Effectiveness and External Noise of Transverse Rumble Strip Designs

Prepared By
Ghassan Chehab

University of Illinois Urbana-Champaign

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Effectiveness and External Noise of Transverse Rumble Strip Designs

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## Effectiveness and External Noise of Transverse Rumble Strip Designs

The report presents a case study motivated by comments and concerns from residents regarding high levels of noise originating from vehicles passing transverse rumble strips at the intersection of US-41 northbound and West Park Avenue in Highland Park, Illinois. The Illinois Department of Transportation seeks to reduce the exterior noise the rumble strips generate without compromising the safety they deliver. A review of the latest literature on the topic and state of practice by other state departments of transportation revealed the absence of an existing standard that mandates specific designs and, thus, lack of consistency among the agencies on a configuration that could be followed. To decide whether changes to the existing design are appropriate, a performance comparison with other candidate designs needs to be conducted. To that end, measurements of exterior noise levels at the rumble strips on US-41 and at the adjacent neighborhood were collected in the presence of continuous flow of traffic. The collected measurements serve as a baseline for comparison with noise emanating from modified or new transverse rumble strip designs that would be investigated for possible implementation in the future. Similar measurements were conducted for interior noise in a vehicle passing over the rumble strips at different speeds to study their effectiveness in alerting drivers of cautions ahead.

### Key Words
Transverse Rumble Strips, Noise, Traffic Safety
ACKNOWLEDGMENT, DISCLAIMER, MANUFACTURERS’ NAMES

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Members of the Technical Review Panel (TRP) were the following:

- Issam Rayyan, IDOT, TRP Chair
- John Baczek, IDOT
- Alan Ho, FHWA
- Jonathan Lloyd, IDOT
- Marshall Metcalf, IDOT
- Tim Peters, IDOT
- Vanessa Ruiz, IDOT
- Ken Runkle, IDOT
- Steve Schilke, IDOT
- Kari Smith, IDOT
- Megan Swanson, IDOT
- Janel Veile, IDOT
- Cynthia Watters, IDOT

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EXECUTIVE SUMMARY

The purpose of this project was to address citizens’ comments and concerns in relation to elevated noise levels delivered to their neighborhood from vehicles travelling over transverse rumble strips on the nearby highway US-41 in Highland Park, Illinois.

To achieve this goal, a methodology was crafted that encompassed the following objectives:

- Conduct a literature review on the latest research and state of the art on transverse rumble strips (TRS) in relation to their design, placement, and effectiveness in alerting distracted drivers to take necessary action, reducing speeds, crashes, and fatalities.

- Conduct a review of the state of practice by various highway agencies on the design, specifications, implementation, and effectiveness of transverse rumble strips in those states or regions. Alternative designs or modifications that have exhibited or were deemed promising in lowering exterior noise while maintaining required safety would be considered for future investigation and possible implementation by the Illinois Department of Transportation (IDOT).

- Measure the exterior and interior noise levels emanating from passage of vehicles over the existing TRS on US-41 and at a selected location at the nearby neighborhood. The measured noise levels would serve as a reference for comparison to those associated with new or modified designs to be implemented in the future.

A review of literature was conducted covering the latest in peer-reviewed journals, conference papers, completed and in-progress research reports, in addition to DOT specifications, standards, and design drawings. The state of practice in relation to the configuration of permanent transverse strips for 16 states, in addition to any research being conducted on the topic, were obtained. Unfortunately, the review revealed prevalent inconsistency in the configuration and implementation practices of transverse rumble strips among the reviewed states. That was not the case for centerline and shoulder strips. Additionally, federal standards and specifications provided only generic and high-level guidelines on TRS without defining specific recommendations on configuration and implementation details. Simply stated, in studying more than 16 states, no consensus on a complete set of configurations and implementation guidelines existed, except for some commonalities.

Comparison of the effectiveness among the different configurations was scarce, particularly considering the goal and conditions of this study. Considering the stated limitations, IDOT decided to conduct its own comparative study on the effectiveness of candidate configurations and implementation guidelines for the specific location on US-41 and the prevailing conditions.

In achieving the stated objective, exterior noise measurements at the location of the last rumble strip on US-41 and at the 1800 block of McCraren Road in the adjacent neighborhood were collected in the presence of normal traffic flow. Internal noise measurements were also recorded in a vehicle traveling over the rumble strips at different speeds to study their effectiveness.
Two microphones were used to collect the noise measurements: one was placed 25 ft away from the rumble strips and 5 ft higher than the surface of the pavement and the other was placed 50 ft away at a height of 12 ft. The measurements were made in continuous-flow traffic conditions, following the AASHTO TP 390-20 continuous-flow traffic time-integrated method. A weather station was used to record temperature, wind speed, and direction. A portable traffic counter and classification device was also used.

Noise measurements were recorded at US-41 using A-weighting at two intervals for different traffic volumes and speeds. Noise measurements were collected as a function of time, along with determination of the sound descriptors L10, L50, L90, and Leq. The descriptor values were higher at 25 ft by an average of 3 dBA than those 50 ft away. The average value of Leq was 84 dBA. The values of the descriptors are a function of location, vehicle speed, vehicle volume and type, ambient noise, number of lanes, weather, among other factors. They are meant to be used to compare with descriptor values measured at the same conditions, in addition to the location and configuration of measurement instrumentation and equipment used. Thus, in the context of this study, the values measured are to be utilized to serve as a baseline for comparison with values from future studies on different types of transverse rumble strips.

Noise measurements were recorded on McCraren Road over various intervals spread over two blocks, one during daytime from 12:00 p.m. to 1:30 p.m. and another at nighttime from 5:00 p.m. to 10:00 p.m. The noise measurements recorded were highly contaminated by passing vehicles on McCraren Road, airplanes flying over the location, and passing vehicles on US-41 at locations other than on the rumble strips. Minimum noise levels measured during daytime averaged 51 dBA and averaged 48 dBA during evening and nighttime. The average noise level of the rumble strips alone was 3 dBA during both day and night. Average noise level for the whole day was 54 dBA.

Additionally, internal measurements were conducted at night while driving on the rumble strips at 25, 35, and 45 mph. The baseline noise level while driving over pavement without rumble strips averaged 63 dBA, while that of driving over the rumble strips averaged 74 dBA.
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CHAPTER 1: INTRODUCTION

BACKGROUND

Transverse rumble strips are constructed in pavement to provide a warning for drivers to slow down as they approach an intersection, stop sign, traffic light, work zone, among other areas where speed reduction or a total stop are necessary. As a vehicle drives over the rumble strips, interior noise and vibrations are generated to caution the driver. However, a drawback of rumble strips is the external noise generated often causes nuisance to nearby residents (Horne et al., 2020).

Recently, residents in Highland Park, Illinois, expressed comments and concerns of noise pollution in their neighborhood from noise emitted by vehicles passing over transverse rumble strips on US-41 northbound south of the intersection with West Park Avenue. Residents have stated that the elevated noise was affecting their health and livelihood and requested that the rumble strips be removed. The Illinois Department of Transportation (IDOT) maintains that the rumble strips are necessary to ensure traffic safety, as US-41 ends in an urban road where the first intersection includes West Park Avenue. The rumble strips warn drivers to slow down as they approach the traffic light at that intersection. The existing rumble strips were constructed at the location of pre-existing ones during an overlay project in 2019. It is worth noting that the pre-existing transverse rumble strips did not seem to generate a similarly high level of noise and did not prompt similar concerns from the neighbors.

States generally handle rumble strip noise concerns by limiting their use in residential areas, applying an adhesive filler material, changing their design, or persuading residents of their safety benefits. In attempting to solve the problem at hand, IDOT has initiated this project to evaluate various transverse rumble strip designs, among other options, that would reduce environmental noise without compromising traffic safety.

GOAL AND OBJECTIVES

The overall goal of this project is to address citizen comments and concerns regarding elevated noise levels originating from vehicles traveling over transverse rumble strips on US-41 in Highland Park, Illinois.

To accomplish this goal, the following objectives are pursued: 1) a literature review that explores the various configurations, designs, and effectiveness of transverse rumble strips (TRS); the state of the art and practice; and past and ongoing related research; 2) a survey of state DOTs on the design, use, and experience with TRS; 3) collection of effective TRS designs and specifications; and 4) baseline measurements of internal and external noise at the location of the rumble strips on US-41 and on McCraren Road.
CHAPTER 2: LITERATURE REVIEW

Rumble strips are a texture added to a road’s lane width, centerline, edge, or shoulder. They are meant to alert drivers to take necessary action through the generation of noise and vibration inside the vehicle. To be effective, rumble strips must generate sufficient internal cabin noise and vibration to refocus the driver without being so loud or agitating that they trigger an undesired surprise response (FHWA, 2015). There are four types of rumble strips. Shoulder and edge rumble strips, often classified in one category, help avoid drift-off crashes. Centerline rumble strips reduce head-on and opposite-direction sideswipe collisions (NCHRP, 2009), while transverse strips warn drivers to reduce their speed as they approach a stop sign, traffic light, hidden intersection, work zone, or to produce a general calming effect. Edge and centerline rumble strips are much more widely used than transverse strips. In an extensive review of literature, very few studies tackled the aspects of transverse rumble strips in relation to other types.

OVERVIEW OF TRANSVERSE RUMBLE STRIPS

Transverse rumble strips are mainly installed on approaches to intersections, toll plazas, horizontal curves, and work zones (Yang et al., 2016). One study found that transverse rumble strips reduce vehicle speeds and crashes by 20% to 30% (Thomson et al., 2006). In another study on five intersection approaches on US-280 in Alabama, transverse rumble strips were shown to significantly reduce travel speeds and trigger earlier braking (Yang et al., 2016). Traffic safety data in 2009 revealed that 21% of all crashes and 24% of all fatalities and injury collisions occurred at signalized intersections and the most frequently occurring collisions are rear-end crashes, which illustrates the importance of TRS (FHWA, 2013). Harwood et al. (1993) suggested transverse rumble strips are effective in reducing accident types that are susceptible to correction by more than 50%, and that they be placed at locations where rear-end accidents are prevalent.

Transverse rumble strips are utilized in rural areas as a countermeasure to crashes at T-intersections and those with limited stopping distance (Fitzpatrick, 2002). Other documented uses of TRS include warning drivers of a lane change and change in travel alignment (Harwood et al., 1993).

A critical drawback of TRS, however, is the exterior noise they produce. In semi-urban or urban areas where intersections are adjacent to neighborhoods, rumble strips may generate elevated noise levels for local residents (Finley et al., 2007) and, thus, are less likely to be used (Alberta Government, 2011). This is the case in Arizona, where rumble strips are not typically placed in urban or suburban areas due to noise considerations (ADOT, 2013). Residents living adjacent to roadways in Oregon have complained to the Oregon Department of Transportation about the noise generated by TRS (Horne et al., 2020). In cases where neighborhoods lie far away from TRS locations, sound barrier walls might not be effective because noise walls are typically only most effective within approximately 200 feet of a highway and would no longer be effective at such distances. However, previous research suggests modifying TRS specifications, such as TRS placement, configuration, and design, can reduce noise pollution in nearby neighborhoods (An et al., 2016). Thus, careful balance should be maintained between reducing elevated noise in proximity of the rumble strips and providing traffic safety at hazardous locations and conditions (Alberta Government, 2011). Other
drawbacks include the risk to bicyclists and motorists, ponding and icing, and, to a lesser extent, erratic driver response.

**EFFECTIVENESS OF TRANSVERSE RUMBLE STRIPS**

For transverse rumble strips to function effectively, it is recommended that the additional ambient cabin noise level produced range from a minimum of 3 dBA to a maximum of 15 dBA (NCHRP, 2009). One study has shown that the presence of TRS on roadways adds 7 dBA to 11 dBA to the interior vehicle noise compared to that from flat road pavements (Yang et al., 2016). In North Carolina, one county installed several safety improvements, including TRS, and noted a significant crash reduction rate (Robinson, 2012). That study involved a before-and-after analysis of the installation of TRS on the intersection of State Route 1605 (Paul Payne Store Road) and State Route 1610 (Millersville Road) in Alexander County. Two fatal crashes occurred at this intersection before TRS installation, along with other elements, including stop signs, stop-ahead signs, and an overhead flash. Researchers estimate a resulting crash reduction range of 60% to 80% (Zhou et al., 2018).

To gauge the effectiveness of TRS on driver speeds, rumble strips were installed in a rural area targeting 14 approaches to intersections. An analysis of the speed data revealed a small and statistically significant decrease, generally 1 to 2 mph in mean and 85th percentile speeds on the approaches (Fitzpatrick et al., 2002). These findings echo results from a similar study conducted in Texas on TRS at various time frames during day and night conditions on both weekends and weekdays (Thomson et al., 2006). Similar to the study by Fitzpatrick et al. (2002), speed reductions of approximately 1 mph were observed at a statistically significant level of 95% (p ≤ 0.05). There were no clear indications that the transverse rumble strips had a greater or smaller impact during day, night, weekend, or weekday periods. In a research study conducted in Minnesota on the effectiveness of TRS, the speeds of 400 vehicles on 274 approaches were studied before and after the installation of TRS. Findings showed that the first set of TRS did slow down drivers by an average of 2 to 5 mph (Harder et al., 2006).

Recently, researchers in Oregon (Hurwitz et al., 2019) conducted a study to investigate the ability of reducing exterior noise from TRS by rendering them shallower using epoxy. When compared, average noise level from regular TRS dropped from 93 dBA to 88 dBA when epoxy filler was used. Other trials in the study showed that regular TRS was four times louder than epoxy-filled TRS. The study did not investigate the impact of such reduction on interior noise and resulting crashes and fatalities.

Other research studies did not support or were inconclusive regarding the effectiveness of TRS. The Transportation Association of Canada revealed after rigorous research that the “effectiveness of TRS on speed reduction ranges from minimal to no effect.” It also discourages the widespread use of TRS and adds: “Locations, such as on US-41, where there is an over representation and where conventional warning methods, such as signs and signals, are inadequate could be considered for TRS installation” (Bahar et al., 2005). Research conducted in Texas on data collected before and after 10 stop-controlled intersection sites and at 5 horizontal curve sites revealed ineffectiveness of TRS at most sites. Only in three sites did installation of TRS show speed reductions that were larger than 1 mile per hour. While the study concluded that transverse rumble strips offer a low-cost and easy-to-
install option, they “did not seem to be successful at reducing approach speeds at the project sites” (Miles et al., 2005; Carlson & Miles, 2005). Despite the low cost of this treatment, the researchers do not feel that the findings warrant widespread implementation and recommend a limited use of TRS until follow-up work determines their safety impacts.

In a study on transverse rumble strips in Minnesota, Corkle et al. (2002) mentioned that past studies of the effectiveness of transverse rumble strips have been inconclusive. The Transportation Association of Canada refers to TRS as an “extraordinary traffic control measure” to use when other methods are not successful (Bahar et al., 2005). The Ohio Department of Transportation (2014) prefers that transverse rumble strips be avoided, unless they provide a solution to excessive speed or inattention resulting in crashes at narrow or one-lane bridges, at locations with abrupt changes in vertical or horizontal alignment, and at major commercial driveways with inadequate stopping distance because of horizontal or vertical alignment.

As for ongoing research, sample projects assessing the configurations and effectiveness of rumble strips are the ongoing NCHRP 15-68 project “Effective Low Noise Rumble Strips” (National Cooperative Highway Research Program, 2022) and a research project in Minnesota (Minnesota Local Research Board, 2020), the objective of which is to assess and optimize transverse rumble strip configurations at critical rural intersections. Researchers will mainly focus on driver behavior. Three to five strips of variable designs will be constructed and studied for their effectiveness by collecting video recordings of driver behavior before and after installation.

In the review of literature, there is a noticeable lack of data on the effect of various configurations and treatments applied to TRS on crashes and fatalities as compared to centerline and edge rumble strips. This renders preference and endorsement of a specific type and configuration of transverse rumble strip for reduction of crashes and fatalities while limiting exterior noise inconclusive. More research on TRS and collection of data is needed before a high-performing configuration is favored.

**Note on Sinusoidal Rumble Strips (Mumble Strips)**

In recent years there has been a tendency to investigate and adopt the use of rumble strips with a sinusoidal cross section, often referred to as mumble strips. Mumble strip design was shown effective in California (Donavan, 2018) in reducing higher frequency noise but not narrow-band lower frequency noise that could pose nuisance to nearby residents. The internal noise generated is similar to other rumble strip configurations. These conclusions are similar to those for the Pennsylvania mumble strip design, as reported by the Minnesota DOT (2015) in their evaluation of rumble strip noise. However, a later study by Minnesota DOT (Terharr et al., 2016) showed that modifications to sinusoidal rumble strip design did improve their overall effectiveness.

It is worth noting that the effectiveness of mumble strips in reducing noise is of less importance than the risk they pose. Mumble strips have only been applied to centerline and edge longitudinal strips. There is no evidence that they have been applied for transverse strips. One of the critical obstacles that would render their implementation as transverse strips risky is their long wavelengths reaching 14” (Donavan, 2018). Ponding and icing in such large portions of the roadway creates extremely hazardous conditions.
CONFIGURATIONS OF TRANSVERSE RUMBLE STRIPS

A study for the Federal Highway Administration (FHWA) (Torbic et al., 2015) discusses the existence of various configurations of transverse rumble strips. Configurations vary in aspects such as placement, number of sets of rumble strips, number of strips per set, distance between sets, and distance between the closest set and the intersection. Other details such as dimensions of the strips and indentations are fairly consistent. There are no studies that compare the various types and details of TRS in their effectiveness to slow traffic, reduce exterior noise while maintaining sufficient internal noise, and reduce fatalities. As stated earlier, a significant number of states follow FHWA’s Manual on Uniform Traffic Control Devices for Streets and Highways (MUTCD), which does not explicitly dictate design of the strips, as shown in the verbatim excerpt at the end of this chapter. Other states do not allow the use of transverse rumble strips on roadways in suburban and urban areas.

General configurations for transverse rumble strips are provided in this section and are shown in Figure 1 through Figure 7. Specific details adopted by the states are included in the summary in Table 1 and drawings in the appendix.

**Continuous Full-lane Configuration**

In this configuration, the strips are continuous throughout the lane(s) and perpendicular to traffic, as seen in the sketch in Figure 1. The number of strips per set can vary between 5 and 25, depending on the configuration adopted by the state. The difference in the number of strips per set varies for all configurations not only for the continuous full-lane configuration.

![Figure 1. Schematic. Continuous full-lane transverse rumble strips.](image)

Where: \( L_s \) is the length of the transverse strip set in the direction of traffic, \( d_{1-2} \) is the distance between the first and the second set of strips, and \( d_{stop} \) is the distance of the first set of strips to the intersection, or a critical factor that requires speed reduction such as a work zone or change in road
characteristics. In some states, $d_{\text{stop}}$ is a function of speed or sight distance. Distances between the second strip and other strips (if available), “$n_i$,” often vary between variants of this configuration. Illinois is one state that adopts such configuration.

**Offset Full-lane Configuration**
Another type of configuration is the offset lane configuration, where the strips are continuous across one lane only. The set of strips for the other lane are offset from those of the first one, as seen in the schematic in Figure 2.

![Figure 2. Schematic. Offset full-lane configuration for transverse rumble strips.](image)

**Skewed Full-lane Configuration**
The configuration shown in Figure 3 has the strips extending to both lanes at a skew angle. Among designs of skewed strips from states sampled in this report, only a $10^\circ$ design was used by all states. Example states adopting such configuration are Kansas and Missouri.

**Wheel Path Configuration**
In this configuration, rumble strips are constructed under the vehicle wheel path only, as seen in Figure 4. New Mexico is one state that adopts this configuration.

**Alternating in-Lane Segments**
In this configuration, shown in Figure 5, segments of transverse rumble strips alternate and extend the entire lane. Oklahoma is an example state that follows such configuration.
Figure 3. Schematic. Skewed full-lane rumble strip configuration.

Figure 4. Schematic. Transverse rumble strips under the wheel path.
Cross Sections of Transverse Rumble Strips

The configurations above can be associated with a variety of cross sections. Cross sections can either be grooved in a rectangular or rounded shape. They can also be raised and have either a rectangular or rounded shape. A less common cross section is the speed table. The cross-section designs are shown in Figure 6. A relatively new design where the cross section follows a sinusoidal shape, as shown in Figure 7, has been investigated and installed on centerline and edge strips for monitoring purposes. While it has shown promising performance, it has not yet been used for transverse rumble strips.
Figure 7. Schematic. Sinusoidal cross-section design also referred to as mumble strip.

Source: Terharr et al. (2016)
Table 1. Configurations and Specifications of Transverse Rumble Strips in Various States

<table>
<thead>
<tr>
<th>State</th>
<th>Figure in Appendix</th>
<th>Sets of Strips</th>
<th>Strips Per Set</th>
<th>Distance Between Sets (ft)</th>
<th>Indentation Depth (in.) × Width (in.)</th>
<th>Distance between Indentations (ft)</th>
<th>Indentation Cross Section</th>
<th>Strip Skew Angle (°)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colorado</td>
<td>Figure 55</td>
<td>3 or 4</td>
<td>12</td>
<td>Variable</td>
<td>1/2 × 4</td>
<td>12</td>
<td>Rectangular</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Florida</td>
<td>Figure 56</td>
<td>4</td>
<td>4</td>
<td>Variable</td>
<td>1/2 × 2</td>
<td>12</td>
<td>Rectangular</td>
<td>–</td>
<td>Raised one lane</td>
</tr>
<tr>
<td>Kansas</td>
<td>Figure 57</td>
<td>3</td>
<td>25</td>
<td>100</td>
<td>3/8 × 4</td>
<td>12</td>
<td>N/A</td>
<td>10</td>
<td>Skewed</td>
</tr>
<tr>
<td>Illinois</td>
<td>Figure 58</td>
<td>3</td>
<td>25</td>
<td>200</td>
<td>1/4 × 4</td>
<td>12</td>
<td>Rectangular</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Indiana</td>
<td>Figure 59</td>
<td>6</td>
<td>6</td>
<td>Depends on sight distance</td>
<td>1/4 × 4</td>
<td>12</td>
<td>Rectangular</td>
<td>–</td>
<td>Raised</td>
</tr>
<tr>
<td>Iowa</td>
<td>Figure 60</td>
<td>2</td>
<td>N/A</td>
<td>Variable</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Maryland</td>
<td>Figure 61</td>
<td>4</td>
<td>10</td>
<td>200 then 90</td>
<td>N/A</td>
<td>4.5” or 6”</td>
<td>Rectangular</td>
<td>–</td>
<td>Raised thermoplastic</td>
</tr>
<tr>
<td>Minnesota (1)</td>
<td>Figure 62</td>
<td>5</td>
<td>6</td>
<td>6 m</td>
<td>10 mm × 150 mm (2/5”×6”)</td>
<td>300 mm (12”)</td>
<td>Rectangular</td>
<td>–</td>
<td>Under wheel path</td>
</tr>
<tr>
<td>Minnesota (2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3/8 depth Width =7”</td>
<td>12”</td>
<td>Round</td>
<td>–</td>
<td>Not clear if for transverse strip</td>
</tr>
<tr>
<td>Minnesota (3)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>14 length Depth max = 1/2</td>
<td>Continuous</td>
<td>Mumble</td>
<td>–</td>
<td>Not for transverse strips yet</td>
</tr>
<tr>
<td>Missouri</td>
<td>Figure 63</td>
<td>2</td>
<td>25</td>
<td>Depends on Speed</td>
<td>3/8 × 4</td>
<td>12</td>
<td>Rectangular</td>
<td>10</td>
<td>Skewed</td>
</tr>
<tr>
<td>State</td>
<td>Figure in Appendix</td>
<td>Sets of Strips</td>
<td>Strips Per Set</td>
<td>Distance Between Sets (ft)</td>
<td>Indentation Depth (in.) × Width (in.)</td>
<td>Distance between Indentations (ft)</td>
<td>Indentation Cross Section</td>
<td>Strip Skew Angle (°)</td>
<td>Notes</td>
</tr>
<tr>
<td>-------------</td>
<td>--------------------</td>
<td>----------------</td>
<td>----------------</td>
<td>---------------------------</td>
<td>---------------------------------------</td>
<td>-----------------------------------</td>
<td>--------------------------</td>
<td>-------------------</td>
<td>-------------------------------------------</td>
</tr>
<tr>
<td>New Mexico</td>
<td>Figure 64</td>
<td>5</td>
<td>12</td>
<td>100 ft and depends on speed</td>
<td>3/8 depth × 12 (max) radius</td>
<td>12</td>
<td>Round</td>
<td>–</td>
<td>Under wheel path</td>
</tr>
<tr>
<td>North Dakota</td>
<td>Figure 65</td>
<td>N/A</td>
<td>25 or 15</td>
<td>Variable (50–250)</td>
<td>(1/2 to 5/8) × 4</td>
<td>12</td>
<td>Rectangular</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Ohio</td>
<td>Figure 66</td>
<td>3</td>
<td>15</td>
<td>Depends on speed</td>
<td>(1/2 to 5/8) × 4</td>
<td>12</td>
<td>Rectangular</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Oklahoma</td>
<td>Figure 67</td>
<td>4</td>
<td>10</td>
<td>200 ft</td>
<td>R = 12, Depth: 1/2 to 5/8 Length = 7</td>
<td>12</td>
<td>Round</td>
<td>–</td>
<td>Alternate wheel paths</td>
</tr>
<tr>
<td>Oregon</td>
<td>Figure 68</td>
<td>3 to 5</td>
<td>6</td>
<td>Depends on speed</td>
<td>1/2 × 6</td>
<td>12</td>
<td>Rectangular</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Texas</td>
<td>Figure 69</td>
<td>5</td>
<td>12</td>
<td>Variable</td>
<td>N/A</td>
<td>24</td>
<td>N/A</td>
<td>–</td>
<td>Under wheel path or alternating</td>
</tr>
<tr>
<td>Wisconsin</td>
<td>Figure 70</td>
<td>3</td>
<td>25</td>
<td>Depends on speed</td>
<td>1/2 × 4</td>
<td>N/A</td>
<td>N/A</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>
STANDARDS FOR MEASUREMENT OF NOISE

Three standards for the evaluation of noise from pavement surfaces have been developed by the American Association of State Highway Transportation Officials (AASHTO). These include (1) the on-board sound intensity method (AASHTO T-360-16) for directly measuring noise generated at the tire-pavement interface in isolation of other noise sources, (2) the statistical isolated pass-by method (AASHTO TP 389-20) of measuring noise from isolated vehicles driving on road surfaces, and (3) the continuous-flow traffic time integrate method (AASHTO TP 390-20) of capturing the sound from existing traffic for all vehicles on all roadway lanes. Guidelines and recommendations from FHWA’s Noise Measurement Handbook (2018) are also followed, along with the very commonly adopted Manual on Uniform Traffic Control Devices for Streets and Highways (MUTCD) (FHWA, 2021).

Significant number of states adopt the MUTCD for specifications on construction of rumble strips, including TRS. Most refer to MUTCD Section 6F.84 as is, while others add slight modifications. It is thus important to present excerpts from MUTCD 6F.84 that are related to TRS in the context of the current study.

Section 6F.87 Rumble Strips

Support:
01 Transverse rumble strips consist of intermittent narrow, transverse areas of rough-textured or slightly raised or depressed road surface that extend across the travel lanes to alert drivers to unusual vehicular traffic conditions. Through noise and vibration they attract the driver’s attention to such features as unexpected changes in alignment and to conditions requiring a stop.

02 Longitudinal rumble strips consist of a series of rough-textured or slightly raised or depressed road surfaces located along the shoulder to alert road users that they are leaving the travel lanes.

Standard:
03 If it is desirable to use a color other than the color of the pavement for a longitudinal rumble strip, the color of the rumble strip shall be the same color as the longitudinal line the rumble strip supplements.

04 If the color of a transverse rumble strip used within a travel lane is not the color of the pavement, the color of the rumble strip shall be white, black, or orange.

Option:
05 Intervals between transverse rumble strips may be reduced as the distance to the approached conditions is diminished in order to convey an impression that a closure speed is too fast and/or that an action is imminent. A sign warning drivers of the onset of rumble strips may be placed in advance of any transverse rumble strip installation.

Guidance:
06 Transverse rumble strips should be placed transverse to vehicular traffic movement. They should not adversely affect overall pavement skid resistance under wet or dry conditions.
07 In urban areas, even though a closer spacing might be warranted, transverse rumble strips should be designed in a manner that does not promote unnecessary braking or erratic steering maneuvers by road users.

08 Transverse rumble strips should not be placed on sharp horizontal or vertical curves.

09 Rumble strips should not be placed through pedestrian crossings or on bicycle routes.

10 Transverse rumble strips should not be placed on roadways used by bicyclists unless a minimum clear path of 4 feet is provided at each edge of the roadway or on each paved shoulder as described in AASHTO’s “Guide to the Development of Bicycle Facilities” (see Section 1A.11).

11 Longitudinal rumble strips should not be placed on the shoulder of a roadway that is used by bicyclists unless a minimum clear path of 4 feet is also provided on the shoulder.
CHAPTER 3: CONFIGURATION OF RUMBLE STRIPS ON US-41

LOCATION

Figure 8 presents an aerial image of a section of Highland Park, Illinois. Present in the figure are US-41 and locations of the three sets of rumble strips northbound of the highway, the intersection with West Park Avenue, and the neighborhood that has voiced concerns regarding the noise emitted from the rumble strips. Table 2 documents distances between locations of interest.

Figure 8. Photo. Aerial view showing US-41, West Park Avenue, location of rumble strips, and the nearby neighborhood.
Table 2. Distances between the Three Sets of Rumble Strips and Distance to McCraren Road

<table>
<thead>
<tr>
<th>Distance</th>
<th>Measurement (ft) (0.305 m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strips 1 to Strips 2</td>
<td>240</td>
</tr>
<tr>
<td>Strips 2 to Strips 3</td>
<td>200</td>
</tr>
<tr>
<td>Strips 3 to Park Ave</td>
<td>1150</td>
</tr>
<tr>
<td>McCraren Rd. (Neighborhood) to Rumble Strips</td>
<td>~950</td>
</tr>
</tbody>
</table>

CONFIGURATION OF EXISTING STRIPS

The configuration of the new transverse rumble strips that had been constructed in 2019 comprises of three sets, each set comprising of 25 strips. The length of each set is 25 ft with 200 ft separating one set from the other. Each strip covers the whole lane transversely. The grooves are 4” wide and 1/4” deep, with an 8” gap. All grooves are constructed on a Portland cement concrete (PCC) pavement layer. Figure 9 presents a picture of one set of grooves, while Figure 10 presents a drawing with groove configuration and dimensions.

Figure 9. Photo. Newly constructed rumble strips.
CONFIGURATION OF ORIGINAL STRIPS

The original strips and new strips had been constructed at the same location. The configuration of the rumble strips prior to construction of the existing ones is presented in Figure 11. The only difference is that each set in the original configuration consisted of 20 strips with 1/2” depth, compared to the 25 strips with 1/4” depth in the new configuration.

Figure 10. Schematic. Layout and cross section of new rumble strips.

Figure 11. Schematic. Cross section of original rumble strips prior to overlay in 2019.

Figure 12 presents a picture of the original rumble strips prior to reconstruction. It is apparent that the PCC surface is polished, thus reducing the depth of the grooves from what they were at their original construction, and the grooves are filled with debris.
Figure 12. Photo. Rumble strips on US-41 prior to overlay in 2019.
CHAPTER 4: EXPERIMENTAL PROCEDURES AND SETUP

This chapter provides details of the experimental setup, describing the instrumentation, conditions, procedures, and installation locations for external as well as internal monitoring of noise from the transverse rumble strips at US-41.

PROCEDURE


External Measurements

Noise measurements for the project were conducted at locations on two separate days in 2021: November 18 at US-41 and December 3 at McCraren Road.

*Monitoring Locations*

**US-41 NB**

The location of the setup for the measurement of external noise was on the right-of-way of US-41 northbound (NB) adjacent to the third and last set of rumble strips before the intersection with West Park Avenue. Tripods for two microphones were placed on the grass of the right-of-way, to the left of the access ramp leading to the parking lot of the shopping center on the easternmost lane of US-41 NB. The first microphone was installed on a tripod 25 ft away from the center of the easternmost lane (measured perpendicular to the lane). The base of the microphone was situated at an absolute elevation of 630 ft, with the microphone set 5 ft higher than the elevation of the pavement surface of the right lane. The coordinates of the microphone were 42°11′10.55″N, 87°49′23.70″W. The other microphone was installed 50 ft away from the center of the easternmost lane. The base of the tripod was situated at an absolute ground elevation of 631 ft, with the microphone set 12 ft higher than the elevation of the pavement surface of the easternmost lane. Its coordinates were 42°11′10.72″N, 87°49′23.45″W. A phone camera was installed on a third tripod for picture and video documentation. The photo in Figure 13 presents a view of the monitoring equipment setup at the location.

**McCraren Road**

McCraren Road is a two-way local road located approximately 900 ft to the west of US-41 at the location of the rumble strips. The microphones were located at the PCC roadway pavement. The tripods were situated adjacent to the curb on the right-of-way of the western side of McCraren Road at the 1800 block. Both tripods were placed adjacent to each other, approximately 950 ft from the center of the easternmost lane of US-41 NB. The coordinates of the microphones were 42°11′5.47″N and 87°49′34.7″W with an absolute elevation of 631 ft. The photo in Figure 14 presents a view of the
monitoring equipment setup, while Figure 15 provides an aerial view showing locations of monitoring stations on US-41 and McCraren Road.

**Dates and Times of Measurements**

External noise measurements were conducted on two days in 2021: November 18 for the measurements on US-41 and December 3 for the measurements on McCraren Road. Measurements along US-41 were conducted in two intervals within 10:30 a.m. to 2:00 p.m., while intervals of measurements on McCraren Road were conducted between 12:00 p.m. to 1:30 p.m. and from 5:00 p.m. to 10:00 p.m.

**Climatic Conditions**

**US-41**

No accumulated precipitation was present on the ground or in the rumble strips during noise measurements on US-41. The temperatures recorded on-site by the weather station, which was installed 12 ft high, varied between 33°F and 35°F, with wind varying between 9 and 16 mph N-NW. The temperature recorded by the online weather service (www.weather.com) at the time of testing for Highland, Illinois, was 32°F, with wind speed measuring 9 mph.

![Figure 13. Photo. Monitoring location in US-41 with recording equipment.](image-url)
Figure 14. Photo. Sound-level meters on tripods and weather station on McCraren Road.

Figure 15. Photo. Aerial view of Highland Park showing the locations of microphones on US-41 and microphone locations on McCraren Road.
McCraren Road
Measurements at McCraren Road were conducted on December 3 at various intervals throughout the measurement period. There was no precipitation on the day of measurement nor for several days before measurement. The wind recorded by the weather station varied between 0 and 5 mph SW, while average wind recorded by the online weather service, www.weather.com, varied between 6 and 8 mph S-SW. The temperatures recorded by the weather station at 12 ft above the ground varied between a maximum of 50°F at noon and 39°F at night. This matches closely the temperatures recorded by www.weather.com.

Equipment and Devices

Tripods
Three tripods were used in this study. Two tripods supported the sound meters and weather station. The first tripod, set 5 ft high, supported the CEM-8551 microphone, and the other, set at 12 ft, supported the PCE-430 microphone and the weather station. The third tripod was used to support the phone.

Weather Station
A Taylor 2752N portable wireless weather station (Figure 16) was used to measure air temperature, wind speed, and direction. It transfers measured data through Bluetooth to a digital display that can be placed as far as 500 ft away. The weather station was fixed on top of the 12 ft tripod with the display unit at ground level, handy for readout and documentation measured data.

Sound-level Meters
Noise measurements were obtained using two sound-level meters: Class 1 PCE-430 and Class 2 CEM-8551.

PCE-430
The Class 1 PCE-430 sound-level meter meets relevant American National Standards Institute (ANSI) and International Electrotechnical Commission (IEC) requirements with octave band filtering, both 1/1 and 1/3. The PCE-430 also acts as a data logger, recording measurements on a microSD card and eliminating the need for connection to a laptop during measurements. The device measures from 22 to 135 dBA at a frequency of 3 Hz to 20 kHz. It features A, B, C, and Z frequency weightings. Measurements were recorded every 0.1 seconds. A windscreen was used to eliminate any noise from wind. A 30 ft extension cable was used to connect the microphone placed 12 ft high on the tripod with the sound meter and display unit at ground level. The microphone was placed at normal incidence. Figure 17 presents the PCE sound-level meter device.

CEM-8551
The CEM-8551 is a Class 2 sound-level meter meeting major IEC and ANSI standards. The device can cover a frequency range of 31.5 Hz to 8 kHz with a dynamic range of 50 dB. It has an A/C frequency weighting with a 1/2” condenser microphone. It does not have data storage capabilities; thus, it has to be continuously connected to an accompanying software on a computer. Measurements were
recorded every 0.5 seconds. The CEM-8551 sound-level meter was fixed to the 5 ft tripod. The microphone was placed at normal incidence with a wind screen. Figure 18 presents the CEM-8551 sound-level meter device.

Figure 16. Photo. Taylor portable wireless weather station.

Figure 17. Photo. Class 1 PCE-430 sound-level meter.
Traffic Counter
IDOT installed a portable traffic counter on US-41 on poles north of the rumble strips for vehicle count and classification, as presented in Figure 19. Vehicle counts were made available for every 15-minute period from 6:00 a.m. to 6:00 p.m. Traffic was classified as passenger cars (four tire), medium trucks (SU), and heavy trucks (MU).

Sound Calibrator
A sound-level calibrator, PCE-SC 09, that is compatible with both Class 1 and Class 2 meters was used after every noise-measurement round to calibrate both the PCE-430 and CEM-8551. This ensures accuracy of ±0.3 dB for each meter and consistency in measurements between both sound meters. Calibration was done at a sound pressure level of 94db for weighting filter A.

Camera
Videos and images were taken during noise measurements at US-41. The camera used was that of an iPhone 12 Pro.
Figure 19. Photo. Portable traffic counters on poles on US-41 NB after the rumble strips.

Laser Level
A laser level meter was used to determine the appropriate height of the microphones relative to the road surface.

Laptop
A Dell Latitude 7410 with Core I7 processor and 16 GM RAM was used for collection, analysis, and storage of the CEM-8551 measurements.

Laser Speed Gun
A Bushnell laser speed gun, presented in Figure 20, was used to measure the speed of incoming vehicles as they approach the last set of rumble strips.

Vehicle
The car used for measurement of internal noise was a 2021 Volkswagen Atlas SUV (Figure 21). The tires were Force UHP 36 255/50R20 with inflation pressure of 36 psi (250 kPa). The gross weight of the vehicle is approximately 5,800 lb. The car was driven by the principal investigator of the project.

Internal Measurements
Internal noise measurements were recorded using the PCE-430 sound meter. The sound meter was fixed firmly to the center console. The vehicle did not have noise-canceling technology, and all windows were closed. The radio, flashers, signals, air conditioner, heating, and other sources of internal noise were shut off. The only noise heard internally other than that from the tire-pavement interaction was engine noise and noise emanating from nearby vehicles.
Figure 20. Photo. Laser speed gun.

Figure 21. Photo. 2021 Volkswagen Atlas SUV used in internal noise measurement procedure.
CHAPTER 5: NOISE MEASUREMENTS

The chapter provides the external and internal noise measured by both sound meters, along with elaboration on the synchronization of measurements between both sound meters and establishment of baseline measurements.

SYNCHRONIZATION OF NOISE MEASUREMENTS

The two sound-level meters, PCE-430 and CEM 8551, were synchronized following a manual procedure. A noise event produced from an air horn served as a trigger that marked a common starting point for recorded noise measurements on both sound-level meters. As presented in Figure 22, the recorded external noise measurements from the two sound-level meters overlap. The microphone at 25 ft recorded higher noise signals than that at 50 ft due to its proximity to the rumble strips and lower height. Figure 23 provides 100 seconds of the noise signals for better resolution. The trough that begins at 190 seconds, ends at 210 seconds, and dips to 57 dBA corresponds to a period during which no vehicles were traveling in both directions of US-41 at the measurement location and its proximity. It was the lowest noise level recorded during the measurement intervals. The time synchronization between both microphones is very discernable.

Figure 22. Graph. Time synchronization between the PCE-430 microphone at 50 ft away and the CEM-8551 microphone at 25 ft away.
TRAFFIC CHARACTERISTICS ON US-41

As stated previously, IDOT provided counts and characterization of traffic from 6:00 a.m. to 6:00 p.m. on November 18, 2021, the day of noise measurement on US-41. Data was collected every 15 minutes. Collected traffic data for a specific interval such as from 11:45 a.m. to 12:00 p.m. was used to obtain traffic data corresponding to the noise measurement period from 11:50 a.m. to 12:00 p.m., as presented in Table 3. As presented, 317 vehicles passed by during the first measurement interval from 11:50 a.m. to 12:00 p.m., while 566 vehicles passed by during the second measurement interval from 12:40 p.m. to 1:00 p.m. The overall hourly traffic distribution over the whole day is presented in Figure 24.

Table 3. Collected Traffic Data with Necessary Adjustments for the Various Measurement Intervals

<table>
<thead>
<tr>
<th>Traffic Data</th>
<th>Period 1</th>
<th>Passenger</th>
<th>SU</th>
<th>MU</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collected</td>
<td>11:45 a.m. to 12:00 p.m.</td>
<td>434</td>
<td>16</td>
<td>26</td>
<td>476</td>
</tr>
<tr>
<td>Adjusted</td>
<td>11:50 a.m. to 12:00 p.m.</td>
<td>289</td>
<td>11</td>
<td>17</td>
<td>317</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Traffic Data</th>
<th>Period 2</th>
<th>Passenger</th>
<th>SU</th>
<th>MU</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collected</td>
<td>12:30 p.m. to 12:45 p.m.</td>
<td>391</td>
<td>13</td>
<td>16</td>
<td>420</td>
</tr>
<tr>
<td>Collected</td>
<td>12:45 p.m. to 1:00 p.m.</td>
<td>400</td>
<td>15</td>
<td>11</td>
<td>426</td>
</tr>
<tr>
<td>Adjusted</td>
<td>12:40 p.m. to 1:00 p.m.</td>
<td>530</td>
<td>19</td>
<td>16</td>
<td>566</td>
</tr>
</tbody>
</table>

Figure 23. Graph. Time synchronization between the PCE-430 microphone at 50 ft away and the CEM-8551 microphone at 25 ft away, measured between 150 to 250 seconds from start of recording.
Figure 24. Graph. Hourly traffic distribution over 24 hours on November 18, 2021.

BASELINE MEASUREMENTS

Exterior Measurements

US-41
Developing a baseline for noise measurements is necessary to determine the noise generated from sources other than ambient, or non-rumble strip, noise. The baseline for external noise recorded on US-41 corresponded to ambient noise, in the absence of noise generated from vehicles passing over any of the rumble strip sets.

McCraren Road
On McCraren Road, recorded noise measurements were considered as a baseline when all the following applied:

- No vehicles were traveling on McCraren Road, not only in the proximity of the microphones, but also approximately 1000 ft away in both directions as they approach or leave the noise-monitoring location.
- No pedestrians were walking on the sidewalk.
- No dogs were barking.
- No sound was heard from lawn mowers or leaf blowers.
- No low-passing aircrafts were in the sky.
All such noises reduced or masked the measurements emanating from the rumble strips on US-41. The dominant source of disruptive noise was cars driving on McCraren Road. The noise was particularly high because the PCC pavement is not in good condition and emitted relatively loud noise generated from vehicle tires striking the edges of the uneven PCC slabs and from the rough pavement surface, as depicted in Figure 25.

**Internal Measurements**

As for internal noise inside the test vehicle, measurements recorded before and after driving on the rumble strips were regarded as baseline.

![Figure 25. Photo. Rough PCC surface and uneven slabs on McCraren Road.](image)

**SOUND-LEVEL DESCRIPTORS**

In comparing noise levels from the same measurement event or across events, it may not be enough to compare average noise levels and maximum and/or minimum peaks. Each sound profile is characterized by sound-level descriptors calculated over a specific measurement interval, as presented in Figure 26. The following sound-level descriptors will be used as the basis for characterizing noise measurements over a period, as per FHWA (2017):
• **L10** is a statistical descriptor of the sound level exceeded for 10% of the time of the measurement period.

• **L50** is a statistical descriptor of the sound level exceeded for 50% of the time of the measurement period.

• **L90** is a statistical descriptor of the sound level exceeded for 90% of the time of the measurement period. “Where the noise emissions from a source of interest are constant (such as noise from a fan, air conditioner or pool pump) and the ambient noise level has a degree of variability (for example, due to traffic noise), the L90 descriptor may adequately describe the noise source” (FHWA, 2017).

• **Leq**, time-equivalent sound level, is a descriptor that “accounts for noise fluctuations from moment to moment by averaging the louder and quieter moments, and giving more weight to the louder moments. It represents the equivalent continuous sound pressure level over a given period of time” (FHWA, 2017).

![Graph](image_url)

**Figure 26.** Graph. Sound descriptors characterizing a sound profile as a function of time.

*Source: FHWA (2017)*

**EXTERNAL NOISE MEASUREMENTS**

**Measurements on US-41**

Noise measurements on US-41 were conducted during two intervals on November 18. All noise measurements correspond to the average values recorded by the sound meter. The first interval
spanned from 11:50 p.m. to 12:00 p.m., while the other interval spanned from 12:40 p.m. to 1:00 p.m. Two microphones were used. The PCE-430 sound meter was fixed atop the 12 ft tripod, 50 ft away from the center of the right lane facing the third set of rumble strips; the CEM-8551 sound meter was fixed atop the 5 ft tripod, 25 ft away. Both were placed at zero incidence.

The first interval was characterized by relatively low traffic count and high vehicle speed traveling over the rumble strips. The radar gun registered speeds up to 50 mph, 10 mph higher than the posted speed limit. The second interval was characterized by relatively slower, about 40 mph, and heavier traffic. In the later afternoon and evening hours, traffic was extremely heavy and slow, at times backing up to the proximity of the rumble strips.

Figure 27 provides noise measurements recorded over 10 minutes of the second interval from the microphone placed 25 ft away. The minimum noise recorded is close to 70 dBA with minimum peaks reaching below 65 dBA, while maximum peaks ranged from 85 to 90 dBA. As seen from such noise profile, it is difficult to discern the individual sound waves from measured noise unless the observation period is shortened. Figure 28 presents the sound waves over 40 seconds to enable visualization of the sound waves. One can observe sets of three waves with, to some extent, similar time and amplitude. Those waves likely correspond to the noise emanating from the three sets of rumble strips with amplitudes ranging from 5 to 7 dBA. While this analysis procedure helps identify noise events from rumble strikes, measuring the exact amplitude of all waves is time consuming and lacks precision. This illustrates the need to use sound descriptors to compare one noise profile to the other and derive accurate conclusions.

Figure 27. Graph. Measurements for time interval 2 from the microphone 25 ft away.
Figure 28. Graph. Measurements for time interval 2 from 210 seconds to 250 seconds recorded from 25 ft away.

Figure 29 through Figure 32 exhibit recorded noise measurements for time intervals 1 and 2 at US-41 from both microphones at 25 and 50 ft away, respectively. In addition to the noise recordings, the sound-level descriptors are included on the plots and presented in Table 4. The noise levels range predominantly from low levels of 70 to 75 dBA to high levels of 85 to 90 dBA. The average amplitudes of the sound waves range approximately from 15 to 20 dBA. These values are close to those measured by other researchers on highways with and without rumble strips, albeit for different levels and type of traffic, number of lanes, and speed. For example, FHWA (2015) cites measured noise levels at 50 ft offset and 5 ft high without and with rumble strips of 70 and 84 dBA, respectively.

The sound descriptors for interval 1 corresponding to both microphones are plotted in Figure 33, while those for interval 2 are plotted in Figure 34. As expected, all descriptors corresponding to the 5 ft high microphone that is 25 ft away are larger than those at 50 ft away and 12 ft high. The L10 descriptor is most affected by location of the microphone, where the one at 25 ft measured 4 dBA higher than the one at 50 ft. The L90 was the one least affected, with differences not exceeding 1 to 2 dBA. Both the L50 and the Leq measured 2 to 3 dBA higher for the 25 ft microphone.

It is worth observing that L50 for all cases range from 78 to 80 dBA, with Leq ranging from 83 to 85 dBA for the 25 and 50 ft microphones, respectively, indicating that Leq is not necessarily equal to the average or to L50. The difference between L10 and Leq for 25 ft away is 4.4%, which is slightly higher than the maximum of 3% recommended by FHWA. The difference at 50 ft away is 2.3%, which is below the recommended percentage (FHWA, 2018).
The values of the descriptors are a function of location vehicle speed, vehicle volume and type, ambient noise, number of lanes, weather, among other factors. They are meant to be used to compare with descriptor values measured at the same conditions, in addition to the location and configuration of measurement instrumentation and equipment used. The sound descriptors determined in this study cannot be compared to sound descriptors for other highways in other locations and conditions. Values from literature on studies similar to this are not only scarce, but also inapplicable. The measurements for such studies are conducted in the presence of continuous flowing traffic as per AASHTO T390-20, the continuous-flow traffic time-integrated method. Thus, in the context of this study, the values measured are to be utilized to serve as a baseline for comparison with values from future studies on different types of transverse rumble strips. The sound descriptors can be used to measure noise pollution and compared with thresholds to determine compliance with noise and environmental regulations.

Some studies have measured the effect of different types of TRS, speed, and vehicle type on interior and exterior noise, but those studies were conducted on a probe vehicle with no traffic, according to AASHTO T-389-20, the isolated pass-by method. In such cases it is appropriate to conduct various comparisons on TRS. One such study by Hurwitz et al. (2019) in Oregon studies the effect of epoxy-filled TRS.

Figure 29. Graph. Noise measurements for a 10-minute period from interval 1 measured 25 ft away along with sound-level descriptors.

\[
\begin{align*}
\text{Leq} & \quad \text{L90} & \quad \text{L50} & \quad \text{L10}
\end{align*}
\]
Figure 30. Graph. Noise measurements for a 10-minute period from interval 1 measured 50 ft away along with its sound-level descriptors.

Figure 31. Graph. Noise measurements for a 10-minute period from interval 2 measured 25 ft away along with its sound-level descriptors.
Figure 32. Graph. Noise measurements for a 10-minute period from interval 2 measured 50 ft away along with its sound-level descriptors.

Figure 33. Graph. Sound-level descriptors from interval 1 for both microphones plotted together. For every descriptor, the noise levels recorded 25 ft away were higher than those 50 ft away.
Figure 34. Graph. Sound-level descriptors from interval 2 for both microphones plotted together. For every descriptor, the noise levels recorded 25 ft away were higher than those 50 ft away.

Table 4. Sound-level Descriptors (dBA) for Interval 1 and 2 25 ft and 50 ft Away

<table>
<thead>
<tr>
<th>Interval</th>
<th>Distance</th>
<th>Leq</th>
<th>L90</th>
<th>L50</th>
<th>L10</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25</td>
<td>84</td>
<td>70</td>
<td>80</td>
<td>89</td>
</tr>
<tr>
<td>2</td>
<td>25</td>
<td>85</td>
<td>72</td>
<td>80</td>
<td>89</td>
</tr>
<tr>
<td>Avg</td>
<td>25</td>
<td>85</td>
<td>71</td>
<td>80</td>
<td>89</td>
</tr>
<tr>
<td>1</td>
<td>50</td>
<td>82</td>
<td>69</td>
<td>77</td>
<td>84</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>84</td>
<td>71</td>
<td>78</td>
<td>86</td>
</tr>
<tr>
<td>Avg</td>
<td>50</td>
<td>83</td>
<td>70</td>
<td>78</td>
<td>85</td>
</tr>
</tbody>
</table>

Noise Measurements on McCraren Road

Noise measurements were recorded on McCraren Road over various intervals spread over two blocks, one during daytime from 12:00 p.m. to 1:30 p.m. and another at nighttime from 5:00 p.m. to 10:00 p.m. The two microphones were placed adjacent to each other at the curb on the western side of the 1800 block of McCraren Road. Measurement of noise from the rumble strips was contaminated by various noise sources, the major ones being:

1. Passing of vehicles on McCraren Road: The noise was particularly high due to the proximity of passing vehicles on McCraren Road given that the microphones were placed at the curb 10 ft away from the travel lane. The noise was exacerbated by the rough pavement surface and uneven PCC slabs. Measurement started at 785 seconds from start of recording at 12:15 p.m. Figure 35 presents a fingerprint of a noise wave corresponding to a passing vehicle, with a noise amplitude of approximately 20 dBA and a period of 30 seconds. The noise effect of vehicles starts about 20 seconds prior to the peak and subsides around 20 seconds after the peak, depending on the speed of the vehicle and...
ambient noise. The peak occurs at the location of the microphones, with vehicles often slowing down to observe the noise-measuring setup. The presence of other noise sources, speed, and type of vehicle, among other factors, will slightly change characteristics of the noise wave.

![Graph]

**Figure 35.** Graph. Measured noise wave of passing vehicles on McCraren Road starting 785 seconds from 12:15 p.m.

2. **Airplane noise:** Noise from passing airplanes, both light airplanes flying at low elevations and heavy airplanes flying at higher elevations, was high enough to contaminate the noise measurements. Figure 36 presents a noise wave from an airplane flying over McCraren Road. The noise amplitude is about 18 dBA with a period of 130 seconds. Similar to the case of the passing vehicle above, the characteristics of the airplane noise wave is specific to this case and can vary depending on the various conditions mentioned earlier, in addition to airplane type and its elevation.

3. **Passing of vehicles on US-41:** The passing of vehicles on US-41 in both directions was relatively loud and contributed to elevating the ambient noise. This should be expected given that US-41 is among the busiest routes in Highland Park and its vicinity, as observed in Figure 37. The white circle points to the intersection of US-41 and West Park Avenue.

The noises above were prevalent throughout the day and evening time. Noise from vehicles on US-41 started to subside at nighttime around 8:00 p.m. Noise from passing vehicles on McCraren Road and airplanes started to subside around 9:00 p.m. In the absence of passing vehicles or airplanes, the minimum noise levels ranged from 45 to 50 dBA.
Figure 36. Graph. Measured noise wave of airplane flying over on McCraren Road starting 785 seconds from 12:15 p.m.
Figure 37. Map. Traffic noise map for Highland Park and its vicinity.

Source: Bureau of Transportation Statistics (2020)
With the highly contaminated noise at McCraren Road from passing vehicles and airplanes producing high peaks with respect to ambient noise levels, applying sound-level descriptors would lead to erroneous results, particularly in the context of this study. As witnessed in Figure 38, there are at least 10 vehicles and planes passing by in a span of 15 minutes. *The plotted peaks in the figure match the timing of passing vehicles or planes, as observed at the measurement location.* The notations in the upcoming figures refer to a vehicle as “V,” plane as “P,” and rumble strip as “R.”

As observed, the noise from vehicles and planes are significantly higher than those from the rumble strips.

![Graph of noise measurements at McCraren Road](image)

**Figure 38.** Graph. Noise measurements at McCraren Road recorded 12 ft high from 12:15 p.m. to 12:30 p.m., where “P” corresponds to planes, “V” to vehicles, and “R” to rumble strips.

Figure 39 presents a noise measurement interval spanning from 5:15 p.m. to 5:35 p.m. The interval is highly contaminated with vehicle and aircraft noise. Taking advantage of an uncontaminated period from 110 to 170 seconds, one observes from Figure 40 that the resulting noise profile contains several sets of three consecutive peaks with similar noise amplitudes ranging from 3 to 5 dBA with a period of 5 to 10 seconds. Such characteristics constitute a fingerprint of noise from the rumble strips, as discussed previously and presented in Figure 28. Additionally, the timing of the noise waves matches the time that rumble strip noise was heard and documented at McCraren Road (at 2 to 3 minutes after start of recording). Figure 41 presents noise period ranging from 320 to 400 seconds. As can be observed, the transverse rumble strip amplitudes average 3 dBA; whereas a vehicle passing on McCraren Road registers a noise amplitude of more than 25dBA, which is significantly higher than that of the rumble strips. High noise amplitudes produce more noise pollution than lower ones, such as those of the rumble strips.

Figure 42 presents another noise measurement interval from 8:10 p.m. to 8:35 p.m. The large number of peaks recorded correspond to heavy aircraft passing above the measurement location.
Similar to the previous measurement interval, the noise of vehicles passing over the rumble strips on US-41 could be heard during periods when vehicles on McCraren Road or airplanes were not present. Focusing on a part of that time window, Figure 43 presents the noise measurements recorded from 125 to 145 seconds after start of recording. One could observe two sets of three noise waves, each with a period of 7 seconds and amplitudes ranging from 2 to 4 dBA. Figure 44 provides another noise signal heard at McCraren Road that could be attributed to rumble strips. It can be witnessed by plotting from 150 seconds of start of recording to 158 seconds, with noise amplitudes averaging 5 dBA. Similarly, by plotting from 880 to 892 seconds, as presented in Figure 45, a fingerprint of rumble strip noise is discernable with an 8 second period and a range of 5 to 8 dBA noise amplitude. Such amplitudes were among the highest measured for the various intervals. Although the amplitudes of the noise from TRS is relatively low with respect to those from vehicles and planes, they do raise the minimum level of noise at night from the upper 40 dBA range to the low 50 dBA level.

Figure 39. Graph. Noise measurements at McCraren Road 12 ft high from 5:15 p.m. to 5:35 p.m.
Figure 40. Graph. Noise measurements at McCraren Road 12 ft high from 5:15 p.m. to 5:35 p.m. plotted from 110 to 170 seconds from start of recording.

Figure 41. Graph. Noise measurements at McCraren Road 12 ft high from 5:15 p.m. to 5:35 p.m. plotted from 320 to 400 seconds from start of recording.
Figure 42. Graph. Noise measurements at McCraren Road recorded 12 ft high from 8:10 p.m. to 8:35 p.m.

Figure 43. Graph. Noise measurements at McCraren Road 12 ft high from 8:10 p.m. to 8:35 p.m. plotted from 125 sec to 145 sec from start of recording.
Figure 44. Graph. Noise measurements at McCraren Road 12 ft high from 8:10 p.m. to 8:35 p.m. plotted from 145 sec to 165 sec from start of recording.

Figure 45. Graph. Noise measurements at McCraren Road 12 ft high from 8:10 p.m. to 8:35 p.m. plotted from 880 sec to 892 sec from start of recording.
The last interval spanned 9:00 p.m. to 9:20 p.m. with very limited contamination from passing vehicles and airplanes. Due to problems in the sound-level meter, only the first 500 seconds were collected. The noise measurement window in Figure 46 presents noise signals originating from a vehicle, airplane, and rumble strips. For the period spanning from 790 to 830 seconds, multiple sets of rumble strip noise waves are observed. This was confirmed from the sounds heard at that particular time on McCraren Road. Interestingly, the minimum noise levels were slightly higher than those measured at 8:10 p.m. The amplitude of the rumble strip noise signals averaged about 3 dBA, which is less than those measured at 8:10 p.m. The minimum noise level ranged from 50 to 55 dBA, which is higher than that measured at 8:10 p.m. as well.

![Figure 46. Graph. Noise measurements at McCraren Road 12 ft high from 9:00 p.m. to 9:20 p.m. starting at 500 seconds from start of recording.](image)

Characteristics of the noise profiles measured at various intervals on McCraren Road are collated in Table 5. Several observations could be made. The minimum noise levels averaged 49 dBA, with the lowest recorded being 45 dBA starting at 8:15 p.m. The average noise from the rumble strips was 3 dBA compared to 15 dBA from vehicles and airplanes. The maximum noise levels peaked at measurements made at 6:30 p.m. and 7:30 p.m. and then dropped after 8:15 p.m. As witnessed at the measurement location, the high maximum peak levels and their frequency correspond to an increase in airplane passes and vehicles of residents returning home.
INTERNAL NOISE MEASUREMENTS

Internal noise measurements were recorded to evaluate the effectiveness of rumble strips on US-41 in producing enough noise in the vehicle to raise awareness of distracted drivers. The measurements, conducted on December 3, 2021, were performed at night so that the vehicle could travel over the rumble strips at varying speeds. This allows the researchers to find the relationship between internal noise from the rumble strips and speed. Table 6 presents the baseline noise level for segments of the road without rumble strips for three speeds: 25, 35, and 45 mph. The speed limit for US-41 is 40 mph.

Figure 48 plots the noise profile for the vehicle traveling at 45 mph, while Figure 49 presents the characteristics of the interior noise produced in the vehicle by the three rumble strips. Figure 50 and

Table 5. Noise Characteristics, in dBA, at McCraren Road as Measured Dec. 3, 2021

<table>
<thead>
<tr>
<th>Time</th>
<th>Minimum</th>
<th>Rumble Strip</th>
<th>Vehicle/Plane</th>
<th>Average</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>12:15</td>
<td>50–52</td>
<td>3–4</td>
<td>15–25</td>
<td>50–55</td>
<td>77</td>
</tr>
<tr>
<td>1:00</td>
<td>51–52</td>
<td>0</td>
<td>10–25</td>
<td>53–54</td>
<td>77</td>
</tr>
<tr>
<td>5:15</td>
<td>46–50</td>
<td>2–4</td>
<td>15–27</td>
<td>50–55</td>
<td>77</td>
</tr>
<tr>
<td>6:30</td>
<td>49–51</td>
<td>2</td>
<td>15–27</td>
<td>55–57</td>
<td>83</td>
</tr>
<tr>
<td>7:30</td>
<td>50–52</td>
<td>2</td>
<td>10–27</td>
<td>53–55</td>
<td>80</td>
</tr>
<tr>
<td>8:15</td>
<td>45–47</td>
<td>3–5</td>
<td>10–25</td>
<td>50–55</td>
<td>75</td>
</tr>
<tr>
<td>9:00</td>
<td>45–50</td>
<td>2–4</td>
<td>10–25</td>
<td>50–55</td>
<td>75</td>
</tr>
<tr>
<td>Avg</td>
<td>49</td>
<td>3</td>
<td>15</td>
<td>54</td>
<td>78</td>
</tr>
</tbody>
</table>
Figure 51 presents the same information and data for a speed of 35 mph, while Figure 52 and Figure 53 present them for a speed of 25 mph.

As presented in Table 7 and Figure 54, the interior noise levels over the rumble strips vary slightly among the three strips, with an increasing trend with speed, although not significant. The amplitudes range between 71 and 77 dBA. The average increase in sound level by 10 dBA is consistent with those documented in research studies (Lank & Steinauer, 2011; Schrock et al., 2010). Additionally, the interior noise produced for all speeds falls within the range of 3 to 15 dBA recommended by FHWA (NCHRP, 2009).

![Graph](image1)

Figure 48. Graph. Internal noise levels before and after rumble strips at 45 mph.

![Graph](image2)

Figure 49. Graph. Internal noise levels on rumble strips at 45 mph.
Figure 50. Graph. Internal noise levels before and after rumble strips at 35 mph.

Figure 51. Graph. Internal noise levels on rumble strips at 35 mph.
Table 6. Baseline Noise Levels for Various Speeds

<table>
<thead>
<tr>
<th>Speed (mph)</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>62</td>
</tr>
<tr>
<td>35</td>
<td>63</td>
</tr>
<tr>
<td>45</td>
<td>64</td>
</tr>
</tbody>
</table>
Table 7. Noise Over Rumble Strip Sets at Various Speeds

<table>
<thead>
<tr>
<th>Speed (mph)</th>
<th>Set 1</th>
<th>Set 2</th>
<th>Set 3</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>73</td>
<td>72</td>
<td>72</td>
<td>73</td>
</tr>
<tr>
<td>35</td>
<td>75</td>
<td>71</td>
<td>74</td>
<td>73</td>
</tr>
<tr>
<td>45</td>
<td>76</td>
<td>75</td>
<td>77</td>
<td>76</td>
</tr>
</tbody>
</table>

Figure 54. Graph. Baseline and on-rumble strip noise levels for various speeds.
CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

This study was instigated in response to comments and concerns expressed by residents in Highland Park, Illinois, about noise emanating by transverse rumble strips (TRS) on US-41 northbound before the intersection with West Park Avenue. The residents voiced concerns that the noise reaching the neighborhood at night creates annoyance and health risks. IDOT decided to carry out this study to address those concerns, although another comprehensive study evaluating all types of rumble strips is underway. The study at hand encompassed a review of literature on TRS, focusing on the state of practice by other state highway agencies as well as the design of the strips, their placement, and implementation. Standards and specifications for various states were obtained for review. Baseline measurements of the exterior noise generated by vehicles passing over the TRS were made at the location of the TRS. Exterior noise measurements were also made at McCraren Road in the affected neighborhood. Moreover, interior noise measurements were conducted on US-41 to evaluate the performance of the TRS. All measurements comprise a baseline for comparison to other types of TRS that might be constructed at the site as part of an evaluation study in the future.

While US-41 northbound is a busy highway, low-amplitude noise signals from TRS could be heard at McCraren Road during the day and night. The range of noise amplitudes are less than those of other sources of noise such as ambient noise from the vehicles travelling on both directions of US-41; vehicles passing on McCraren Road, which is composed of rough, uneven PCC slabs; and planes passing over the neighborhood. The noise level from the rumble strips reaching the neighborhood ranges from 2 to 4 dBA, depending on prevailing conditions; however, the repetition of the noise, irrespective of its amplitude, might be the source of annoyance to the residents at night.

Despite the message boards and flashing signs warning drivers that the freeway has ended and a signalized intersection lies ahead, IDOT considers the TRS an effective and necessary warning tool to slow down drivers and avoid crashes at the intersection. Thus, the removal of the TRS would compromise safety. IDOT is open to modifications of the existing TRS if they reduce the exterior noise while maintaining the needed level of safety.

There are no detailed and specific standards that dictate the design, configuration, and placement of TRS in the United States. This has led to inconsistencies in TRS attributes and guidelines among the states. As such it is recommended that IDOT review the various design options, such as shortening the number of strips, applying a skew angle, using rounded cross sections, applying a checkered configuration, using more sets of strips with less strips per set, or a combination thereof.
REFERENCES


Robinson, B. (2012). *Spot safety project evaluation of the guardrail installation on both approaches to bridge #8 on US 158 over Cole Creek Gates County* (Spot Safety Project # 01-03-210). Safety Evaluation Group, Traffic Safety Systems Management Section, Transportation Mobility and Safety Division, North Carolina Department of Transportation.


APPENDIX: STANDARD DRAWINGS OF TRANSVERSE RUMBLE STRIPS FOR VARIOUS STATES
Figure 55. Schematic. Configuration of transverse rumble strips in Colorado.
Figure 56. Schematic. Configuration of transverse rumble strips in Florida.
Figure 57. Schematic. Configuration of transverse rumble strips in Kansas.
Figure 58. Schematic. Configuration of transverse rumble strips in Illinois.
Figure 59. Schematic. Configuration of transverse rumble strips in Indiana.

Source: INDOT Design Memorandum No 19-01 (2019)
Figure 60. Schematic. Configuration of transverse rumble strips in Iowa.
Figure 61. Schematic. Configuration of transverse rumble strips in Maryland.

Source: Maryland DOT (Book of Standards for Highway & Incidental Structures)
Figure 62. Schematic. Configuration of transverse rumble strips in Minnesota.

Source: MnDot Road Design Manual
Figure 63. Schematic. Configuration of transverse rumble strips in Missouri.

*Source: Missouri standard plans for highway construction*
Figure 64. Schematic. Configuration of transverse rumble strips in New Mexico.
Figure 65. Schematic. Configuration of transverse rumble strips in North Dakota.

Source: NDDOT standard Drawings, Drawing D760-05
Figure 66. Schematic. Configuration of transverse rumble strips in Ohio.

Source: ODOT, Standard Construction Drawings
Figure 67. Schematic. Configuration of transverse rumble strips in Oklahoma.
Figure 68. Schematic. Configuration of transverse rumble strips in Oregon.
Figure 69. Schematic. Configuration of transverse rumble strips in Texas.
Figure 70. Schematic. Configuration of transverse rumble strips in Wisconsin.