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Development of Temporary Rumble Strip Specifications

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Threshold limits for movements, rotation, and sound generation of the temporary rumble strips at each of the speeds were calculated for developing the classification table. Annual Average Daily Traffic (AADT) and Average Daily Truck Traffic (ADTT) were used in calculating threshold limits for movement and rotation, and sound threshold limits were based on CIP strips' sound data. A matrix consisting of all the classes, which incorporates various work zone conditions ranging from low-speed, low-volume to high-speed, high-volume work zone conditions was developed. This matrix in combination with the classification table provides a basis for a recommended method of 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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PREFACE

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

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Abstract

The objective of this study was to develop specifications for portable reusable temporary rumble strips for their applications in different work zone settings in Kansas. A detailed literature review, a survey of practice, and a closed-course test were performed regarding temporary rumble strips. Additionally, data from permanent cut-in-place (CIP) rumble strips at six locations in Kansas were collected. All commercially available portable reusable temporary rumble strips were tested at once in a closed-course setting using a standard dump truck and a full-size car. The rumble strips' rotational movement, linear movement, and sound produced by a traversing vehicle were chosen as parameters in developing the decision matrix. Measurements of the strips' linear and angular movements and sound 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 67.5 mph. 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 movements, rotation, and sound generation of the temporary rumble strips at each of the speeds were calculated for developing the classification table. Annual Average Daily Traffic (AADT) and Average Daily Truck Traffic (ADTT) were used in calculating threshold limits for movement and rotation, and sound threshold limits were based on CIP strips' sound data. A matrix consisting of all the classes, which incorporates various work zone conditions ranging from low-speed, low-volume to high-speed, high-volume work zone conditions was developed. This matrix in combination with the classification table provides a basis for a recommended method of 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.

Acknowledgements

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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, including asphalt temporary rumble strips and adhesive-backed temporary stick-down type rumble strips, in their ability to stay in their installed position without the use of adhesives, depending on their weight and friction with the road surface.

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, 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. A closed-course study testing commercially-available portable reusable temporary rumble strips was conducted. Movement, rotation, and sound generation of all the available rumble strips were tested at different pre-designated speeds for developing class intervals for the matrix. Additionally, cut-in-place (CIP) permanent rumble strips' sound data were gathered from six locations in Kansas for standardizing the sound threshold limits.

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, and sound generation of the temporary rumble strips were studied. As a part of this research, known 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:

- Determine the threshold values for movement and rotation of the temporary rumble strips at various speeds that would be suitable for determining acceptable field performance;
- Determine threshold limits for generated sound at various speeds when compared to permanent 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 objective of this research is to develop a classification matrix to help determine which current and future portable reusable rumble strips are suitable for which various combinations of roadway volumes and approach speeds.

1.2 Work Plan

This research was divided into a work plan consisting of seven different tasks. The following are the seven tasks followed for this research: a summary of previous research studies with detailed literature review, a survey of practice, field data collection and reduction, analysis, development of matrix, and preparation of report.

The literature review is presented in Chapter 2, the survey summary in Chapter 3, the field test and data collection are presented in Chapter 4, analysis in Chapter 5, and the development of matrix is presented in Chapter 6. Conclusions and final thoughts are provided in Chapter 7.

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 helps in developing the specifications as well as 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). The orange rumble strips used for the test were manufactured as 73-ft rolls with a thickness of 0.125 inches. 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. Meyer evaluated the removable rumble strips and their application against the existing norm of putting up cold-mix asphalt rumble strips at highway work zones. The tests were carried out on a rural bridge repair project in western Kansas, where the posted speed limit for the work zone was 30 mph on a highway with a normal speed limit of 65 mph. The removable strips were installed on the 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 (18 strips in total), were installed upstream of the standard asphalt rumble strips, with each strip placed at a distance of 1 ft apart. Vehicles with less than 5 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 inches 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 to use a double layer.

Fontaine, Carlson, and Hawkins (2000) also evaluated the effectiveness of adhesive orange rumble strips made by ATM. 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, which were placed at spacing of 18 inches parallel to each other and perpendicular to the road. Light Detection and Ranging (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 inches wide, and about 0.15-0.25 inches in thickness. These were attached to the pavement by the adhesive backing, 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 7-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 was more visible compared to conventional rumble strips.

Manjunath, Virkler, and Sanford Bernhardt (2002) also evaluated the effectiveness of the Rumbler. The study was conducted in 2001 on a work zone section of US-65 in Springfield, Missouri. They evaluated the device effectiveness on three criteria: the ability to reduce the mean speed and speed variance of vehicles, the ease of installation of the device, and durability. Speed data were collected in the northbound 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 confidence 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 considerable wear and tear. The data collected did not reveal any significant reductions in the mean speeds.

2.2 Comparison Studies

Horowitz and Notbohm (2005) conducted evaluation tests on existing temporary rumble strips to identify the optimal strip for work zones. The researchers carried out a psychological scaling experiment on a group of anonymous drivers to evaluate temporary rumble strips compared to CIP rumble strips. The team tested the Recycled Technology, Inc. (RTI) rectangular rumble strips, which can be installed on the pavement without the use of an adhesive, and ATM rumble strips, which use 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 7 ft apart. The RTI strips of 0.75-inch 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 of the 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. Both the RTI and ATM strips had not shown any major deterioration, but the RTI strips had displaced a little when speeds began exceeding 47 mph. The researchers concluded that the ATM strips were effective as a warning device when traversed at speeds more than 55 mph but were ineffective at speeds lower than 40 mph. The RTI strips were found to be effective in acting as a warning device for speeds ranging from 10 to 40 mph but they began to be displaced from their installed locations at higher speeds.

2.3 Multi-Rope Temporary Rumble Strips

Tests were conducted in the Canadian province of Saskatchewan to evaluate the effectiveness of the multi-rope rumble strips at work zones (Wyatt, 1998). The device used for this study consisted of a series of rumble ropes about 1.25 inches 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 the 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. 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 inches wide and 1.25 inches 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, Hale, Taghavi, Olafsen, and Mathur (2006) as prototypes and were reused by Schrock et al. for this research. The narrow rumble strips were 4 ft long, 4 inches wide, and 1.25 inches in thickness, while the wide rumble strips were 6 inches 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 inches compared to that of 1.1 inches for the wide rumble strips. This limitation in vertical displacement has confined the lateral movement in the narrow strip to a lesser extent than 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 this 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. As the rumble strips were relatively new to the market at the time of the test, various configurations, with changes in spacing (3 to 6 ft) 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 of 45, 53, and 60 mph. The in-vehicle vibration was measured with a triaxial accelerometer. The data collected included vehicle vibrations and sound generated by the vehicles. A least significant difference (LSD) test was conducted at 95 percent confidence level, 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 and 85.0 dB, while for the cars the values are in the range of 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 to 27.4 dB increase for cars compared to 5.7 to 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 marking 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 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 can be 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 the least movement which can be attributed to its low vertical displacement when the trucks passed over them, which the research team identified to be the most reasonable choice to install. It was also a reflection of the improvements that Plastic Safety Systems, Inc., had made among the generations of the RoadQuake.

Sun, Edara, and Ervin (2011) investigated the effectiveness of non-adhesive portable rumble strips in improving safety in highway work zones. The research team tested RoadQuake, an all-weather portable temporary rumble strip of 11-ft length, 1-ft width, and $^{13}/_{16}$ inches in thickness. 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 an angle of 60° 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 and any partial or complete centerline crossovers. The results showed that though there were no major differences in the percentage of drivers who braked between the results of angled and perpendicular rumble strips, on the positive side, these values were considerably higher when compared with no rumble strip configuration. Overall the rumble strips were effective in increasing the percentage of braking vehicles by an average of 10.5 percent and increasing speed compliance by 2.9 percent, however, they also caused an increase in 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, Schrock, Bai, and Rescot (2011). They evaluated these devices at short-term work zones in Kansas. Three chosen sites near Oskaloosa, Kansas, were used for data collection. Two sets of RoadQuakes were placed at each study location perpendicular to the road at a spacing of 36 inches on center. Tube counters and video cameras were used in data collection, which collected around 10 hours of data. An LSD test was conducted for mean speeds comparison, and grouping at a 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 by 5.0 to 11.7 mph (except for one test site with non-significant results). The research team proposed two sets of four rumble strips at 36-inch spacing to be used at short-term work zones in addition to other standard traffic control devices. The study identified about 5 percent of drivers swerving around the portable plastic rumble strips (PPRS), which led researchers to recommend additional driver information and appropriate signage alerting drivers to the presence of the rumble strips.

El-Rayes, Liu, and Elghamrawy (2013) conducted an evaluation of the RoadQuake series of rumble strips. 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, the ATM and Rumbler rumble strips, was 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 the 26-ft truck as the test vehicle, the RoadQuake strips generated a 28-dB sound level change, compared to 23- and 14-dB sound level change of Rumbler and ATM strips, respectively. The study concluded that all 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.

2.6 Summary of the Literature Review:

- Wang et al. (2011) 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 work zones.
- Sun et al. (2011) 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. 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 and increasing speed compliance by 2.9 percent; however, there was also an increase in centerline crossovers by 8.8 percent.
- El-Rayes et al. (2013) showed that the auditory stimulus generated inside the cabin of a truck was 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) 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 focuses 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 the decision matrix presented in Chapter 4.

Chapter 3: Survey of Practice

3.1 Survey Design

A regional survey was conducted asking state Departments of Transportation (besides KDOT) about their publicly 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 (DOT) 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 (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 Results

A total of 22 states responded to the survey. Responses from the states for each of the questions are discussed and summarized here; more detailed responses from each of the states are listed in Appendix A.

Question 1: Does your Department of Transportation use temporary rumble strips on state/federally funded projects?

This question refers to the state DOT's prior experience with 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.

Question 2: Are there guidance/specifications/standard drawings for using temporary rumble strips? How these were 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. The Missouri Department of Transportation had contractors state their opinions and requirements they would like to see in such a product. The Oregon Department of Transportation had consulted the previous studies and data available from other states. The Pennsylvania Department of Transportation evaluated the effectiveness of the materials used in the manufacturing of rumble strips. But the specifications developed by these states were physical specifications specifying the appearance of the rumble strip, maximum dimensions of the strip, and the places where they can be installed. Performance related specifications, the objective of this report, are yet to be developed.

Question 3: Does the DOT have an approval process for temporary rumble strips (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 Department of Transportation 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.

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?

No surveyed state has yet developed any standard inspection procedure.

Question 5: 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 multi-lane highways and in high-speed, high-volume conditions.

Question 6: 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.

3.3 Survey Summary

The survey of 22 state DOTs at the time of this study revealed the following basic facts:

- Most of the surveyed states (14 of 22) had at some point experimented with the use of temporary rumble strips, which included both the portable temporary rumble strips and the adhesive-backed strips.
- Six states in total have either included the temporary rumble strips in their approved products list or have specifications about the physical characteristics of the strips.
- The DOTs which developed specifications recommended the use of only one set/array of strips per direction of travel for installation.
- The portable rumble strips are found to be a suitable and satisfactory traffic control device for installation in advance of flagging operations, lane closure on multi-lane, detour of intersections, and ahead of a temporary signal.
- No state has yet developed performance-based specifications for temporary rumble strips.

Chapter 4: Methodology

4.1 Rumble Strips

The research team identified known 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, Inc., and TrafFix Alert rumble strips from TrafFix Devices, Inc., 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 project during the closed-course evaluation.

The RoadQuake 2F rumble strip from Plastic Safety Systems, Inc., is a folding type, one-piece design as shown in Figure 4.1. The strips rely on their weight and friction to stay intact in their place of installation. Each of the rumble strips is 11 ft long, 13 inches wide, 0.75 inches thick, and weighs 110 lbs.

The TrafFix Alert rumble strip from TrafFix Devices, Inc., is made up of three individual strips which are joined together to form one individual rumble strip of 11-ft length which weighs about 72 lbs. The three individual strips are 46.5 inches long, 12 inches wide, 1 inch thick, and connected through a jigsaw connection, as shown in Figure 4.2.

Figure 4.1: RoadQuake 2F Rumble Strips

(a) Installed TrafFix Alert Rumble Strips

(b) Close-Up of the Jigsaw Connection

Figure 4.2: TrafFix Alert Rumble Strips

4.2 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 6.1), 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 of 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. Similarly, if a rumble strip 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 of 57.5 mph or lower.

4.3 Thresholds

Variables considered in this test included movement, rotation, and sound generation. These were evaluated by comparing the test results with calculated threshold values (for relative movement and rotation) and sound (for the sound measurements) for the strips at each of the tested speeds. The threshold values for movement and rotation of strips were based on the average annual daily truck traffic, while the sound thresholds were calculated based on the results from CIP strips' sound generation. 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). Studies conducted by Schrock et al. (2010) and Wang et al. (2011) showed that the impact of trucks on the strips linear and angular displacements was much higher than that of cars. So, the research team developed the threshold values for movement and rotation based on truck traffic volumes only, rather than using total road volumes.

4.3.1 Rotational Movement Threshold

The portable temporary rumble strips rely wholly on their weight and the friction between them and the road surface to stay intact in its initial place of installation. But previous studies (Sun et al., 2011; Schrock et al., 2010) 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 safety issue, the research team came up with a numerical threshold limit for rotational movement.

The research team conducted preliminary testing at the West Park & Ride lot at the University of Kansas on three temporary rumble strips spaced 6 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, drove 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 research team came up with the rotational value of 26 degrees, above which team members found the rumble strips to be appearing “too skewed” and no longer properly placed. So, 26° was chosen as the rotational threshold value which will be useful in evaluating the rotational movement of temporary rumble strips in Chapter 5.

4.3.1.1 Calculations and Assumptions

The calculations were carried out with the assumptions that a normal short-term work zone consists of one full day with inspections carried out every four hours after the rumble strips were installed. It was assumed that a typical work zone would consist of 9 hours of work, and this would take part during daylight hours. So, the following assumptions were used for later calculations:

- Rotational threshold: no more than 26° over any 4 hours of the working day.
- Typical work zone lasts 9 hours.

4.3.1.2 Rotational Threshold for 67.5 mph

From examination of the state traffic count maps (KDOT, 2014), the annual average daily truck traffic volumes at roads with speeds above 57.5 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 to 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 average annual daily truck traffic volume = 3,000.
- Assumed that 50 percent of total traffic of the day is observed during work zone hours. So, the truck volume (during work zone hours) = 1,500.
- As determined, the maximum threshold for rotation is 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 would be 670.
- So, for a total of 670 truck passes, the rumble strips can rotate up to 26°.
- During a closed-course test, for 40 truck passes the strips should not rotate more than 1.5°.

4.3.1.3 Rotational Threshold for 57.5 mph

Heavy vehicle volumes on roads with speed limits between 37.5 and 57.5 mph were examined from the state traffic count maps (KDOT, 2014). 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 to 1,000 trucks per day and total volumes ranging from 500 to 5,000. The second type was more commonly urban arterials with total volumes ranging from 5,000 to 30,000 with low truck volumes. Passenger cars appeared to be the major contributors for these high volumes in urban arterials. In order to take these car volumes into account, a truck volume of 2,000 was chosen for calculating threshold limits at a speed of 57.5 mph. The calculations for acceptable rotation were determined as follows:

- Assumed average annual daily truck traffic volume = 2,000.
- Assuming 50 percent of total traffic of the day observed during work zone hours. So, the truck volume (work zone hours) = 1,000.
- As determined, the maximum threshold for rotation is 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 would be 450.
- So, for a total of 450 passes of trucks, the rumble strips can rotate up to 26°.
- During a closed-course test, for 40 truck passes the strips should not rotate more than 2.5°.

4.3.1.4 Rotational Threshold for 37.5 mph

Truck volumes on roads with speed limits between 22.5 and 37.5 mph were examined from the state traffic count maps (KDOT, 2014). Urban arterials, collector roads, 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 roads in urban areas experienced similar high car volumes such as arterials. In order to consider the effect of high passenger car volumes on urban roads, 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:

- Assumed average annual daily truck traffic volume = 2,000.
- Assuming 50 percent of total traffic of the day observed during work zone hours. So, the truck volume (work zone hours) = 1,000.
- As determined, the maximum threshold for rotation is 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 would be 450.
- So, for a total of 450 passes of trucks, the rumble strips can rotate up to 26°.
- During a closed-course test, for 40 truck passes the strips should not rotate more than 2.5°.

4.3.1.5 Rotational Threshold for 22.5 mph:

Truck volumes on roads with speed limits below 22.5 mph were examined on the state traffic count maps (KDOT, 2014). Low-volume rural road and city street volumes were considered for determining the threshold limits. The volumes on these roads ranged from 0 to 3,000 and the truck traffic ranged between 0 and 500. Because of the wide variety of local and urban roadways 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:

- Assumed average annual daily truck traffic volume = 1,000.
- Assuming 50 percent of total traffic of the day observed during work zone hours. So, the truck volume (work zone hours) = 500.
- As determined, the maximum threshold for rotation is 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 would be 230.
- So, for a total of 230 passes of trucks, the rumble strips can rotate up to 26°.
- During a closed-course test, for 40 truck passes the strips should not rotate more than 5°.

4.3.2 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.

4.3.2.1 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 the shoulder lane or onto the adjoining lane.

4.3.2.2 Relative Displacement

The longitudinal movement thresholds were based on 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 4.3, 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.

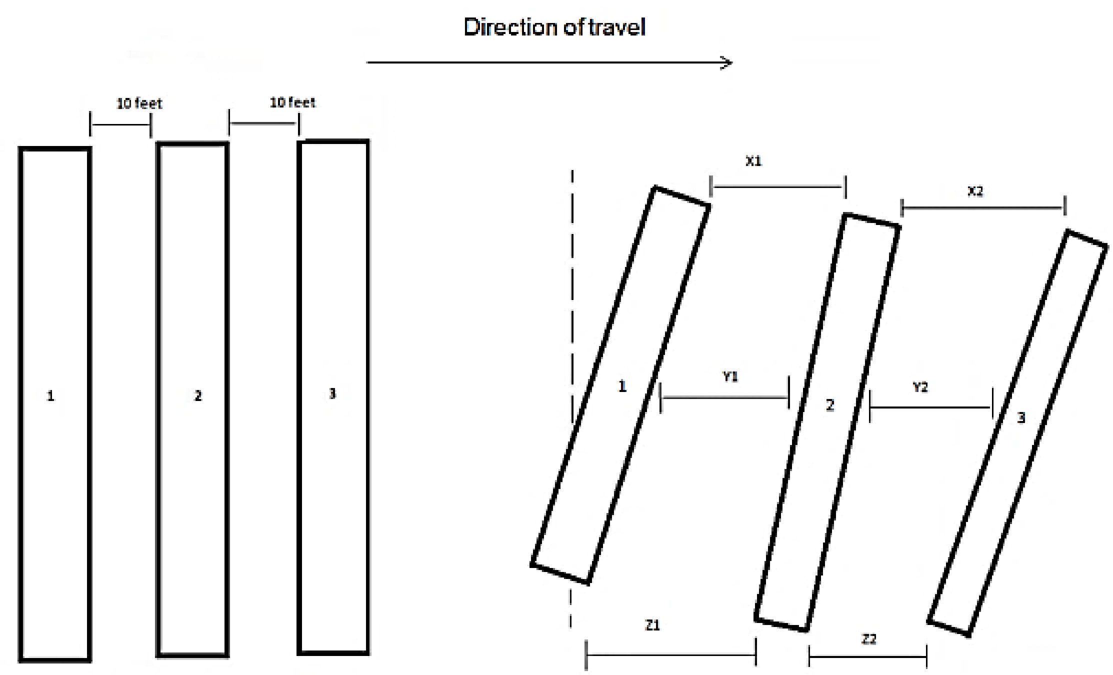

Figure 4.3: Relative Displacement

4.3.2.3 Longitudinal Movement Threshold

The longitudinal movement thresholds were determined by taking into account the inspection procedure followed by the work zone crew adjusting the rumble strips' position every 4 hours. The threshold for longitudinal movement was determined from previous studies conducted on these rumble strips, survey results, and practices followed by other states regarding maximum movement thresholds. The average longitudinal movement for each strip relative to the others was determined not to be more than 8 inches between two inspections.

Calculations

The maximum longitudinal threshold value for the rumble strips is 8 inches at a normal work zone between two inspection periods. Using this basic threshold value, the maximum limit for longitudinal movements was 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 inches and volume calculations identical to the rotation calculations from Section 4.3.1 of this report.

For 67.5 mph

For 670 truck passes, the strips can move up to a maximum of 8 inches. So, for 40 truck passes, the strips should not move more than 0.5 inches.

For 57.5 mph

For 450 truck passes, the strips can move up to a maximum of 8 inches. So, for 40 truck passes, the strips should not move more than 1 inch.

For 37.5 mph

For 450 truck passes, the strips can move up to a maximum of 8 inches. So, for 40 truck passes, the strips should not move more than 1 inch.

For 22.5 mph

For 230 truck passes, the strips can move up to a maximum of 8 inches. So, for 40 truck passes, the strips should not move more than 1.5 inches.

4.4 Closed-Course Test

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, with one being a standard full-size passenger car shown in Figure 4.4 and the other a standard tandem-axle dump truck as shown in Figure 4.5, with front and rear axle loads of 18,000 and 20,000 lbs, respectively. The test was carried out on October 30 and 31, 2014, with one test vehicle used each day. The vehicles traveled at speeds of 22.5, 37.5, 57.5, and 67.5 mph in order to create class intervals for developing specifications. The race track section provided a length of 4,200 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 4.4: Standard Full-Size Car

Figure 4.5: Standard Tandem-Axle Truck Used for the Test

The portable rumble strips available on the market (see Chapter 1) 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 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 at 10 ft from each other, as shown in Figures 4.6 and 4.7. The two different types of rumble strips were spaced at 25 ft apart to provide separation of the sound recordings and to make sure 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 4.8 shows the overview of the setup at Heartland Park, Topeka. The vehicles traversed 40 times over the rumble strips at each speed for measuring movement and rotational variations from the strips initial position 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 – Viewed Longitudinally

(b) Rumble Strip Layout – Viewed Laterally

(c) Rumble Strip

Figure 4.6: Layout of RoadQuake 2F Rumble Strips

(a) Rumble Strips Layout – Viewed Longitudinally

(b) Rumble Strip

Figure 4.7: Layout of TrafFix Alert Rumble Strips

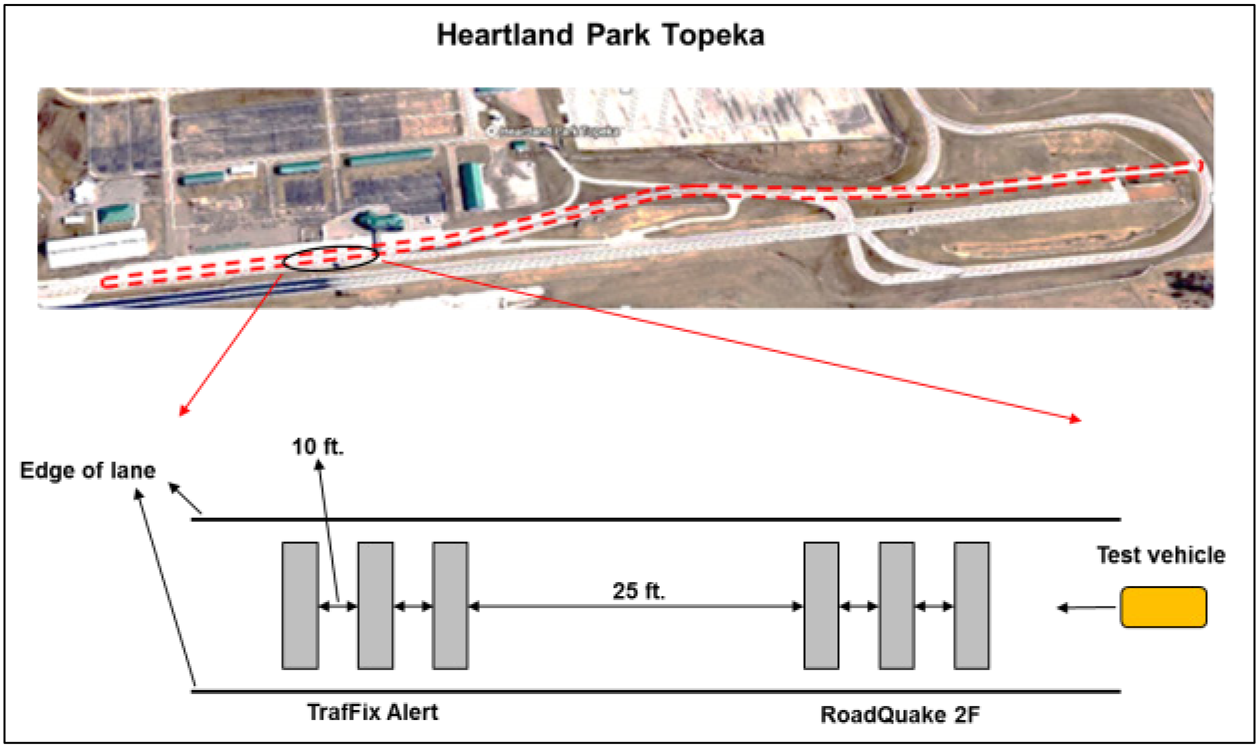

Figure 4.8: Overview of the Closed Course Study Setup

A sound meter was used to measure sound generated by vehicles passing over the rumble strips as shown in Figures 4.9 and 4.10. The sound level meter measured frequency-weighted sound pressure levels, giving the output in dB-SPL (decibels-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 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., 2013; Miles & Finley, 2007). But the design of the car and the insulating materials used for the construction of cars increase the variability in sound produced inside 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 10 measurements was collected for each type of rumble strip at each of the speeds. The sound meter was positioned 6 ft away from the edge of lane facing the center of the three middle rumble strips of each type.

(a) Brüel and Kjær Sound Meter (b) Sound Meter Mounted on a Tripod

Figure 4.9: Sound Meter

Figure 4.10: Arrangement of Sound Meter at Closed-Course Facility

In order to standardize the test, the baseline sound measurements from the permanent CIP rumble strips were collected from six locations as shown in Table 4.1. These locations were all in Douglas County, Kansas. The sound meter was placed identically as in the case of the closed-course study for measuring sound readings. At each of the locations, three passes were made with a 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 find the difference of sound in decibels due to the presence of rumble strips.

Table 4.1: 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

Chapter 5: Analysis

5.1 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 is 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 5.1. 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 both edge points. The lateral measurements were recorded as positive if they moved left with respective edge points and negative if the strips moved right with respect to the strips' initial edge position. The difference of longitudinal movements between two strips was calculated to obtain relative displacements. From Figure 5.2, X1 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 5.2, the average movement observed in the set of strips to the left side is $\left|\frac{(X_1-10)+(X_2-10)}{2}\right|$. 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.

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 5.1 to 5.8.

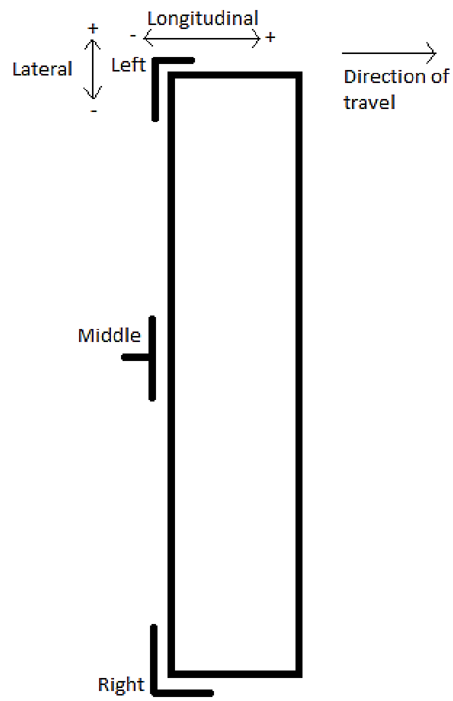

Figure 5.1: Rumble Strip Movement Measurement

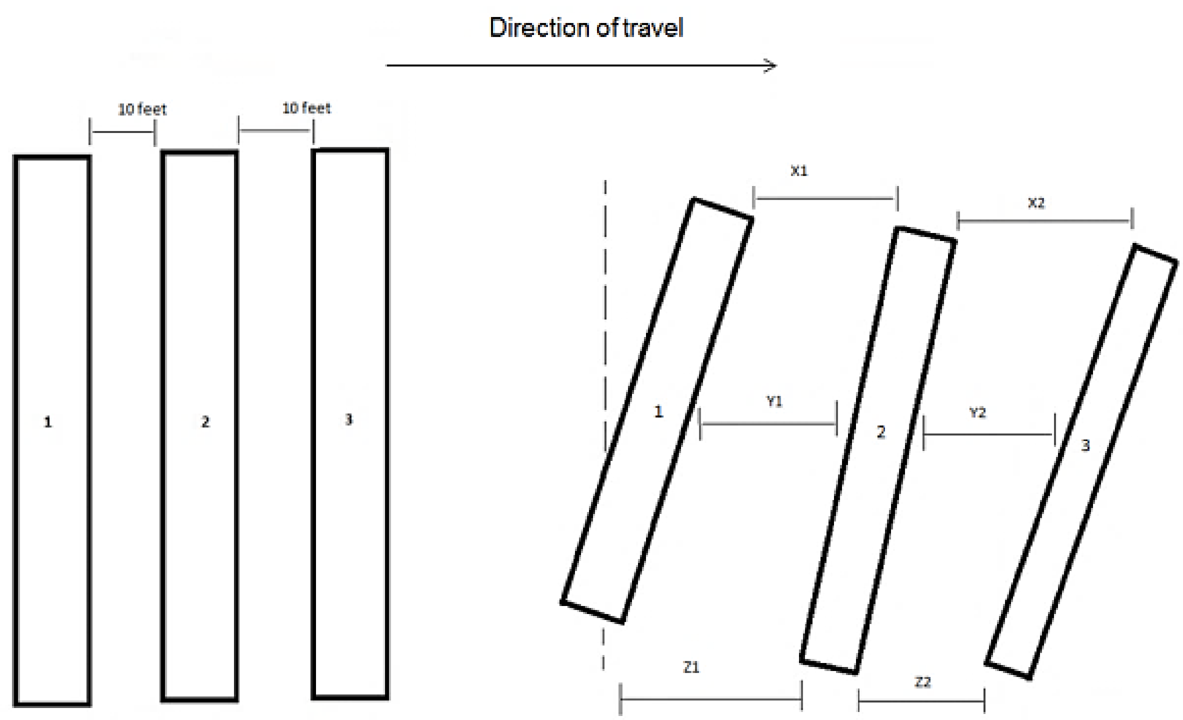

Figure 5.2: Relative Displacement

Table 5.1: Movement Due to Truck Passes at 22.5 mph

Rumble Strip	Speed: 22.5 mph	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

Table 5.2: Movement Due to Truck Passes at 37.5 mph

Rumble strip	Speed: 37.5 mph	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 5.3: Movement Due to Truck Passes at 57.5 mph

Rumble Strip	Speed: 57.5 mph	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	5	9.5

Table 5.4: Movement Due to Truck Passes at 67.5 mph

Rumble Strip	Speed: 67.5 mph	Right (in.)	Middle (in.)	Left (in.)
RoadQuake 2F	Average Relative Displacement (in.)	0.19	0.31	0.44
TrafFix Alert	Average Relative Displacement (in.)	29	13.88	-8.5

Table 5.5: Movement Due to Car Passes at 22.5 mph

Rumble Strip	Speed: 22.5 mph	Right (in.)	Middle (in.)	Left (in.)
RoadQuake 2F	Average Relative Displacement (in.)	0.063	-0.063	0
TrafFix Alert	Average Relative Displacement (in.)	0.438	-0.375	-0.938

Table 5.6: Movement Due to Car Passes at 37.5 mph

Rumble Strip	Speed: 37.5 mph	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 5.7: Movement Due to Car Passes at 57.5 mph

Rumble Strip	Speed: 57.5 mph	Right (in.)	Middle (in.)	Left (in.)
RoadQuake 2F	Average Relative Displacement (in.)	0.13	0	-0.063
TrafFix Alert	Average Relative Displacement (in.)	0.31	0.56	0.38

Table 5.8: Movement Due to Car Passes at 67.5 mph

Rumble Strip	Speed: 67.5 mph	Right (in.)	Middle (in.)	Left (in.)
RoadQuake 2F	Average Relative Displacement (in.)	0	-0.13	-0.19
TrafFix Alert	Average Relative Displacement (in.)	1.19	1.75	2.13

5.2 Rotation

Rotation of the rumble strips was calculated with respect to the left edge using trigonometry. The length of the rumble strips and the longitudinal movements observed were used in calculating the angle to which the rumble strips rotated from their initial position. Strips rotating in the counterclockwise direction 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, with the results shown in Tables 5.9 and 5.10.

Table 5.9: Rotation of Strips Due to Truck Passes

Rumble Strip	**Speed (mph)**			
	22.5	**37.5**	**57.5**	**67.5**
Roadquake 2F	0.02°	1°	0.85°	1.1°
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 of that strip, and then averaged with the two strips that remained intact.

Table 5.10: Rotation of Strips Due to Car Passes

Rumble Strip	**Speed (mph)**			
	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°

5.3 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 base roadway condition (no rumble strips present) was evaluated for temporary and CIP rumble strips to observe the relative change.

Sound measurements were recorded when the vehicle passed over the rumble strips. At each of the speeds of 22.5, 37.5, 57.5, and 67.5 mph, 10 measurements were recorded for each set of rumble strips. In addition, sound of the vehicle was also measured at each of these speeds without any rumble strips installed to understand the change in sound level due to the rumble strips. Peak sound level observed during each pass is taken into consideration for analysis.

5.3.1 Sound Data for Truck Passes

The sound data were observed to determine if there was 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 5.11 summarizes the average sound decibel readings observed from the 10 truck passes traversing the temporary rumble strips at each of the speeds.

Table 5.11: Sound Generated by Truck Passes

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

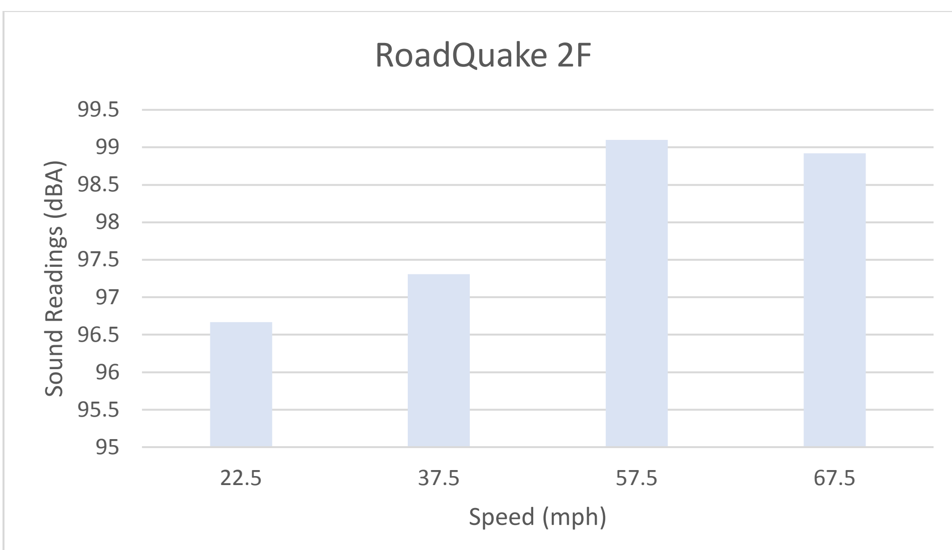

Figure 5.3: Change in Sound Level for Truck Traversing RoadQuake 2F Rumble Strips

Figure 5.4: Change in Sound Level for Truck Traversing TrafFix Alert Rumble Strips

Figures 5.3 and 5.4 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 to 57.5 mph and then decreased slightly for 67.5 mph. For the TrafFix Alert data it can be seen that 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 conducted 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 5.12 and 5.14 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 does not provide which values significantly differ 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 5.13 and 5.15 showed that the sound levels produced at different speeds by truck passes were not significantly different from each other for both 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 the speed comparison between 22.5 and 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 5.12: 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 5.13: 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 5.14: 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 5.15: 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

5.3.2 Sound Data for Car

A total of 80 sound-level readings were collected for car passes. All the readings were measured in decibels. Table 5.16 summarizes the average sound decibel readings observed from 10 car passes traversing the temporary rumble strips at each of the speeds.

Table 5.16: Mean Sound Generated by Car Passes

Rumble Strip	Speed (mph)			
	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. Figures 5.5 and 5.6 show 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 3 decibels.

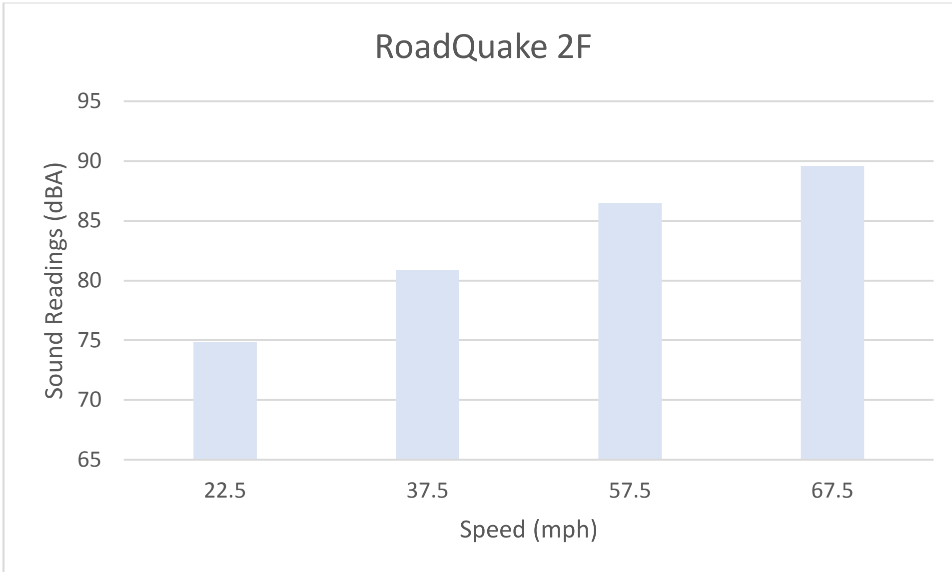

Figure 5.5: Change in Sound Level for Car Traversing RoadQuake 2F Rumble Strips

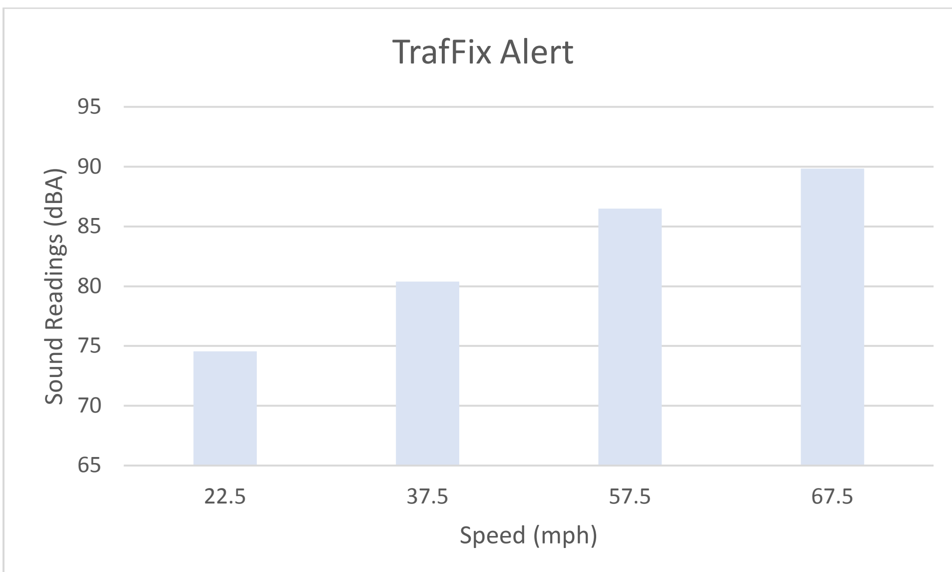

Figure 5.6: Change in Sound Level for Car Traversing TrafFix Alert Rumble Strips

A statistical analysis of the data included the one-way ANOVA test, which showed that there were significant differences among the values. See Tables 5.17 and 5.19 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 types of rumble strips, the differences in mean sound decibel levels were statistically significant.

Table 5.17: One-Way ANOVA – Mean Sound Levels at Different Speeds versus Car on RoadQuake 2F Strips

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	43.014	1263.42075	3	421.14025	258.66359	2.09499E-24
Within Groups	59.246	58.613	36	1.628138889		
Total	102.26	1322.03375	39			

Table 5.18: 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 5.19: One-Way ANOVA – Mean Sound Levels at Different Speeds versus Car on TrafFix Alert Strips

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1369.737	3	456.579	415.3025418	5.69041E-28	2.866265551
Within Groups	39.578	36	1.099388889			
Total	1409.315	39				

Table 5.20: 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 and car passing indicated that the data from the car was more promising and consistent with an observed speed versus sound relation. Due to the inconsistent results from the truck's sound data, the threshold limits for sound generation were based only on the passenger car's 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.

CIP strips at six different locations (Table 4.1) were used in collecting cars' sound generation at each of the speeds. At each speed, three sound measurements were made at each of the six locations. These different types of CIP strips, whose widths and depths varied slightly from location to location, gave the research team diverse sound data which then were averaged to get a more standardized sound decibel value reflective of CIP rumble strips in Kansas.

Table 5.21 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 was not seen as a detriment if they made more noise. Therefore, a sound level of 3 decibels below the average CIP strips sound level was established as a lower threshold limit, whereas an upper threshold limit was not specified.

Table 5.21: 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	83.85	82.38 – 85.46	80.9	2.95	80.4	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

Chapter 6 discusses the decision matrix and the classification tables with threshold limits for various parameters at tested speeds. Based on the information from the classification table and the decision matrix, the performance of both types of tested strips, the class in which they belong, and the work zones where they can be installed are discussed in Chapter 7.

Chapter 6: Development of Decision Matrix

From the established threshold values for the variables like 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 easily able to be collected in straightforward and repeatable measures using basic equipment and vehicles:

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

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

The decision matrix shown in Figure 6.1 specifies the class to which a particular temporary 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 to 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 6.2, and so on for the remaining classifications shown in Figures 6.3 to 6.5. It is intended that a product that achieves a Class 1 rating would be allowed for use on any Kansas roadway, but that lower classes would be limited in their applications so as not to exceed the criteria for that class.

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 a heavy vehicle and a full-size passenger car. Assuming at a 67.5 mph speed after 40 passes, the strips stayed within the edges of the lane (laterally), moved a distance of 1 inch (relative displacement), rotated 2°, and produced an average sound decibel value of 89 dB. From Figure 6.2, the classification table for a speed of 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 the performance criteria set for a Class 1 rumble strip product. Similar comparisons of rumble strip 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 is suitable.

The matrix has annual average daily traffic (AADT) and average daily truck traffic (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. 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. The research team came up with this condition because the movement of temporary rumble strips depends both on the speed of the vehicle and the 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, the top right corner for each class is the criteria for which the temporary rumble strips are tested, which is a high-speed high-volume condition.

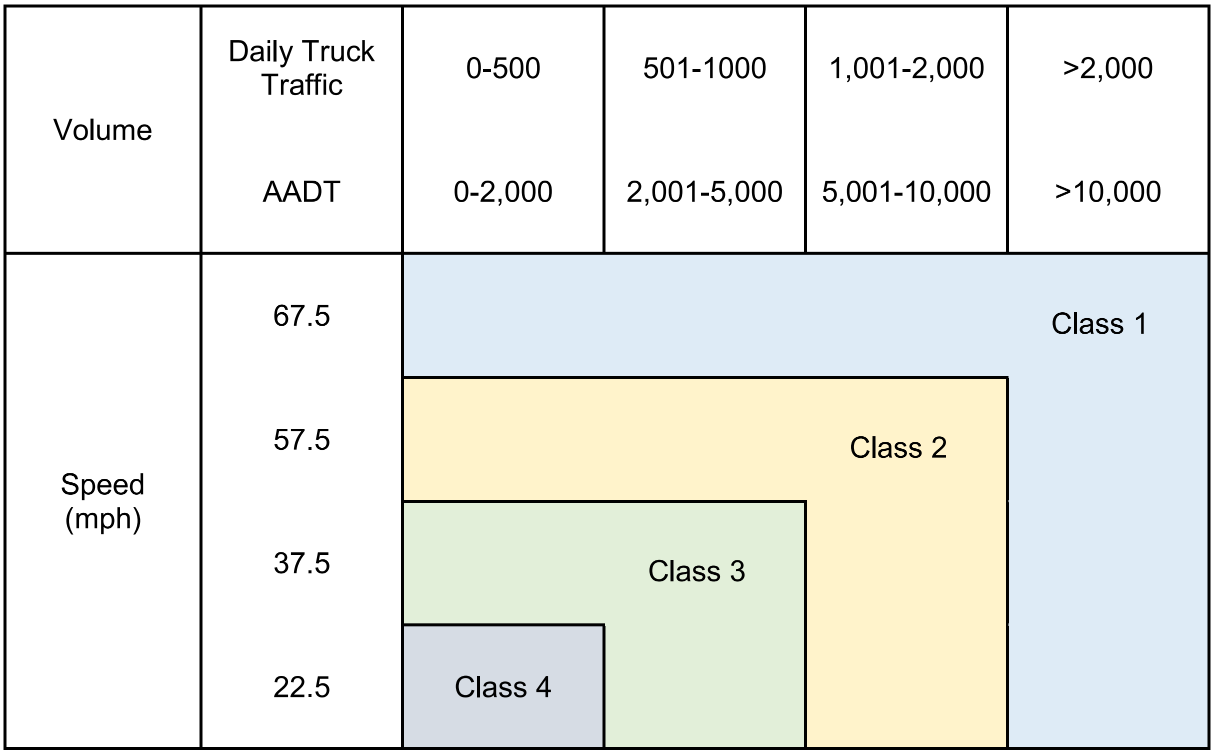

Figure 6.1: Decision Matrix

At the time of this report, as per KDOT standard, three temporary rumble strips were installed as a set. If KDOT standards change to include more or fewer strips in one installation, the process could be modified to reflect the change in the number of strips. The concept of calculating the average of the relative movements between strips would still be a valid approach to determining how the rumble strips would perform.

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.

To qualify as a Class 1 device, the tested rumble strip needs to successfully pass the following procedure:

Procedure:
• On a clean and dry surface, place three rumble strips spaced as per manufacturer's recommendation, centered in a 12-ft lane at a closed-course facility that will safely allow vehicles to traverse the strips at speed.
• Traverse the strips with a standard dump truck (nominal maximum rated axle weights of 18,000 lbs and 20,000 lbs, respectively) 40 passes at 67.5 mph.
    o Measure relative movement and rotation as described in this report.
• Reset the strips and repeat the test using a standard full-size passenger car.
    o Measure sound levels for 10 of the passes using an electronic sound measuring device.
    o 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:
    o The average relative displacements of the left end, midpoint, and right edge of the set of strips move less than 0.5 inches; and
    o Average rotation of the strips is less than 1.5°; and
    o The ends of the strips do not leave the traveled lane; and
    o Each of the three units remain in one piece.
• For the car portion of the test:
    o The average relative displacements of the left end, midpoint, and right edge of the set of strips move less than or equal to 0.5 inches; and
    o Average rotation of the strips is less than 1.5°; and
    o The ends of the strips do not leave the traveled lane; and
    o The average peak sound (L_{eq}) generated when traversing the strips is at least 89 dB.

Figure 6.2: Classification Table to Support the Decision Matrix for Class 1 Device

To qualify as a Class 2 device, the tested rumble strip needs to successfully pass the following procedure:

Procedure:
• On a clean and dry surface, place three rumble strips spaced as per manufacturer's recommendation, centered in a 12-ft lane at a closed-course facility that will safely allow vehicles to traverse the strips at speed.
• Traverse the strips with a standard dump truck (nominal maximum rated axle weights of 18,000 lbs and 20,000 lbs, respectively) 40 passes at 57.5 mph.
    o Measure relative movement and rotation as described in this report.
• Reset the strips and repeat the test using a standard full-size passenger car.
    o Measure sound levels for 10 of the passes using an electronic sound measuring device.
    o 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:
    o The average relative displacements of the left end, midpoint, and right edge of the set of strips move less than 1.5 inches; and
    o Average rotation of the strips is less than 2.5°; and
    o The ends of the strips do not leave the traveled lane; and
    o Each of the three units remain in one piece.
• For the car portion of the test:
    o The average relative displacements of the left end, midpoint, and right edge of the set of strips move less than or equal to 1 inch; and
    o Average rotation of the strips is less than 2.5°; and
    o The ends of the strips do not leave the traveled lane; and
    o The average peak sound (L_{eq}) generated when traversing the strips is at least 86 dB.

Figure 6.3: Classification Table to Support the Decision Matrix for Class 2 Device

To qualify as a Class 3 device, the tested rumble strip needs to successfully pass the following procedure:

Procedure:
• On a clean and dry surface, place three rumble strips spaced as per manufacturer's recommendation, centered in a 12-ft lane at a closed-course facility that will safely allow vehicles to traverse the strips at speed.
• Traverse the strips with a standard dump truck (nominal maximum rated axle weights of 18,000 lbs and 20,000 lbs, respectively) 40 passes at 37.5 mph.
    o Measure relative movement and rotation as described in this report.
• Reset the strips and repeat the test using a standard full-size passenger car.
    o Measure sound levels for 10 of the passes using an electronic sound measuring device.
    o 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:
    o The average relative displacements of the left end, midpoint, and right edge of the set of strips move less than 1.5 inches; and
    o Average rotation of the strips is less than 2.5°; and
    o The ends of the strips do not leave the traveled lane; and
    o Each of the three units remain in one piece.
• For the car portion of the test:
    o The average relative displacements of the left end, midpoint, and right edge of the set of strips move less than or equal to 1 inch; and
    o Average rotation of the strips is less than 2.5°; and
    o The ends of the strips do not leave the traveled lane; and
    o The average peak sound (L_{eq}) generated when traversing the strips is at least 79 dB.

Figure 6.4: Classification Table to Support the Decision Matrix for Class 3 Device

To qualify as a Class 4 device, the tested rumble strip needs to successfully pass the following procedure:

Procedure:
• On a clean and dry surface, place three rumble strips spaced as per manufacturer's recommendation, centered in a 12-ft lane at a closed-course facility that will safely allow vehicles to traverse the strips at speed.
• Traverse the strips with a standard dump truck (nominal maximum rated axle weights of 18,000 lbs and 20,000 lbs, respectively) 40 passes at 22.5 mph.
    o Measure relative movement and rotation as described in this report.
• Reset the strips and repeat the test using a standard full-size passenger car.
    o Measure sound levels for 10 of the passes using an electronic sound measuring device.
    o 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:
    o The average relative displacements of the left end, midpoint, and right edge of the set of strips move less than 2 inches; and
    o Average rotation of the strips is less than 5°; and
    o The ends of the strips do not leave the traveled lane; and
    o Each of the three units remain in one piece.
• For the car portion of the test:
    o The average relative displacements of the left end, midpoint, and right edge of the set of strips move less than or equal to 1.5 inches; and
    o Average rotation of the strips is less than 5°; and
    o The ends of the strips do not leave the traveled lane; and
    o The average peak sound (L_{eq}) generated when traversing the strips is at least 72 dB.

Figure 6.5: Classification Table to Support the Decision Matrix for Class 4 Device

Chapter 7: Conclusions

Both the rumble strips have performed well in their sound generating ability and their sound decibel values have fallen within the acceptable threshold limits for all test speeds. The RoadQuake strips' linear and rotational movement values were all within the threshold limits at the highest test speed of 67.5 mph and are hence classified as Class 1 portable temporary rumble strips. On the other hand, the TrafFix Alert rumble strips performed with values of linear and rotational movement within the threshold limits for the test speed of 22.5 mph and have marginally exceeded the movement threshold limit for 37.5 mph test speed. Considering the test results, the TrafFix Alert strips are classified as a Class 4 portable temporary rumble strips.

Overall, this research has shown that the impact of cars on the movement and rotation of the temporary rumble strips was low compared to that of trucks. In contrast, the sound generated by truck passes were inconsistent with no relatable relation between the speed and the sound generated, whereas the car's 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, so the research team developed the matrix and classification tables 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 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.
- Vibration that is generated to the vehicle interior by the rumble strips was originally considered as a measure to be studied based on previous literature. However, in practice this would require specialized accelerometers attached to interior components of the vehicle (the steering wheel for example). More work would 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. More research is needed before a minimum (or maximum) vibration level could be specified with confidence that it would be appropriate as well as easily-evaluated.
- 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. Regardless, 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 responses:

Alabama Department of Transportation (ALDOT)

At the time of this survey, ALDOT had used portable plastic rumble strips on a very 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 ALDOT's product evaluation board. These products were approved after a successful field test with movement as the main criteria. But specifications were not yet developed for temporary rumble strips.

Arkansas State Highway and Transportation Department (AHTD)

At the time of this survey, AHTD was evaluating temporary rumble strips. The AHTD began assessing portable plastic rumble strips temporarily 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 Department of Transportation (ConnDOT)

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

Florida Department of Transportation (FDOT)

At the time of this survey, the Florida DOT had used both portable plastic rumble strips and adhesive-type rumble strips in their projects. FDOT has an approval process for anything which has to be put out in the public right of way. But it does not mean every device is tested. In the case of temporary rumble strips, the application of the device plays an important role for the

DOT. The portable plastic rumble strips and adhesive rumble strips are used as supplemental devices in addition to a series of advanced warning signs and shall be installed and removed when the signs are 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 Department of Transportation (GDOT)

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 which are bolted down into the road surface for its intact position. They had no specifications or approval process developed for temporary rumble strips.

Iowa Department of Transportation (IowaDOT)

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, but the Iowa DOT had yet to develop specifications for their use. Based on the present installed devices performance and the public interest, the approval of the devices will take place in the future. The portable plastic rumble strips are being tested for their ability to stay in place and also for 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 type of projects; and
- Their application at work zones in advance of flagger operations.

Michigan Department of Transportation (MDOT)

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. MDOT proceeds with an 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 are inspected based on their setup and layout which includes checking the offset distances from their installation point. No particular set of criteria for inspection or frequency of inspection has 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 Department of Transportation (MnDOT)

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, as well as 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 with minimum criteria to be met, which in the case of temporary rumble strips is about their movement from their installed position. The portable plastic rumble strips were found to be suitable for installation:

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

Missouri Department of Transportation (MoDOT)

At the time of this survey, the Missouri DOT 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 signal,
- In advance of lane closures on a multi-lane roadway, and
- Work zones located on a hilly or curved terrain with sight distance issues.

Montana Department of Transportation (MDT)

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

Nebraska Department of Roads (NDOR)

At the time of this survey, NDOR 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 Department of Transportation (NHDOT)

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 Department of Transportation (ODOT)

At the time of this survey, the Oklahoma DOT used temporary rumble strips in their projects, but was 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 for how they work at different speeds with an upper speed limit of 40 mph. The portable plastic rumble strip 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, in the future the DOT was positive about implementing the portable plastic rumble strips in highway high-speed work zones.

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 strip manufactured by Plastic Safety Systems, Inc., would be evaluated based on its ease to transport, its durability, and its effect on motorcycles. Based on their performance, the devices were expected be approved to the Qualified Product List (QPL). The QPL list at present contains two portable plastic rumble strips for alerting drivers entering work zones 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 Department of Transportation (ODOT)

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 Oregon 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 at 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, such as 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 multi-lane highways, the strips' performance on such roads was undermined due to their movement and the task of repositioning them.

Pennsylvania Department of Transportation (PennDOT)

At the time of this survey, PennDOT had used both the adhesive and portable plastic temporary rumble strips in their projects. PennDOT had developed specifications for their use, which were based on in-house testing done by their maintenance crew on their movement and 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 Department of Transportation (SCDOT)

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 an Interstate repair project. As they were implemented on a temporary basis, there have not been any specifications developed for these strips.

Tennessee Department of Transportation (TDOT)

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

Vermont Agency of Transportation (VTrans)

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

Virginia Department of Transportation (VDOT)

At the time of this survey, the Virginia DOT was using portable plastic rumble strips on an experimental basis in 4-5 districts. They had not used the adhesive-backed rumble strips. One set of specifications had been developed. The 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 material or the weight of the portable plastic rumble strips was given as a factor and its application. The procedures for inspection have not been developed yet. The current application of portable plastic rumble strips was limited to:

- Work zones in advance of flagger operations.

Washington State Department of Transportation (WSDOT)

At the time of this survey, WSDOT 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 WSDOT recommending both 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 WSDOT had plans to implement them at work zones:

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

West Virginia Department of Transportation (WVDOT)

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 Department of Transportation (WYDOT)

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

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

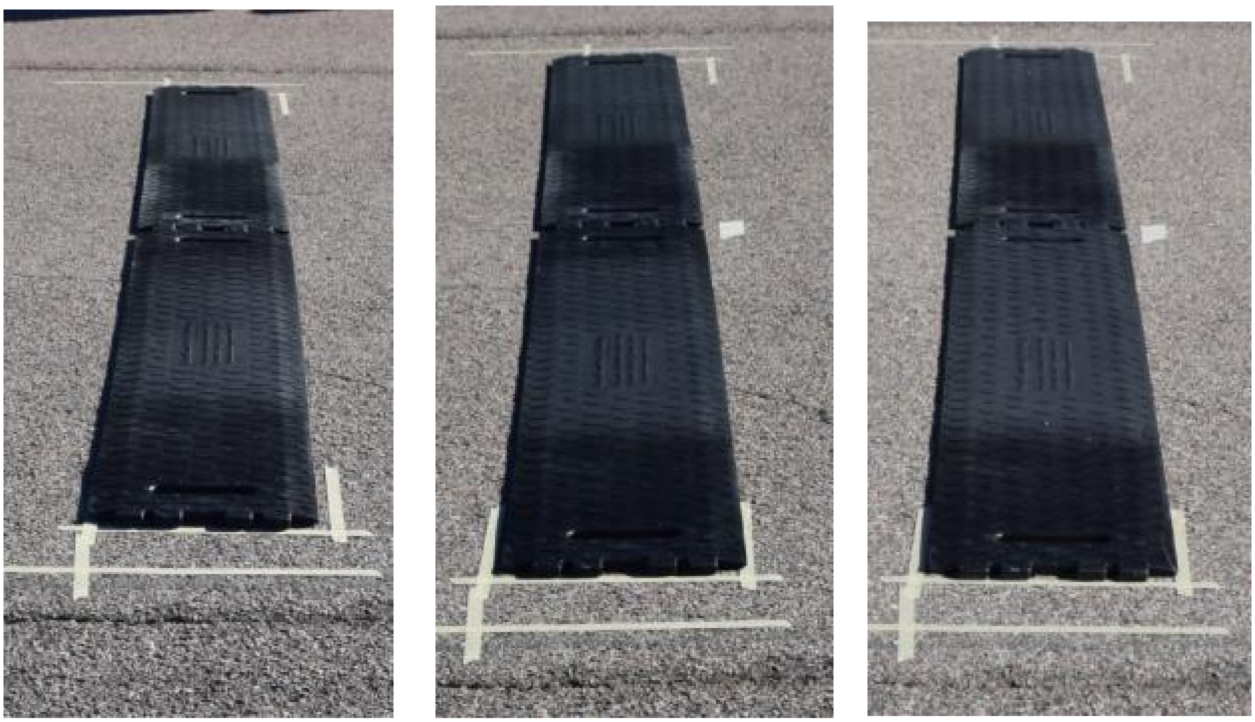
US-56 and US-59 Northbound				
Rumble Strip	**22.5 mph**	**37.5 mph**	**57.5 mph**	**67.5 mph**
CIP Rumble Strips	80.7	87.2	92.6	95.9
	77	87.2	92.2	95.9
	77.3	87.1	93.4	92.3

Northbound 1061 at US-56				
Rumble Strip	**22.5 mph**	**37.5 mph**	**57.5 mph**	**67.5 mph**
CIP 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

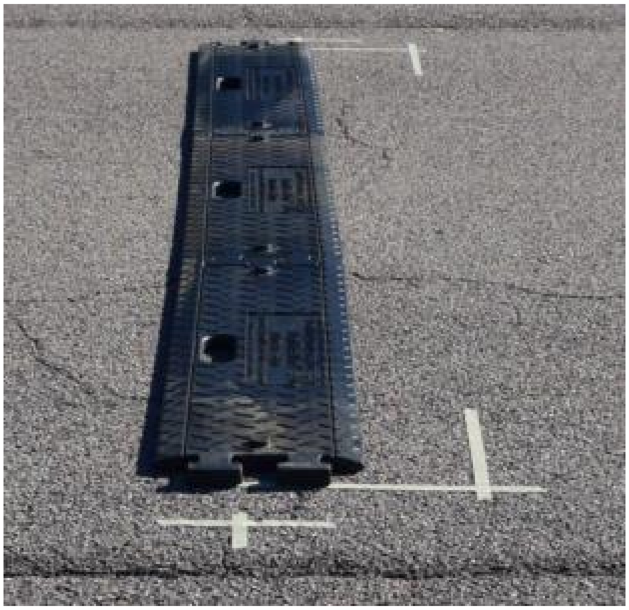
Appendix C: Pictures

The direction of travel for all pictures is from the right to the left.



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

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

Figure C.3: CIP Strips on K-32 Near Intersection at K-32 and US-24/US-40

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

Figure C.5: CIP Strips on Southbound 1061 Near US-56

Figure C.6: CIP Strips on N 1150 Rd Near Intersection at N 1150 Rd and E 1000 Rd

Figure C.7: CIP Strips on Southbound E 1250 Rd Near US-56

Appendix D: Procedure Manual

This section consists of a procedure manual which can assist any testing crew with conducting a performance evaluation on any portable temporary rumble strip. The procedure manual provides instructions about the equipment to be used, closed-course test setup, and the testing procedure to be followed.

Closed-Course Test Setup

- A closed-course test location should constitute a flat section of paved roadway with length enough for the test vehicle to reach the maximum speed and decelerate after it traversed the rumble strips, which for a truck may take up to 0.75 miles. A facility such as a local race track is ideal for this.
- The location for the testing should be broomed clean to prevent any small rocks or debris from ending up under the strips.
- Test vehicles to be considered for this testing include a standard full-size passenger car and a standard tandem-axle dump truck. It is intended that some flexibility should exist in the specific vehicle chosen, and should not be make, model, or year specific.
- Test speeds are 22.5, 37.5, 57.5, and 67.5 mph.
- The strips to be tested should constitute at least one set with three strips per set.
- The spacing between the strips in a single set is per the manufacturer's recommendation.
- If more than one set of strips are tested at once, then the different set of strips should be spaced a minimum of 25 ft apart from each other to minimize the likelihood of interaction during the testing.
- The rumble strips are to be installed in such a way that they align with each other in the center of the lane, equal lengths from the lane edges. Duct tape can be used to simulate the lane edges of a 12-ft lane if the testing is done on an unstriped location.
- Once in place, duct tape should be placed in a 'plus-sign' pattern by each of the two upstream corners of each strip, and a single strip along the center of the upstream side

of each strip. These will be used as a convenient reference point to measure lateral and longitudinal movement, and will also make it easy to reset the strips to their original locations for subsequent tests.

- A sound meter needs to be installed 6 ft away from the edge of the lane facing the center of the middle rumble strip out of the three strips in a set. The sound meter needs to be capable of measuring and storing decibel level readings, and should be placed off of the ground, preferably on a tripod.
- The test should be conducted in the absence of other loud noises, such as large volumes of adjacent traffic, construction activity, or other similar noises that could confound the sound meter readings.

Closed-Course Test Procedure

- Each test vehicle conducts 40 passes at the lowest speed (22.5 mph), traversing the strips at each of the test speeds with one vehicle.
- A sample of 10 sound measurements are to be collected from the passes for each test speed.
- After 40 passes at each test speed, measure the linear and rotational movement of the strips. Longitudinal measurements are taken by measuring between two adjacent rumble strips (from the downstream left corner of the first to the upstream left corner of the next). For a set of three strips, six measurements will be needed: the left, center, and right distances between each strips.
- The relative longitudinal movement is denoted as negative if the strips tend to come closer to each other after 40 passes and positive if the strips moved away from each other. The six measurements are then averaged together.
- Lateral movements should be taken from the left-most duct tape reference point (the 'plus-sign'). For the lateral movement threshold, the strips need to stay within the lane edges.
- Rotation of the strips can either be measured directly or calculated using trigonometry based on the longitudinal and lateral measurements.

- When the measurements have been collected, reset the strips to the starting location and repeat the test with 40 more passes at the next higher speed. Keep repeating until all speeds have been tested. Then repeat the entire process again with the second test vehicle.

Data Analysis

- If not measured directly during testing, the rotation is calculated using trigonometry based on the longitudinal and lateral measurements. The rotation value reported should be the average of each strip in the set.
- The average rotation after 40 passes, average longitudinal relative displacement measured at the left, center, and right edges of the strips after 40 passes, and average sound generated from the sample of 10 measurements of the set of strips are to be taken into consideration.
- The peak sound generated from each pass is to be taken from the data recordings and the 10 readings are then averaged.
- The measured readings of the strips' performance, which include linear and rotational movement and sound generation, are then compared with the threshold values present in the classification tables. The classification tables provide the details as to the performance characteristics a set of rumble strip has to achieve to be termed as a particular class. For a set of strips to be classified as Class 1, they would have to meet each of the criteria shown in the Class 1 table of minimum requirements. If the set of strips fails to meet one or more of the criteria, it will not be classified as Class 1. Re-evaluate the set of strips using the Class 2 table, then Class 3, and finally Class 4, stopping as soon as a set of requirements is completely met.

K-TRAN

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