrafFix Alert	Average Relative Displacement (in.)	-8.00	-5.00	-9.50

Table 7. Movement Due to Truck Passes at 67.5 mph

Rumble Strip	Speed: 67.5mph	Right (in.)	Middle (in.)	Left (in.)
Roadquake 2F	Average Relative Displacement (in.)	-0.19	-0.31	-0.69
TrafFix Alert	Average Relative Displacement (in.)	-29	-13.88	8.50

Table 8. Movement Due to Car Passes at 22.5 mph

Rumble Strip	Speed: 22.5mph	Right (in.)	Middle (in.)	Left (in.)
Roadquake 2F	Average Relative Displacement (in.)	-0.063	0.063	0.00
TrafFix Alert	Average Relative Displacement (in.)	-0.438	0.375	0.938

Table 9. Movement Due to Car Passes at 37.5 mph

Rumble Strip	Speed: 37.5mph	Right (in.)	Middle (in.)	Left (in.)
Roadquake 2F	Average Relative Displacement (in.)	-0.06	0.06	0.13
TrafFix Alert	Average Relative Displacement (in.)	-0.25	-0.56	-0.56

Table 10. Movement Due to Car Passes at 57.5 mph

Rumble Strip	Speed: 57.5mph	Right (in.)	Middle (in.)	Left (in.)
Roadquake 2F	Average Relative Displacement (in.)	-0.13	0.00	0.063
TrafFix Alert	Average Relative Displacement (in.)	-0.31	-0.56	-0.38

Table 11. Movement Due to Car Passes at 67.5 mph

Rumble Strip	Speed: 67.5mph	Right (in.)	Middle (in.)	Left (in.)
Roadquake 2F	Average Relative Displacement (in.)	0.00	0.13	0.19
TrafFix Alert	Average Relative Displacement (in.)	-1.19	-1.75	-2.13

4.2.2 Rotation

The average rotation of the strips due to truck and car passes are shown in Tables 10 and 11. The negative sign indicates that the strips rotated clockwise direction and positive sign indicates rotation of the strips in counterclockwise direction due to the impact of test vehicle's passes.

Table 12. Rotation of Strips Due to Truck Passes

	Speed (mph)			
Rumble Strip	**22.5**	**37.5**	**57.5**	**67.5**
Roadquake 2F	0.02°	1.00°	0.85°	1.10°
TrafFix Alert	1.12°	1.68°	24.21°	7.98°[A]

[A.] At this speed one of the rumble strips separated at the connection points, so the rotation was determined for the remaining two-thirds for that strip, and then averaged with the two strips that remained intact.

Table 13. Rotation of Strips Due to Car Passes

	Speed (mph)			
Rumble Strip	**22.5**	**37.5**	**57.5**	**67.5**
Roadquake 2F	-0.04°	-0.09°	-0.11°	-0.22°
TrafFix Alert	-0.41°	-0.36°	-0.51°	-1.92°

4.2.3 Sound

Sound measurements from the closed-course test were compared with sound data collected from CIP rumble strips. A comparison of changes in sound level relative to the base roadway condition (no rumble strips present) was evaluated for temporary and CIP rumble strips to observe the relative change.

4.2.3.1 Sound Data for Truck Passes

A total of 80 sound-level readings were collected for truck passes. All the readings were measured in decibels. Table 12 and 13 show the sound decibel readings observed from truck passes for both the rumble strips.

Table 14. Sound Generated by Truck Passes on RoadQuake 2F Strips

Speed (mph)	22.5	37.5	57.5	67.5
Pass 1	96	97.3	98.6	100.9
Pass 2	97.2	97.2	98.7	98.7
Pass 3	96	98.6	98.4	93.5
Pass 4	95.8	95.9	98.8	100.1
Pass 5	95.2	98.5	98.1	100.3
Pass 6	97.6	97.6	100.2	98.5
Pass 7	97.4	97.6	99.7	99.5
Pass 8	96.5	95.9	99.5	100.2
Pass 9	97.4	97.9	99	99.4
Pass 10	97.6	96.6	100	98.1
Mean	96.67	97.31	99.1	98.92

Table 15. Sound Generated by Truck Passes on TrafFix Alert Strips

Speed (mph)	22.5	37.5	57.5	67.5
Pass 1	98	100.1	100.6	101.5
Pass 2	99.1	100	99.2	98.5
Pass 3	100.9	100.5	98.8	99.8
Pass 4	99.2	100.8	98.7	100.3
Pass 5	102.3	99.3	99.3	100.9
Pass 6	98.7	100	99.9	100.6
Pass 7	98.1	99.8	98.6	101
Pass 8	97.3	99.8	98.4	100.8
Pass 9	99.3	99.9	98.9	98.7
Pass 10	98.6	96.2	99.3	100.7
Mean	99.15	99.64	99.17	100.28

4.2.3.2 Sound Data for Car Passes

A total of 80 sound-level readings were collected for car passes. All the readings were measured in decibels. Tables 14 and 15 show the sound decibel readings observed from car passes for both the rumble strips.

Table 16 Sound Generated by Car Passes on RoadQuake 2F Strips

Speed (mph)	22.5	37.5	57.5	67.5
Pass 1	75.1	80.8	88	89.6
Pass 2	77.1	80.7	87.7	90.2
Pass 3	73.8	78.1	84.8	86.8
Pass 4	74.7	80.8	87.8	90.4
Pass 5	74.6	79.1	87.1	90.8
Pass 6	74.5	81.4	87.1	89.3
Pass 7	74.7	82	85.6	90.9
Pass 8	72.2	81.8	85.1	89.9
Pass 9	75.9	81.8	86.1	88.5
Pass 10	76	82.5	85.7	89.5
Mean	74.86	80.9	86.5	89.59

Table 17 Sound Generated by Car Passes on TrafFix Alert Strips

Speed (mph)	22.5	37.5	57.5	67.5
Pass 1	76.1	80.7	83.7	90.1
Pass 2	74.1	79.9	87.1	89.7
Pass 3	74.7	79	87.1	90.6
Pass 4	72.9	81.4	86.9	90.1
Pass 5	75.8	80.7	87.3	90.2
Pass 6	72.9	80.5	88.2	88.6
Pass 7	73.5	81	85.9	90.1
Pass 8	75.2	80.9	87.1	89.4
Pass 9	73.8	79.5	85.7	88.8
Pass 10	76.6	80.4	85.9	90.9
Mean	74.56	80.4	86.49	89.85

4.2.4 Vibration

The vibration values gathered by the shock recorder were transferred on to a laptop and analyzed using a data logger software. The data obtained from the shock recorder was in the values of g-forces. ‘g-force’ by definition is the force acting on a body due to acceleration or gravity (Wyrick & Brown, 2009) *(16)*. This g-force acts on a body in three directions depending on the direction of travel. A body experiencing no external force and acceleration, should at all times be acted upon by a g-force magnitude of zero. But any object on earth with no acceleration in upward or downward direction experiences a standard 1g (9.81 m/s^2) downwards due to earth’s gravity. So, the y-direction in the shock recorder facing upwards always experiences 1g in normal conditions. It should also be noted that any g-force value above 1.5 g's is noticeable. To put this in perspective, an average person experiences about 1.2 – 1.5 g's on a commercial airplane while it take-offs (Davis, Johnson, Stepanek, & Fogarty, 2008) *(17)*. But the g-forces experienced by drivers traversing rumble strips would experience far less discomfort as the time of traversing the strips is a fraction of a second.

4.2.4.1 Truck Vibrations

A total of 80 vibration readings were collected for truck passes. All the readings were measured in g-forces. Tables 16 and 17 show the vibration levels observed from truck passes for both the rumble strips.

Table. 18 g-force Values from Truck Passes on RoadQuake 2F Strips

Speed (mph)	**22.5**	**37.5**	**57.5**	**67.5**
Pass 1	6.2	7.0	6.8	4.8
Pass 2	7.2	7.4	6.8	3.4
Pass 3	6.8	7.4	8.2	3.0
Pass 4	8.0	6.8	8.6	3.2
Pass 5	5.6	6.4	6.8	3.0
Pass 6	7.4	7.0	7.4	3.8
Pass 7	5.4	6.8	6.2	3.2
Pass 8	6.4	7.6	7.0	3.2
Pass 9	7.0	6.2	8.4	3.0
Pass 10	6.8	7.4	7.0	3.8
Mean	6.68	7.00	7.32	3.44

Table. 19 g-force Values from Truck Passes on TrafFix Alert Strips

Speed (mph)	22.5	37.5	57.5	67.5
Pass 1	8.8	7.2	11.6	7.4
Pass 2	8.8	7.6	13.6	9.4
Pass 3	8.8	8.0	15.8	7.4
Pass 4	9.4	8.8	14.0	6.2
Pass 5	7.6	7.6	12.6	6.4
Pass 6	7.4	9.2	12.6	6.2
Pass 7	6.4	7.2	13.8	7.2
Pass 8	7.8	6.8	12.8	7.6
Pass 9	8.8	7.2	12.2	6.4
Pass 10	7.4	9.8	12.8	7.2
Mean	8.12	7.94	13.18	7.14

4.2.4.2 Car Vibrations

A total of 80 vibration readings were collected for car passes. All the readings were measured in g-forces. Tables 18 and 19 show the vibration levels observed from car passes for both the rumble strips.

Table 20. g-force Values from Car Passes on RoadQuake 2F Strips

Speed (mph)	22.5	37.5	57.5	67.5
Pass 1	2.2	2.0	2.0	2.2
Pass 2	2.4	2.2	2.0	2.4
Pass 3	2.2	2.0	2.2	2.2
Pass 4	2.4	2.0	2.0	2.0
Pass 5	2.4	2.0	2.0	2.4
Pass 6	2.2	2.0	2.0	2.2
Pass 7	2.4	2.0	2.0	2.2
Pass 8	2.2	2.2	2.2	2.2
Pass 9	2.2	2.0	2.4	2.4
Pass 10	2.2	2.2	2.4	2.2
Mean	2.28	2.06	2.12	2.24

Table 21. g-force Values from Car Passes on TrafFix Alert Strips

Speed (mph)	**22.5**	**37.5**	**57.5**	**67.5**
Pass 1	2.6	2.8	2.6	2.4
Pass 2	2.6	3.0	2.8	2.0
Pass 3	2.4	2.8	2.6	2.2
Pass 4	2.6	2.8	2.8	2.4
Pass 5	2.4	2.6	2.6	2.4
Pass 6	2.4	2.6	2.6	2.4
Pass 7	2.4	2.4	2.8	2.6
Pass 8	2.6	3.0	3.0	2.2
Pass 9	2.6	2.2	3.0	2.4
Pass 10	2.6	2.8	3.0	2.4
Mean	2.52	2.70	2.78	2.34

The data reduced were analyzed in the next chapter as per the statistical method discussed in Section 3.4.

CHAPTER 5 ANALYSIS

The previous chapter presented how the data were reduced for different parameters. In this chapter, the data were analyzed. The objectives of the data analysis was:

- To check for any relationship between the different test speeds and the change in magnitude of the considered parameters.
- To determine if the relationship was strong enough to consider the parameter to be included in the decision matrix for developing the specifications.
- To compare the test results of the temporary rumble strips with that of the CIP strips.

5.1 Sound Generation

5.1.1 Sound Generation by Trucks

The sound data were observed to determine if there were any linear relationship between the speeds of the vehicle traversing the strip to the amount of sound generated. No linear trend, either increase or decrease with increase in speed, was observed. Table 20 summarizes the average sound decibel readings observed from the trucks traversing the temporary rumble strips at each of the speeds.

Table. 22 Mean Sound Generated by Truck Passes

	Speed			
Rumble Strip	**22.5 mph**	**37.5 mph**	**57.5**	**67.5**
RoadQuake 2F	96.67dB	97.31dB	99.1dB	98.92dB
TrafFix Alert	99.15dB	99.64dB	99.17dB	100.28dB

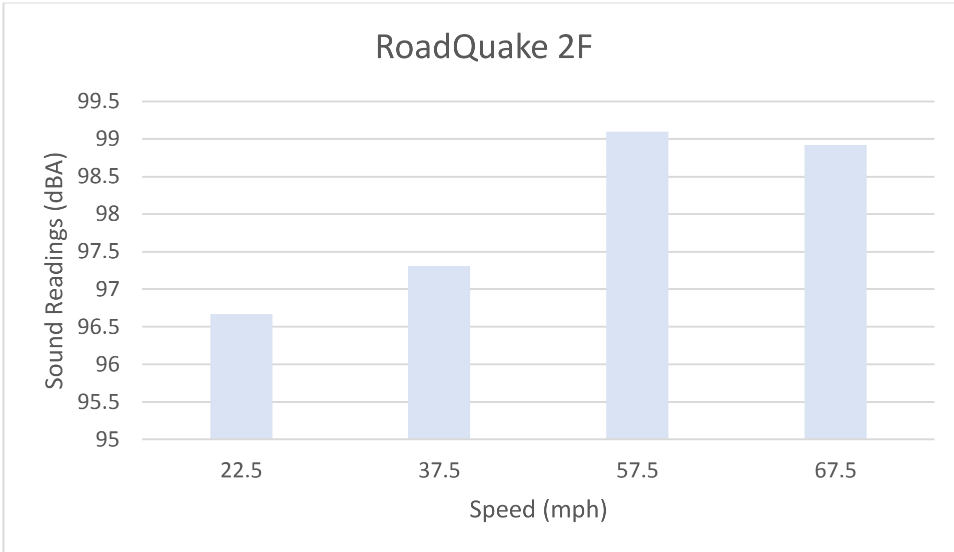

Figure 18. Change in sound level for Truck traversing RoadQuake 2F rumble strips

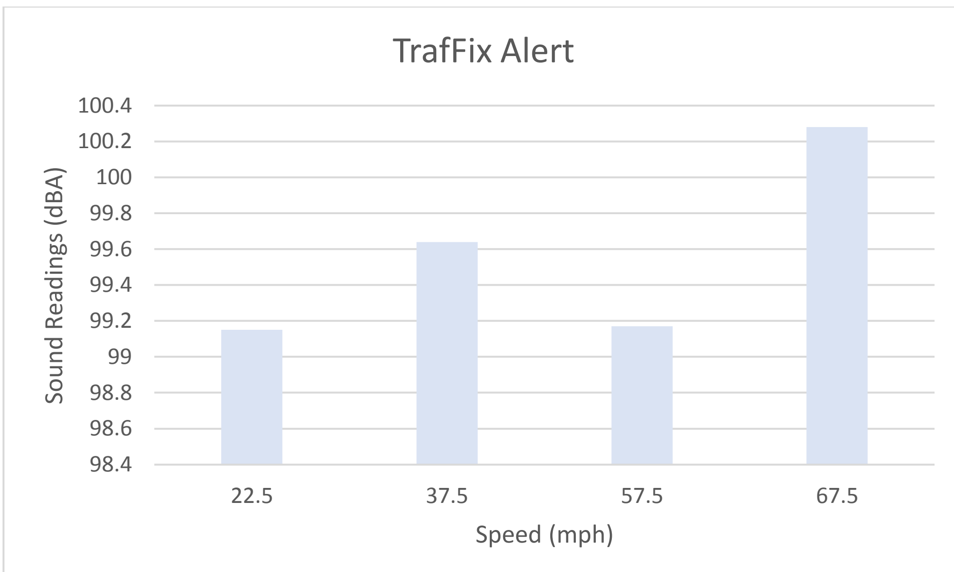

Figure 19. Change in sound level for Truck traversing TrafFix Alert rumble strips

Figure 18 and Figure 19 did not show any particular trend with respect to the speed of the vehicle and sound generated. For example, for the RoadQuake data, the average sound decibel readings increased from 22.5 mph until 57.5 mph and then decreased slightly for 67.5 mph. And for the TrafFix Alert data it can be seen the decibel levels increased from 22.5 to 37.5 mph and then decreased for 57.5 mph and again increased for passes at 67.5 mph. This in part can be attributed to the tailgate of the truck slamming onto the back of the truck while passing over the rumble strips. This additional sound was large enough to obscure changes in sound generated by the rumble strips, attributing to an almost similar range of sound levels at all speeds. The effects of the additional noise generated by the truck used for this study will be discussed later in this chapter.

A statistical analysis was concluded to test for significant differences in the average decibel levels at different speeds. A one-way ANOVA test was performed at a 0.05 level of significance. Tables 21 and 23 show the results from the test, where the p-value was less than 0.05 which indicated that there are significant differences among the values. But the ANOVA test do not provide with which values significantly differing from one another. As there are more than 3 factors (4 different speeds), Tukey's test was conducted instead of a paired t-test. Tukey's test considers all the parameters to be compared at once creating a common confidence interval, thereby reducing the type I error which usually appears while conducting a paired t-test for similar kind of data. Tukey's test was conducted comparing the mean sound decibel levels of all the different speeds at a 0.05 level of significance. Multiplication of the studentized range q value (obtained from statistical tables) and standard error obtained from ANOVA data gave the required Tukey Yardstick number. This Yardstick number was then used in comparing the differences in the means. All possible combinations of the means were arranged in table for comparing the differences between them and the Tukey Yardstick number. If the differences in the means were higher than the Tukey Yardstick number, then the two means are significantly different from each other and vice versa. The results from Tables 22 and 24 showed that the sound levels produced at different speeds by truck passes were not significantly different from each other for both the types of rumble strips. All the mean sound levels for TrafFix Alert rumble strips were not statistically different from each other. On the other hand, except for speed comparison between 22.5and 37.5 mph, and between 57.5 and 67.5 mph the rest of the comparisons between different speeds were found to be statistically significant for RoadQuake rumble strips data. Nevertheless, the overall data for both the rumble strips from truck passes were found to be statistically not significant at different speeds.

Table. 23 One-way ANOVA: Mean Sound Levels at Different Speeds versus Truck on RoadQuake 2F Strips

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	43.014	3	14.338	8.7124	0.0001	2.866
Within Groups	59.246	36	1.645			
Total	102.26	39				

Table. 24 Tukey's Test on RoadQuake 2F Strips Sound Data from Truck Passes

Speed (mph)	Mean sound (dB)	Tukey Yardstick value	Difference from 1st mean value	Difference from 2nd mean value	Difference from 3rd mean value
57.5	99.1	1.545			
67.5	98.92	1.545	0.18		
37.5	97.31	1.545	1.79	1.61	
22.5	96.67	1.545	2.43	2.25	0.64

Table. 25 One-way ANOVA: Mean Sound levels at Different speeds versus Truck on TrafFix Alert Strips

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	8.45	3	2.816	2.167	0.1088	2.866
Within Groups	46.786	36	1.299			
Total	55.236	39				

Table. 26 Tukey's Test on TrafFix Alert Strips Sound Data from Truck Passes

Speed (mph)	Mean sound (dB)	Tukey Yardstick value	Difference from 1st mean value	Difference from 2nd mean value	Difference from 3rd mean value
67.5	100.28	1.373			
37.5	99.64	1.373	0.64		
57.5	99.17	1.373	1.11	0.47	
22.5	99.15	1.373	1.13	0.49	0.02

5.1.2 Sound Generation by Cars

A total of 80 sound-level readings were collected for car passes. All the readings were measured in decibels. Table 25 summarizes the average sound decibel readings observed from the cars traversing the temporary rumble strips at each of the speeds.

Table. 27 Mean Sound Generated by Car Passes

	Speed (mph)			
Rumble Strip	**22.5**	**37.5**	**57.5**	**67.5**
Road Quake 2F	74.86 dB	80.9 dB	86.5 dB	89.59 dB
TrafFix Alert	74.56	80.4	86.49	89.85

Unlike sound levels of the truck, sound generated by the car followed an increasing trend of decibel levels with increase in speed. Figure 20 and Figure 21 shows the increase in sound levels with respect to speed for both the rumble strips. Additionally, it was noted that with each increase in speed both rumble strip systems provided an increase of at least three decibels.

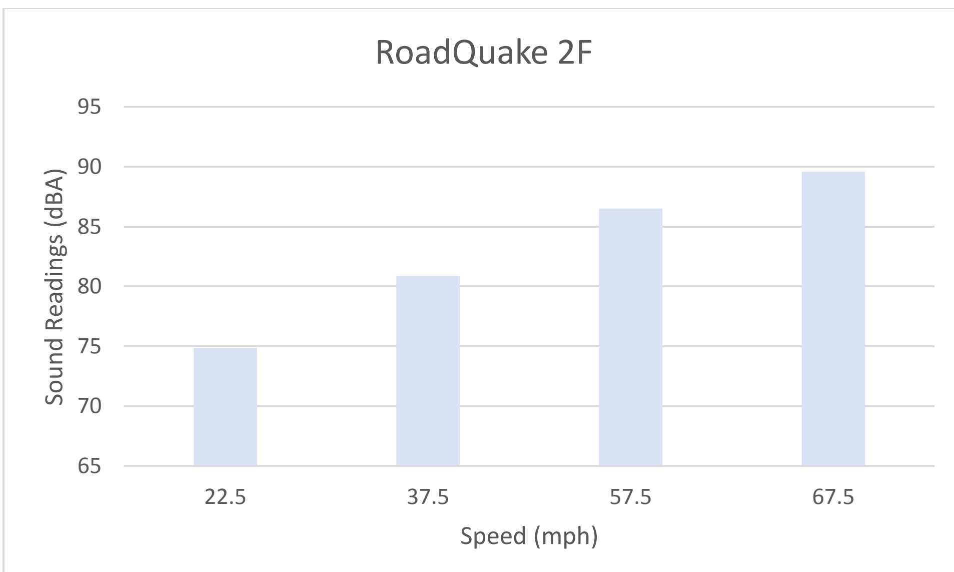

Figure 20. Change in sound level for Car traversing RoadQuake 2F rumble strips

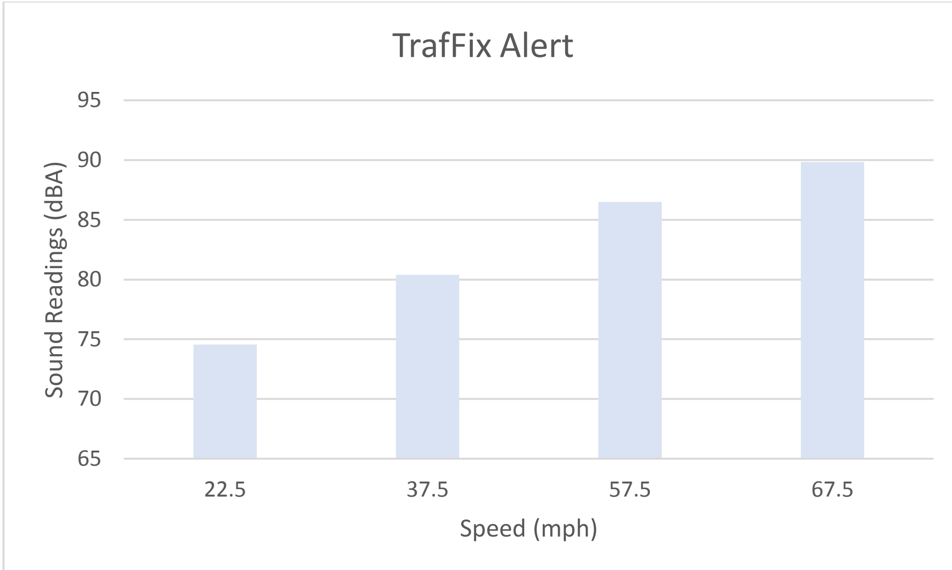

Figure 21. Change in sound level for Car traversing TrafFix Alert rumble strips

A statistical analysis of the data included the one-way ANOVA test, which showed that there were significant differences among the values. See Appendix C for ANOVA calculations. Tukey's test was then conducted to determine which speeds were varying with significant difference. The Tukey Yardstick number was then calculated using the standard error and the studentized q value. The Tukey Yardstick number was compared against the differences of means of all possible combinations of speeds to check for their significance. It was observed that for both the type of rumble strips, the differences in mean sound decibel levels were statistically significant.

Table. 28 Tukey's Test on RoadQuake 2F Strips Sound Data from Car Passes

Speed (mph)	Mean sound (dB)	Tukey Yardstick value	Difference from 1st mean value	Difference from 2nd mean value	Difference from 3rd mean value
67.5	89.59	1.536			
57.5	86.5	1.536	3.09		
37.5	80.9	1.536	8.69	5.6	
22.5	74.86	1.536	14.73	11.64	6.04

Table. 29 Tukey's Test on TrafFix Alert Strips Sound Data from Car Passes

Speed (mph)	Mean sound (dB)	Tukey Yardstick value	Difference from 1st mean value	Difference from 2nd mean value	Difference from 3rd mean value
67.5	89.85	1.263			
57.5	86.49	1.263	3.36		
37.5	80.4	1.263	9.45	6.09	
22.5	74.56	1.263	15.29	11.93	5.84

Sound readings of both the truck's and car's passing indicated that the data from the car was more promising and consistent with an observed speed vs sound relation. Due to the inconsistent results from truck's sound data, the threshold limits for sound generation were based only on the passenger cars sound data. In terms of creating a repeatable testing specification, it appears that using a car will provide more repeatable and useful results than a truck, given the amount of noise that resulted from the truck's tailgate.

5.1.3 Comparison of Sound Data from CIP Strips and Temporary Rumble Strips

CIP strips at six different locations (see Table 1 Rotation Threshold Values) were used in collecting car sound levels at each of the speeds. At each speed, three sound measurements were made at each of the six locations. Based on these different types of CIP strips whose widths and depths varied slightly from location to location, they gave diverse sound data which then were averaged to get a more standardized sound decibel value reflective of CIP rumble strips in Kansas.

Table 28 shows the summarized data from the six different CIP strip locations. The mean sound levels observed at each of the speeds and their 95 percent confidence intervals are shown in the second and third columns. The RoadQuake and TrafFix Alert rumble strips average sound levels at those speeds and their decibel level differences when compared with CIP strips sound levels are also shown in the next columns. Sound decibel readings follow a logarithmic scale and a confidence interval, for example, an 82.34 to 85.28 dB range can be hard to achieve realistically due to many other factors such as sound due to wind, condition of the vehicle, and condition of the road. In establishing a range for a threshold sound limit, a more qualitative measure of sound than a statistical confidence interval was considered, which can provide vendors or any other testing crew the ability to obtain results more realistically. It was considered important that the temporary reusable rumble strips make roughly as much noise as the CIP strips, but did not see it as a detriment if they made more noise. Therefore, a sound level of three decibels below the average CIP strips sound level was established as a lower threshold limit whereas an upper threshold limit was not specified. Table 29 shows the lower threshold limit values for sound generation at different test speeds.

Table. 30 Comparison of Sound Data from CIP Strips and Temporary Rumble Strips

Speed (mph)	CIP Rumble Strips (dB)	CIP 95% Confidence Interval Range (dB)	RoadQuake (dB)	Difference (dB)	TrafFix Alert (dB)	Difference (dB)
22.5	75.38	73.89 – 76.87	74.86	0.52	74.56	0.82
37.5	83.81	82.34 – 85.28	80.90	2.95	80.40	3.45
57.5	89.48	87.82 – 91.14	86.5	2.98	86.49	2.99
67.5	92.27	90.79 – 93.75	89.59	2.68	89.85	2.42

Table. 31 Sound Threshold values

Speed	Threshold decibel value
22.5	72
37.5	79
57.5	86
67.5	89

5.2 Vibration

Statistical analysis for the vibration data collected was conducted using Tukey's test. Tukey's test was carried out to identify the differences in the vibration levels at different speeds in statistical terms.

5.2.1 Vibration Data for Truck Passes

Table 30 summarizes the average vibration levels (g-force) observed from the truck passes. The data showed that the vibration levels for RoadQuake strips increased from 6.68g at 22.5 mph passes until 57.5 mph (7.32 g) and then decreased to a mean vibration level of 3.44 g at 67.5 mph passes. On the other hand, for the TrafFix Alert rumble strips the vibration levels decreased from 22.5 mph to 37.5mph, then increased from 37.5 mph to 57.5 mph and again decreased from 57.5

mph to 67.5 mph passes. The above data from both the rumble strips did not provide any observable relationship between an increase in speed to the vibration generated.

Table. 32 Mean Truck Vibrations of the Rumble Strips in g-force

Speed (mph)	22.5	37.5	57.5	67.5
RoadQuake 2F	6.68	7.00	7.32	3.44
TrafFix Alert	8.12	7.94	13.18	7.14

A one-way ANOVA test was carried out which concluded with a p-value less than 0.05, indicating significant differences among the vibrations at different speeds. See Appendix C for ANOVA calculations. Tukey's test was then used for further analysis. Table 31 shows the Tukey Yardstick value for the RoadQuake rumble strips, which is compared with the differences in vibration values between two speeds. If the difference in magnitude of vibrations between two strips was greater than the Tukey Yardstick value, then the two vibration levels are said to be significantly different from each other and if the difference was less than the Tukey Yardstick number, then the vibration levels are said to be statistically not significant. For RoadQuake rumble strips, the difference in vibration levels between 37.5 and 57.5 mph, 22.5 mph and 57.5 mph, 22.5 and 37.5 mph were not significant. Similarly, Table 32 shows the Tukey Yardstick value for TrafFix Alert rumble strips for which the differences in vibration levels between 57.5 mph and 67.5 mph, and between 37.5 mph and 57.5 mph were found to be not significant. This showed that both rumble strips produced vibrations at different speeds which were not significantly different from each other and additionally they were observed of not having any relation between the speed and the vibrations generated.

Table. 33 Tukey's Test on RoadQuake 2F Strips Vibration Data from Truck Passes

Speed (mph)	Mean vibration (g-force)	Tukey Yardstick value	Difference from 1st mean value	Difference from 2nd mean value	Difference from 3rd mean value
57.5	7.32	0.813			
37.5	7.00	0.813	0.32		
22.5	6.68	0.813	0.64	0.32	
67.5	3.44	0.813	3.88	3.56	3.24

Table. 34 Tukey's Test on TrafFix Alert Strips Vibration Data from Truck Passes

Speed (mph)	Mean vibration (g-force)	Tukey Yardstick value	Difference from 1st mean value	Difference from 2nd mean value	Difference from 3rd mean value
57.5	13.18	1.232			
22.5	8.12	1.232	5.06		
37.5	7.94	1.232	5.24	0.18	
67.5	7.14	1.232	6.04	0.98	0.8

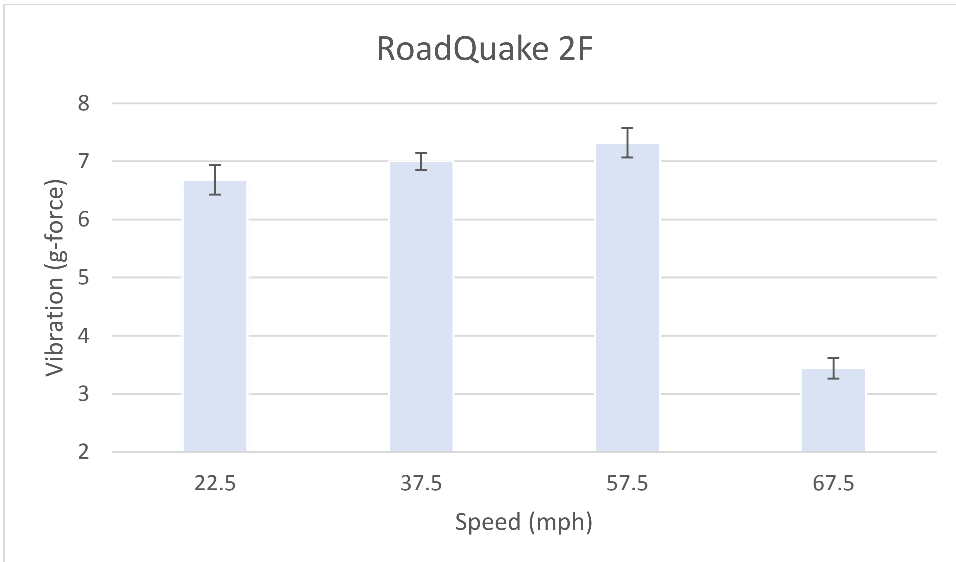

Figure 22. Truck Standard error chart comparing means – RoadQuake 2F

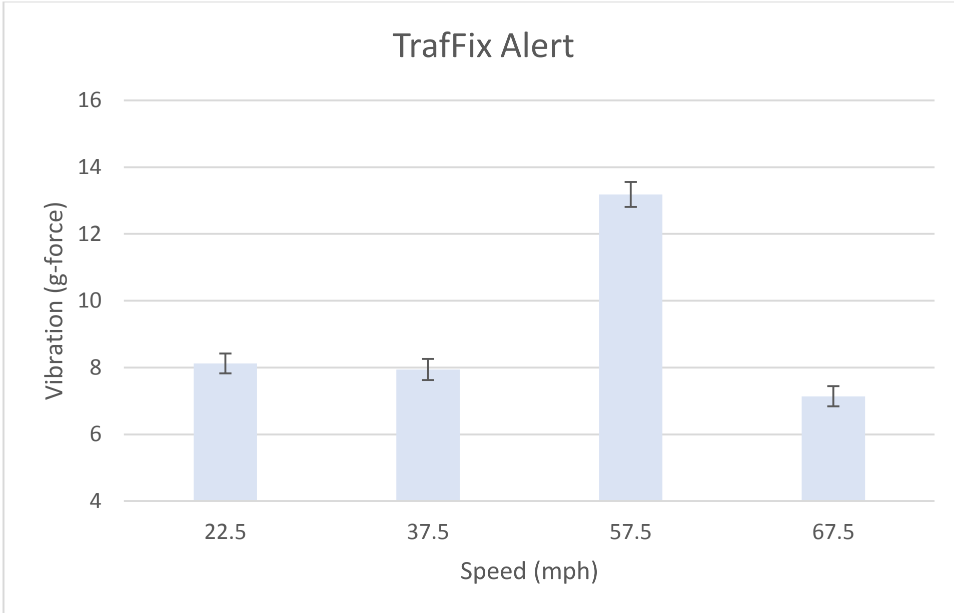

Figure 23. Truck Standard Error chart comparing means- TrafFix Alert

Additionally, the Standard Error of the Mean (SEM) error bar charts were created comparing the mean vibration values and standard error values which show the data graphically in Figures 22 and 23. Charts for both the rumble strips show an overlap of the error bars indicating that the p-value is higher than 0.05, meaning that values were not statistically different from each other.

5.2.2 Vibration Data for Car Passes

From the Table 33 we can observe that the vibration levels from the RoadQuake rumble strips decreased from 22.5 mph to 37.5 mph and then increased in magnitude with increases in speed up to 67.5 mph passes. On the other hand, for the TrafFix Alert rumble strips, the vibrations increased from 22.5 mph until 57.5 mph and then decreased for the 67.5 mph passes. The variation in the passenger cars readings were more consistent compared to that of the truck but overall they failed to establish any linear relationship between speed of the vehicle and vibration observed.

Table. 35 Mean Car Vibrations of the Rumble Strips in g-force

Speed (mph)	22.5	37.5	57.5	67.5
RoadQuake 2F	2.28	2.06	2.12	2.24
TrafFix Alert	2.52	2.70	2.78	2.34

See Appendix C for ANOVA calculations. ANOVA test concluded that there were significant differences among vibrations at different speeds. For further analysis, Tukey’s test was conducted.

Table 34 and Table 35 show the Tukey's test conducted for the RoadQuake and TrafFix Alert rumble strips, respectively. The results showed that for the RoadQuake rumble strips the vibration levels between 22.5 and 67.5, 57.5 and 67.5, and 37.5 and 57.5 mph were not significantly different from each other. For the TrafFix Alert strips, the vibration levels between 37.5 and 57.5, 22.5 and 37.5, and 22.5 and 67.5 mph were not significantly different from each other.

Table. 36 Tukey's Test on RoadQuake 2F Strips Vibration Data from Car Passes

Speed (mph)	Mean vibration (g-force)	Tukey Yardstick value	Difference from 1st	Difference from 2nd	Difference from 3rd
22.5	2.28	0.153			
67.5	2.24	0.153	0.04		
57.5	2.12	0.153	0.16	0.12	
37.5	2.06	0.153	0.22	0.18	0.06

Table. 37 Tukey's Test on TrafFix Alert Strips Vibration Data from Car Passes

Speed (mph)	Mean vibration (g-force)	Tukey Yardstick value	Difference from 1st	Difference from 2nd	Difference from 3rd
57.5	2.78	0.220			
37.5	2.7	0.220	0.08		
22.5	2.52	0.220	0.26	0.18	
67.5	2.34	0.220	0.44	0.36	0.18

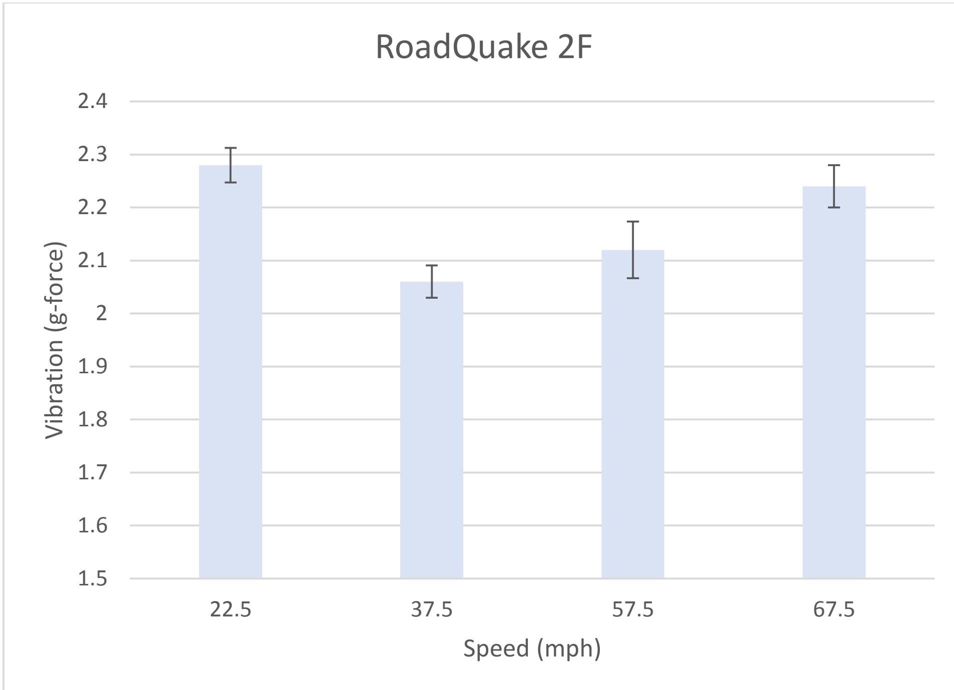

Figure 24. Car Standard error chart comparing means – RoadQuake 2F

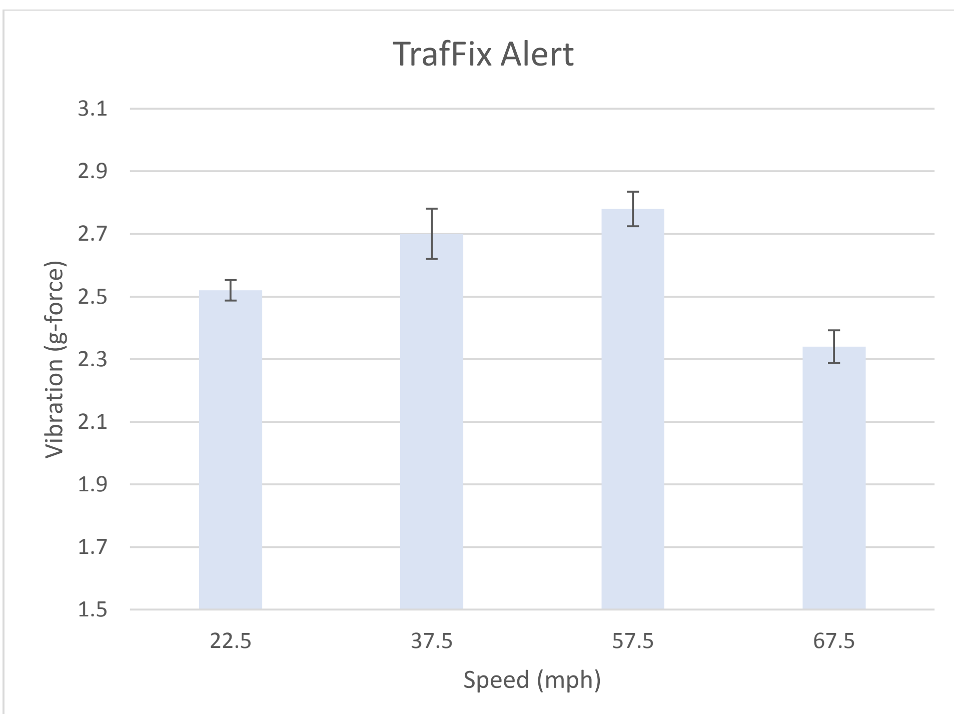

Figure 25. Car Standard Error chart comparing means – TrafFix Alert

Additionally, SEM error bar charts from Figures 24 and 25 for car passes also show overlapping of the error bars, indicating that the variations in the vibrations were not statistically significant.

This shows that the vibration levels for both the test vehicles were not significantly different at different speeds. It would be easier if any linear relationship was observed or significant variation in magnitude of vibration levels were produced, which helps in the process of establishing vibration thresholds and also including vibration as a parameter to be assessed along with other parameters in the decision matrix.

The closed course test at Heartland Park was conducted with speeds of 22.5, 37.5, 57.5 and 67.5 mph. But the test speeds were not equally spaced in magnitude. It should be noted that these speeds were considered because the specifications developed would include all work zone conditions where the speeds range from low to high. The variations in vibration levels between these speeds were not statistically significant in the closed course test. So, the researcher conducted an exclusive test for vibration where the objective of the test was to observe any relation between the speed and the vibration. It should be noted that this test is more of an evaluation test where the vibration parameter's efficiency was tested. So, instead of work zone related speeds, equally spaced speeds were used for this study. This would provide the ability to observe the change in vibration levels for equally spaced speeds to that of the vibration levels observed at the closed course test speeds.

Next chapter (chapter 6) discusses the additional vibration test conducted at University of Kansas evaluating vibration parameter's efficiency.

CHAPTER 6 ADDITIONAL VIBRATION TESTING

A vibration test was conducted in the west campus park and ride parking lot at the University of Kansas on March 8, 2015. As with the case of sound generation by trucks (see Section 5.3.1), the truck is a heavy vehicle with more parts causing irregular and varying results. A passenger car might obtain better results pertaining to vibration data. As this test aimed at standardizing the test procedure for any research team or developer to emulate the same test, a standard full size car was used in performing the test. This consideration of only passenger cars data for comparison of sound and vibration data for developing a decision matrix will help in standardizing the test procedure. A Ford Fusion passenger car was used as a test vehicle. The temporary rumble strips were aligned ten feet apart. One set of three rumble strips of each type were tested. Speeds of 25, 35 and 45 mph were chosen as the test speeds and ten passes traversing the strips at each of the speeds were made. The speeds chosen for this test were equally spaced in magnitude to observe for any linear trend in the change of vibrations. To make sure that the vibration results were as accurate as possible, the position of the rumble strips were checked periodically for any observed movement from their initial position and were arranged back if any were found. It should be noted that this test was intended for collecting only vibration data, so the movement of strips play a minimal role and hence a little variation in the movement of the strips during vehicle passes are not accounted for in the analysis.

The shock recorder was installed on the steering wheel of the test vehicle which then was connected to a laptop for observing the readings. To accurately operate the shock recorder, an assistant was present in the vehicle at all times. The shock recorder was started when the vehicle was on a straight path arriving at the rumble strips and stopped once it traversed the strips which produced a spike in the graph generated. This procedure was continued for each pass. A total of ten passes were conducted at each of the speeds for each type of rumble strip. An example of one of the vehicles traversing the strips can be seen in Figure 26. Figure 27 shows a vibration recording depicting the peaks where the vehicle passed over the rumble strips.

Figure 26. One of the test vehicles traversing the temporary rumble strips during testing

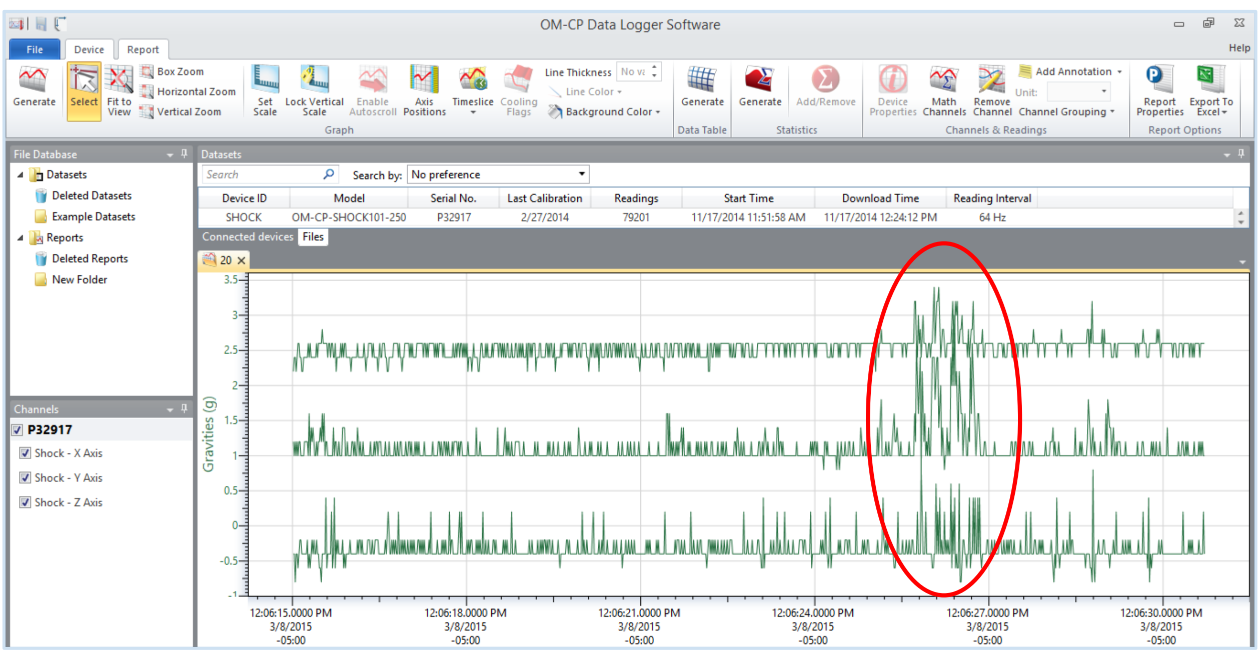

Figure 27. Screen shot of vibration data reading of Ford Fusion at 45 mph

The results obtained from the shock recorder were in the g-force values which can then be converted to m/s^2 or ft/s^2. Tables 36 and 37 shows the mean vibration values observed from passes of the Ford Fusion over the rumble strips. It can be seen that for RoadQuake rumble strips, the vibrations increased from 25 to 35 mph and decreased again for 45 mph. For TrafFix Alert strips, the vibration levels increased for 25 to 35 mph passes and remained the same for the 45 mph passes.

Table. 38 Ford Fusion Vibrations for RoadQuake 2F Strips

Speed	Vibration (g-force)	Vibration (m/s^2)
25	2.82	27.65
35	2.88	28.24
45	2.40	23.54

Table. 39 Ford Fusion Vibrations for TrafFix Alert Strips

Speed	Vibration (g-force)	Vibration (m/s^2)
25	2.54	24.91
35	2.78	27.26
45	2.78	27.26

A one-way ANOVA test was conducted at 0.05 level of significance. Both, Table 38 and Table 40 show that the p-values were less than 0.05. Tukey's test was then performed for both strips data as shown in Tables 39 and 41. For RoadQuake strips the vibrations between 25 and 35 mph were not statistically significant. On the other hand, for TrafFix Alert strips the vibrations between 35 and 45 mph were not statistically significant. For both the rumble strips, the data did not hold any relationship between the speed of the vehicle and vibration observed. In addition, the differences in the vibration levels observed at different speeds were also statistically not significant.

Table. 40 One-way ANOVA: Mean Vibrations at Different Speeds versus Ford Fusion on RoadQuake 2F Strips

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1.3670658	2	0.6835329	10.662818	0.0003864	3.3541308
Within Groups	1.7308173	27	0.0641043			
Total	3.0978831	29				

Table. 41 Tukey's Test on RoadQuake 2F Strips Vibration Data from Ford Fusion Passes

Speed (mph)	Mean vibration (g-force)	Tukey Yardstick value	Difference from 1st mean value	Difference from 2nd mean value
35	2.88	0.281		
25	2.82	0.281	0.06	
45	2.40	0.281	0.48	0.42

Table. 42 One-way ANOVA: Mean Vibrations at Different Speeds versus Ford Fusion on TrafFix Alert Strips

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.3837378	2	0.1918689	5.9178082	0.0073927	3.3541308
Within Groups	0.8754018	27	0.0324223			
Total	1.2591396	29				

Table. 43 Tukey's Test on TrafFix Alert Strips Vibration Data from Ford Fusion Passes

Speed (mph)	Mean vibration (g-force)	Tukey Yardstick value	Difference from 1st mean value	Difference from 2nd mean value
45	2.78	0.200		
35	2.78	0.200	0.00	
25	2.54	0.200	0.24	0.24

This may in partly be due to the fact that the shock recorder was installed inside the vehicle on its steering wheel. Whereas vibrations experienced inside any vehicle depends upon the vehicle's suspension. Considering this scenario, the insignificant differences in vibration may be attributed to good suspension system of the vehicle. As this test was to evaluate the vibration parameter's efficiency, other standard passenger cars were also evaluated to observe similar or different results and also to have a larger sample size. Similar testing discussed above with the above mentioned speeds was conducted with two more cars, namely a Dodge Charger and a Chrysler 200 on March 18, 2015. Tables 42 and 43 show the vibration levels observed from the Charger's passes over the rumble strips. With the Charger as test vehicle, it was observed that for both types of rumble strips, the vibration levels increased for 25 mph to 35 mph and then decreased for 45 mph.

Table. 44 Dodge Charger Vibrations for RoadQuake 2F Strips

Speed	Vibration (g-force)	Vibration (m/s²)
25	3.12	30.60
35	3.70	36.28
45	3.20	31.38

Table. 45 Dodge Charger Vibrations for TrafFix Alert Strips

Speed	Vibration (g-force)	Vibration (m/s²)
25	3.92	38.44
35	4.20	41.19
45	3.52	34.52

Tables 44 and 45 show the vibration levels observed from the Chrysler's passes over the rumble strips. For RoadQuake strips the vibrations increased for the 25 mph to the 35 mph passes and then decreased for 45 mph. For TrafFix Alert strips the vibrations decreased with increases in speed from 25 mph to 45 mph.

Table. 46 Chrysler 200 Vibrations for RoadQuake 2F Strips

Speed	**Vibration (g-force)**	**Vibration (m/s²)**
25	2.60	25.50
35	2.92	28.64
45	2.56	25.11

Table. 47 Chrysler 200 Vibrations for TrafFix Alert Strips

Speed	Vibration (g-force)	Vibration (m/s²)
25	3.30	32.36
35	3.04	29.81
45	2.80	27.46

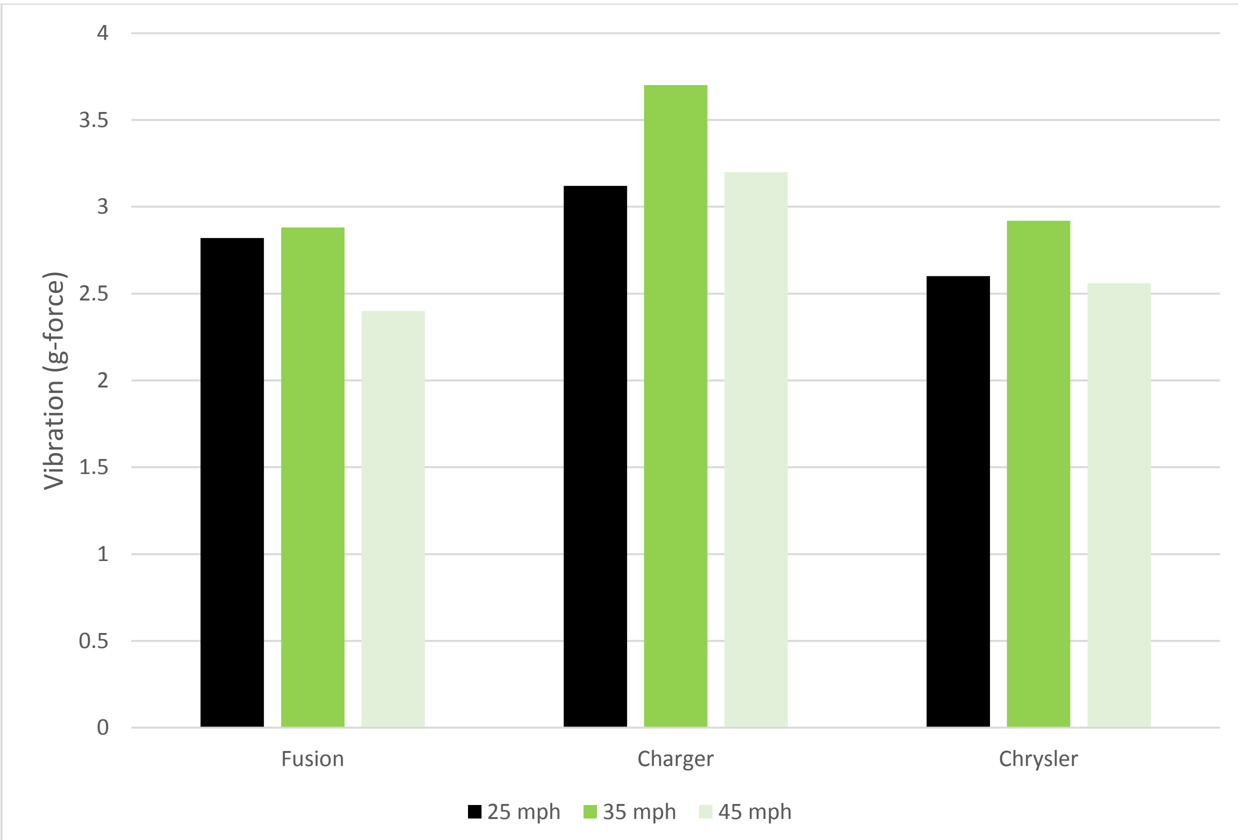

Figure 28. Mean Vibrations of the Three Test Vehicles Traversing RoadQuake 2F Strips

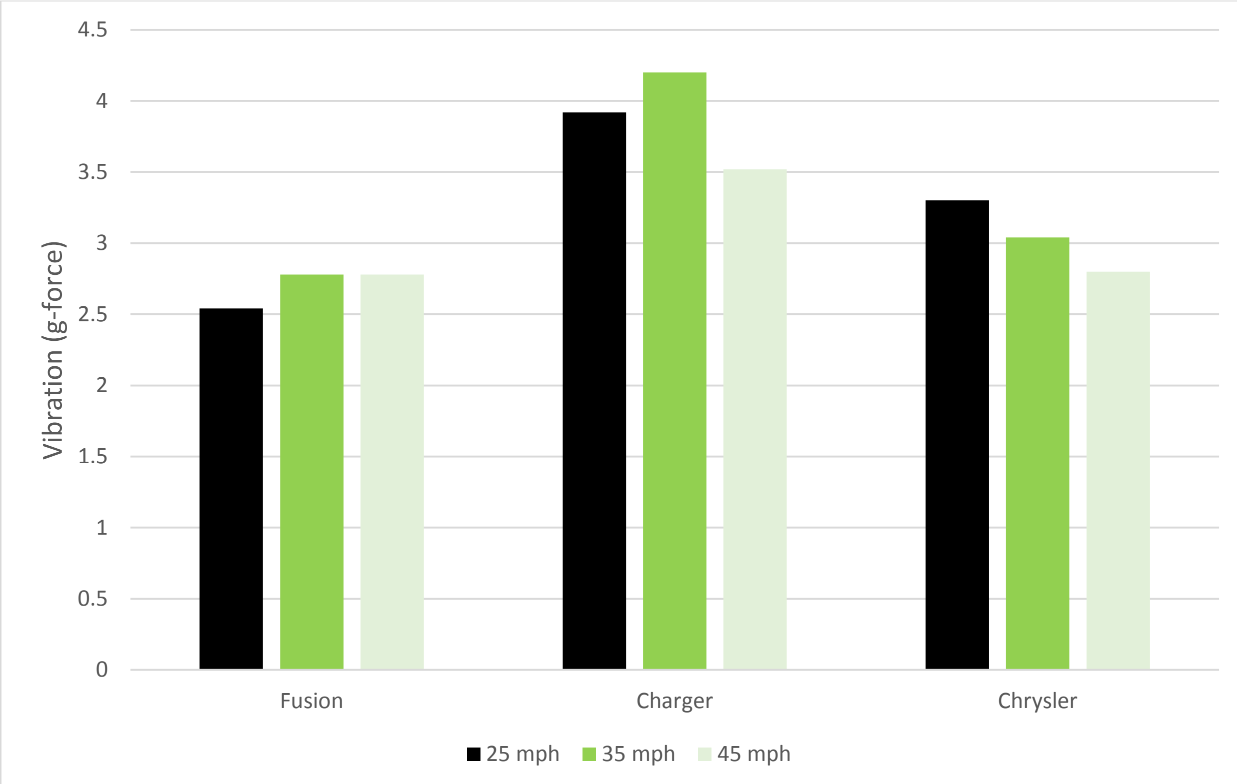

Figure 29 Mean Vibrations of the Three Test Vehicles Traversing TrafFix Alert Strips

Figures 28 and 29 graphically shows the Road Quake 2F and TrafFix Alert strips' vibration data of all three cars. Both the strips showed no linear relationship between the vibrations produced and the speeds of the vehicle, for all the three cars. Statistical analysis including Tukey's test was conducted to test for any observable significance within the vibrations of different speeds. Two Tukey's tests were performed on the data. As different cars were used for the testing, the first Tukey's test was conducted by taking a particular speeds vibration data from all the cars and comparing them for any significant differences in the vibration produced (see Tables C.15 –C.26 in Appendix C). The second Tukey's test compared all the speeds of a particular car to observe for any significant differences in the vibration produced by the same car at different speeds (see Tables C.3 –C.14 in Appendix C). The first Tukey's test showed that the vibration levels produced by different cars at same speed were not significantly different from each other. The results from the second Tukey's test also showed that the vibration levels of the cars at different speeds were not statistically significant for both the strips.

Along with the closed course test at Heartland Park, this exclusive closed course vibration test at the University of Kansas also showed that the vibration generated by a test vehicle does not depend on speed of the vehicle. As the vibration levels does not have a correlation with speed, the vibration levels generated are not necessarily statistically significant at different speeds.

6.1 Comparison of Vibration Data from CIP Strips and Temporary Rumble Strips

Table 46 shows the summarized data from the six different CIP strip locations. The mean vibration levels observed at each of the speeds and their 95 percent confidence intervals are shown in the second and third columns. The RoadQuake and TrafFix Alert rumble strips' average vibration levels at those speeds and their vibration level differences when compared with CIP strips values are also shown in the next columns.

Table. 48 Comparison of Vibration Data from CIP Strips and Temporary Rumble Strips

Speed (mph)	CIP Rumble Strips (g-force)	CIP 95% Confidence Interval Range	RoadQuake (g-force)	Difference (g-force)	TrafFix Alert (g-force)	Difference (g-force)
22.5	2.69	2.49 - 2.89	2.28	0.41	2.52	0.17
37.5	2.54	2.36 - 2.72	2.06	0.48	2.7	0.16
57.5	2.36	2 - 2.72	2.12	0.24	2.78	0.66
67.5	2.37	2.02-2.72	2.24	0.13	2.34	0.03

6.2 Vibration Threshold

As discussed in the sound threshold development (see Section 4.3.2.1), achieving a vibration level realistically within the 95 percent confidence interval would be hard due to many external factors such as the condition of the road surface and the suspension of the test vehicle.

In addition, unlike the sound level readings, vibration levels were not linearly increasing or decreasing with respect to speed. The test vehicle did not make any difference in the case of vibration. But the mean vibration readings for both the temporary rumble strips are within ±1 g-force of the mean vibrations of CIP strips. In this scenario where the vibration values at different speeds were neither statistically different from each other nor were they having any relation with change in speed, creating threshold limits and including vibration values in the decision matrix as a parameter would not be strong compared to other parameters. Based on the results from this study, the researcher would not recommend vibration as a parameter to be considered in developing the decision matrix. Chapter 8 discusses the findings and recommendations regarding future research to assess vibration.

At this point of research, for future studies the researcher developed threshold limits for vibration based on the data which showed that the vibration levels were consistently ± 1 g-force among different cars and also when compared with CIP strips at a particular speed. Even though these threshold limits were not included in the decision matrix, the data from this study and the Table 47 can be helpful for further studies on vibration. Therefore, a vibration level of ± 1 g-force value with respect to the average CIP strips vibration level was established as a threshold limit. Table 47 shows the threshold limit values for vibration at different test speeds.

Table. 49 Vibration Threshold Limits

Speed (mph)	CIP Rumble Strips mean vibration (g-force)	Lower threshold limit (g-force)	Upper threshold limit (g-force)
22.5	2.69	1.7	3.7
37.5	2.54	1.5	3.5
57.5	2.36	1.4	3.4
67.5	2.37	1.4	3.4

Based on the additional vibration test, the vibration parameter was opted out from including in the decision matrix. The next chapter discusses the decision matrix developed with the remaining considered parameters.

CHAPTER 7 DEVELOPMENT OF DECISION MATRIX

From the established threshold values for the variables such as movement, rotation, and sound, a matrix and a classification table was created incorporating all these variables. The purpose of this decision matrix is to form an objective basis for approving current and future temporary rumble strips using performance-based criteria. From the previous chapters it was determined that the following measures were easy to collect in straightforward and repeatable measures using basic equipment and vehicles:

- Average relative movement of a set of three rumble strips;
- Average sound generated compared to Kansas CIP rumble strips; and

Also included in the decision matrix are considerations on the speed of the roadway that the rumble strips will be used as well as the estimated ADTT of the roadway.

The decision matrix shown in Figure 30 specifies the class to which a particular temporary rumble strip belongs. The classes act as performance based rankings given to the rumble strips. Each class has its own classification table defining the performance thresholds for the rumble strips to achieve through closed course testing. The performance thresholds such as movement, rotation, and sound specified in classification tables (see Figures 31-34) provides the information as to which class a particular rumble strip belongs. The matrix consists of four different classes, with each class having definitive threshold limits which a temporary rumble strip has to surpass in order to achieve that level of classification. The division of classes is in numerical order ranging from 1 to 4 with Class 1 being superior in performance than Class 2 and so on. For a temporary reusable rumble strip to be regarded as Class 1, it would have to pass all the threshold values specified in the classification table relating to Class 1 as shown in Figure 31, and so on for the remaining classifications shown in Figures 32 - 34.

For example, a rumble strip set was tested in a closed course setting with four speeds (22.5, 37.5, 57.5, and 67.5 mph) with heavy vehicle and a full-size passenger car. Assuming at 67.5 mph speed after 40 passes, the strips stayed within the edges of the lane (laterally), moved a distance of 1.2 in. (relative displacement), rotated 2°, and produced an average sound decibel value of 89 dB. From Figure 31, the classification table for speed 67.5 mph, it can be observed that except for sound generation, the rumble strips' movement and rotation values were not within the threshold values specified for Class 1. This means that the particular rumble strip was unable to achieve performance criteria set for a Class1 rumble strip product. Similar comparisons of rumble strips performance at other speeds (22.5, 37.5, and 57.5 mph) with classification tables for those particular speeds provides information as to which particular class a rumble strip would belong. The decision matrix indicates the work zone conditions where a particular class of portable temporary rumble strips are suitable.

The matrix has AADT and ADTT volumes indicating the roads or work zone areas where a particular class of temporary reusable rumble strip is considered suitable. These volumes were finalized upon observing the AADT and ADTT volumes from the maps and consulting with KDOT officials. From the matrix, it can be inferred that a Class 1 temporary rumble strip can be used at work zones whose speed limit is between 57.5 and 67.5 mph irrespective of the volume. And also Class 1 temporary rumble strips can be used on roads with volumes of AADT or ADTT exceeding 10,000 and 2,000 respectively irrespective of the speed of the roadway. This is because the movement of temporary rumble strips depend both on speed of the vehicles and number of vehicle passes. On a high-speed condition even with lower volumes, it was observed that the strips tended to move larger distances for each vehicle pass compared to passes at considerably lower speeds. On a similar note, for a high-volume condition, the high number of vehicle passes over the strips within a given time attribute to greater movement of the strips.

To the left in the Class 1 row, it can be seen that conditions include high-speed low-volume work zone conditions, and if one moves down the column of Class 1, it can be seen that conditions include reaching low speed high-volume conditions. In order to consider all the conditions in a particular class, the rumble strips are tested at each particular speed for the most extreme case i.e., the high-speed high-volume condition. In the matrix, for each class the top right corner is the criteria for which the temporary rumble strips are tested, which is a high-speed high-volume condition.

Volume	ADTT	0-500	501-1000	1,001-2,000	>2,000
	AADT	0-2,000	2,001-5,000	5,001-10,000	>10,000
Speed (mph)	67.5				Class1
	57.5			Class2	
	37.5		Class3		
	22.5	Class4			

Figure 30. Decision Matrix

To qualify as a Class 1 device, the tested rumble strip needs to successfully pass the following procedure:
Procedure: - Place three rumble strips 10 ft. on center, centered in a 12-ft. lane, at a closed course facility that will safely allow vehicles to traverse the strips at speed. - Traverse the vehicle with a standard dump truck (nominal maximum rated axle weights of 18,000 lb. and 20,000 lb., respectively) 40 passes at 67.5 mph. - Measure relative movement and rotation as described in this thesis. - Reset the strips and repeat the test using a standard full-size passenger car. - Measure sound levels for ten of the passes using an electronic sound measuring device. - Measure relative movement and rotation as described in this report.
To Achieve a Class 1 rating, after the 40 passes by the different vehicles: For the truck portion of the test: - The average relative displacements of the left end, midpoint, and right edge of the set of strips move less than 0.5 in.; and - Average rotation of the strips is less than 1.5°; and - The ends of the strips do not leave the traveled lane; and - Each of the three units remain in one piece. For the car portion of the test: - The average relative displacements of the left end, midpoint, and right edge of the set of strips move less than 0.5 in.; and - Average rotation of the strips is less than 1.5°; and - The ends of the strips do not leave the traveled lane; and - The average sound generated when traversing the strips is at least 89 dB.

Figure 31. Classification Table to Support the Decision Matrix

To qualify as a Class 2 device, the tested rumble strip needs to successfully pass the following procedure:
Procedure: - Place three rumble strips 10 ft. on center, centered in a 12-ft. lane, at a closed course facility that will safely allow vehicles to traverse the strips at speed. - Traverse the vehicle with a standard dump truck (nominal maximum rated axle weights of 18,000 lb. and 20,000 lb., respectively) 40 passes at 57.5 mph. - Measure relative movement and rotation as described in this thesis. - Reset the strips and repeat the test using a standard full-size passenger car. - Measure sound levels for ten of the passes using an electronic sound measuring device. - Measure relative movement and rotation as described in this report.
To Achieve a Class 2 rating, after the 40 passes by the different vehicles: For the truck portion of the test: - The average relative displacements of the left end, midpoint, and right edge of the set of strips move less than 1.5 in.; and - Average rotation of the strips is less than 2.5°; and - The ends of the strips do not leave the traveled lane; and - Each of the three units remain in one piece. For the car portion of the test: - The average relative displacements of the left end, midpoint, and right edge of the set of strips move less than 1.5 in.; and - Average rotation of the strips is less than 2.5°; and - The ends of the strips do not leave the traveled lane; and - The average sound generated when traversing the strips is at least 86 dB.

Figure 32. Classification Table to Support the Decision Matrix

To qualify as a Class 3 device, the tested rumble strip needs to successfully pass the following procedure:
Procedure: - Place three rumble strips 10 ft. on center, centered in a 12-ft. lane, at a closed course facility that will safely allow vehicles to traverse the strips at speed. - Traverse the vehicle with a standard dump truck (nominal maximum rated axle weights of 18,000 lb. and 20,000 lb., respectively) 40 passes at 37.5 mph. - Measure relative movement and rotation as described in this thesis. - Reset the strips and repeat the test using a standard full-size passenger car. - Measure sound levels for ten of the passes using an electronic sound measuring device. - Measure relative movement and rotation as described in this report.
To Achieve a Class 3 rating, after the 40 passes by the different vehicles: For the truck portion of the test: - The average relative displacements of the left end, midpoint, and right edge of the set of strips move less than 1.5 in.; and - Average rotation of the strips is less than 2.5°; and - The ends of the strips do not leave the traveled lane; and - Each of the three units remain in one piece. For the car portion of the test: - The average relative displacements of the left end, midpoint, and right edge of the set of strips move less than 1.5 in.; and - Average rotation of the strips is less than 2.5°; and - The ends of the strips do not leave the traveled lane; and - The average sound generated when traversing the strips is at least 79 dB.

Figure 33. Classification Table to Support the Decision Matrix

To qualify as a Class 4 device, the tested rumble strip needs to successfully pass the following procedure:
Procedure: - Place three rumble strips 10 ft. on center, centered in a 12-ft. lane, at a closed course facility that will safely allow vehicles to traverse the strips at speed. - Traverse the vehicle with a standard dump truck (nominal maximum rated axle weights of 18,000 lb. and 20,000 lb., respectively) 40 passes. - Measure relative movement and rotation as described in this thesis. - Reset the strips and repeat the test using a standard full-size passenger car. - Measure sound levels for ten of the passes using an electronic sound measuring device. - Measure relative movement and rotation as described in this report.
To Achieve a Class 4 rating, after the 40 passes by the different vehicles: For the truck portion of the test: - The average relative displacements of the left end, midpoint, and right edge of the set of strips move less than 2 in.; and - Average rotation of the strips is less than 5°; and - The ends of the strips do not leave the traveled lane; and - Each of the three units remain in one piece. For the car portion of the test: - The average relative displacements of the left end, midpoint, and right edge of the set of strips move less than 2 in.; and - Average rotation of the strips is less than 5°; and - The ends of the strips do not leave the traveled lane; and - The average sound generated when traversing the strips is at least 72 dB.

Figure 34. Classification Table to Support the Decision Matrix

It is expected that the proposed matrix and supporting classification tables could be used to provide recommendations for current and future portable reusable rumble strips to be approved for use based on objective performance measures that relate directly to field conditions, yet with enough flexibility that the testing process can be replicated with a minimal amount of equipment and time. As noted in previous chapters, such measures as noise generated by traversing with a truck have been removed from consideration, which should also eliminate any variance from the process, and should provide a more consistent result regardless of the vehicles used.

CHAPTER 8 FINDINGS AND RECOMMENDATIONS

Overall this research has shown that the impact of cars on movement and rotation of the temporary rumble strips were low compared to that of trucks. In contrast, the sound generated by truck passes were inconsistent with no relationship between the speed and the sound generated, whereas the cars sound readings were more consistent with increasing patterns of sound generation with increase of speed. Moreover, the mean sound readings from trucks at different speeds were statistically not significant from each other. On the other hand, the vibration readings for both the truck and car passes showed no relationship between the speed of the vehicle and vibration generated. The mean vibration readings of both the vehicles were not statistically significant from each other. Even though no relationship was established, the vibration levels produced by both the rumble strips for all speeds at each pass were significantly larger than standard vibrations felt without any rumble strips. The CIP strips data were used as base magnitude for comparing the sound and vibration levels of the temporary rumble strips. Hence, the matrix and classification tables were developed by using truck volumes in calculating movement and rotational thresholds and cars sound generation from CIP strips for calculating sound threshold limits.

The developed matrix and classification table provides any vendor or DOT staff with a guideline to test the performance of any temporary reusable rumble strips currently on the market or those that may enter the market in the future. The process described will provide necessary information regarding the class they belong to and the type of work zone where they can be installed, to ensure that the product can perform appropriately and not be used in conditions for which it is not suited. The matrix provides us with appropriate results for all situations ranging from low speed low-volume work zone conditions to high-speed high-volume conditions encompassing various other extreme scenarios such as low speed high-volume or high-speed low-volume work zone conditions.

There were a few areas that were identified in this research where more work remains to be done. Specifically:

- The sound generated by the truck used when traversing the rumble strips was surprisingly consistent in terms of the decibel level. More research should be conducted to determine if a consistent and repeatable process can be developed to limit the noise generated from individual truck parts (e.g., in this case the tailgate banging). If a process can be developed then it would seem appropriate to add a truck-based sound threshold into the classification table procedures.

- Vibrations generated by the trucks were inconsistent in their magnitude at different speeds. On the other hand the vibrations were consistent for the passes made by cars. However, for both test vehicles the vibrations generated at the steering wheel level did not show any relationship between the variables considered and also did not provide vibrations which varied significantly at different speeds. To fully understand why, this would require additional accelerometers to be installed at different places of the test vehicle (including both interior and exterior of the vehicle), and observe how the vehicle experiences vibrations at different parts. More work would also be needed to see how various changes in vehicle suspension would change the amount of vibration passed to the steering wheel. For example, the type of tire, the level of tire inflation, the type of suspension system, etc. could all have an impact on the amount of vibration. If a process can be developed, then a more robust confidence interval for the threshold limit can be specified which can be easily evaluated, even for the trucks.
- Finally, it is clear that such a matrix could be expanded to include other types of temporary on-pavement warning devices, such as adhesive-type or temporary asphalt rumble strips. Each of these would have specific characteristics that would likely include additional variables that were not considered in this research. Specific variables might include installation time, removal time, permanent damage to the pavement, and the length of time that a work zone would remain at one location. If thresholds and testing procedures for these variables could be determined the matrix provided here could be expanded into a more comprehensive tool for determining the appropriateness of a wider range of work zone safety tools.

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APPENDIX A (SURVEY OF PRACTICE)

Survey design

A National survey was conducted asking State DOTs (beside KDOT) about their publically available guidance or specifications regarding temporary rumble strips and their operations in work zones. The survey mainly focused on the current usage of different temporary rumble strips and consisted of six principal questions:

- Question 1: Does your Department of Transportation use temporary rumble strips on state/federally funded projects?
- Question 2: Are there guidance/specifications/standard drawings for using temporary rumble strips? How were these developed (in-house testing, anecdotal experiences with field personnel or contractors, modeled after other states, other?)?
- Question 3: Does the DOT have an approval process for temporary rumble strips (again, both for adhesive types and portable types)? Are there minimum criteria (either in material or in application) that must be met for the product to be considered for use?
- Question 4: Are there any specific procedures for inspecting temporary rumble strips (adhesive and portable)? Procedures could include how they are inspected, how frequently, etc. Also, what would result in a failed inspection?
- Question 5: Are there any specific work zone projects for which temporary rumble strips have been found to be unsuitable?
- Question 6: Are there any specific work zone projects for which temporary rumble strips have been found to be ideally suited?

3.2 Survey Implementation

The survey was conducted through telephone and email conversations from June 1, 2014 to June 27, 2014. Phone calls were made to the appropriate personnel related to workzone maintenance in their respective state DOTs. The researcher asked the questions in the questionnaire and also requested any publicly available specifications or guidance for temporary rumble strips.

3.2 Survey Results

A total of 22 states responded to the survey. Responses of the states for each of the questions are discussed and summarized here; more detailed responses of each of the states follow:

Does your Department of Transportation use temporary rumble strips on state/federally funded projects?

This question refers to the state DOT's prior experience of implementing any kind of temporary rumble strips which include reusable portable temporary rumble strips and temporary rumble strips with adhesive backing. A total of 14 states have implemented some kind of temporary rumble strips in their projects. Of these 14 states, 12 states have used portable reusable temporary rumble strips previously in their roadway projects.

Are there guidance/specifications/standard drawings for using temporary rumble strips? How were these developed (in-house testing, anecdotal experiences with field personnel or contractors, modeled after other states, other?)?

Only four states (Missouri, Oregon, Pennsylvania, and Virginia) of the total surveyed states have developed specifications for usage of temporary rumble strips in their work zones. The specifications for all of these states were developed through in-house testing with movement and sound generated by the strips taken as major variables. The Missouri DOT (MoDOT) had the contractors' state their opinions and requirements they would like to see in such a product. Oregon had consulted the previous studies and data available from other states. Pennsylvania DOT evaluated the effectiveness of the materials used in the manufacturing of rumble strips.

Does the DOT have an approval process for temporary rumble strips (again, both for adhesive types and portable types)? Are there minimum criteria (either in material or in application) that must be met for the product to be considered for use?

The vast majority of the surveyed state DOTs evaluated rumble strips through a series of anecdotal field trials, either with contractors or with in-house maintenance crews. Approval is dependent on successful performance from these field trials, but these trials appeared to lack objective numeric criteria for the evaluation. The Alabama DOT has a slightly different process with a product evaluation board which approves new products, but again objective criteria were not included in the evaluation, meaning that subjective results were used in the evaluation of rumble strips including movement.

Are there any specific procedures for inspecting temporary rumble strips (adhesive and portable)? Procedures could include how they are inspected, how frequently, etc. Also, what would result in a failed inspection?

No surveyed state has yet developed any standard inspection procedure.

Are there any specific work zone projects for which temporary rumble strips have been found to be unsuitable?

The rumble strips were observed to not perform well on multilane highways and on high-speed high-volume conditions.

Are there any specific work zone projects for which temporary rumble strips have been found to be ideally suited?

The temporary rumble strips have yielded good results when implemented in advance of flagger operations in a work zone, detour of intersections, temporary traffic signals and lane closures on multilane highways.

Survey Responses

Alabama DOT

At the time of this survey, the Alabama DOT had used portable plastic rumble strips on a limited basis on past construction projects and were currently looking at the possibility of more widespread use. All temporary rumble strips must be approved through ALDOT's Product Evaluation Board. Currently three types of portable plastic rumble strips were approved for use by ALDOTs product evaluation board. These products were approved after a successful field test with movement as main criteria, but specifications were not yet developed for temporary rumble strips.

Arkansas DOT

At the time of this survey, the Arkansas DOT was evaluating temporary rumble strips. The DOT began assessing portable plastic rumble strips and had not tested adhesive-type rumble strips. There had not been any specifications developed for their usage. At present the portable plastic rumble strips were deployed only at one active project on a trial basis and they had not drafted any approval process and inspection procedures.

Connecticut DOT

At the time of this survey, the State DOT of Connecticut had not developed specifications for temporary rumble strips and had not used any kind of temporary rumble strips in their projects.

Florida DOT

At the time of this survey, the Florida DOT had used both portable plastic rumble strips and adhesive-type rumble strips in their projects. The Florida DOT has an approval process for anything which has to be put out in public right of way. But it does not mean every device was tested. In the case of temporary rumble strips, the application of the device played an important role for the DOT. The portable plastic rumble strips and adhesive rumble strips were used as supplemental devices in addition to a series of advanced warning signs and were installed and removed when the signs were installed and removed. The portable plastic rumble strips and adhesive rumble strips were found to be useful as a warning device when placed:

- In advance of flagging station at work zones.

Georgia DOT

At the time of this survey, the Georgia DOT had not used either the adhesive rumble strips or portable plastic rumble strips, but rather used speed bumps made up of plastic or vulcanized rubber and were bolted down into the road surface for its intact position. They had no specifications or approval process developed for temporary rumble strips.

Iowa DOT

At the time of this survey, the Iowa DOT was installing portable plastic rumble strips in their projects on an experimental basis. About a dozen projects were installed with these devices and were yet to develop specifications for their use. Based on the installed devices' performance and public interest, the approval of the devices will takes place in the future. The portable plastic rumble strips were being tested for their ability to stay in place and also their weight, which helps in reducing movement. There were no inspection procedures developed. The DOT was optimistic about the portable plastic rumble strips' usage in work zones, primarily for:

- Moving types of projects; and
- Their application at work zones in advance of flagger operations.

Michigan DOT

At the time of this research, the Michigan DOT used temporary adhesive rumble strips as a warning device at work zones, and the portable plastic rumble strips were under evaluation. The orange rumble strips, which contain an adhesive backing, were used at work zones containing shorter and narrower roads.

Two different sets of specifications were developed for the rumble strips, depending on their installation site, one set of specifications detailing the rumble strips application in advance of a STOP condition and the other set when used at the approach to a work zone. The Michigan DOT proceeds with approval process for a device only if the need arises. Then they evaluate and determine its effectiveness through testing and engineering judgment. The rumble strips once installed were inspected based on their setup and layout which included checking the offset distances from their installation point. No particular set of criteria for inspection or their frequency of inspection had been developed. Work zones near freeways were found not to be suitable for installing temporary rumble strips due to the expected queues forming on freeways. The following locations were considered acceptable locations for their use:

- Intersections which have their configuration changed from free flow to a STOP-controlled intersection, and
- Intersections with temporary STOP conditions.

Minnesota DOT

At the time of this research, the Minnesota DOT used portable plastic rumble strips in work zones. There have been specifications developed for these portable plastic rumble strips after field testing and anecdotal experiences with the field personnel. The testing of the devices was conducted to evaluate their movement, and the tactile and auditory warnings generated by these devices. The temporary rumble strips present in the approved products list were qualified through an approval process, which had minimum criteria based on their movement from their installed position. The portable plastic rumble strips were found to be suitable for installation:

- In advance of flagger operations, and
- The Minnesota DOT was considering installing the strips at intersection detours and temporary signals.

Missouri DOT

At the time of this survey, the Missouri DOT (MoDOT) had developed specifications for usage of both adhesive and plastic portable rumble strips in their projects. Specifications were developed through in-house testing regarding the strips' movement, and also contractors were asked about the requirements they would like to see for such a product. MoDOT classified the strips as long-term and short-term rumble strips based on their application. The adhesive rumble strips were termed as long-term rumble strips which are intended to be used for work zones which were stationary and lasted for longer times. The portable plastic rumble strips were classified as short-term rumble strips when they were intended mainly for usage at short-term, short-duration and mobile work zones. The applications of these strips ranged from:

- In advance of flagging operations,
- In advance of a temporary traffic signals,
- In advance of lane closures on a multilane roadway, and
- Work zones located on a hilly or curved terrain with sight distance issues.

Montana DOT

At the time of this survey, the Montana DOT had no prior experience of using temporary rumble strips and had not developed any specifications.

Nebraska DOT

At the time of this survey, the Nebraska Department of Roads used temporary asphalt rumble strips as a warning device at work zones. They had not yet implemented portable plastic rumble strips, but had plans to introduce them in advance of temporary signals in the future.

New Hampshire DOT

At the time of this survey, the New Hampshire DOT had not used any kind of temporary rumble strips in their roadway projects, and had conducted no tests or developed specifications for temporary rumble strips.

Oklahoma DOT

At the time of this survey, the Oklahoma DOT used temporary rumble strips in their projects, but were still in the experimental stage. The portable plastic rumble strips were only used in their projects and they had not tested the adhesive backed temporary rumble strips. As they were still experimenting, they had not developed any specifications. At the time of this survey, the field division of the Oklahoma DOT was testing these devices at different speeds with an upper speed limit of 40 mph. The portable plastic rumble strips applications in low-speed work zones in front of flaggers showed good results. Based on the results of the devices in low-speed work zones, the

DOT was positive about implementing the portable plastic rumble strips in highway high-speed work zones in the future.

The Oklahoma DOT had an approval process for implementing a new device. For the portable plastic rumble strips to be approved, they have to undergo testing on a temporary basis in work zones for one or two evaluations. The evaluation criteria varies with the products usage and its applications. For example, the RoadQuake 2, a portable plastic rumble strips manufactured by Plastic Safety Systems Ltd, would be evaluated based on: its ease to transport, its durability and its effect on motorcycles. Based on their performance, the devices was expected to be approved into the Qualified Product List (QPL). The QPL list at present contains two portable plastic rumble strips for alerting drivers entering work zone with conditional approval status.

The portable plastic rumble strips were found to be suitable in its application at the following locations:

- In advance of flaggers alerting the drivers they are entering the work zone.

Oregon DOT

At the time of this survey, the Oregon DOT had used both the adhesive and plastic portable temporary rumble strips in their work zone projects. The DOT had also used temporary milled-in rumble strips. The DOT conducted pilot projects on the portable rumble strips, collected data from other state DOTs and collected feedback and information from manufacturers in the process of developing specifications for using these rumble strips. The temporary rumble strips have an approval process in the Oregon DOT, which must be approved by regional traffic engineer. For the approved products to be considered for use, they have to meet certain criteria like: durability of material and their movement from their installed location. For thermoplastic tape strips - which are usually installed for longer durations - they would have to meet the DOT standards in their material durability, whereas portable plastic rumble strips once installed should be able to remain intact in their position. The temporary rumble strips were found to be suitable and satisfactory with:

- Installation on lower-volume roads with not more than two-lanes per direction,

- In advance of flagging operations, and
- At nighttime operations

However, studies showed that more people are swerving around the strips, bringing the need to supplement the strips with additional signage. Even though the Oregon DOT had not conducted any tests on multilane highways, the strips' performance on such roads was undermined due to their movement and the task of repositioning them.

Pennsylvania DOT

At the time of this survey, the Pennsylvania DOT had used both the adhesive and portable plastic temporary rumble strips in their projects. The Pennsylvania DOT had developed specifications for their use, which were based on in-house testing done by their maintenance crew on: their movement and also on the type of material. No inspection procedures were developed and the flagging personnel checked the position of the strips without any requirement for consistent times.

South Carolina DOT

At the time of this survey, the South Carolina DOT had past experience in using temporary adhesive rumble strips. The adhesive rumble strips were used for a short time period on a project-by-project basis, with their implementation on one Interstate repair project. As they were implemented on a temporary basis, there have not been any specifications developed for these strips.

Tennessee DOT

At the time of this survey, the Tennessee DOT had not used any type of portable temporary rumble strips but had limited implementation of adhesive temporary rumble strips. No specifications were developed for temporary rumble strips.

Vermont DOT

At the time of this survey, the Vermont DOT had prior experience of implementing portable reusable temporary rumble strips in their projects. But the Vermont DOT had not yet done any testing for developing specifications.

Virginia DOT

At the time of this survey, the Virginia DOT was using PPRS on an experimental basis in 4-5 districts. They had not used the adhesive-backed rumble strips. One set of specifications had been developed. These specifications were developed based on field trials and testing was focused on aspects such as the movement of rumble strips. It was concluded that one set of strips were more ideal in work zones compared to two sets, as more drivers seemed to swerve around the second set after they passed over the first one. After the successful testing of motorcycles running over the portable plastic rumble strips, they were being used at work zones. The usage of this product was approved both due to its application and its material performance. The weight of the portable plastic rumble strips was given as a factor in its application. The procedures for inspection have not been developed yet. The current application of PPRSs was limited to:

- Work zones in advance of flagger operations.

Washington DOT

At the time of this survey, the Washington DOT had used both the portable plastic rumble strips and adhesive rumble strips on a trial basis for their evaluation. The evaluation tests were done and the devices were recommended for use but no specifications were developed for those products. The temporary rumble strips were used at a project, with the strips installed:

- In advance of a temporary traffic signal.

The results were found to be satisfactory with the Washington DOT recommending both of the devices for future use. However, concerns were raised about the portable plastic rumble strips implementation on high-speed roadways and on the safety of motorcyclists, with a need for further study and usage of supplemental signage. The Washington DOT had plans to implement them at work zones:

- In advance of flagging operation, and
- Near pilot car operations.

West Virginia DOT

At the time of this survey, the West Virginia DOT had not implemented temporary rumble strips on their road projects and had not developed any specifications regarding them.

Wyoming DOT

At the time of this survey, the Wyoming DOT had not used any portable temporary rumble strips in their projects but rather used temporary CIP rumble strips. The DOT was planning to implement the portable plastic rumble strips in their maintenance work zones.

APPENDIX B (CIP STRIPS SOUND DECIBEL DATA)

Tables:

Table B.1 CIP Strips Sound Decibel Data from Six Locations:

At K-32 and US-24/US-40				
Rumble Strip	**22.5 mph**	**37.5 mph**	**57.5 mph**	**67.5 mph**
CIP Rumble Strips	72.2	81	85.3	87.2
	71.4	81.5	83.9	88
	72.2	79.8	84.5	85.1

At N1150 Rd and E1000 Rd				
Rumble Strip	**22.5 mph**	**37.5 mph**	**57.5 mph**	**67.5 mph**
CIP Rumble Strips	75	80.3	89.2	91
	74.8	82.1	87.5	92.1
	75.1	81.2	87.3	91.2

US-56 and US-59 Southbound				
Rumble Strip	**22.5 mph**	**37.5 mph**	**57.5 mph**	**67.5 mph**
CIP Rumble Strips	79.2	89.7	95.6	94.6
	78.6	88.8	94.9	97
	77.3	87.6	94.6	96.7

US-56 and US-59 Northbound				
Rumble Strip	**22.5 mph**	**37.5 mph**	**57.5 mph**	**67.5 mph**
CIP Rumble Strips	80.7	87.2	92.6	95.9
	77	87.2	92.2	95.9
	77.3	87.1	93.4	92.3

Northbound 1061 at US-56				
Rumble Strip	**22.5 mph**	**37.5 mph**	**57.5 mph**	**67.5 mph**
Cut-in-place Rumble Strips	67.2	82.6	87.5	91.6
	74	83.4	87.8	92.3
	74.7	82.4	87.9	91.9

Southbound 1061 at US-56				
Rumble Strip	**22.5 mph**	**37.5 mph**	**57.5 mph**	**67.5 mph**
CIP Rumble Strips Rumble Strips	75.5	83.2	88.8	92.7
	77.2	0	89.6	93.1
	77.5	81.7	88.1	92.3

APPENDIX C (STATISTICAL ANALYSIS)

Table C.1 One-way ANOVA: Mean Vibrations at Different Speeds versus Truck on RoadQuake 2F Strips

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1263.42	3	421.14	258.66	2.09499E-24	2.866
Within Groups	58.613	36	1.62			
Total	1322.03	39				

Table C.2 One-way ANOVA: Mean Vibrations at Different Speeds versus Truck on TrafFix Alert Strips

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1369.73	3	456.579	415.302	5.69041E-28	2.866
Within Groups	39.578	36	1.099			
Total	1409.31	39				

Table C.3 One-way ANOVA: Mean Vibrations at Different Speeds versus Ford Fusion on RoadQuake 2F Strips

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1.367	2	0.683	10.66	0.00038	3.354
Within Groups	1.730	27	0.0641			
Total	3.097	29				

Table C.4 Tukey's Test on RoadQuake 2F Strips Vibration Data from Ford Fusion Passes

Treatment	Mean	Tukey Yardstick	Difference from 1st	Difference from 2nd
35	2.88	0.281		
25	2.82	0.281	0.06	
45	2.4	0.281	0.48	0.42

Table C.5 One-way ANOVA: Mean Vibrations at Different Speeds versus Ford Fusion on TrafFix Alert Strips

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.383	2	0.191	5.917	0.0073	3.354
Within Groups	0.875	27	0.032			
Total	1.259	29				

Table C.6 Tukey's Test on TrafFix Alert Strips Vibration Data from Ford Fusion Passes

Treatment	Mean	Tukey Yardstick	Difference from 1st	Difference from 2nd
45	2.78	0.200		
35	2.78	0.200	0	
25	2.54	0.200	0.24	0.24

Table C.7 One-way ANOVA: Mean Vibrations at Different Speeds versus Dodge Charger on RoadQuake 2F Strips

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1.974	2	0.987	12.606	0.000	3.354
Within Groups	2.114	27	0.078			
Total	4.089	29				

Table C.8 Tukey's Test on RoadQuake 2F Strips Vibration Data from Charger Passes

Treatment	Mean	Tukey Yardstick	Difference from 1st	Difference from 2nd
35	3.7	0.310		
45	3.2	0.310	0.5	
25	3.12	0.310	0.58	0.08

Table C.9 One-way ANOVA: Mean Vibrations at Different Speeds versus Dodge Charger on TrafFix Alert Strips

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	2.334	2	1.167	12.967	0.00011	3.354
Within Groups	2.430	27	0.090			
Total	4.764	29				

Table C.10 Tukey's Test on TrafFix Alert Strips Vibration Data from Charger Passes

Treatment	Mean	Tukey Yardstick	Difference from 1st	Difference from 2nd
35	4.2	0.333		
25	3.92	0.333	0.28	
45	3.52	0.333	0.68	0.4

Table C.11 One-way ANOVA: Mean Vibrations at Different Speeds versus Chrysler 200 on RoadQuake 2F Strips

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.778	2	0.389	6.2571	0.0058	3.354
Within Groups	1.678	27	0.062			
Total	2.456	29				

Table C.12 Tukey's Test on RoadQuake 2F Strips Vibration Data from Chrysler 200 Passes

Treatment	Mean	Tukey Yardstick	Difference from 1st	Difference from 2nd
35	2.92	0.276		
25	2.6	0.276	0.32	
45	2.56	0.276	0.36	0.04

Table C.13 One-way ANOVA: Mean Vibrations at different speeds versus Chrysler 200 on TrafFix Alert Strips

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1.249	2	0.624	5.854	0.007	3.354
Within Groups	2.882	27	0.106			
Total	4.131	29				

Table C.14 Tukey's Test on TrafFix Alert Strips Vibration Data from Chrysler 200 Passes

Treatment	Mean	Tukey Yardstick	Difference from 1st	Difference from 2nd
25	3.3	0.362		
35	3.04	0.362	0.26	
45	2.8	0.362	0.5	0.24

Table C.15 One-way ANOVA: Mean Vibrations of Cars versus 25 mph Speed on RoadQuake 2F Strips

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	131.048	2	65.524	8.316	0.0015	3.354
Within Groups	212.728	27	7.8788			
Total	343.777	29				

Table C.16 Tukey's Test on RoadQuake 2F Strips Vibration Data at 25 mph

Treatment	Mean	Tukey Yardstick	Difference from 1st	Difference from 2nd
Charger	30.6	3.112026		
Fusion	27.65	3.112026	2.95	
Chrysler	25.5	3.112026	5.1	2.15

Table C.17 One-way ANOVA: Mean Vibrations of Cars versus 25 mph Speed on TrafFix Alert Strips

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	918.875	2	459.437	82.684	3.073E-12	3.354
Within Groups	150.025	27	5.556			
Total	1068.901	29				

Table C.18 Tukey's Test on TrafFix Alert Strips Vibration Data at 25 mph

Treatment	Mean	Tukey Yardstick	Difference from 1st	Difference from 2nd
Charger	38.44	2.613443		
Chrysler	32.36	2.613443	6.08	
Fusion	24.91	2.613443	13.53	7.45

Table C.19 One-way ANOVA: Mean Vibrations of Cars versus 35 mph Speed on RoadQuake 2F Strips

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	411.096	2	205.548	30.501	1.182E-07	3.354
Within Groups	181.954	27	6.739			
Total	593.050	29				

Table C.20 Tukey's Test on RoadQuake 2F Strips Vibration Data at 35 mph

Treatment	Mean	Tukey Yardstick	Difference from 1st	Difference from 2nd
Charger	36.28	2.878136		
Chrysler	28.64	2.878136	7.64	
Fusion	28.24	2.878136	8.04	0.4

Table C.21 One-way ANOVA: Mean vibrations of Cars versus 35 mph speed on TrafFix Alert Strips

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1099.419	2	549.709	41.711	5.522E-09	3.354
Within Groups	355.830	27	13.178			
Total	1455.250	29				

Table C.22 Tukey's Test on TrafFix Alert Strips Vibration Data at 35 mph

Treatment	Mean	Tukey Yardstick	Difference from 1st	Difference from 2nd
Charger	41.19	4.024867		
Chrysler	29.81	4.024867	11.38	
Fusion	27.26	4.024867	13.93	2.55

Table C.23 One-way ANOVA: Mean vibrations of Cars versus 45 mph Speed on RoadQuake 2F Strips

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	344.674	2	172.337	33.977	4.236E-08	3.354
Within Groups	136.946	27	5.072			
Total	481.621	29				

Table C.24 Tukey's Test on RoadQuake 2F Strips Vibration Data at 45 mph

Treatment	Mean	Tukey Yardstick	Difference from 1st	Difference from 2nd
Charger	31.38	2.496926		
Chrysler	25.11	2.496926	6.27	
Fusion	23.54	2.496926	7.84	1.57

Table C.25 One-way ANOVA: Mean Vibrations of Cars versus 45 mph Speed on TrafFix Alert Strips

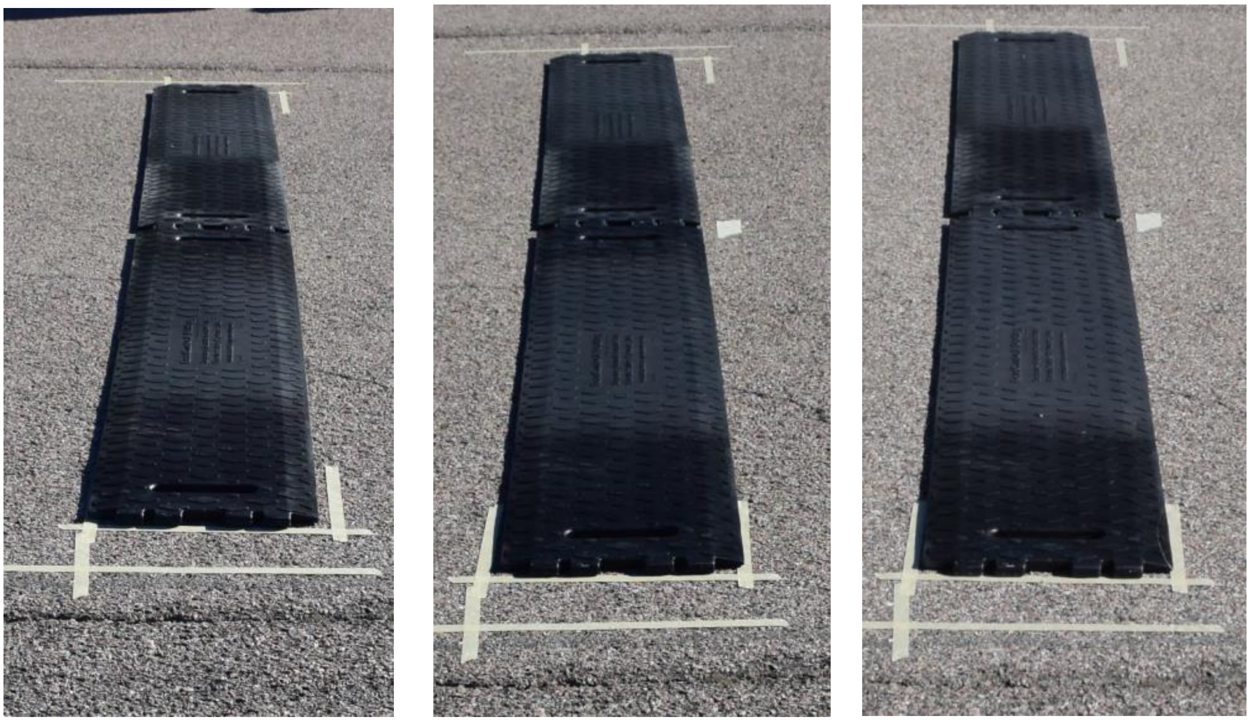
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	341.853	2	170.926	51.489	6.111E-10	3.354
Within Groups	89.630	27	3.319			
Total	431.484	29				

Table C.26 Tukey's Test on TrafFix Alert Strips Vibration Data at 45 mph

Treatment	Mean	Tukey Yardstick	Difference from 1st	Difference from 2nd
Charger	34.52	2.020034		
Chrysler	27.46	2.020034	7.06	
Fusion	27.26	2.020034	7.26	0.2

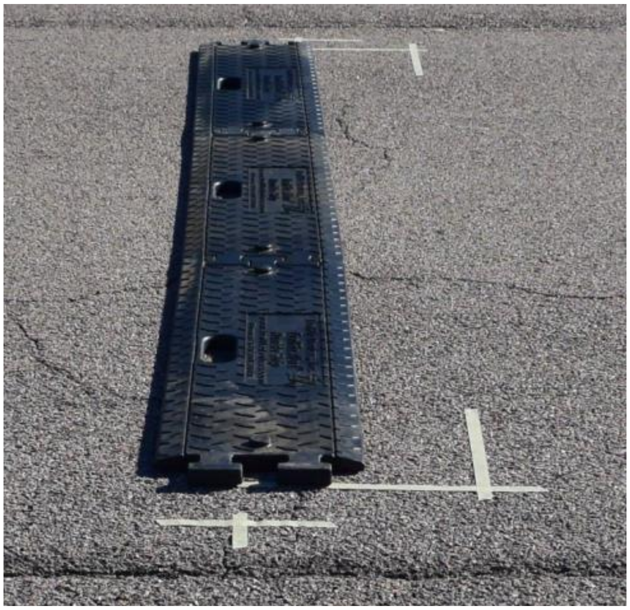
APPENDIX D (PICTURES)

Pictures: The direction of travel for all pictures is <u>from the right to the left</u>.



(a) 22.5 mph (b) 37.5 mph (c) 57.5 mph

Figure D.1 Observed Rotational and Linear Displacements in Roadquake 2F at Speeds of 22.5, 37.5 and 57.5 mph.



(a) 22.5 mph **(b) 37.5 mph**

(c) 57.5 mph

Figure D.2 Observed Rotational and Linear Displacements in TrafFix Alert Rumble Strips at Speeds of 22.5, 37.5 and 57.5 mph.

CIP strips:

Figure D.3 On K-32 near Intersection of K-32 and U.S.24/ U.S.40

Figure D.4 Sound Meter Installation at 6 ft. from Edge of Lane

Figure D.5 On Southbound 1061 near U.S.56

Figure D.6 On N 1150 Rd near Intersection of N1150 Rd and E 1000 Rd

Figure D.7 On Southbound E 1250 Rd near U.S.56