DEPARTMENT OF TRANSPORTATION

Transverse Rumble Strips at Rural Intersections

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Research Project
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As a low-cost countermeasure to rural intersection crashes, transverse rumble strips (TRS) provide an audible and tactile warning to drivers approaching an intersection with the primary goal of decreasing crashes that result from running a stop sign. The objective of this project is to evaluate the effectiveness of different TRS patterns on stopping behavior at rural stop-controlled intersections.

Eight rural intersections in St. Louis County, Minnesota, were selected as test sites. Milled-in rumble strips were installed at the sites that varied in terms of number of panels (2 or 3) and number of rumble strips per panel (6 or 12). Speed, traffic volume, and video data were collected at each site before, 1 month after, and 9 months after TRS installation to evaluate various crash surrogate metrics. The most significant metrics affected by TRS configuration included percentage of vehicles engaging in a full/rolling stop at the intersection, change in average speeds on the approach near the intersection, percent of vehicles traveling 45 mph or more, and percent of vehicles engaging in late braking. A qualitative summary of the various metrics suggested that the 3-panel, 12-rumble strip design performed the best.

Noise analyses were also conducted to assess whether the number of rumble strips per panel (6 or 12) affected exterior and in-vehicle noise. No significant differences in exterior noise were found, and both panels produced sufficient in-vehicle noise to alert a drowsy driver. As a result, noise was not a factor in selecting one panel type over another.

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TRANSVERSE RUMBLE STRIPS AT RURAL INTERSECTIONS

FINAL REPORT

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EXECUTIVE SUMMARY

As a low-cost countermeasure to rural intersection crashes, transverse rumble strips (TRS) provide an audible and tactile warning to drivers approaching an intersection with the primary goal of decreasing crashes that result from a driver running a stop sign. The objective of this project is to evaluate the effectiveness of different TRS patterns on stopping behavior at rural stop-controlled intersections.

To gather background information on TRS patterns, studies assessing the effectiveness of TRS were reviewed, the standards or requirements related to TRS were summarized for each state, and a brief survey was sent to states and counties regarding the TRS designs they used.

Eight rural intersections in St. Louis County, Minnesota, which had been identified as having issues with stopping behavior were selected as test sites to evaluate the effectiveness of different TRS patterns. At each site, milled-in rumble strips were installed that had the dimensions described in the Minnesota Department of Transportation (MnDOT) standard design. The number of TRS panels used (2 or 3) and the number of rumble strips per panel (6 or 12) were varied as follows:

- Two sites with 2 panels of 6 rumble strips
- Two sites with 2 panels of 12 rumble strips
- One site with 3 panels of 6 rumble strips (Initially two installations of each design were planned, but due to issues in the field one location was changed to 3 panels with 12 rumble strips.)
- Three sites with 3 panels of 12 rumble strips

Two data collection trailers at each site were used to collect speed, traffic volume, and video data several weeks before TRS installation, 1 month after installation, and 9 months after installation. The following metrics were used to assess the effectiveness of the different TRS patterns:

- Change in average speeds on the approach near the intersection
- Change in speeds from upstream (before the TRS) to downstream (near the intersection)
- Percentage of vehicles traveling over 40 mph and over 45 mph just upstream of the intersection
- Change in percentage of vehicles engaging in a full/rolling stop
- Change in percentage of vehicles stopping before the stop bar
- Change in percentage of vehicles braking late

Key findings for each metric were provided in Chapter 3. The most significant metric was found to be change in percentage of vehicles engaging in a full/rolling stop. At 1 month after installation, the following resulted:

- Three sites experienced no change or decreases in full/rolling stops (Sites 106 and 112, which had 2 panels and 6 rumble strips, and Site 104, which had 3 panels and 12 rumble strips).
- Five sites experienced improvements (Sites 103 and 111, which had 2 panels and 12 rumble strips; Site 108 West, which had 3 panels and 6 rumble strips; and Sites 108 East and 117, which had 3 panels and 12 rumble strips).

At 9 months after installation, the following resulted:

- Two sites experienced no change or decreases in full/rolling stops (Site 106, which had 2 panels and 6 rumble strips, and Site 104, which had 3 panels and 12 rumble strips).
- Five sites experienced improvements (Sites 103 and 111, which had 2 panels and 12 rumble strips; Site 108 West which had 3 panels and 6 rumble strips; and Sites 108 East and 117, which had 3 panels and 12 rumble strips).
- Data was not collected at one site due to construction.

To conduct a quantitative comparison, the metrics that the research team felt were most likely to show an actual safety improvement were compared. **Reduction in average speed** and **reduction in drivers traveling over 45 mph** were considered important because drivers may be less likely to stop if they are traveling faster than appropriate as they approach the intersection. **Increases in full/rolling stops** was also considered an important metric. **Decreases in the number of drivers who brake late** were considered important because the metric indicates that drivers are more likely to begin braking at an appropriate location upstream of the stop sign.

Change in speed from the upstream to downstream location did not show much improvement overall. This may be because drivers began slowing sooner upstream once they became aware the rumble strips were in place. As a result, it was difficult to determine the importance of this metric. Similarly, the location where drivers stopped (at/before or after the stop bar) was included as a metric. However, as long as drivers stopped, the location of the stop may not be that important.

A qualitative analysis was conducted that assigned a score for improvements. The four metrics (bolded above) that were determined by the team to be the most important metrics were scored. The scoring was used to compare the metrics across designs for the 1-month before and 9-month after periods using the following criteria:

- 1 point given for a moderate improvement in the metric
- 2 points given for a major improvement in the metric
- 0 points given for no change in the metric
- 0 points given when the metric worsened

It was assumed that a metric that worsened was likely to involve factors other than the rumble strips. As a result, metrics that worsened were assigned a 0 rather than a negative value. When a metric was not collected for a particular time period, the cell was not included in the count. Values for each cell were added and then divided by the number of cells.

The 3-panel, 12-rumble strip design had the highest score (1.33). This design included three sites, and even with one of the sites not performing as well as the others (Site 104), this design ranked at the top. The 3-panel, 6-rumble strip design had the second highest score for both counts (0.88). However, this design only included one site that performed well overall, so the results should be used with caution. The 2-panel design with 6 rumble strips performed the next best (0.67), with the 2-panel design with 12 rumble strips having the lowest score (0.44).

A review of the various metrics indicated that the 3-panel, 12-rumble strip design performed well. This was reinforced by the results of the scoring, which showed significantly higher scores for this design than for the others.

In addition to the analysis of stopping behavior, noise analyses were conducted to assess the impact of a 6-rumble strip design versus a 12-rumble strip design on exterior and in-vehicle noise. In general, no significant differences were noted in the exterior noise produced by the two designs, and both designs produced an in-vehicle noise increase greater than the 6 dB needed to alert a drowsy driver. As a result, there is no reason to select one design or the other due to noise.

CHAPTER 1: BACKGROUND

1.1 INTRODUCTION

Rural intersections account for 30% of crashes in rural areas and 6% of all fatal crashes, representing a significant but poorly understood safety problem. Crashes at rural intersections are particularly problematic when high speeds on intersection approaches are present. Fatal injury crash rates are two times higher in rural areas than in urban areas (FHWA 2019, Zwerling et al. 2005).

Drivers failing to yield on the minor approach account for 25% of right-angle crashes (Harder et al. 2003), and these crashes are more likely to result in injuries than crashes where drivers stopped (Retting et al. 2003). Characteristics correlated with failure to yield right-of-way include age (McGwin and Brown 1999, Keay et al. 2009), speeding, vision obstruction, and inattention/distraction (Campbell et al. 2004).

Rural intersection crashes in 2018 cost the state of Minnesota an estimated $90,000,000 (Morris et al. 2019). Transverse rumble strips (TRS) are a low-cost countermeasure that provide an audible and tactile warning to drivers when traversed. Rumble strips can either be grooved into the pavement or installed as elevated strips. TRS are widely deployed in some states (e.g., Iowa) and have the advantage of being effective in low-visibility conditions (e.g., rain, fog, darkness). The primary purpose of TRS at rural intersections is to warn drivers of an upcoming stop sign; this countermeasure is not generally expected to reduce crashes that result from inappropriate gap selection. However, TRS are often applied at high-crash locations regardless of crash type.

1.2 PROJECT OBJECTIVE

The objective of this project was to evaluate the effectiveness of different TRS patterns on stopping behavior at rural stop-controlled intersections. This report summarizes the literature review, describes site selection and data collection, and provides initial findings on the effectiveness of the TRS patterns evaluated.

1.3 EFFECTIVENESS OF TRANSVERSE RUMBLE STRIPS

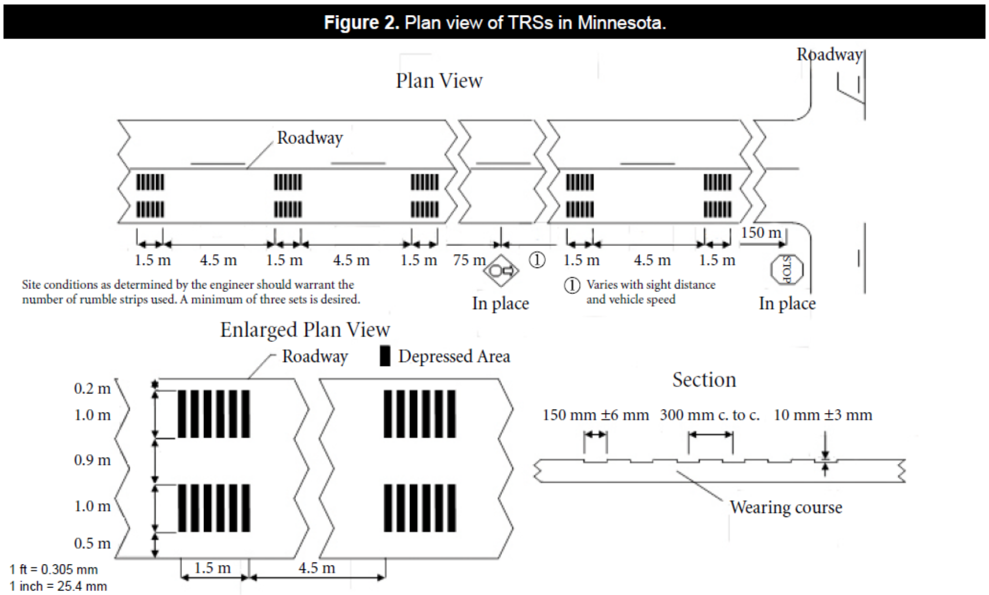
Studies evaluating the effectiveness of TRS are summarized below.

1.3.1 Crash Studies

Several studies were identified that evaluated the effectiveness of transverse rumble strips. The majority were dated prior to 1991 and were summarized by Harwood (1993), who evaluated 10 before-and-after crash studies conducted between 1962 and 1991. He noted that the majority of the studies looked only at crashes and not at crash rates, most did not utilize control sites, and only two of the studies confirmed that their results were statistically significant. These two studies included one by Carstens and Woo (1982), which utilized 21 sites in Iowa and found a significant reduction in crash rate of 51% when looking at all crashes at intersections on the primary highway system. However, he noted that there may be regression to the mean present, as the decreases in crashes were only seen at intersections with more than 2.0 crashes per million entering vehicles. The other study was from the UK (Sumner and Shippey 1977) and included 10 sites, not all of which were at stop-controlled intersections. Some of the sites included horizontal curves or were located in small towns and at entrances to roundabouts.

Two more recent studies, both of which were performed using Empirical bayes before-after crash analysis, found reductions in crashes due to TRS. Srinivasan et al. (2012) found a reduction in fatal and injury crashes of 21.5%, and a study by Torbic et al. (2015) found a reduction in crashes of 37% at three-legged intersections. The study by Srinivasan et al. (2012) also found an increase in property damage-only (PDO) crashes of 19.1%. However, the study by Torbic et al. (2015) found either no significant change or a decrease in PDO crashes. The reasons for the mixed results could be due to the fact that the right-angle crashes used in determining sites for TRS installation were caused by improper gap selection and not drivers failing to recognize the intersection (MnDOT 2017). These studies, while quite robust, were not able to differentiate between rumble strip patterns. Therefore, they show that TRS appear to be effective in increasing safety at rural intersections; however, they are not able to say whether a specific pattern is better than others.

For instance, in the study by Srinivasan et al. (2012), sites in Iowa and Minnesota were used. The data from Iowa were collected before 2006, when three panels of lane-width TRS were used and the panels were spaced such that the first panel a driver encountered was 200 ft upstream of the Stop Ahead sign, the panel closest to the intersection was 300 ft upstream of the stop bar, and the middle panel was spaced equally between those two panels. In Minnesota for the time period in which the data were collected, at least three and up to five panels of wheel path rumble strips were required, with the panel closest to the intersection located 500 ft upstream of the stop sign and the second closest panel located 15 ft upstream of that, as seen in Figure 1-1. When three panels were used, the furthest panel upstream would be 250 ft upstream of the Stop Ahead sign. Unfortunately, there was not sufficient data to determine the effectiveness of each state’s pattern alone. Instead, the data for the states were combined, and the three- and four-legged intersection data were also combined.

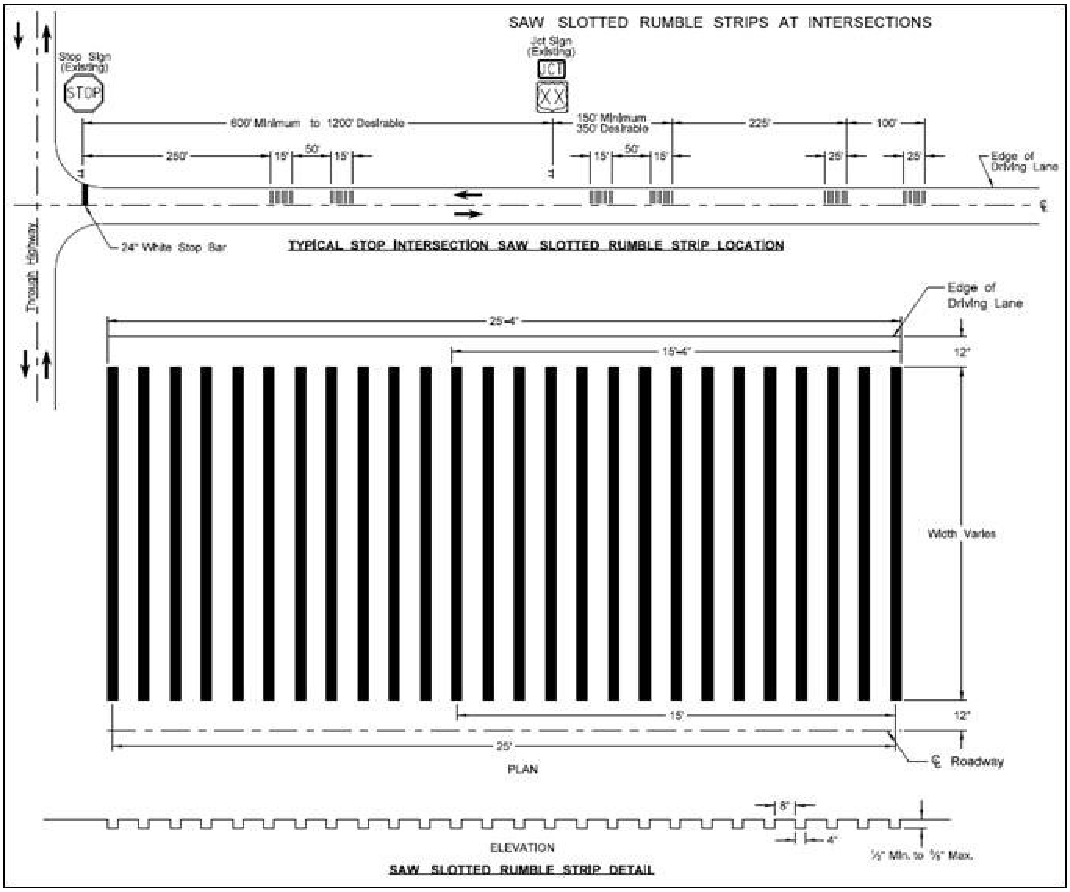


Srinivasan et al. 2012

Figure 1-1. Example of transverse rumble strip pattern in Minnesota

Torbic et al. (2015) evaluated the effectiveness of TRS at three- and four-legged intersections in Arkansas, Kansas, Missouri, North Dakota, and Oregon. Each of these states uses slightly different configurations, which are briefly described below. These different configurations were summarized but not studied separately. Therefore, since the data were aggregated, it is hard to evaluate whether any layout performed better than the others.

- Kansas requires three panels of TRS spaced 100 ft apart, with the panel closest to the intersection located 100 ft upstream of the Stop Ahead sign.
- Missouri utilizes one panel for speed limits of 45 mph or below, with the panel located 175 ft before the Stop Ahead sign, or two panels for speed limits greater than 45 mph. When two panels are used, the first is placed 175 ft upstream of the Stop Ahead sign and the second is placed anywhere from 250 to 425 ft upstream of the stop sign, depending on the speed limit of the road.
- North Dakota utilizes 6 panels of TRS spaced as shown in Figure 1-2.
- Oregon utilizes a minimum of 3 panels, with up to 5 panels possible. When three panels are utilized, they are all placed upstream of the Stop Ahead sign, with the closest placed 200 ft upstream. The other two panels are then spaced 15 ft apart.
- For Arkansas, no standard plans could be found.



Torbic et al. 2015

Figure 1-2. Transverse rumble strip pattern in North Dakota

1.3.2 Speed and Stopping Behavior Studies

In addition to the crash studies mentioned above, other studies have been completed that have evaluated the effectiveness of TRS at intersections using crash surrogates. These include speed and stopping behavior. Studies using these surrogates assume that a reduction in speed as drivers approach the intersection correlates to a reduction in crashes and that an increase in the percentage of drivers coming to a full stop results in a reduction in intersection crashes. Overall, studies have generally found that the use of TRS results in a reduction in speed ranging from 1 to 5 mph, as described below (Harder et al. 2006, Ray et al. 2008). No changes have been found in stopping behavior (Ray et al. 2008) or erratic movements due to the implementation of TRS (Miles et al. 2006).

A study looking at reductions in speed approaching intersections found that TRS in Minnesota reduced drivers' speeds by 2 to 5 mph (Harder et al. 2006). As part of NCHRP 3-74, Ray et al. (2008) looked at the impact of transverse rumble strips on five high-speed intersection approaches in Texas. The approaches utilized the Texas Department of Transportation (TxDOT) standard of raised rumble strips that are 4 ft in length and cover the two-wheel paths of vehicles. The strips are spaced 2 ft apart. The authors evaluated changes in speeds downstream of the TRS at the perception-reaction point (approximately 250 ft upstream of the intersection) and saw and average reduction of 1.3 mph. Data were also collected at the location of the TRS and 100 ft upstream of the intersection, where no significant changes were found.

A study by Zaidel et al. (1986) looked at the impact of 1/2 in. to 5/8 in. high TRS on speed, deceleration behavior, and stopping behavior at a rural intersection. The authors found that speeds significantly decreased upstream of the rumble strips in the year after installation (by approximately 40%). However, they did notice an increase in speed variation. They also noticed no change in stopping behavior but did note that before installation compliance was already quite high at 82%.

A study by Miles et al. (2006) evaluated the same rumble strip pattern as that used in the NCHRP 3-74 study at two rural intersections in Texas to determine if placement of the TRS resulted in drivers making erratic maneuvers (i.e., sudden braking or swerving). Using over 15 hours of video, the authors found no erratic maneuvers. They did note that some drivers shifted their position to avoid the rumble strips. However, the shift was a smooth movement, and no drivers entered into the opposite lane.

No studies could be found that attempted to evaluate how different TRS designs affect crash surrogates such as speed, stopping behavior, and erratic movements.

1.3.3 Transverse Rumble Strips and Noise

One of the major complaints made about TRS is that they result in noise pollution. In order to get an audible response inside a vehicle, noise will result outside the vehicle. This is why distance to homes is often a consideration when determining whether TRS should be placed. Research has found that the noise produced by rumble strips varies based on the designs of the individual rumble strips. Miles and Finley (2007) studied how the dimensions (length, width, depth, and spacing) of rumble strips affect the noise produced. The authors were only able to look at milled-in edge line, lane line, and centerline rumble strips but did find that as width increased to a certain point, noise also increased. They also found that length and spacing also had an effect on noise. They did not look at rumble strips of different depths, but previous research has found that as depth increases, noise increases as well (Bucko and Khorashadi 2001).

A more recent study was conducted that evaluated a method for modifying previously installed TRS to reduce noise pollution. Hurwitz et al. (2019) tested epoxy-filled transverse rumble strips (EFTRS), which are traditional milled-in rumble strips to which an epoxy is added to reduce the depth of the rumble strip to less than 1/4 in., to see whether the modification would reduce the exterior noises produced. Using a probe vehicle, the authors found that the exterior noise generated by the EFTRS was an average of 3.49 dB quieter than the noise generated by traditional rumble strips but still four times as loud as ambient road noise. This test, however, did not measure to see whether there were any changes to the audible or tactile warning within the vehicle.

A recently published study based in Korea further looked at the impact of TRS design on noise. An et al. (2017) studied four different TRS designs, as summarized below, and measured both the exterior and interior noise and the interior vibration produced by three test vehicles that traveled over the TRS at multiple speeds. The authors found that a design 1 cm deep with a 10 cm radius and a 20 cm distance between strips (Type C) performed the best in terms of reduced exterior noise while providing the greatest tactile warning within the test vehicles. The following designs were tested:

- Type A: 10 cm wide x 1 cm deep x 20 cm spacing between strips
- Type B: 5 cm wide x 1 cm deep x 15 cm spacing between strips
- Type C: 10 cm radius x 1 cm deep x 20 cm spacing between strips
- Type D: 0.9 cm wide x 0.6 cm deep x 3.8 cm spacing between strips

Further research is needed to see how the results of research like that by An et al. (2017) translate to the United States and the vehicle types driven here as well as to test how changing the length of the rumble strip, for example, placing it within the wheel path only, may also affect the noise produced.

1.3.4 Other Transverse Rumble Strip Deployments

In addition to studies looking at the effectiveness of TRS at stop-controlled intersections, TRS have been deployed in various other settings where drivers need to be alerted to a change in roadway conditions such geometrics or potential hazards. For instance, transverse rumble strips have been found to be effective when utilized in advance of work zones (Wang et al. 2013), at mid-block pedestrian crossings in China to reduce drivers' speeds (Wang et al. 2017), and upstream of curves (Agent and Creasey 1986).

The use of TRS is also being studied to alert drivers in certain situations. Zhou and Xue (2019) evaluated the use of directional TRS to alert drivers who are driving the wrong way on a freeway ramp and, as stated in the report, to provide a "normal level of stimuli warning to drivers needing to slow down as they exit the freeway." This application of TRS was found to significantly reduce the number of wrong-way driving incidents as well as reduce mean and 85th percentile speeds on the ramps. Another application, referred to as a demand-responsive transverse rumble strip (DRTRS), only becomes active when deemed necessary to alert drivers of a downstream risk such as a school zone, toll booth, or work zone. It works by raising or lowering an array of rumble strips. Because it is only active when necessary, for instance, only during student arrival and dismissal times if deployed in a school zone, drivers do not become as accustomed to its presence (Paz and Trabia 2018).

1.4 TRANSVERSE RUMBLE STRIP CONFIGURATIONS UTILIZED

A thorough search of each state department of transportation's (DOT's) website, including any standard plans and specifications, was conducted to determine each state's standards or requirements for TRS.

In addition to this search, a brief survey was sent to states and counties to gather further information on the designs they utilize for TRS and any information on the rationale for the designs used. The survey was distributed through the Federal Highway Administration (FHWA), the National Association of County Engineers (NACE), and the Minnesota County Engineers Association. As part of the survey, agencies were asked how many rumble strip panels were used and the distance to the first (D3) and last encountered (D1) panels. Questions were also included related to the number of rumble strips and the distances between rumble strips and panels. A schematic of a transverse rumble strip configuration, shown in Figure 1-3, was provided to clarify terms. A total of 119 responses to the survey were received from counties and states across the country. In some cases, the responses differed from those found in the respective states' standard plans for rumble strips. In such cases the updated responses were incorporated into the information corresponding to that state's standards and requirements.

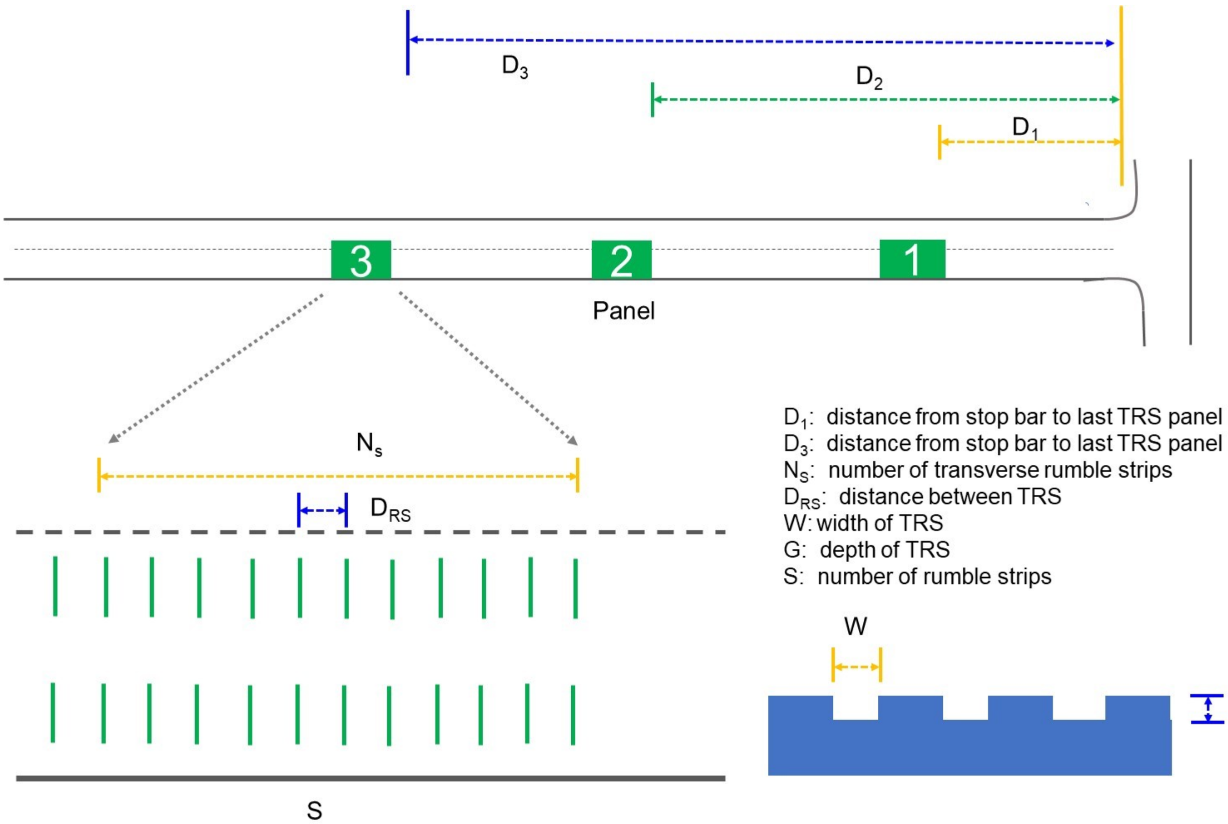


Figure 1-3. Schematic of rumble strip design

A summary of each state's standards and requirements related to the use of transverse rumble strips can be found in Sections 1.4.1 through 1.4.50. This information was gathered from the review of states' TRS standards and requirements or from the survey, which provided information on a total of 24 states.

As described in the summaries, the main components of TRS include the following:

- Panel: block of continuous rumble strips
- Number of panels
- Number of rumble strips in a panel
- Distance between individual rumble strips measured center to center
- Width of an individual rumble strip
- Depth of an individual rumble strip
- Distance each panel is located in reference to the corresponding intersection or other reference point such as advance intersection warning sign

A summary of TRS dimensions by state is provided in Table 1-1.

Table 1-1. Summary of transverse rumble strip dimensions by state

State	Depth	Width	Length	Spacing	Angle
Alabama*	5/8 in.	8 in.	Lane width	10 in. edge to edge	45°
Arizona	3/8 in.	4 in.	Lane width (unless shoulder width is < 4 ft, then they should end 4 ft from end of paved shoulder)	12 in.	15°
Colorado	1/2 in.	4 in.	Lane width	8 in.	0°
Delaware	2 panels of white raised strips	6 in. and 4 in. strips	Not listed	24–36 in. depending on speed	0°
Florida	1/2 in.	2 in. (asphalt) 4 in. (thermoplastic)	Lane width unless no paved shoulder, in which case lane width minus 1.5 ft	10 in. (asphalt) 5 ft (thermoplastic)	0°
Georgia	1 in.	4 in.	Lane width	8 in. on center	0°
Illinois	3/8 in.	4 in. (grooved) 8 in. (raised)	Lane width	8 in.	0°
Indiana	1/4 in.	8 in.	Not listed	8 in.	0°
Kansas	3/8 in.	4 in.	Lane width minus 24 in. (6 in. near centerline and 18 in. from edge of roadway)	12 in.	10°
Kentucky (milled)	3/8 in.	7 in.	Lane width minus 2 ft, unless there is a minimum of 4 ft of paved shoulder beyond any shoulder rumble strips	24 in.	0°
Kentucky (thermoplastic)	3/8 in.	6 in.	Lane width minus 2 ft, unless there is a minimum of 4 ft of paved shoulder beyond any shoulder rumble strips	24 in.	0°
Maryland	Not stated	5 or 10 in.	Depends on whether bicycles are present	4.5–6 in.	0°
Minnesota	3/8–5/8 in.	5.75–6.25 in.	Two panels of 3 ft 4 in.	12 in. on center	0°
Missouri	3/8 in.	4 in.	Lane width minus 2.5 ft	8 in.	10°
Nevada	3/8 in.	4 in.	Lane width	12 in.	0°
New Jersey	2 layers of 125 mils thermoplastic	6 in.	Lane width minus 6 in. unless there is not a bicycle lane or shoulder for bicyclists, then 3–4 ft from lane line or curb	18 in.	0°
New Mexico	3/8 in.	6 in.	Two panels of 4 ft wide with 2 ft spacing between	6 in.	0°
North Dakota	1/2–5/8 in.	4 in.	Lane width minus 2 ft	12 in.	0°
Ohio	Not listed	4 in.	Lane width minus 22 in.	12 in.	0°
Oklahoma	1/2–5/8 in.	6–8 in.	18 in. (uses cyclic groups, see Figure 20)	12 in.	0°
Oregon	3/8–5/8 in.	5.75–6.25 in.	Lane width minus 2 ft	6 in.	0°
South Dakota	7/16–9/16 in.	6 in.	Varies	12 in.	0°
Texas	Not listed	Not listed	Two panels of 4 ft wide with 6 in. to 2 ft (preferred) spacing between	2 ft on center	0°

State	Depth	Width	Length	Spacing	Angle
Wisconsin (formed)	1/2–5/8 in.	Trapezoid with 3 in. at smallest and 4 in. at largest	Lane width minus 2.5 in. (12 in. from CL and 18 in. from edge of traveled way)	8 in.	0°
Wisconsin (milled in)	1/2–5/8 in.	4 in.	Lane width minus 2.5 ft (12 in. from CL and 18 in. from edge of traveled way)	8 in.	0°

* Indicates the data were gathered through the survey.

The review of TRS dimensions by state revealed that while some dimensions are similar across states (e.g., the depth and width of TRS), others vary greatly across states (e.g., number of strips per panel, number of panels, spacing between panels). It was found that no two states have the exact same standard plans in terms of strip dimensions, number of panels, spacing of panels, and placement of panels. However, the most common rumble strip depth is 3/8 in. (9 of 24 states). Another 6 states use depths between 1/2 and 5/8 in. The most common rumble strip width is 4 in. (13 states), with another 8 states using widths of 6 in. States are equally likely to use rumble strips that extend the width of the lane (9 states) or that extend the lane width minus 22 to 30 in. Only 3 states use wheel path rumble strips (Minnesota, New Mexico, and Texas). Nine states space rumble strips at 8 in., and 8 space them at 12 in. The majority of states place the rumble strips perpendicular to the roadway, while 4 place them at some angle (10 to 45 degrees).

Table 1-2 summarizes the rumble strip panel and location configurations used by states.

Table 1-2. Summary of transverse rumble strip locations by state

State	Number of Panels	Number of Rumble Strips per Panel	Location of Panel Closest to Intersection	Location of First Panel Encountered
Alabama	5	6	Based on speed limit D3 = D1 + 300 ft At 30 mph = 250 ft At 40 mph = 350 ft At 50 mph = 450 ft At 60 mph = 600 ft	300 ft upstream of first panel
Arizona	3	6	At location of intersection warning sign	250–400 ft upstream of intersection warning sign (depending on speed)
Colorado	4	12	300 ft upstream of stop bar	1,000 ft upstream of stop bar
Larimer County, Colorado*	2		One before the advance stop sign and in advance of the stop	
Delaware	4–5	5	Not listed	Not listed
Florida	4	4 (thermoplastic) 6 (asphalt)	500 ft upstream of stop bar	900 ft upstream of stop bar

State	Number of Panels	Number of Rumble Strips per Panel	Location of Panel Closest to Intersection	Location of First Panel Encountered
Georgia	2	20	200 ft upstream of stop bar (speed limit 40–55 mph) 300 ft upstream of stop bar (speed limit 60 or 65 mph)	475–850 ft upstream of stop bar depending on speed limit
Illinois	3	25	Not listed	Not listed
Indiana	2–6	6	0.5 x SSD upstream of action point	Typically, 1 x stopping sight distance (SSD) upstream of action point; up to 3 x SSD upstream of action point
Kansas	3	25	100 ft upstream of W3-1 Stop Ahead sign	300 ft upstream of W3-1 Stop Ahead sign
Kentucky	3	8	Not listed	Approximately 400 ft upstream of closest panel
Maryland	3–4	10	200 ft upstream of the stop bar or 200 ft upstream of the W3-1 Stop Ahead sign	475 ft upstream of W3-1 Stop Ahead sign
Michigan*	3	15,15, 20	780 ft, which includes 600 ft for the Stop Ahead advance warning sign plus 180 ft for the sign legibility distance	1,065 ft, which includes 600 ft for the Stop Ahead advance warning sign plus 180 ft for the sign legibility distance plus 285 ft for the bar spacings
Minnesota	5	6	330 ft upstream of stop sign	290 ft upstream of W3-1 Stop Ahead sign
Missouri	1 (speed limit ≤ 45); 2 (speed limit > 45)	25	175 ft upstream of intersection warning sign (only sign); 250–425 ft upstream of stop sign (depends on speed)	175 ft upstream of intersection warning sign
Nevada	3–5	5	3 panels at warning sign or 5 panels 300–650 ft upstream of stop bar (depending on speed)	3 panels 300 ft upstream of warning sign or 5 panels 500 ft upstream of W3-1 Stop Ahead sign
New Jersey	3	5	75–95 ft upstream of device or condition	Approximately 242–282 ft upstream of device or condition
New Mexico	5	12	100–350 ft upstream of stop sign	500 ft upstream of W3-1 Stop Ahead sign
North Dakota	6	26	250 ft upstream of stop sign	450–650 ft upstream of junction sign
Cass County, North Dakota*	3	10	350	1000 ft
Ohio	3	15	At least 200 ft upstream of stop bar for less than 50 mph speed limit (at least 300 ft for 50+ mph)	500 ft upstream of panel closest to intersection
Oklahoma	4 panels of cyclic groups	10	645 ft upstream of stop bar	1,245 ft upstream of stop bar

State	Number of Panels	Number of Rumble Strips per Panel	Location of Panel Closest to Intersection	Location of First Panel Encountered
Oregon	3–5	6	3 panels 200 ft upstream of W3-1 Stop Ahead sign; 5 panels 200–550 ft upstream of stop bar depending on speed limit	240 ft upstream of W3-1 Stop Ahead sign
South Dakota	2	16	650 ft upstream of stop sign	250 ft upstream of W3-1 Stop Ahead sign
Minnehaha Highway Department, South Dakota*	6	25	350	600–750 ft
Texas	2	5	200 ft downstream of W3-1 Stop Ahead sign	200 ft upstream of W3-1 Stop Ahead sign
Waller County, Texas*	1	3	200 ft upstream of stop bar	
Wisconsin	2 (speed limit < 45); 3 (speed limit ≥ 45)	24	125–425 ft upstream of edge of traveled way depending on speed limit	200 ft upstream of W3-1 Stop Ahead sign. If no Stop Ahead sign is present, 425–1,000 ft upstream of edge of traveled way depending on speed limit

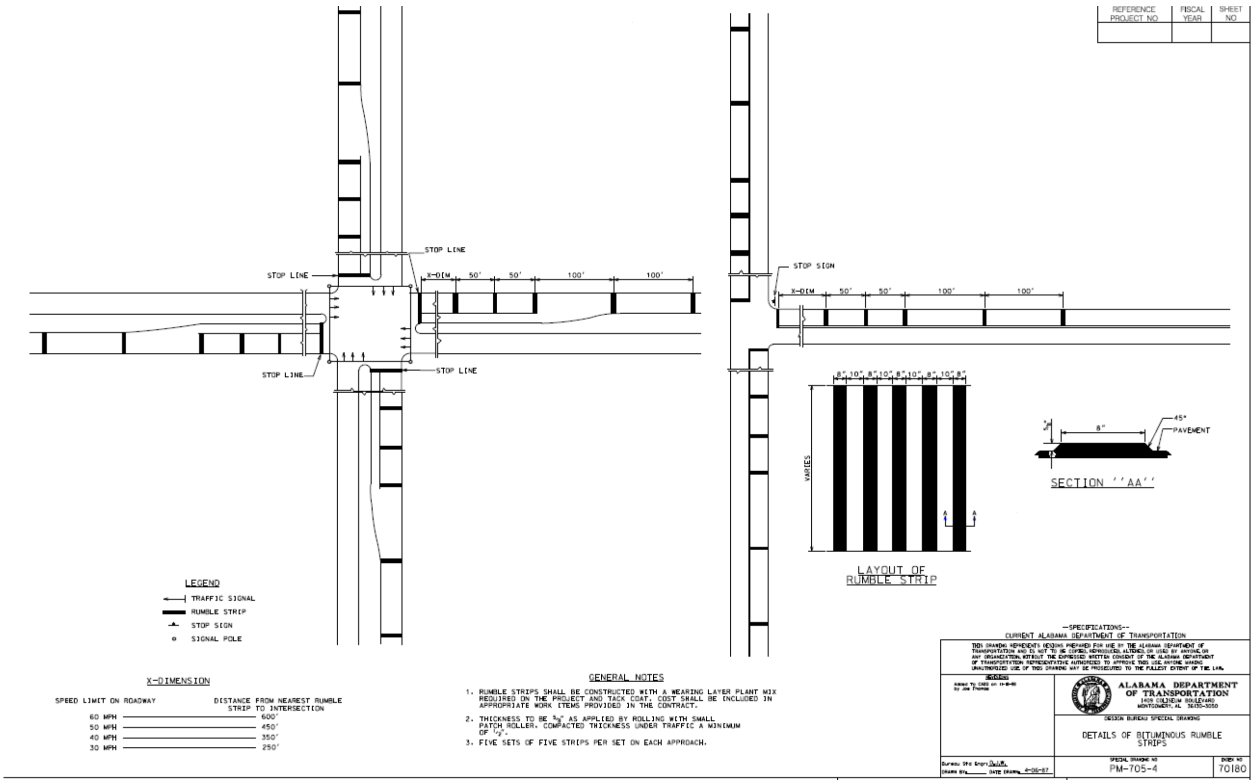
* Indicates the data were gathered through the survey.

The number of rumble strip panels used varies from two to six, with three panels being the most common (5 states) and two panels being the second most common (4 states). Eight states use four or more (four, five, or six) panels, and 7 use a range of panels (e.g., three to five). Ten states include 5 to 6 rumble strips per panel, and 5 states use 10 to 12 rumble strips per panel. Another 10 states use 15/16, 20, 25/25/26 rumble strips per panel. Since the number of panels varies by state, only the placement of the panel closest to the intersection is summarized here. Six states place this panel within 200 ft of the intersection, and 6 states place this panel 300 ft or more from the intersection. Three states place this panel 250 to 300 ft from the intersection, and 7 states vary the distance based on approach speed, stopping distance, or number of panels.

It was noted that the majority of states place the rumble strips so that when a driver traverses them, the driver is either alerted to a Stop Ahead or similar sign or is close enough to the intersection for the driver's attention to be drawn toward the intersection and stop sign. As noted by Harwood (1993), this placement is essential for transverse rumble strips to provide a safety benefit to drivers.

1.4.1 Alabama

Initially, no standard plan or specification could be located for the Alabama DOT describing the use of TRS at intersections. The only plans found were for the use of temporary rumble strips in work zones (ALDOT 2019). However, three agencies in Alabama responded to the survey, and responses related to pattern design were incorporated into the previous summary tables. The respondents' indicated specifications were Special and Standard Drawings of the Alabama Department of Transportation, Specials Drawing No. PM-705-5 (see Figure 1-4).



ALDOT 2019

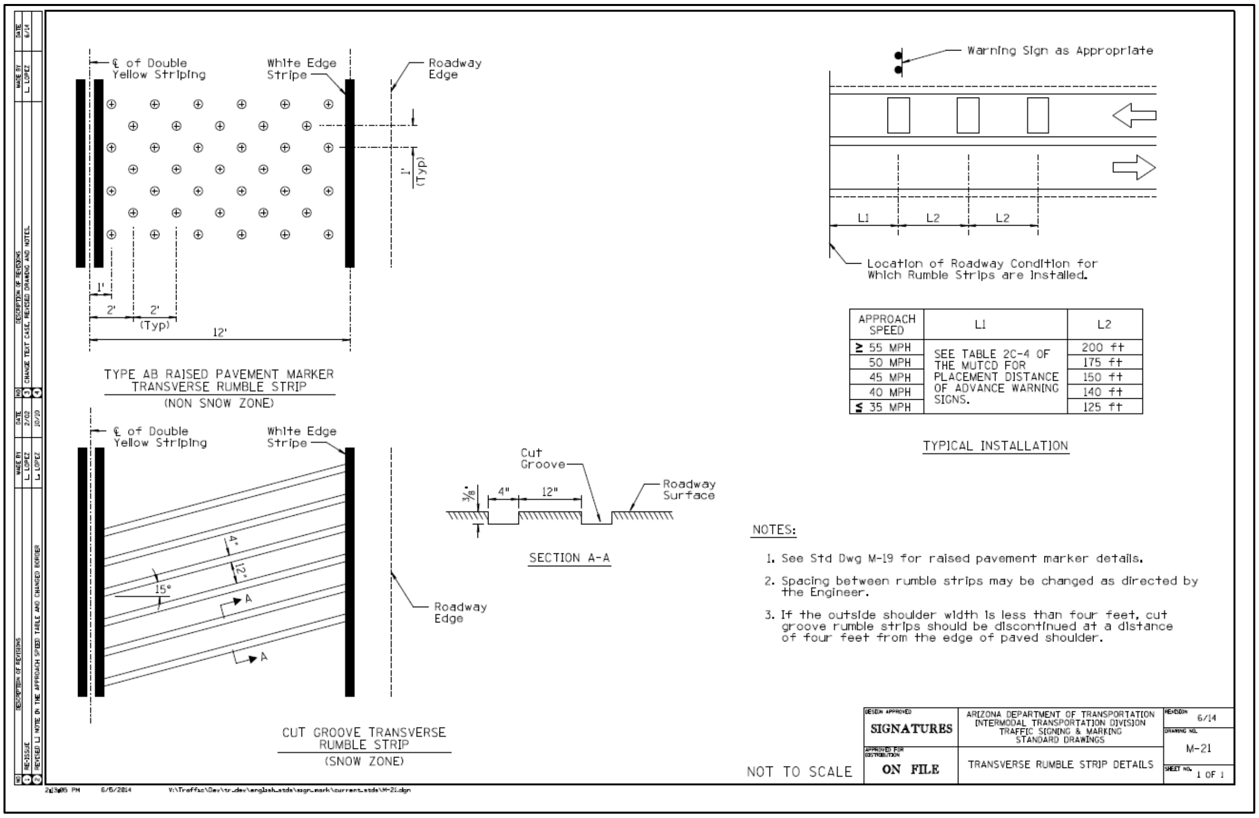
Figure 1-4. Alabama transverse rumble strip detail sheet

1.4.2 Alaska

No standard plan or specification for rumble strips could be located for the Alaska Department of Transportation and Public Facilities (DOT&PF). However, it appears that the state does utilize them (Alaska DOT&PF 2012).

1.4.3 Arizona

Arizona allows for the use of either cut groove TRS or Type AB raised pavement marker TRS. Arizona requires three panels of transverse rumble strips, with the closest located at the warning sign (usually W3-1) and the others spaced anywhere from 125 to 200 ft apart depending on the speed limit of the roadway. For the cut groove TRS, each strip is 4 in. wide by 3/8 in. deep and the length is equal to the lane width, unless the shoulder width is less than 4 ft, in which case the strip should end 4 ft from the edge of the paved shoulder. Each strip is spaced 12 in. apart, and the strips are placed at a 15-degree angle, which can be seen in Figure 1-5 (ADOT 2014).



ADOT 2014

Figure 1-5. Arizona transverse rumble strip detail sheet

1.4.4 Arkansas

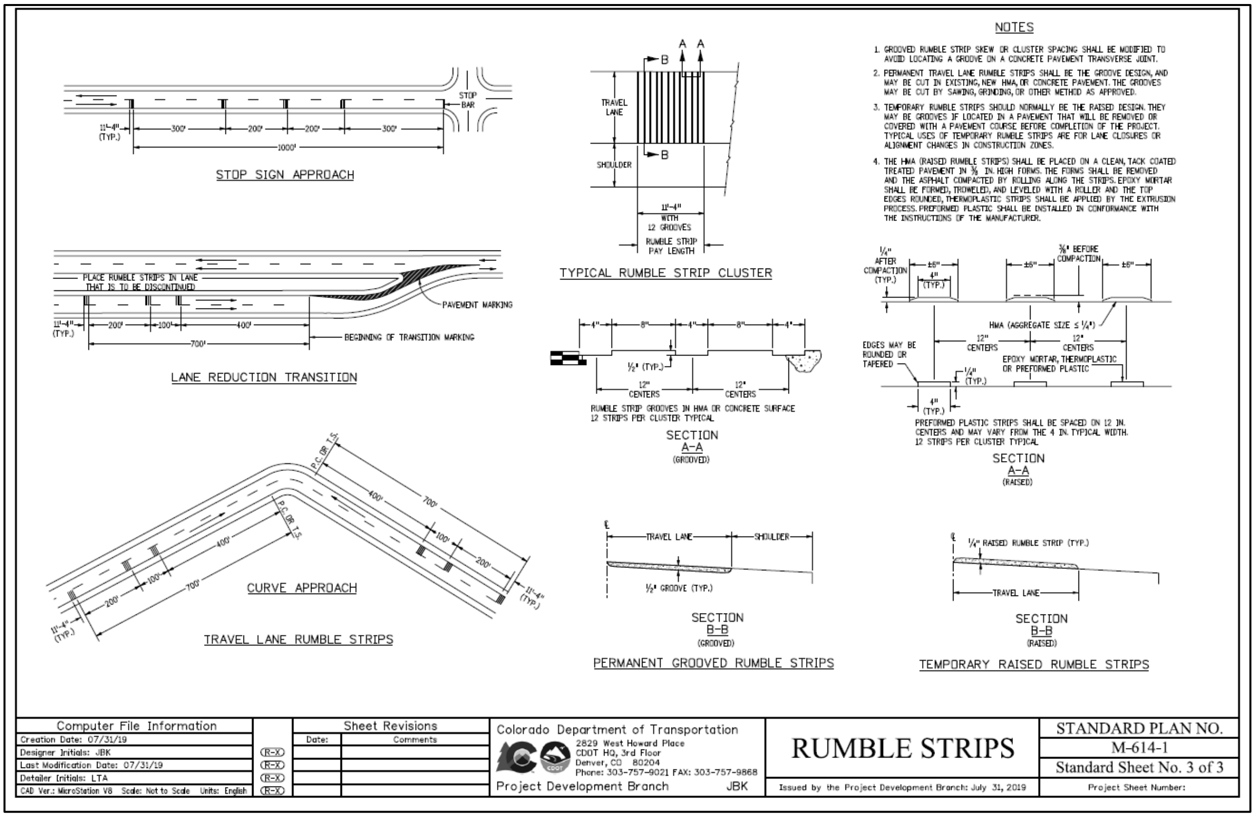
No standard plan or specification for rumble strips could be located for the Arkansas DOT. However, it appears that the state does utilize them per its 2017 Strategic Highway Safety Plan (SHSP) as well as the state's inclusion in the study by Torbic et al. (2015).

1.4.5 California

California only provides standard plans for the use of the portable transverse rumble strips in work zones (Caltrans 2014a). The state does allow for the use of transverse rumble strips at intersections, but the only guidance the research team could find was related to pavement markings associated with rumble strips. The *California Manual on Uniform Traffic Control Devices* (MUTCD) specifies that rumble strips should either be pavement colored or white (Caltrans 2014b).

1.4.6 Colorado

Colorado's standard plans provide dimensions and placement information for TRS at stop sign-controlled intersections. Grooved-in rumble strips are utilized for permanent installations, while raised (either thermoplastic or hot-mix asphalt [HMA]) rumble strips are utilized for temporary installations. Grooved-in strips are 4 in. wide by 1/2 in. deep and have a length equal to the lane width. They are spaced 8 in. apart, and the typical installation consists of 4 panels of 12 rumble strips spaced 200 to 300 ft apart. The dimensions for raised TRS can be seen in Figure 1-6.



CDOT 2019

Figure 1-6. Colorado transverse rumble strip standard plan

1.4.7 Connecticut

No information on the use of TRS by the Connecticut DOT could be found.

1.4.8 Delaware

The only reference to transverse rumble strips that could be found on the Delaware DOT website was under the pavement marking section of the Delaware DOT MUTCD. Section 3J.02 Transverse Rumble Strip Markings Guidance 04A and 04B reads as follows: “04A (DE Revision) Raised white transverse rumble strips used in a travel lane to alert motorists of a stop or other condition should be installed in accordance with Table 3J-1. 04B (DE Revision). Raised white transverse rumble strips should consist of a 4 in. line placed on top of a 6 in. line” (DelDOT 2011). The information in Table 3J-1 is presented in Table 1-3.

Table 1-3. Table 3J-1, Transverse Rumble Strip Placement (Delaware Revision), from Delaware DOT MUTCD

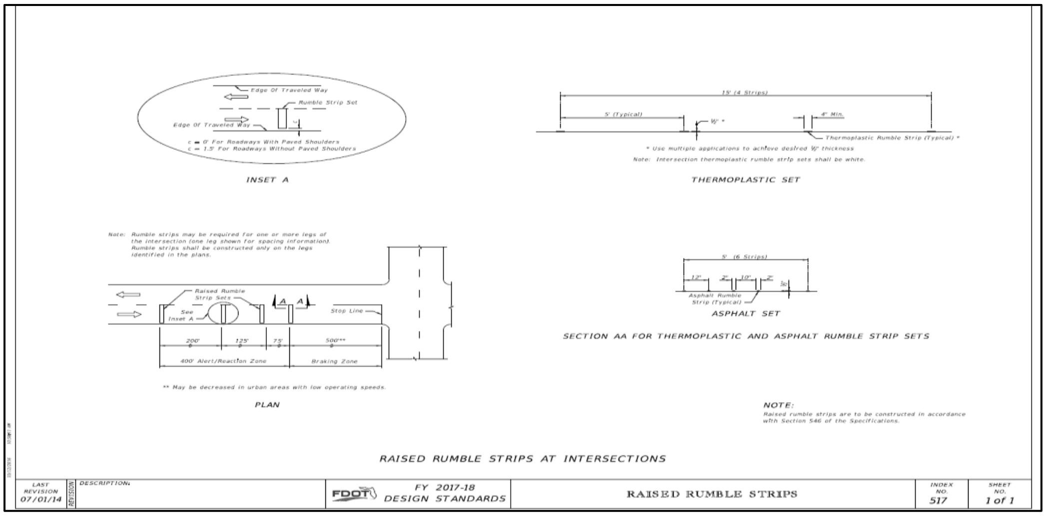
Posted Speed (mph)	Sets of Strips*	Strip Spacing (in.)	Longitudinal Spacing of Each Set (ft)**
25	4–5	24	75
30	4–5	24	100
35	4–5	24	100
40	4–5	30	125
45	4–5	30	125
50	4–5	36	150
55	4–5	36	150

* Each set consists of individual strips.
** Spacing between sets of rumble strips and space required before the point at which a speed reduction must be obtained.
Source: DelDOT 2011

1.4.9 Florida

The Florida DOT provides design standards for the use of raised transverse rumble strips at stop-controlled intersections. As shown in Figure 1-7, the raised asphalt rumble strips are 1/2 in. deep by 2 in. wide and have a 10 in. spacing. They are placed in groupings of six strips. White thermoplastic panels include four strips with minimum dimensions of 1/2 in. by 4 in. and a 5 ft spacing. The length for both applications should be the lane width if the roadway has a paved shoulder or the lane width minus 1.5 ft if the roadway does not have a paved shoulder. The standard installation consists of four panels of rumble strips, with the panel closest to the intersection located 500 ft upstream of the stop line and the furthest upstream panel located 900 ft upstream of the stop bar. The location of the other two panels can be seen in Figure 1-7 (FDOT 2018).

Two counties responded to the survey and indicated two different configurations. However, few details were provided, and the configurations are therefore not included in this summary.

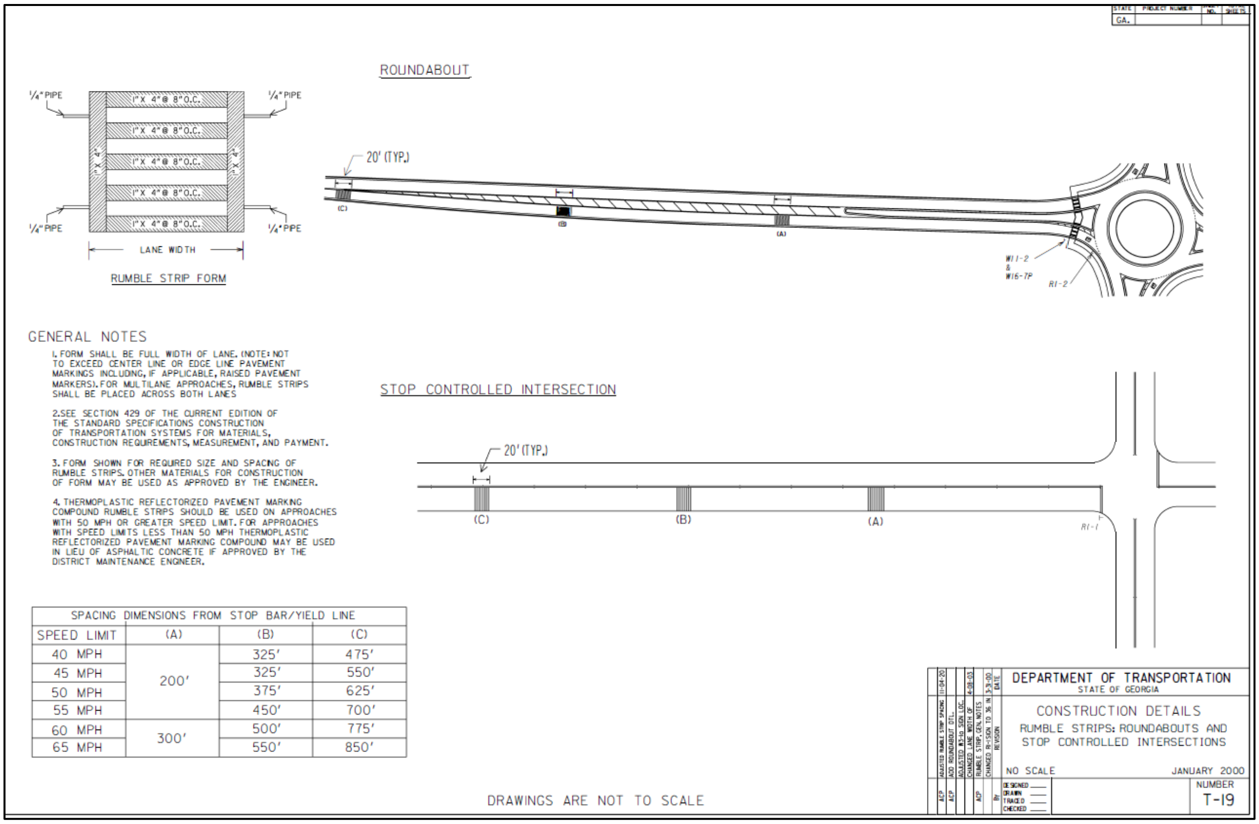


FDOT 2018

Figure 1-7. Florida raised rumble strip design standard

1.4.10 Georgia

Georgia provides standard plans for the use of transverse rumble strips at either stop-controlled intersections or roundabouts. Georgia's standard plans call for thermoplastic reflectorized pavement marking rumble strips on approaches with speed limits above 50 mph. On roads with speed limits below 50 mph, asphaltic concrete strips are called for. The rumble strips are lane width and are 1 in. deep by 4 in. wide and spaced at 8 in. on center. There are approximately 30 rumble strips per panel and three panels per approach, as seen in Figure 1-8. The first panel encountered is anywhere from 475 to 850 ft upstream of the stop bar, depending on the speed limit of the road. The next panel is located 325 to 550 ft upstream of the stop bar, and the closest panel is either 200 ft (on roads with speed limits less than 60 mph) or 300 ft (on roads with 60 mph or 65 mph speed limits) upstream of the stop bar (GDOT 2000).



GDOT 2000

Figure 1-8. Georgia standard drawings for transverse rumble strips at stop-controlled intersections

1.4.11 Hawaii

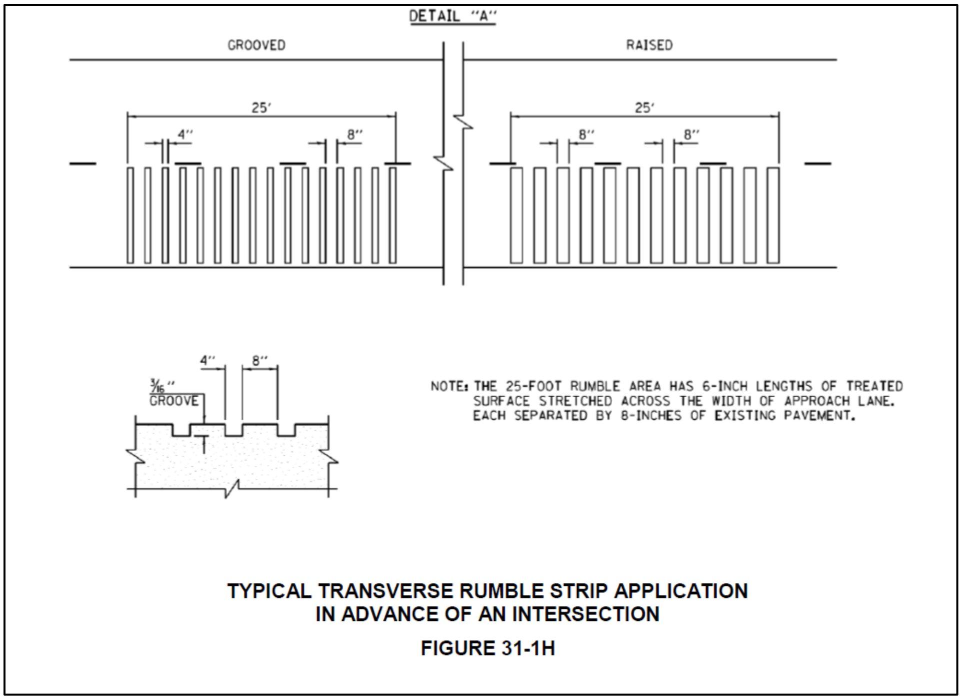
No standard plans or specifications for TRS could be found, nor was there mention of their use.

1.4.12 Idaho

No standard plans or specifications for TRS could be found. However, there was mention of their use.

1.4.13 Illinois

Illinois provides guidance on the use of transverse rumble strips as part of the state's *Bureau of Local Roads and Streets Manual*. The manual states that TRS should be placed in advance of either a Stop Ahead sign or stop sign. However, guidance was unable to be found on the exact location upstream. Rumble strip configurations should include three panels of strips, with each panel being 25 ft long. Recommendations for spacing between the strips was unable to be located. The dimensions of the strips themselves vary based on whether they are grooved in or raised, as seen in Figure 1-9. If they are grooved in, they are 4 in. wide by 3/8 in. deep and spaced 8 in. apart. If they are raised, they are 8 in. wide with an 8 in. spacing.



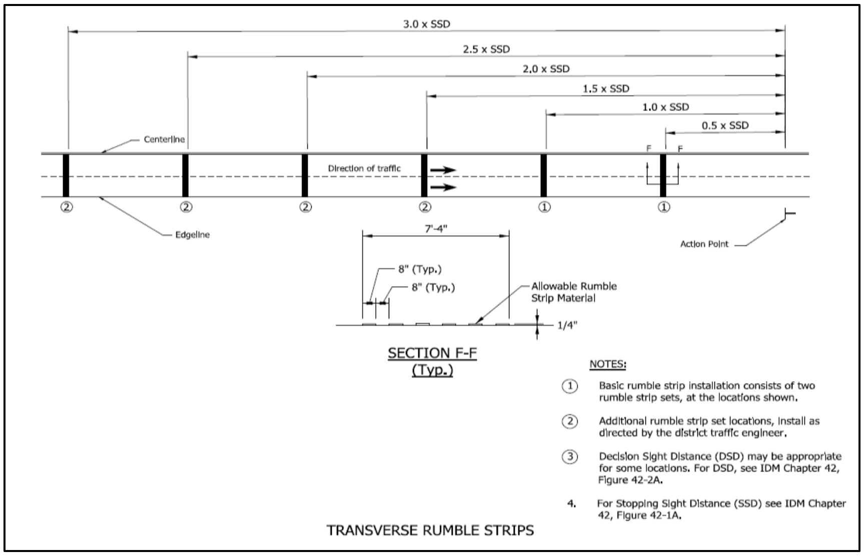
IDOT 2016

Figure 1-9. Typical dimensions of Illinois transverse rumble strips

One county in Illinois responded to the survey. The respondent indicated that four panels are used and that each panel has 12 strips. The first panel encountered is located 1,000 ft upstream of the Stop Ahead sign, and the last is located 100 ft upstream of the stop sign.

1.4.14 Indiana

Indiana provides guidance on the use of transverse rumble strips upstream of the area where drivers are about to encounter unexpected traffic conditions such as an intersection with the approval of the district traffic engineer. As shown in Figure 1-10, the typical application consists of two panels of strips consisting of six strips each that are located 0.5 times the stopping sight distance (SSD) upstream from the action point and 1 times the SSD upstream from the action point. However, up to five panels of rumble strips can be utilized if additional warning is necessary. These rumble strips are typically 1/4 in. deep by 8 in. wide with an 8 in. spacing (INDOT 2019).



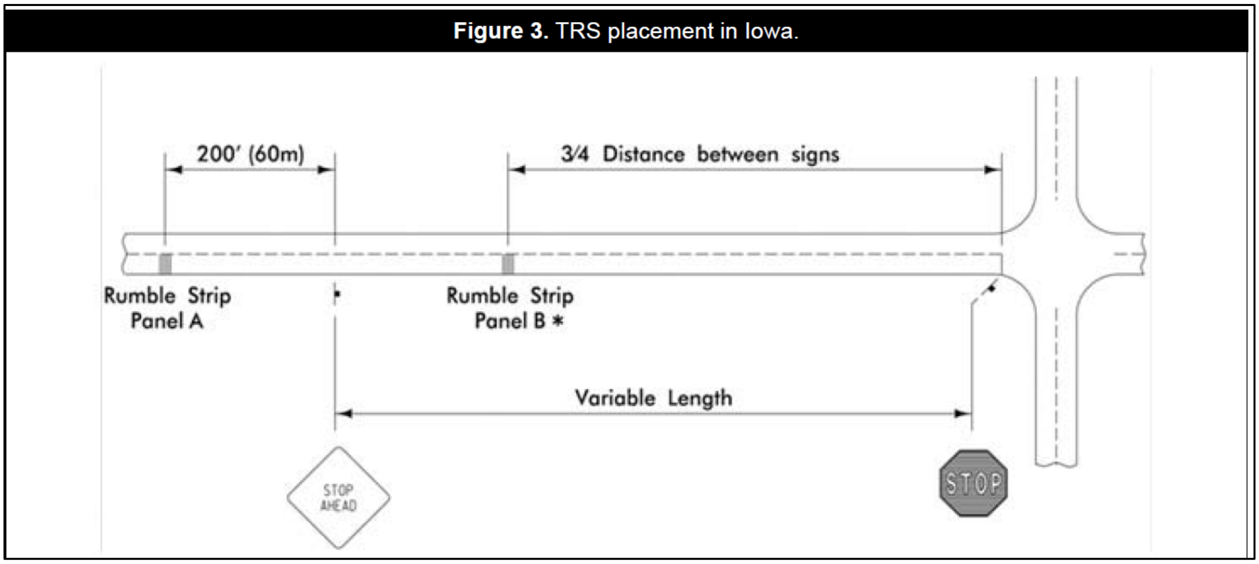
INDOT 2019

Figure 1-10. Indiana typical transverse rumble strip application

1.4.15 Iowa

The most up-to-date information available for the Iowa DOT's plans for transverse rumble strips is featured in Srinivasan et al. (2012). As shown in Figure 1-11, two panels featuring 25 rumble strips are utilized in Iowa, with the first being encountered 200 ft upstream of the W3-1 Stop Ahead sign. The panel closest to the intersection is located upstream of the stop sign three-quarters of the distance between the stop sign and W3-1 sign. The rumble strips themselves are spaced 12 in. apart and have a length equal to 18 in. less than the lane width to accommodate bicycles on the outside edge of the lane.

Eight Iowa county engineers responded to the survey. Three counties indicated that they used three panels, while five counties used two panels. All indicated spacing and dimensions similar to those discussed above.



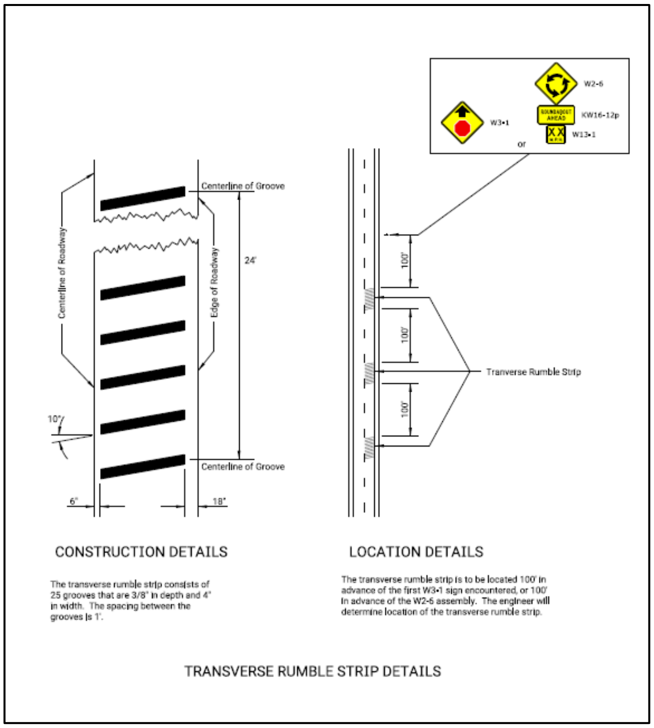
Srinivasan et al. 2012

Figure 1-11. Iowa standard plans for transverse rumble strips

1.4.16 Kansas

The Kansas DOT provides typical details for TRS, as seen in Figure 1-12. Each TRS consists of a groove 3/8 in. deep by 4 in. wide and a length equal to the lane width minus 24 in. Strips are spaced 12 in. apart, and each panel consists of 25 grooves. A typical installation consists of three panels of strips spaced 100 ft apart, with the closest panel located 100 ft upstream of a W3-1 (Stop Ahead) sign. The rumble strips are placed on a 10-degree angle as shown in Figure 1-12 (KDOT 2020).

One county engineer from Kansas answered the survey. The respondent indicated the use of two panels with 25 strips each. The first panel encountered by the driver is placed 500 to 750 ft upstream of the intersection, and the last one encountered is placed 300 to 500 ft upstream of the intersection.



KDOT 2020

Figure 1-12. Kansas transverse rumble strip details

1.4.17 Kentucky

Kentucky allows for transverse rumble strips to be utilized; however, permanent installations require the approval of the Director of the Division of Traffic Operations. TRS are generally only considered when other countermeasures have been installed and have not improved safety. Kentucky allows for extruded thermoplastic material, preformed thermoplastic material, and cut or milled strips. Thermoplastic rumble strips are generally preferred and should be black or gray to match the color of the pavement. (White strips are not allowed because drivers may confuse them with stop bars or crosswalks.)

When thermoplastic strips are used, they should be 3/8 in. and 6 in. wide with a 24 in. spacing. Milled-in or cut strips should be similar dimensions but should be 7 in. wide. The length of the strips should be 2 ft less than lane width to allow for bicycles. However, if at least 4 ft of paved shoulder is present beyond any shoulder rumble strips, the strips can be lane width because bicyclists can utilize the paved shoulder area. Rumble strips should be installed in three panels of eight strips spaced 200 ft apart. The guidance does not state where the panel closest to the intersection should be placed but does mention that panels should not be placed within stopping distance of intersections (KYTC 2020).

1.4.18 Louisiana

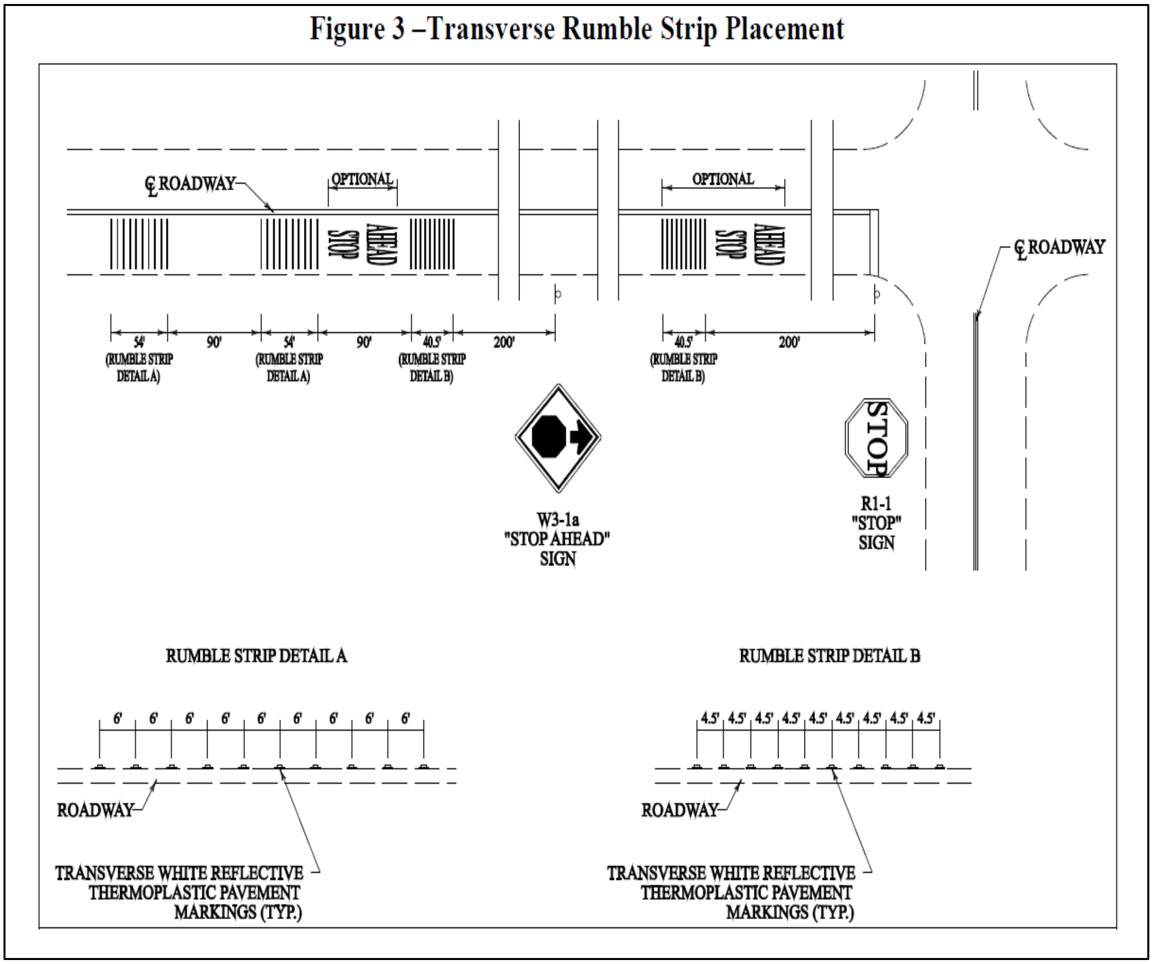
The research team was unable to find any standard plans or specifications related to TRS in Louisiana. Reference to the use of TRS was found in a document entitled *Part III: Guidelines for Conducting a Safety Analysis for Transportation Management Plans and Other Work Zone Activities* (La DOTD 2012).

1.4.19 Maine

No reference to transverse rumble strips could be found on the Maine DOT website.

1.4.20 Maryland

The Maryland DOT (MDOT) State Highway Administration (SHA) provides for the use of transverse rumble strips at stop-controlled intersections, among other locations. Three to four panels of 10 thermoplastic pavement marking rumble strips (milled-in rumble strips can be used with permission of the Director of Traffic and Safety and the Director of the Office of Maintenance) can be placed upstream of stop-controlled intersections. These rumble strips are formed by placing two pieces of thermoplastic pavement marking strips on top of each other. This can be done with two 5 in. wide strips or one 5 in. wide strip and one 10 in. wide strip. The spacing of the rumble strips on these panels can vary, as seen in Figure 1-13. The rumble strips on the two panels closest to the intersection (if four panels are used, otherwise, the closest panel) are spaced 4.5 in. on center, while the rumble strips on the two panels farthest upstream are spaced 6 in. on center. If four panels are used, the closest panel is placed 200 ft upstream of the stop bar, and the next upstream panel is placed 200 ft upstream of the W3-1a Stop Ahead sign. The last two panels are each spaced another 90 ft upstream. It is noted that if bicycles are present, transverse rumble strips should not be used “unless a minimum clear path of 4 ft is provided at each edge of the roadway or each paved shoulder as described in AASHTO’s *Guide to the Development of Bicycle Facilities*” (MDOT SHA 2014).



MDOT SHA 2014

Figure 1-13. Maryland transverse rumble strip placement

1.4.21 Massachusetts

Standards and specifications relating to transverse rumble strips could not be found for the Massachusetts DOT (MassDOT). However, TRS are mentioned in the *MassDOT Safety Alternatives Analysis Guide* (MassDOT 2020).

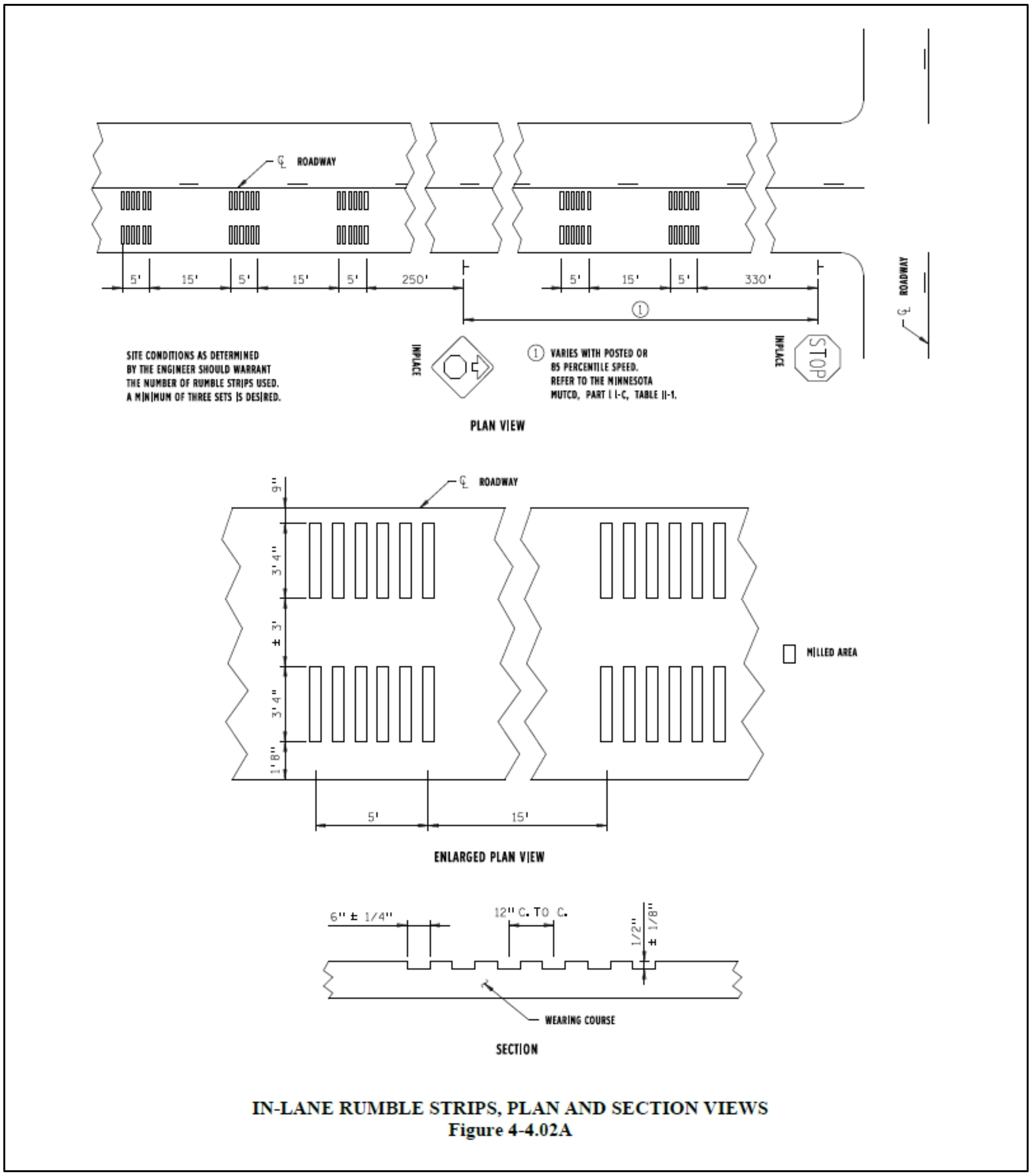
1.4.22 Michigan

No standards or specifications relating to transverse rumble strips could be found on the Michigan DOT website. However, their use is mentioned multiple times in Michigan's Highway Safety Improvement Plan (HSIP) selection lists (MDOT 2020).

A Michigan county engineer answered the survey. The responses from this engineer are provided in Table 1-2.

1.4.23 Minnesota

Minnesota provides a standard detail for the use of transverse rumble strips installed upstream of a stop sign. These consist of five panels of six wheel-path rumble strips spaced 15 ft apart. The panel closest to the intersection is placed 330 ft upstream of the stop sign, with the remaining four panels placed farther upstream, as seen in Figure 1-14. The rumble strips are 3/8 to 5/8 in. deep by 5.75 to 6.25 in. wide and are spaced 12 in. on center. The length of each rumble strip is 3 ft 4 in. (MnDOT 2019).



MnDOT 2019

Figure 1-14. Minnesota transverse rumble plans

Twenty-two agencies in Minnesota responded to the survey. One county responded that it uses one panel, one answered that it uses five panels, and the remainder (20 counties) answered that they use two panels. Most respondents were not aware of the reasons for their counties' practices. Those who responded indicated the following rationales:

- Based on past practice
- Based on what they had seen in other locations
- Two panels used in order to minimize noise (response given by two counties)
- Recommended by contractor
- Based on Minnesota DOT (MnDOT) standards

Most (nine) agencies responded that they use 6 strips per panel, one uses 8 strips, two use 10 strips, two use 12 strips, and one uses 16 strips. One agency indicated that it uses 3 strips, which does not logically make sense; that agency's response may have been regarding the number of panels. The respondents mostly indicated that the number of strips was based on existing practices or that the rationale was unknown. The responses indicated the following rationales for the number of strips:

- Sufficient number needed to create a rumble effect
- Found six to be effective and to minimize noise
- The optimal number so just two passes can be made with the milling machine
- Recommended by contractor

The majority of agencies indicated that the first panel drivers crossed was 900 to 1,000 ft upstream of the stop bar, while one agency responded 1,300 ft. Most agencies responded that the distance was based on standard practice. Other reasons given included the following:

- Based on posted speed limit
- Two times the distance recommended in the *Manual on Uniform Traffic Control Devices* (MUTCD) for the Stop Ahead sign

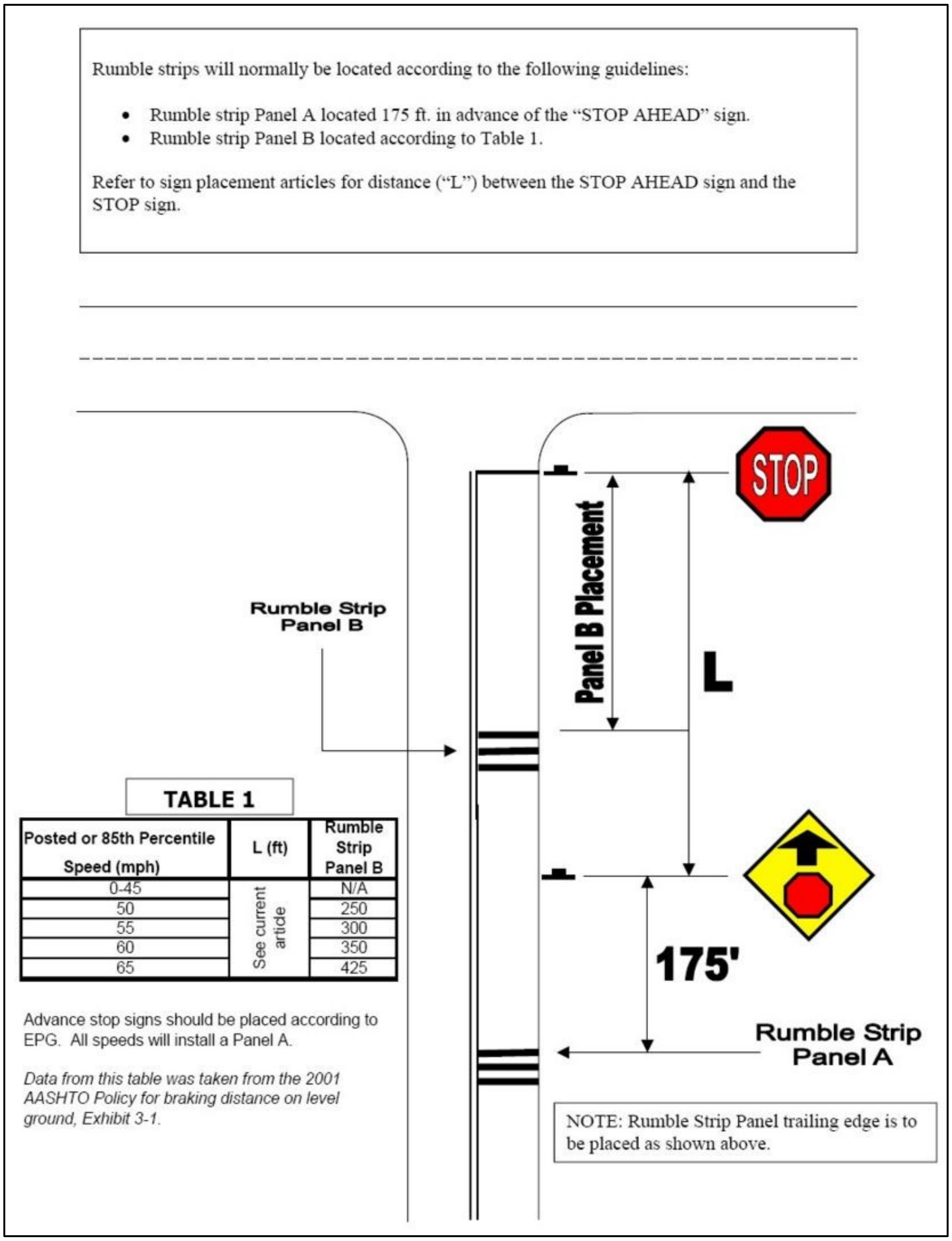
The majority of agencies responded that the last panel of rumble strips a driver would encounter was between 350 to 500 ft upstream of the stop bar, while one agency indicated 800 ft. Only one reason was provided, which indicated that the placement was selected so that the stop sign was visible, and the driver had time to react.

1.4.24 Mississippi

No reference to transverse rumble strips could be found on the Mississippi DOT website.

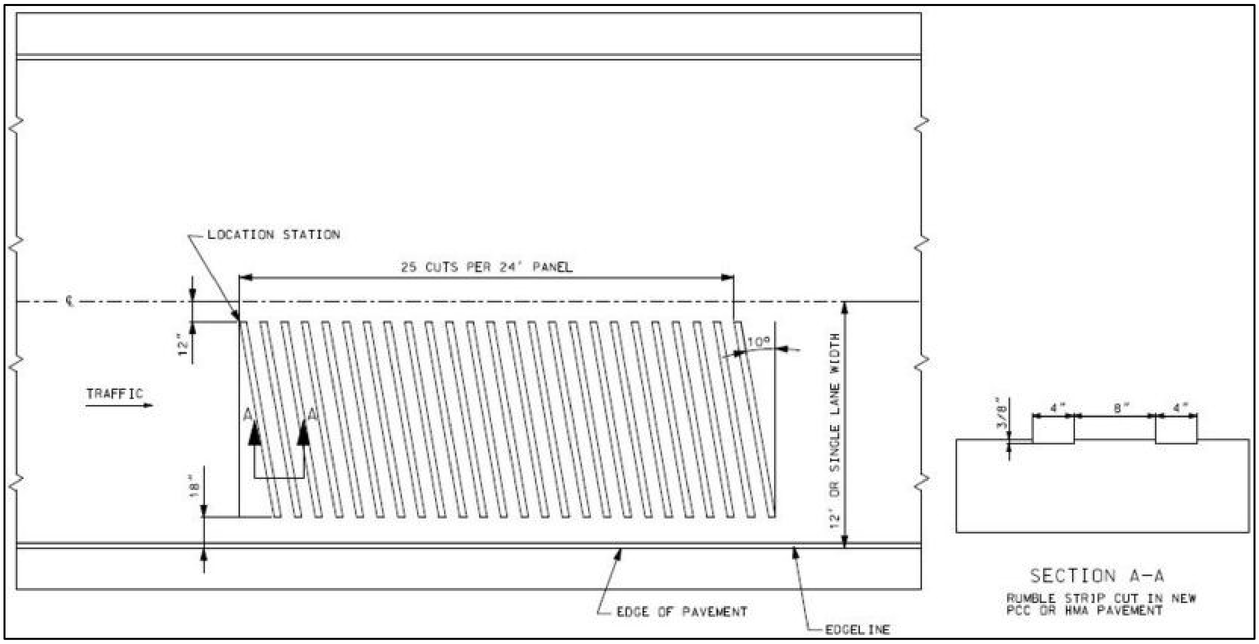
1.4.25 Missouri

Missouri utilizes one panel for speed limits of 45 mph or below, which is located 175 ft before the Stop Ahead sign, or two panels for speed limits greater than 45 mph. When two panels are used, the first is placed 175 ft upstream of the Stop Ahead sign and the second is placed anywhere from 250 to 425 ft upstream of the stop sign depending on the speed limit of the road, as seen in Figures 1-15 and 1-16.



MoDOT 2020

Figure 1-15. Missouri Fig. 626.4.2, typical transverse rumble strip dimensions



MoDOT 2020

Figure 1-16. Missouri Fig. 626.4.1, typical transverse rumble strip dimensions

Each panel of rumble strips is made up of 25 cuts over a 24 ft panel. Each rumble strip is 4 in. wide by 3/8 in. deep and is as long as the lane width minus 2.5 ft. The strips are spaced 8 in. apart and are placed at a 10-degree angle. As shown in Figure 1-16, they are placed 12 in. from the centerline and 18 in. from the edge of the pavement (not including the shoulder) (MoDOT 2020).

1.4.26 Montana

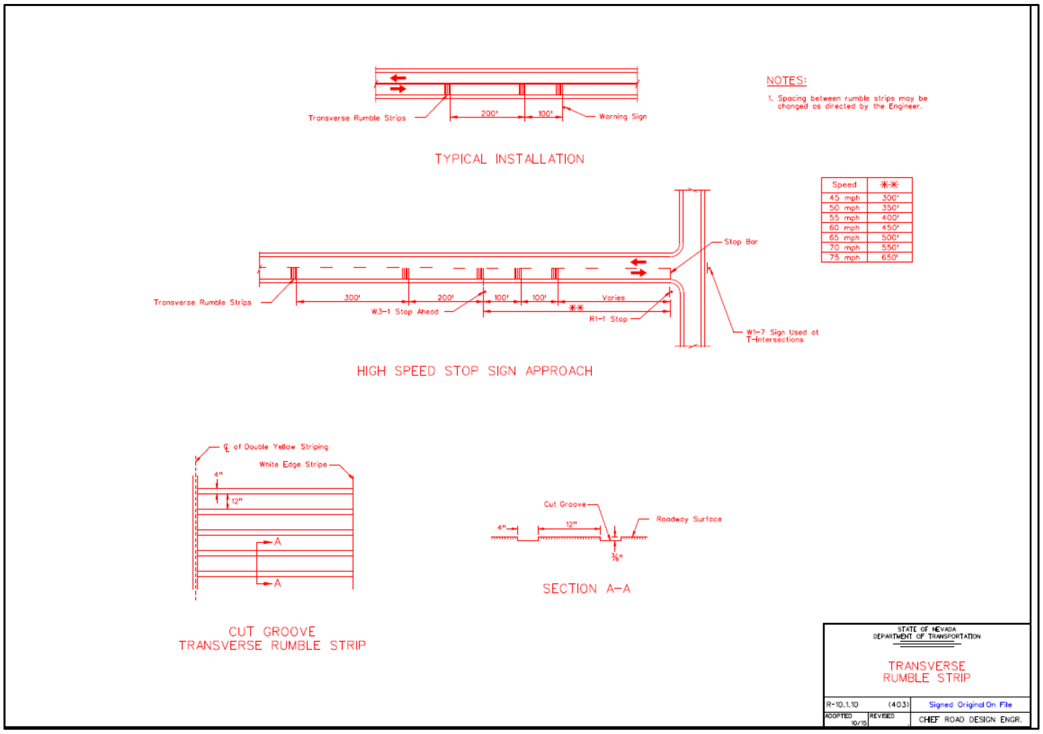
The only standards that could be found related to transverse rumble strips in Montana were related to temporary portable rumble strip usage (Wilde 2019, updated 2021).

1.4.27 Nebraska

The only standards that could be found related to transverse rumble strips in Nebraska were related to temporary rumble strips in the Traffic Control, Construction and Maintenance section of the state's standard plans (NDOT [Nebraska] 2020).

1.4.28 Nevada

Nevada provides a standard plan for TRS use. A typical installation features three panels of five strips, with the first panel placed near the advance warning sign, the second placed 100 ft upstream from the first, and the third placed 200 ft upstream from the second. A high-speed stop sign approach option features five panels of rumble strips with the closest to the intersection being located 300 to 650 ft upstream of the stop bar, depending on the speed limit. The spacing of the remaining panels can be seen in Figure 1-17. The rumble strips are 3/8 in. deep by 4 in. wide with a 12 in. spacing, and the length is equal to the lane width, as shown in Figure 1-17 (NDOT [Nevada] 2017).



NDOT [Nevada] 2017

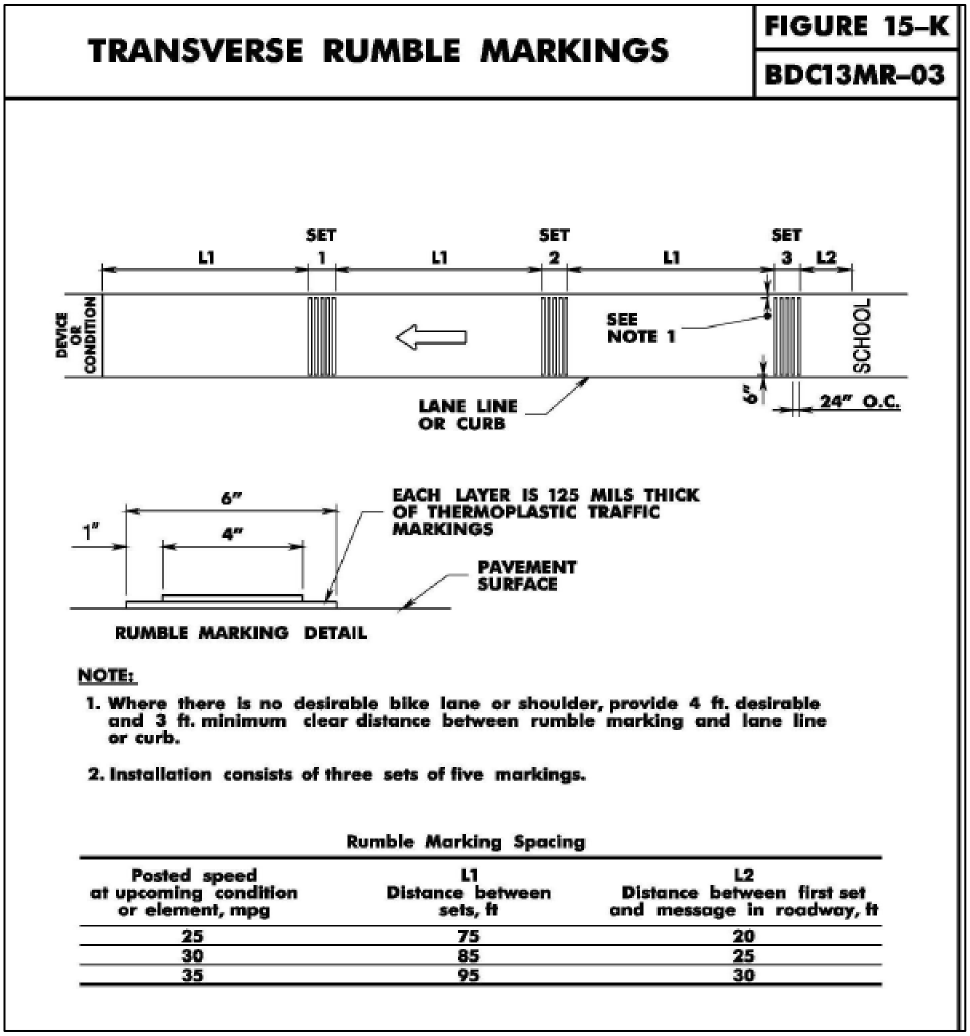
Figure 1-17. Nevada transverse rumble strip plan

1.4.29 New Hampshire

The New Hampshire DOT (NHDOT) provides guidance on milled-in transverse rumble strip dimensions. Rumble strips should be 3.5 to 4.5 in. wide by a maximum of 3/8 in. deep in a trapezoidal fashion, with a minimum length of 11 ft. NHDOT does not provide guidance on spacing nor installation locations besides referring to the patterns shown in the plan (NHDOT 2015).

1.4.30 New Jersey

The New Jersey standard drawing for transverse rumble strips applies to all uses, not just intersections. It features three panels of five thermoplastic markings. Each rumble strip consists of two layers of 125 mils thick thermoplastic material placed on top of each other. The bottom layer is 6 in. wide, and the top layer is 4 in. wide. The strips are placed 18 in. apart. The panels are placed as seen in Figure 1-18. The distances depend on the speed limit of the roadway (NJDOT 2015).



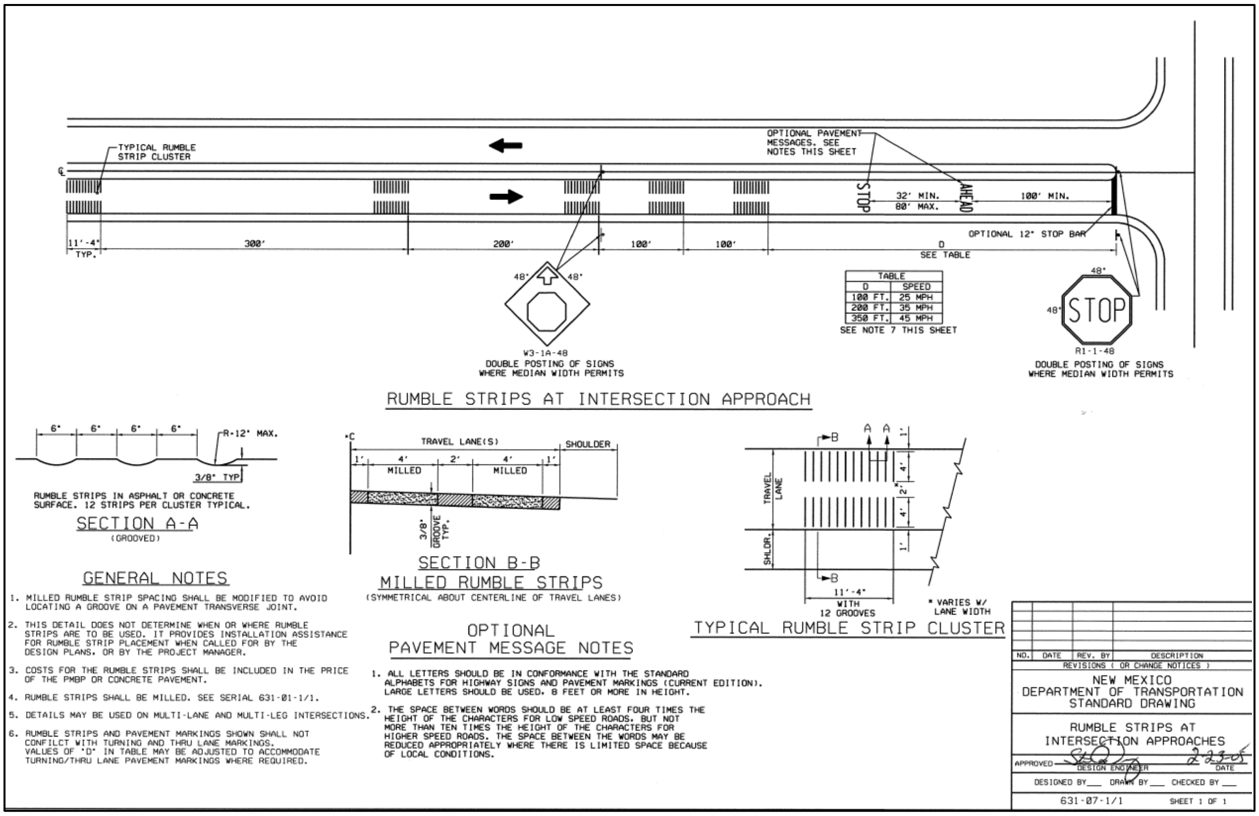
Posted speed at upcoming condition or element, mpg	L1 Distance between sets, ft	L2 Distance between first set and message in roadway, ft
25	75	20
30	85	25
35	95	30

NJDOT 2015

Figure 1-18. New Jersey transverse rumble strip plan

1.4.31 New Mexico

The New Mexico standard plans utilize five panels of wheel-path rumble strips at intersection approaches. Each panel features 12 grooves that are 4 ft long, 6 in. wide, and 3/8 in. deep with a curved design that has a maximum radius of 12 in. The grooves are spaced 6 in. apart with a 2 ft distance between the two panels of wheel-path rumble strips. As seen in Figure 1-19, the closest panel's location varies by speed limit, with the spacing between panels increasing the further upstream one gets (NMDOT 2005).



NMDOT 2005

Figure 1-19. New Mexico transverse rumble strip standard plan

1.4.32 New York

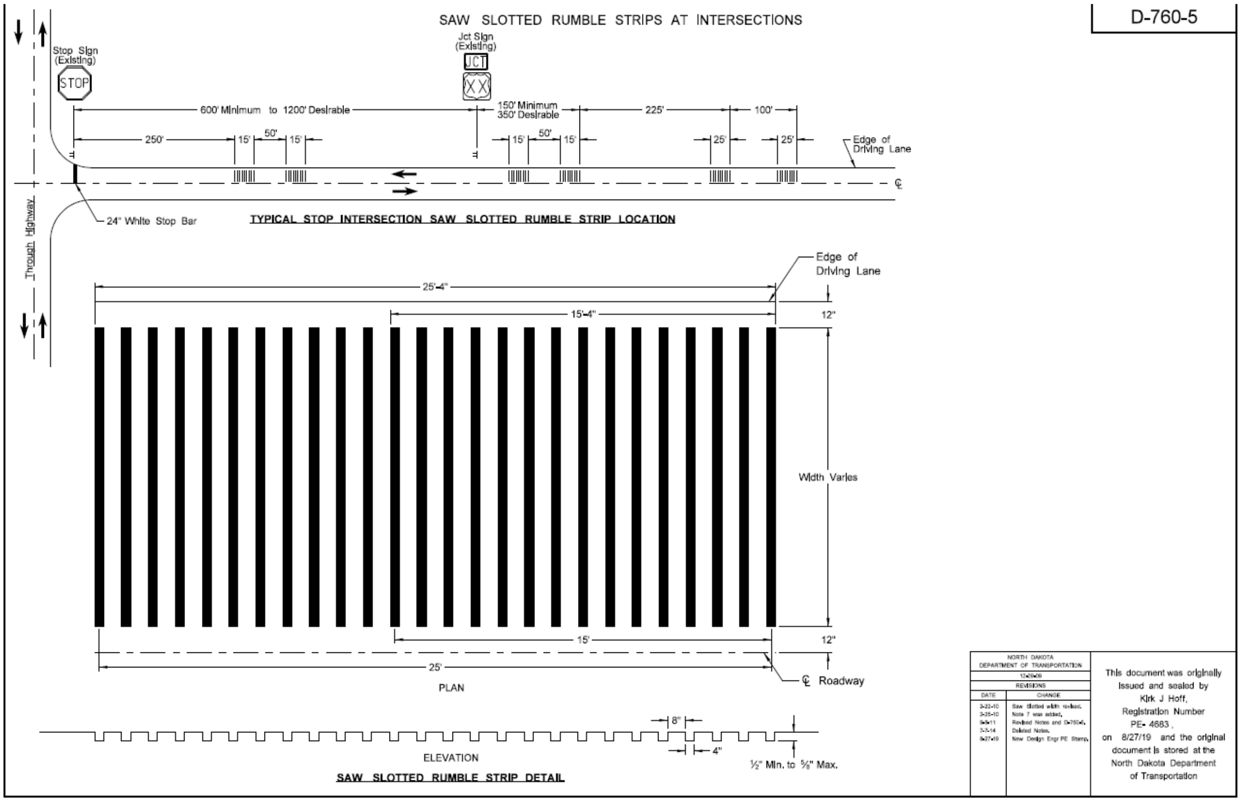
The only standard found for the New York State DOT related to TRS was one that demonstrated the dimensions of TRS but not the location or spacing needed. The rumble strips are 7 in. wide, have a length equal to lane width, and have a circular concave cross section with a depth of 1/2 to 5/8 in. and a maximum radius of 12 in. (NYSDOT 2014).

1.4.33 North Carolina

No reference to transverse rumble strips could be found on the North Carolina DOT website.

1.4.34 North Dakota

The North Dakota standard plans call for six panels of rumble strips (with the four closest to the intersection having 16 strips per panel and two furthest upstream having 26 strips per panel). These rumble strips are 1/2 to 5/8 in. deep, 4 in. wide, the length of the lane width minus 2 ft, and spaced 8 in. apart. As seen in Figure 1-20, the closest panel to the stop bar is 250 ft upstream of the stop sign, and the furthest panel upstream is 450 to 650 ft upstream of a junction sign (NDDOT 2019).



NDDOT 2019

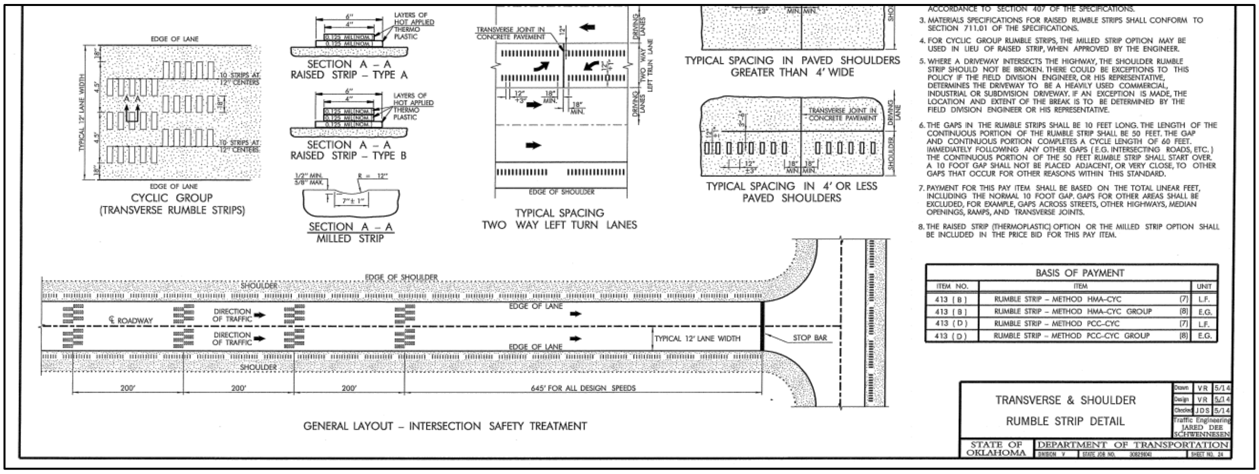
Figure 1-20. North Dakota transverse rumble strip standard

1.4.35 Ohio

Per the Ohio DOT *Traffic Engineering Manual*, transverse rumble strips in Ohio are 4 in. grooves at 12 in. spacing that are the length of the lane width minus 22 in. (4 in. from the centerline and 18 in. from the edge line). TRS may need to be shorter in areas with paved shoulders of 2.5 ft or less and in areas with bicycle traffic. The rumble strips are typically placed in two panels of 15 grooves spaced 250 ft apart. According to the guidance provided for intersections, the location of the rumble strip nearest the intersection should be at least 200 ft upstream of the stop bar for speed limits less than 50 mph or 300 ft for speed limits of 50 mph or greater (ODOT [Ohio] 2014).

1.4.36 Oklahoma

Oklahoma uses four panels of cyclic group rumble strips, as seen in Figure 1-21. These cyclic groups include 10 strips spaced at 12 in. on center. Milled-in strips are 1/2 to 5/8 in. in depth, 6 to 8 in. in width, and 18 in. in length. Oklahoma also includes an option for raised strips, which are thermoplastic strips applied on top of each other. All transverse rumble strips are spaced with the closest panel to the intersection being located 645 ft upstream. The other three panels are spaced 200 ft apart (ODOT [Oklahoma] 2014).

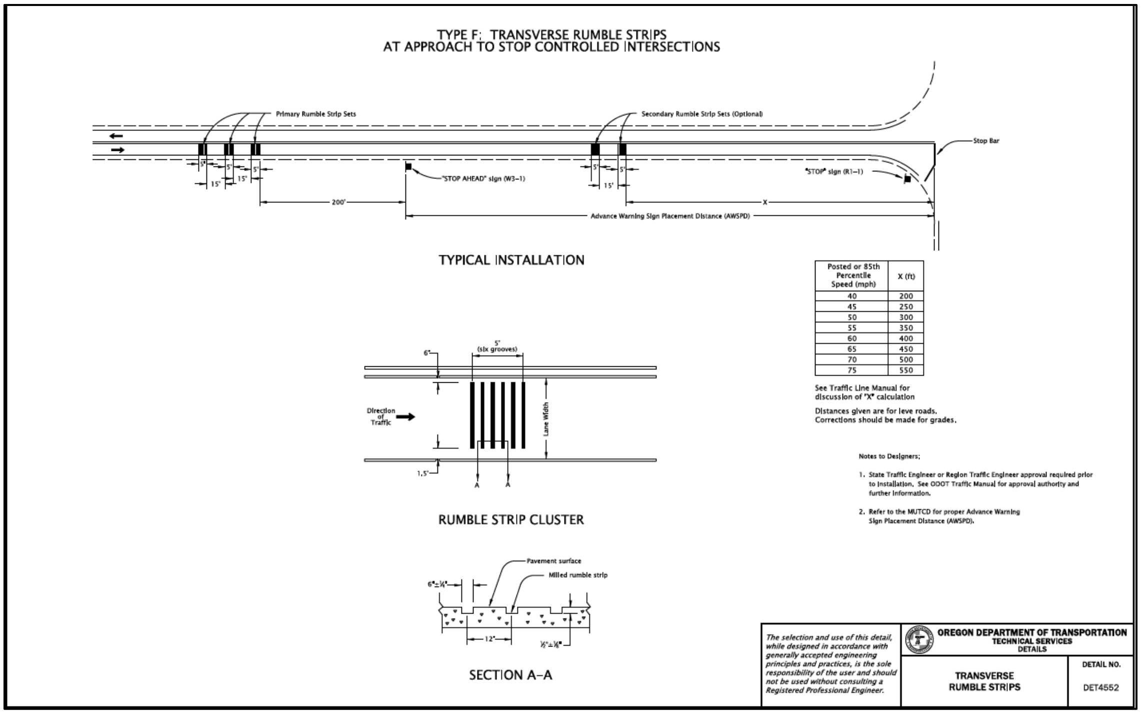


ODOT [Oklahoma] 2014

Figure 1-21. Oklahoma transverse rumble strip detail

1.4.37 Oregon

Oregon's standard plans for TRS involve placing three to five panels of six grooved rumble strips upstream of the stop sign. When three panels are used, they are spaced 15 ft apart starting 200 ft upstream of the Stop Ahead sign. When five panels are used, the first three panels are placed in the same locations as when three panels are used, along with two panels spaced 15 ft apart placed 200 to 550 ft upstream of the stop bar depending on the speed limit. The exact amount for each speed limit can be seen in Figure 1-22. Each rumble strip is 2 ft short of the lane width in length, 3/8 to 5/8 in. in depth, and 5.75 to 6.25 in. in width. Strips are spaced 12 in. on center as well. To be able to utilize TRS, the State Traffic Engineer or Region Traffic Engineer is required to sign off on the installation, as shown in Figure 1-22 (ODOT [Oregon] 2019).



ODOT [Oregon] 2019

Figure 1-22. Oregon transverse rumble strip details

1.4.38 Pennsylvania

Standards and specifications relating to the use of TRS in Pennsylvania could not be found. However, the use of TRS is mentioned in the Pennsylvania DOT *District Highway Safety Guidance Manual* (PennDOT 2019).

1.4.39 Rhode Island

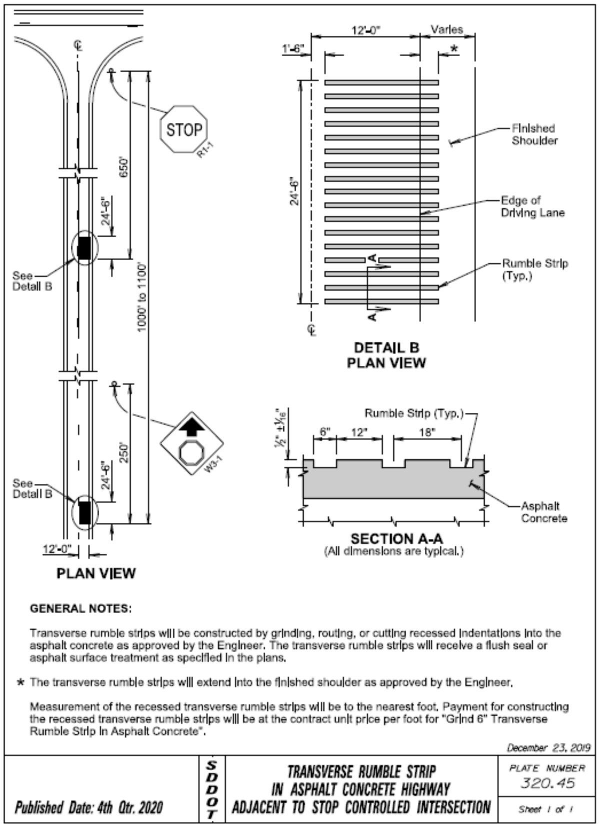
No reference to transverse rumble strips could be found on the Rhode Island DOT website.

1.4.40 South Carolina

The only specifications that could be found relating to transverse rumble strips in South Carolina are related to temporary rumble strips for speed control (SCDOT 2009).

1.4.41 South Dakota

South Dakota's standard plans for TRS involve two panels of 17 rumble strips. The panel nearest the intersection is generally 650 ft upstream of the stop sign, while the second panel is 250 ft upstream of the W3-1 Stop Ahead sign. The rumble strips are 7/16 to 9/16 in. in depth, 6 in. in width, and spaced 12 in. apart. The strips are located 18 in. from the centerline and may extend onto the finished shoulder, as shown in Figure 1-23 (SDDOT 2020).



SDDOT 2020

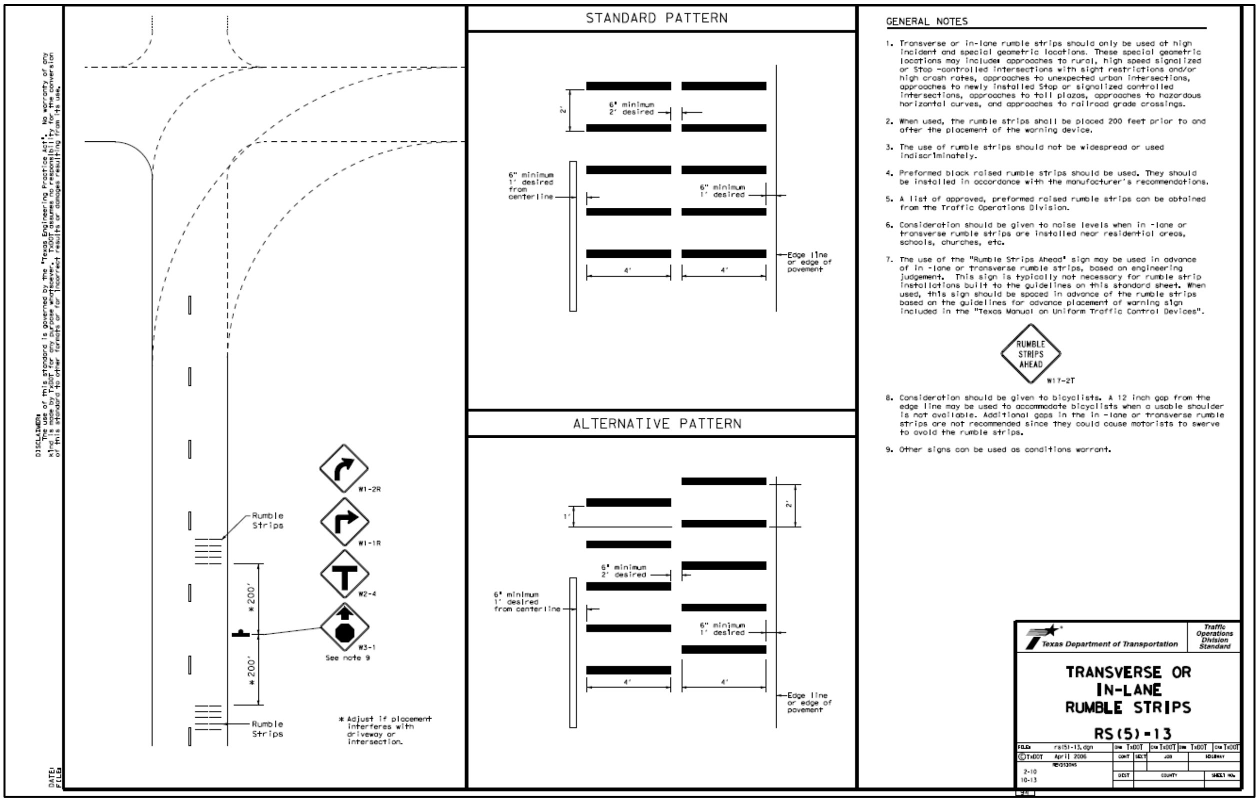
Figure 1-23. South Dakota transverse rumble strip plan

1.4.42 Tennessee

The only mention that could be found regarding the use of TRS by the Tennessee DOT is related to the use of portable temporary rumble strips in work zones (TDOT 2020).

1.4.43 Texas

Texas standard plans for TRS involve two panels of five strips each spaced 2 ft apart and placed 200 ft upstream and downstream of a W3-1 Stop Ahead sign. The guidance does not specify the width and depth of the rumble strips but does specify that they should be raised rumble strips made of preformed blocks. The configuration consists of a 4 ft long panel in each wheel path, with the two panels separated by section that is preferably 2 ft but that can be as small as 6 in. Either a standard pattern or an alternative pattern can be utilized, which can be seen in Figure 1-24 (TxDOT 2006).



TxDOT 2006

Figure 1-24. Texas transverse rumble strip standard

1.4.44 Utah

No mention of the use of transverse rumble strips could be found on the Utah DOT website.

1.4.45 Vermont

The only mention that could be found of the use of TRS by the Vermont DOT is related to temporary traffic control in work zones (VTrans 2011).

1.4.46 Virginia

The only mention that could be found of the use of TRS by the Virginia DOT is related to the use of portable temporary rumble strips in work zones (VDOT 2015).

1.4.47 West Virginia

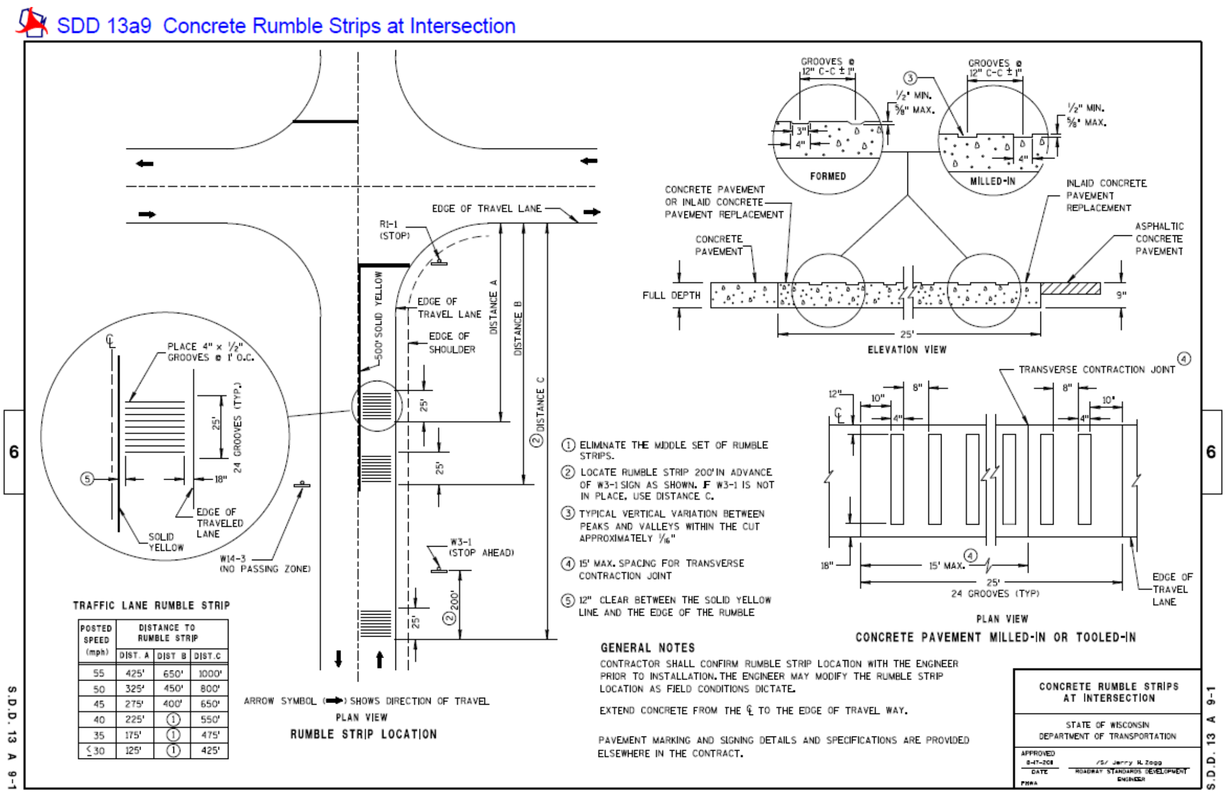
No mention of the use of transverse rumble strips could be found on the West Virginia DOT website.

1.4.48 Washington

Standard drawings or specifications on the use of TRS in Washington State could not be found. However, the use of TRS is allowed per the Washington State DOT design policy (WSDOT 2020).

1.4.49 Wisconsin

The Wisconsin DOT allows for the use of transverse rumble strips at two-way and four-way stop-controlled intersections where there is a fear that drivers may not expect or see the stop-controlled intersection ahead. The state guidelines do note that the noise created by the rumble strips should be considered if there are residences nearby. Wisconsin allows for formed or milled-in rumble strips. Both types have similar dimensions, with a depth of 1/2 to 5/8 in., a length equal to the lane width minus 2.5 ft, and a spacing of 8 in. The only difference is the width. The formed rumble strips are trapezoidal in shape with a width of 3 in. at narrowest point and 4 in. at the widest point, while the milled-in rumble strips are 4 in. wide. TRS at intersections in Wisconsin consist of two to three panels of 24 rumble strips whose location can vary based on speed limit, as seen in Figure 1-25 (WisDOT 2011).



POSTED SPEED (mph)	DISTANCE TO RUMBLE STRIP		
	DIST. A	DIST B	DIST. C
55	425'	650'	1000'
50	325'	450'	800'
45	275'	400'	650'
40	225'	(1)	550'
35	175'	(1)	475'
≤30	125'	(1)	425'

WisDOT 2011

Figure 1-25. Wisconsin standard design of transverse rumble strips at intersections

1.4.50 Wyoming

While documentation was found that TRS are used in Wyoming, no standard plans or specifications could be found (WYDOT 2018).

CHAPTER 2: SITE SELECTION AND DATA COLLECTION

2.1 SITE SELECTION

The Technical Advisory Panel (TAP) for this research project helped identify two potential counties in Minnesota to use for TRS installation sites. These counties included Dakota County, which encompasses the southwestern portion of the Twin Cities and areas to the south, and St. Louis County, which is located in northern Minnesota and includes Duluth and the surrounding area. After working with Dakota County to identify potential sites, there were concerns about traffic volumes and sites being near homes. Therefore, the research team only identified sites in St. Louis County.

The research team worked with Vic Lund (St. Louis Couty Engineer) to identify potential intersections within the county that had experienced issues with vehicles not stopping at the stop sign. The research team took the initial list of suggested sites and evaluated them using the St. Louis County geographic information system (GIS) for aerial views and Google Streetview. Sites were removed if there were multiple homes within 750 ft of the proposed transverse rumble strips. Once the list of sites was narrowed down, the research team visited Duluth to review locations. The research team reviewed factors such as the ability to position a data collection trailer in the ditch, unusual features near the roadway, and so on. Eight approaches were ultimately selected. An additional approach had initially been chosen, but due to a resident's complaints while establishing locations for data collection, it was decided to forgo that site and instead utilize an alternative site (Site 117).

The next decision was regarding the differences in TRS design that should be tested. It was determined that given the number of sites available within the scope of the project, only two factors could be tested. After discussions with the TAP, it was decided to keep the standard rumble strip dimensions described in the MnDOT standard design. This was important since the selected vendor only had the ability to mill within those parameters. Otherwise, more specialized equipment would be necessary. This decision meant that the rumble strips at each site would be 3 ft 4 in. long, 6 in. ± 1/4 in. wide, 1/2 in. ± 1/8 in. deep, and spaced 12 in. center to center. It was decided to vary the number of panels and the number of strips within a panel. It was decided to try 2 versus 3 panels and 6 versus 12 strips per panel. Because there were eight sites available to install strips, four variations were evaluated with two installations of each. The variations tried included the following:

- 2 panels with 6 rumble strips per panel
- 2 panels with 12 rumble strips per panel
- 3 panels with 6 rumble strips per panel
- 3 panels with 12 rumble strips per panel

For the panel locations, it was decided to follow Harwood's (1993) suggestion that the TRS should be located "so that either the upcoming decision point or a sign identifying the action that may be required is clearly visible as the driver passes over the rumble strip and allowing time for drivers to take that action." Therefore, it was decided that the first panel encountered would be 200 ft upstream of the Stop Ahead warning sign for each location. This distance was chosen because it was within the legibility distance of these signs. The closest panel to the intersection would be 250 ft, again because it was within the legibility sight distance of the stop sign. If three panels were used, the third panel was located halfway between the first and last panels. These distances are shown in Figure 2-1.

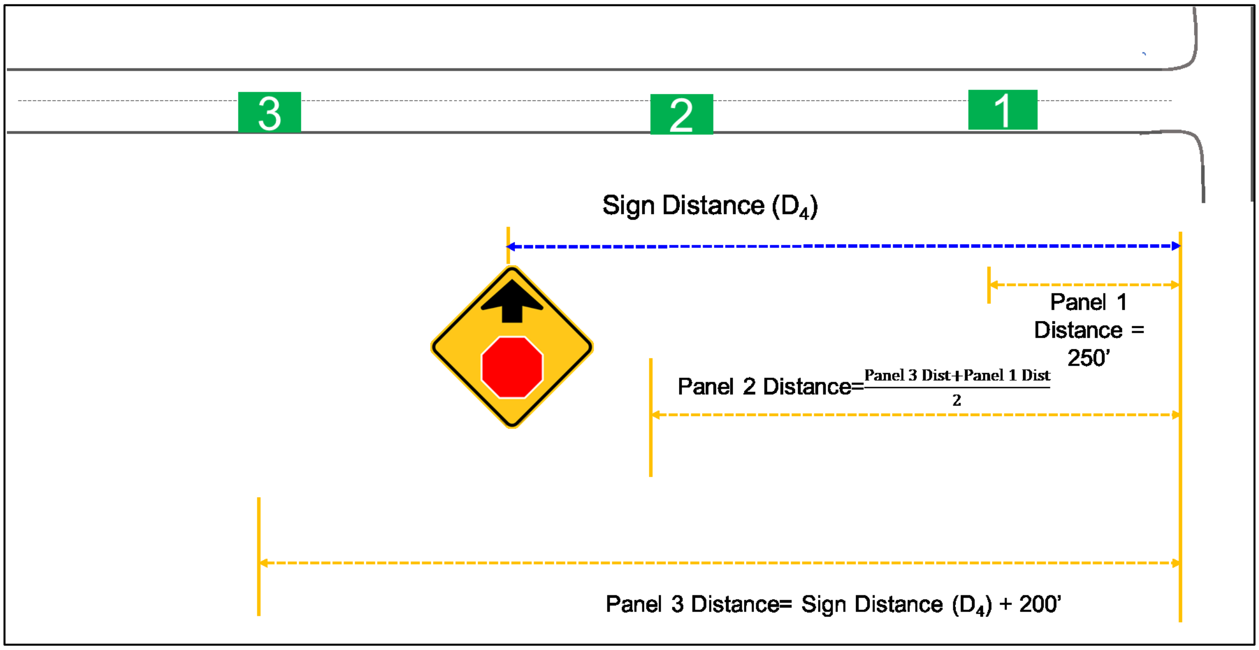


Figure 2-1. Locations of panels

Two sets of each TRS pattern were proposed. However, during milling at Site 111, which was set to have 3 panels with 6 rumble strips, it was found that a number of cracks had been sealed, which made it impossible to place all three panels. Therefore, the configuration at Site 111 was changed to include 2 panels with 12 rumble strips. Because of this, the configuration at Site 104 was changed to include 3 panels, but the number of rumble strips per panel was kept at 12. Therefore, only one site had 3 panels with 6 strips while three sites had 3 panels with 12 strips. The final sites selected and the TRS pattern installed at each approach are listed in Table 2-1. The various designs are provided in Appendix A.

Table 2-1. Summary of sites and TRS pattern installed

SiteID	Streets	TRS Pattern Installed
103	CO 254 and CO 43 West	2 panels with 12 rumble strips
104	CO 295 and CO 4 East	3 panels with 12 rumble strips
106	Hwy 7 and Hwy 133 North	2 panels with 6 rumble strips
108E	Hwy 33 and CSAH 7 East	3 panels with 12 rumble strips
108W	Hwy 33 and CSAH 7 West	3 panels with 6 rumble strips
111	Hwy 33 and CSAH 56 East	2 panels with 12 rumble strips
112	CO 98 and Hwy 2 South	2 panels with 6 rumble strips
117	US 153 and CO 133 West	3 panels with 12 rumble strips

When milling, the contractor placed the rumble strips slightly closer to the centerline than to the edge line to provide additional space near the shoulder. This was done to encourage drivers who chose to circumvent the rumble strips to do so on the shoulder instead of in the opposite lane. A photo of the milled-in rumble strips is shown in Figure 2-2.

Figure 2-2. Transverse rumble strips being milled in

2.2 DATA COLLECTION PROCESS

Data were collected approximately one week before installation and then approximately 1 month and 9 months after. Cameras and speed sensors mounted to trailers, as shown in Figure 2-3, were rented from a vendor (Street Smart).

Figure 2-3. Video data collection array

Two trailers were placed in two locations per approach for each data collection period. Figure 2-4 illustrates the approximate locations of the trailers for Site 106.

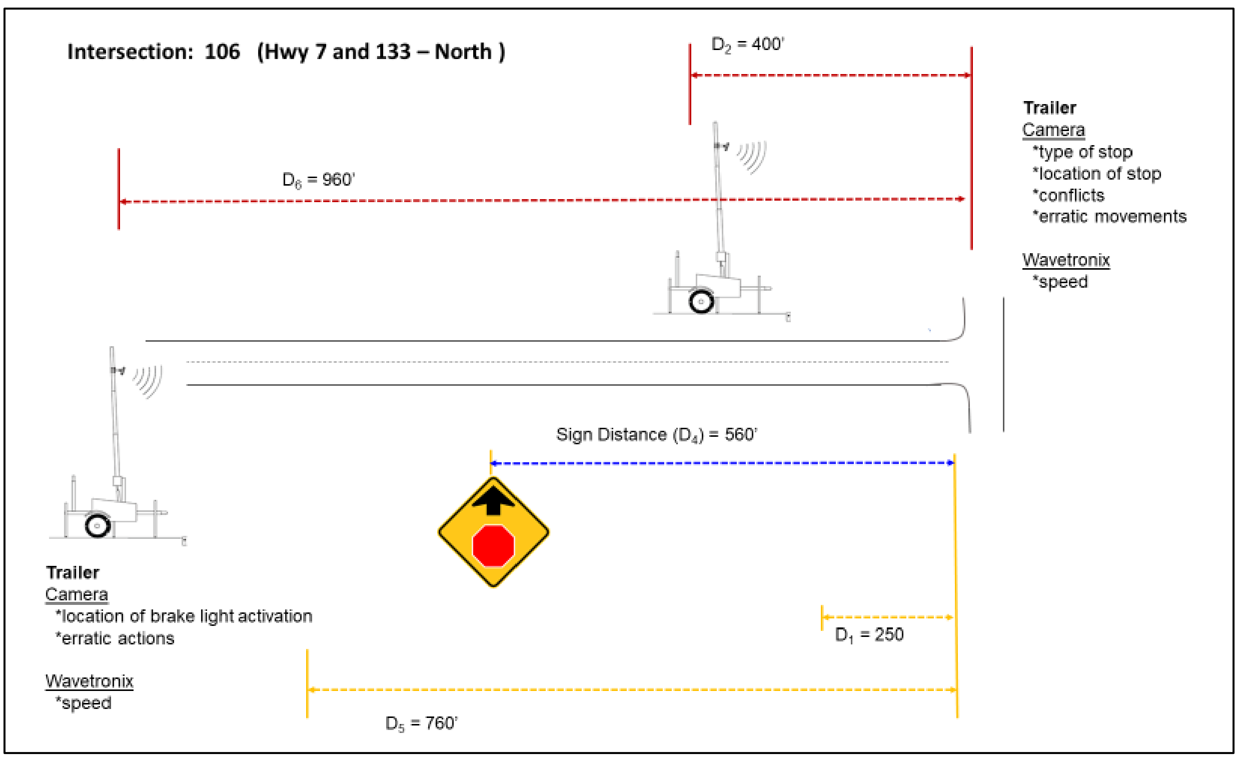


Figure 2-4. Data collection layout for Site 106

The trailer nearest the intersection was placed approximately 400 ft upstream from the stop bar or stop sign if a stop bar was not present. The actual placement varied a bit depending on the availability of a suitable location to place the trailer. The camera on this trailer was utilized to collect driver behavior as they approached the intersection as well as stopping behavior at the intersection. The speed sensor was utilized to determine drivers' speeds as they approached the intersection.

The upstream trailer was placed approximately 400 to 600 ft upstream of the stop ahead warning sign, which was generally 900 to 1,300 ft upstream of the stop bar or stop sign. The exact placement again depended on finding a suitable location to place the trailer. The camera on this trailer was used to help capture drivers' behavior as they approached the rumble strips and was used to help capture initial braking location as well as any erratic behavior. The speed sensor was used to determine upstream speeds for drivers that should have not been influenced by the presence of the TRS.

Data were collected for the four weeks immediately before rumble strips were in place, with two approaches being collected per week. The rumble strips were then installed over two days (August 18 and 19). The following Sunday, August 22, the 1-month after data collection period began. Data were also collected at approximately 9 to 10 months after installation. The approximate dates of data collection for each site can be seen in Table 2-2.

Table 2-2. Data collection periods by site

Site	Before Data Collection Period	1 Month after Data Collection Period	9 Months after Data Collection Period
103	8/10 – 8/16/2021	8/22 - 8/29/2021	5/16 – 5/22, 2022
104	8/10 – 8/16/2021	8/22 - 8/29/2021	5/16 – 5/22, 2022
106	8/2 – 8/9/2021	9/20 – 9/27/2021	5/9 – 5/15, 2022
108E	7/19 - 7/26/2021	9/5 – 9/12/2021	5/23 – 5/31, 2022
108W	7/26 - 8/2/2021	8/30 – 9/6/2021	5/23 – 5/31, 2022
111	7/19 - 7/26/2021	9/5 – 9/12/2021	6/1 – 6/6, 2022
112	7/26 – 7/28/2021	8/30 – 9/6/2021	Did not collect due to construction
117	8/2 – 8/9/2021	9/20 – 9/27/2021	6/7 – 6/13, 2022

2.3 DATA REDUCTION PROCESS

Data collected included speed data and video.

The speed data included a time stamp, vehicle type, and speed. A trace was defined as a single vehicle passing both data collection trailers. The research team attempted to match each vehicle's upstream speed to its downstream speed based on time stamp. This was unfortunately somewhat harder than expected. The speed data were collected based on the nearest second. Therefore, matching speeds when more than one vehicle traveled passed the trailers in one minute was difficult. It was decided to only include the speed data for the first vehicle that passed the trailers within a given minute because it was assumed that any vehicles that followed may not be free flow. Going through the dataset to confirm whether the included vehicles were, in fact, free flow was too resource intensive and therefore outside the scope of what could be accomplished. Therefore, it was assumed that all matching was accurate and that all vehicles were free flow. The same process was used for the data collected before and after installation, so any deviation from the assumption should be similar for both datasets.

The video was reviewed, and speed data were not included when heavy rain, fog, or other events that might affect driving behavior were present. Examples of some of these other events included when shoulder work was being done at one of the sites and when a vehicle was parked on the shoulder near the intersection. After the speed data associated with these events were removed, the remaining traces were used for the speed analysis, and the differences between the upstream and downstream speeds were calculated.

Other metrics were manually reduced from the video data. These included type of stop, location of braking, and stopping position. Due to the resources needed to manually code these metrics, only a sample of vehicles was coded for each approach for each time period. Traces were sampled only during daytime conditions, which lasted from approximately 6 a.m. to 8 p.m. each day. Originally 200 samples were randomly chosen using a random number generator in Microsoft Excel. However, coding was more efficient than originally estimated, so for most of the metrics an additional 50 samples were randomly chosen for a total of 250 traces per site. Since late braking was much more time consuming to code than the other metrics, a target of 100 vehicles was used for data reduction for this metric.

Table 2-3 list the variables that were reduced and the potential options for each variable. After reviewing the coded data, it was found that some of the data had to be thrown out due to non-normal driving behavior, such as drivers making a U-turn or stopping and getting out of their car at the intersection. The remaining data were then used to complete the analyses outlined in the next chapter.

Table 2-3. Manually reduced video variables

Variable	Options	Description
Weather	Sunny	The weather appeared to be sunny.
	Overcast	There were significant clouds that blocked the sun.
	Light rain	There was light rain.
VehicleType	Motorcycle	Driver was riding a motorcycle.
	Passenger car	Examples of passenger car include cars, station wagons, SUVs, and minivans.
	Pickup	Vehicle was a pickup truck.
	Bus	Includes school buses or city buses.
	Single-unit heavy vehicle	Heavy vehicles such as dump trucks, moving trucks, campers, or large trucks where the cab and storage are attached.
	Multi-unit heavy vehicle	Includes heavy vehicles where the cab and storage are separate units that can move independently. A common example is a large semi-truck.
StopType	Full stop	Speed was reduced to approximately zero. The vehicles wheels should pause for approximately 1 second to be considered a full stop.
	Slow rolling stop	Clear braking (or slowing) was noted, and vehicle speed was approximately greater than zero but less than 5 mph. If vehicles tires appear to stop, but the stop is less than approximately 1 second, then the behavior should be considered a slow rolling stop.
	Fast rolling stop	Clear braking (or slowing) was noted, and vehicles speed was approximately greater than 5 mph but less than 10 mph.
	No stop	Vehicle's minimum speed was approximately greater than 10 mph.
StopLoc	In front of stop bar	At least the front two wheels are positioned past the stop bar or in front of the stop sign if a stop bar is not present when the vehicle reaches it at minimum speed. If a vehicle stops behind the stop bar and then pulls forward to obtain adequate sight distance, then code as behind stop bar.
	Behind stop bar	No tires are located beyond the stop when the vehicle reaches its minimum speed at the intersection.
NumVehs	Whole numbers equal to zero or greater	The number of vehicles that pass on the mainline from the time the vehicle is approximately 300 ft from the intersection until the time it maneuvers into the intersection. If the major road is a divided road, only count the number of vehicles in the closest panel of lanes. If the vehicle turns right at the intersection, only count vehicles coming from the left. This value will be any whole number equal to 0 or greater.
Movement	Left	Driver turned left at the intersection.
	Right	Driver turned right at the intersection.
	Through	Driver went straight through at the intersection.
EvasiveManeuver	Yes	Driver made an evasive maneuver such as driving into the opposing lane or on the shoulder.
	No	Driver made no evasive maneuver.
BrakedLate	Yes	Brakes were initiated 290 ft or closer to the stop bar.
	No	Brakes were initiated more than 290 ft from the stop bar.

CHAPTER 3: ANALYSIS AND RESULTS

The reduced speed and video data were used to conduct three main analyses. These analyses included comparisons of changes in speed, stopping behavior, and braking behavior as described in the following sections. Several metrics were used to assess speed and stopping behavior. Simple statistics were used to assess changes in behavior from the before to the after period.

3.1 CHANGE IN AVERAGE SPEED NEAR THE INTERSECTION

Speed metrics were calculated for the location upstream of the intersection, which was intended to serve as a control, and for the location near the intersection (see Section 2.2). Table 3-1 shows average speeds for the data collected just upstream of each intersection. Data were collected in the same location at each approach during each time period, and the trailer was located approximately 400 ft upstream of the stop bar.

Changes in average speed from the before to the after periods were calculated as shown in Table 3-1. Differences that were statistically significant at the 95th percent confidence level are shown in bold with asterisks. For instance, at Site 103, average speed increased from 37.07 mph in the before period to 37.6 mph in the 1-month after period (+0.53 mph). At this location, speeds increased slightly even though the TRS had been installed. It should be noted there were issues with the upstream data collected at Site 108 East at the 9-month after collection period.

A positive value for speed change indicates that speeds increased from the before to the after period. A negative value indicates that the average speed decreased and is treated as a safety benefit; these values are highlighted in blue.

It was anticipated that speeds would be lower just upstream of the intersection after installation of the TRS since drivers would have crossed at least one set of rumble strips. In the 1-month period after installation, speeds had increased or decreased only slightly (less than 0.5 mph) at the majority of the sites (103, 104, 108 West, 117). Average speeds decreased by 2.9 mph at Site 106, by 2.43 mph at Site 108 East, and by 2.27 mph at Site 111. Speeds increased at Site 112 (3.11 mph).

As noted above, data were not collected in the 9-month after period at Site 112. At the remaining locations, average speeds had changed only slightly at four locations (less than 0.5 mph). Average speeds had decreased by 9.3 mph at Site 106, by 1.51 mph at Site 108 West, and by 7.99 mph at Site 117.

Overall, four locations experienced little change (< 1 mph difference) at 1 month after installation, while three sites saw a decrease and one site saw an increase. At 9 months after installation, four locations also experienced little change and three sites experienced a decrease (data were not available for one location). It was expected that speeds would have decreased at all locations after installation of the TRS. Speeds at the upstream locations were evaluated because they served as a control, and speeds may increase or decrease overall at a location independent of the treatment. It was assumed that speeds upstream of the TRS would not be impacted by the TRS. It was found that speeds upstream were reasonably the same or in some cases decreased from the before to the after periods.

Table 3-1. Summary statistics of speed metrics

Site	Time Period	Sample Size	Avg Speed Near Intersection	Change in Speed Near Intersection	SD of Speed Near Intersection
103	Before	2918	37.07		5.47
	1 Mon After	2504	37.6	**0.53***	5.09
	9 Mon After	3693	37.44	**0.37***	5.1
104	Before	1977	38.91		5.64
	1 Mon After	2601	38.85	-0.06	7.12
	9 Mon After	3500	39.44	**0.53***	5.15
106	Before	1026	39.08		7.91
	1 Mon After	850	36.19	**-2.89***	9.45
	9 Mon After	791	29.81	**-9.27***	4.58
108E	Before	993	41.94		7.79
	1 Mon After	915	39.51	**-2.43***	6.98
	9 Mon After	1733	41.53	**-0.41***	6.13
108W	Before	2387	39.18		5.78
	1 Mon After	2071	39.2	0.02	5.78
	9 Mon After	1805	37.67	**-1.51***	6.3
111	Before	1024	35.70		7.92
	After	1322	33.43	**-2.27***	9.1
	9 Mon After	1200	35.51	-0.19	7.19
112	Before	810	34.35		9.31
	After	2328	37.46	**3.11***	7.18
	9 Mon After	N/A	N/A	N/A	N/A
117	Before	1267	39.86		6.59
	After	1051	40.05	0.19	6.12
	9 Mon After	624	31.87	**-7.99***	5.23

*Change is statistically significant at the 95% level of significance.

3.2 CHANGE IN PERCENTAGE EXCEEDING SPEED THRESHOLD

The percentage of drivers who were exceeding a speed that would result in them having to decelerate at an above-average rate was also considered. The percentages of drivers traveling 40 mph or greater and 45 mph or greater near the intersection location were also calculated. Speeds over 40 mph would require drivers to decrease their speed at a rate greater than the average maximum deceleration noted by Wang et al. (2005). Table 3-2 demonstrates the change in the percentage of drivers traveling at speeds greater than 40 and 45 mph. A positive value indicates that the fraction of drivers exceeding the threshold increased. A negative value indicates that the fraction of drivers who were over the defined threshold decreased and is treated as a positive safety benefit; negative values are highlighted in blue.

As noted in Table 3-2, Site 106 saw significant decreases in vehicles traveling over the stated thresholds. At 1 month after installation, the percentage of vehicles that exceeded 40 mph decreased by 6.95%, and at 9 months the decrease was 37.75%. Sites 104 and 108 East saw significant decreases at the 40-mph threshold for both time periods. Sites 108 West, 111, and 112 each saw a significant decrease in at least one after period and a nonsignificant change for the other time periods. Site 112 was the only site that saw an increase at the 40-mph threshold, while site 108 West saw a slight increase in the percentage for the 45-mph threshold at the 1-month after period before seeing a decrease in at the 9-month after period. Site 103 saw no significant change at either threshold or time period. Overall, most sites experienced decreases in vehicles traveling over 40 or 45 mph.

Overall, one site showed little change (< 1%) in the fraction of vehicles exceeding 45 mph at 1 month after installation of the TRS. Five sites showed decreases and two sites showed increases. At 9 months after installation, four sites showed little change and three sites showed decreases.

Table 3-2. Summary statistics of percentage decelerating at an above average rate

Site	Time Period	Number of Samples	Percentage Traveling above 40 mph	Percentage Traveling above 45 mph	Change in % above 40 mph	Change in % above 45 mph
103	Before	2919	22.68%	5.31%		
	1 Mon After	2505	24.23%	5.87%	+1.55%	+0.56%
	9 Mon After	3694	23.20%	6.25%	+0.52%	+0.94%
104	Before	1978	41.30%	12.34%		
	1 Mon After	2602	38.43%	10.38%	**-2.87%***	**-1.96%***
	9 Mon After	3501	38.50%	12.40%	**-2.80%***	+0.06%
106	Before	1027	39.14%	19.77%		
	1 Mon After	851	32.20%	13.75%	**-6.95%***	**-6.02%***
	9 Mon After	792	1.39%	0.63%	**-37.75%***	**-19.13%***
108E	Before	994	63.08%	29.98%		
	1 Mon After	916	44.65%	21.62%	**-18.43%***	**-8.36%***
	9 Mon After	1734	54.79%	29.07%	**-8.29%***	-0.91%
108W	Before	2388	42.71%	11.01%		
	1 Mon After	2072	40.01%	13.61%	-2.70%	**+2.60%***
	9 Mon After	1806	28.52%	9.14%	**-14.20%***	**-1.88%***
111	Before	1025	21.76%	7.22%		
	1 Mon After	1323	18.29%	4.38%	**-3.46%***	**-2.84%***
	9 Mon After	1201	19.40%	7.08%	-2.36%	-0.14%
112	Before	811	23.80%	8.88%		
	1 Mon After	2329	31.99%	10.35%	**+8.19%***	+1.47%
	9 Mon After	N/A	N/A	N/A	N/A	N/A
117	Before	1268	46.69%	20.50%		
	1 Mon After	1052	48.38%	17.40%	+1.70%	-3.11%
	9 Mon After	625	3.04%	0.80%	**-43.65%***	**-19.70%***

*Change is statistically significant at the 95% level of significance.

3.3 CHANGE IN SPEED FROM UPSTREAM TO DOWNSTREAM DATA COLLECTION LOCATIONS

The change in speed from the upstream to downstream locations was also used as a metric to compare the effectiveness of the rumble strip configurations. As noted in Section 2.3, speeds for individual vehicles were matched between the upstream and downstream locations using a time stamp. This metric indicates how much vehicles reduced their speeds after crossing one or more sets of rumble strips. Average speed (Section 3.1) may not always be a clear metric for the effectiveness of a countermeasure since drivers are already reducing their speeds at a stop-controlled approach. The change from upstream to downstream speed was intended to determine whether drivers reduced their speeds to a greater degree as they crossed the rumble strips. Table 3-3 shows the changes in speed from the upstream to downstream locations. Since the metric shows differences in speed reduction, a positive value indicates that speeds were reduced more after installation and is treated as a safety benefit; these values are highlighted in blue.

Table 3-3. Average speed reduction from the upstream to downstream data collection locations

Site	Time Period	Number of Samples	Average Speed Reduction	SD of Speed Reduction	Change in Speed Reduction*
103	Before	2918	16.16	9.03	
	1 Mon After	2504	15.93	9.89	-0.23
	9 Mon After	3693	11.03	7.28	**-5.13****
104	Before	1977	11.51	12.52	
	1 Mon After	2601	12.56	9.57	**1.05****
	9 Mon After	3500	9.84	6.96	**-1.67****
106	Before	1026	13.89	7.16	
	1 Mon After	850	17.86	10.23	**3.97****
	9 Mon After	791	11.48	3.87	**-2.41****
108E	Before	993	9.77	8.67	
	1 Mon After	915	10.77	5.75	**1.00****
	9 Mon After	1733	N/A	N/A	N/A
108W	Before	2387	8.54	6.36	
	1 Mon After	2071	9.85	9.55	**1.31****
	9 Mon After	1805	8.5	9.89	-0.04
111	Before	1024	9.41	9.42	
	After	1322	12.85	10	**3.44****
	9 Mon After	1200	5.63	10.59	**-3.78****
112	Before	810	0.35	12.92	
	After	2328	1.35	12.49	1.00
	9 Mon After	N/A	N/A	N/A	N/A
117	Before	1267	9.47	10.03	
	After	1051	11.39	6.41	**1.92****
	9 Mon After	624	19.1	7.7	**9.63****

* A positive value indicates that average speed near the intersection decreased after TRS were installed compared to before.
**Change is statistically significant at the 95% level of significance.

For example, at Site 103, drivers reduced their speeds from the upstream to downstream location by an average of 16.16 mph before TRS installation. At 1 month after installation, drivers only reduced their speeds by an average of 15.93 mph. This change indicates that drivers were actually less likely to decrease their speeds after TRS installation, which was unexpected.

Since the data were normally distributed, a two-tailed t-test with assumed unequal variance was used to determine whether the change in average speed reduction was statistically significant for each site. A positive value indicates that the average reduction in speeds from upstream to downstream was greater after TRS installation, in other words, that drivers decreased their speeds to a greater degree after installation. A negative value indicates that the average speed reduction decreased after TRS were installed. Bolded values in Table 3-3 indicate that the change was significant at a 95% confidence level.

At 1 month after installation, one location (Site 103) had only minor changes (less 0.5 mph). Site 104 had a 1.05 mph increase in average speed reduction. In the before period, vehicles reduced their speed by an average of 11.5 mph from the upstream location to the location near the intersection. At 1 month after installation, the average reduction in speed was 12.56 mph. This indicates that after TRS installation, vehicles were more likely to decrease their speeds. Significant reductions were also seen for Site 106 (3.97 mph increase), Site 108 East (1.00 mph increase), Site 108 West (1.31 mph increase), Site 111 (3.44 mph increase), and Site 117 (1.92 mph increase). Site 112 saw a 1 mph reduction. However, this was not significant.

It should be noted that the speed reductions seen between the upstream and downstream speeds at Site 112 were quite small compared to other locations. This was due to the fact that a railroad crossing was just upstream of where the upstream speed data were collected, so it is likely that vehicles had slowed to cross that. Additionally, even though data were collected for a week, only two days of speed data could be reduced.

Overall, all but one location experienced increases in the amount of speed reduction during the 1-month after period, suggesting that the TRS were effective in encouraging drivers to reduce their speeds as they approached the intersection at the 1-month after period.

At 9 months after installation, either the change in speed reduction was minimal or the speed reduction was less than that observed before TRS installation. For instance, at Site 105, before TRS installation vehicles decreased their speeds on average by 16.16 mph from the upstream to downstream locations. At 9 months after installation, the average decrease in speeds was 11.03 mph (5.13 less than the before period). This indicates that drivers were less likely to reduce their speeds after crossing the TRS. Only one site (117) saw an increase in the amount drivers reduced their speeds. At this site, drivers decreased their speeds by 9.63 mph more than the before period.

The results for the 9-month after period were unexpected. The data were re-examined to ensure that no errors were made, but no explanation for the results was noted. As noted in Section 2.3, the videos were reviewed for unusual situations (e.g., heavy rain, stopped vehicle by roadway). As a result, there was no reason to believe that an unusual scenario was present that impacted vehicle speeds.

Overall, the speed analysis found that drivers slowed down from the upstream location as they approached the intersection to a greater degree after the TRS were in place. This likely indicates that the TRS increased drivers' awareness of the upcoming intersection. A few intersections, however, saw a decrease in the average speed reduction near the intersection after the TRS were in place.

3.4 TYPE OF STOP

Type of stop was coded using four different categories, as noted in Table 2-3. After examining the data, it was decided to combine the data into two categories: full stop/slow rolling stop and fast rolling stop/no stop. It was decided to combine full stop and slow rolling stop because full stop was heavily influenced by the presence of vehicles on the mainline. For three of the intersections, at least 85% of full stops occurred when at least one vehicle was on the mainline. At the other three intersections, the percentage of full stops occurring in this scenario ranged from 50% to 70%. Additionally, fast rolling stops and no stop were combined because there were very few if any instances in which vehicles did not stop. For clarity in describing results, the term "full/rolling stop" will be used to refer to the category with full stop and slow rolling stop, and the term "no stop" will be used to refer to the category with fast rolling stop and no stop.

Summary statistics of the percentage of stops in each category are shown in Table 3-4. It should be noted that 9-month after data were not collected at Site 112 due to construction at the site. Additionally, the camera angle at Site 111 in the 9-month after period was positioned such that the location of the stop (i.e., in front of/behind stop bar) could not be accurately coded, and therefore this metric was not available at this site. One column shows change in full/rolling stops. An increase indicates that more drivers came to a full or rolling stop after installation, which is treated as a safety benefit. The final column shows the differences in full/rolling stops, with positive values shown in blue. The table also shows the change in the percentage of drivers who engaged in a fast-rolling stop or no stop. This is the inverse of the previous column. For instance, if more drivers engaged in a full/rolling stop, the percentage of no-stops would decrease by the same amount.

Table 3-4. Summary statistics for type of stop

Site	Time Period	Number of Samples	Percentage Full/Rolling Stop	Percentage No Stop	Change in Full/Rolling Stop
103	Before	240	90.42%	9.58%	
	1 Mon After	218	93.58%	6.42%	3.16%
	9 Mon After	213	92.49%	7.51%	2.07%
104	Before	243	95.47%	4.53%	
	1 Mon After	243	94.24%	5.76%	-1.23%
	9 Mon After	244	95.49%	4.51%	0.02%
106	Before	242	94.63%	5.37%	
	1 Mon After	246	89.02%	10.98%	**-5.61%***
	9 Mon After	225	84.00%	16.00%	**-10.63%***
108E	Before	242	83.06%	16.94%	
	1 Mon After	249	88.35%	11.65%	5.29%
	9 Mon After	240	95.42%	4.58%	**12.36%***
108W	Before	246	75.61%	24.39%	
	1 Mon After	245	91.43%	8.57%	**15.82%***
	9 Mon After	207	84.06%	15.94%	**8.45%***
111	Before	245	95.10%	4.90%	
	1 Mon After	241	98.34%	1.66%	**3.24%***
	9 Mon After	215	97.67%	2.33%	2.57%
112	Before	224	92.86%	7.14%	
	1 Mon After	239	93.72%	6.28%	0.86%
	9 Mon After	N/A	N/A	N/A	N/A
117	Before	249	94.38%	5.62%	
	1 Mon After	201	98.51%	1.49%	**4.13%***
	9 Mon After	218	95.87%	4.13%	1.49%

*Change is statistically significant at the 95% level of significance.

A two-tailed test of proportions was conducted to determine whether the change in percentage of drivers who came to a full/rolling stop after TRS were installed was statistically significant. The results of the analysis can be seen in Table 3-4. A positive value in the table indicates that the percentage of drivers who came to a full/rolling stop increased after the TRS were installed, while a negative value indicates that fewer drivers came to a full/rolling stop. Included in the table is the p-value. If the p-value was less than 0.05, the change was significant at a 95% confidence level. Those changes that are significant are bolded in the table.

Changes in percentage are shown as simple arithmetic values. The percentage of vehicles making a full/rolling stop for Site 103 was 90.42% before installation and 93.58% at 1 month after installation, resulting in a simple arithmetic increase of 3.16%. At the 1-month after period, six of the eight sites showed an increase in the percentage of vehicles making a full/rolling stop, with increases from 0.86% to 15.82% (not all changes were statistically significant) after TRS were installed. Decreases in the percentage of vehicles stopping were noted at two locations (1.23% at Site 104 and 5.61% at Site 106).

At 9 months after installation, a decrease in the percentage of vehicles stopping was again noted at Site 106 (corresponding to an increase in the percentage of vehicles making no stop). Increases in the percentage of vehicles making a full/rolling stop were noted at all other locations, although not all changes were statistically significant. Increases ranged from 0.02% to 12.36%. The lack of statistical significance may have been due to sample size. Since stopping behavior had to be manually reduced, only around 200 samples could be reduced for each location for each time period. Overall, the analysis showed that TRS influenced stopping behavior. Although the results were not consistent for all sites, the increases were generally smaller for the 9-month after period than for the 1-month after period.

The percentage of drivers who came to a full/rolling stop before TRS installation and at 1-month after installation is shown as a comparison in Figure 3-1. In general, one site experienced little change at 1 month after installation (<1%), while five sites showed an increase in stops. Two locations experienced decreases in full/rolling stops. At 9 months after installation, five sites had increases in stops while one site experienced a decrease.

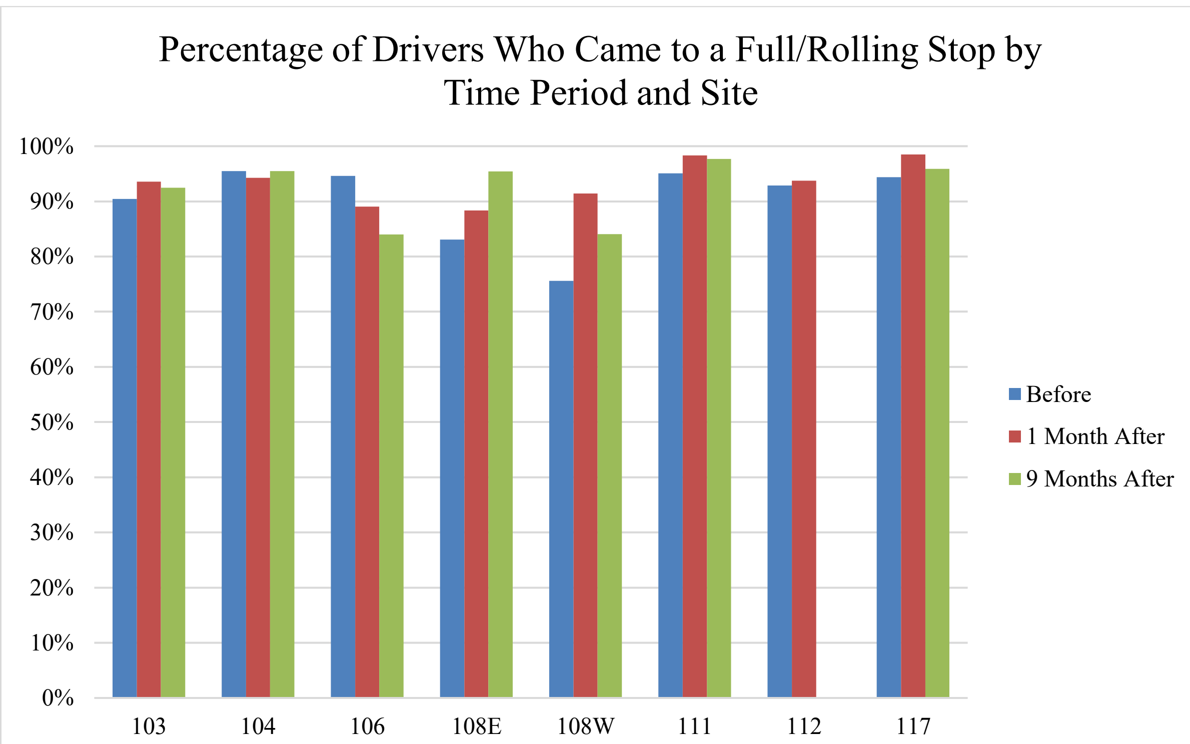


Figure 3-1. Percentage of drivers who came to a full stop or slow rolling stop by site and time period

3.5 STOP LOCATION

Stopping location was reduced for a sample of vehicles, as described in Section 2.3. Stopping location was simplified to before the stop bar or after the stop bar. Although the relationship between stopping location and the likelihood of stop sign running is not known, it was assumed that if drivers stop behind the stop bar, they are more aware of the stop sign and intersection presence and are therefore less likely to run the stop sign. Table 3-5 shows the percentage of vehicles stopping before versus after the stop bar for each site for each time period. It was assumed that stopping at or behind the stop bar was a positive safety benefit, and changes are shown in the last column. Positive values are highlighted in blue.

Table 3-5. Change in stopping behavior

Site	Time Period	Samples	% Stopping in front of Stop Bar	% Stopping behind Stop Bar	Change in Stopping behind Stop Bar
103	Before	240	75.83%	24.17%	
	1 Mon After	218	84.86%	15.14%	**-9.03%***
	9 Mon After	213	50.70%	49.30%	**25.13%***
104	Before	243	70.37%	29.63%	
	1 Mon After	243	74.07%	25.93%	-3.70%
	9 Mon After	244	54.92%	45.08%	**15.45%***
106	Before	242	80.58%	19.42%	
	1 Mon After	246	80.49%	19.51%	0.09%
	9 Mon After	225	73.99%	26.01%	6.59%
108E	Before	242	70.66%	29.34%	
	1 Mon After	249	83.13%	17.27%	**-12.07%***
	9 Mon After	240	51.25%	48.75%	**19.41%***
108W	Before	246	72.76%	27.24%	
	1 Mon After	245	81.63%	18.37%	**-8.87%***
	9 Mon After	207	28.02%	71.98%	**44.74%***
111	Before	245	56.73%	43.27%	
	1 Mon After	241	51.04%	48.96%	**5.69%***
	9 Mon After	N/A	N/A	N/A	N/A
112	Before	224	86.16%	13.84%	
	1 Mon After	239	91.21%	8.79%	-5.05%
	9 Mon After	N/A	N/A	N/A	N/A
117	Before	249	83.94%	16.06%	
	1 Mon After	201	91.04%	8.96%	**-7.10%***
	9 Mon After	218	79.36%	20.64%	4.58%

*Change is statistically significant at the 95% level of significance.

Changes in the percentage of vehicles stopping were calculated as a simple arithmetic difference. A two-tailed test of proportions was used to determine whether changes were statistically significant. Table 3-5 lists the changes in the percentage of drivers stopping behind the stop bar by site. It also includes the p-values for the changes. A p-value less than 0.05 indicates a statistically significant change. A positive value in the column “Change in Stopping behind Stop Bar” indicates that the percentage of drivers who stopped behind the stop bar increased after TRS installation.

Figure 3-2 provides a comparison of the percentage of drivers who stopped behind the stop bar before TRS installation and at 1-month and 9-months after installation.

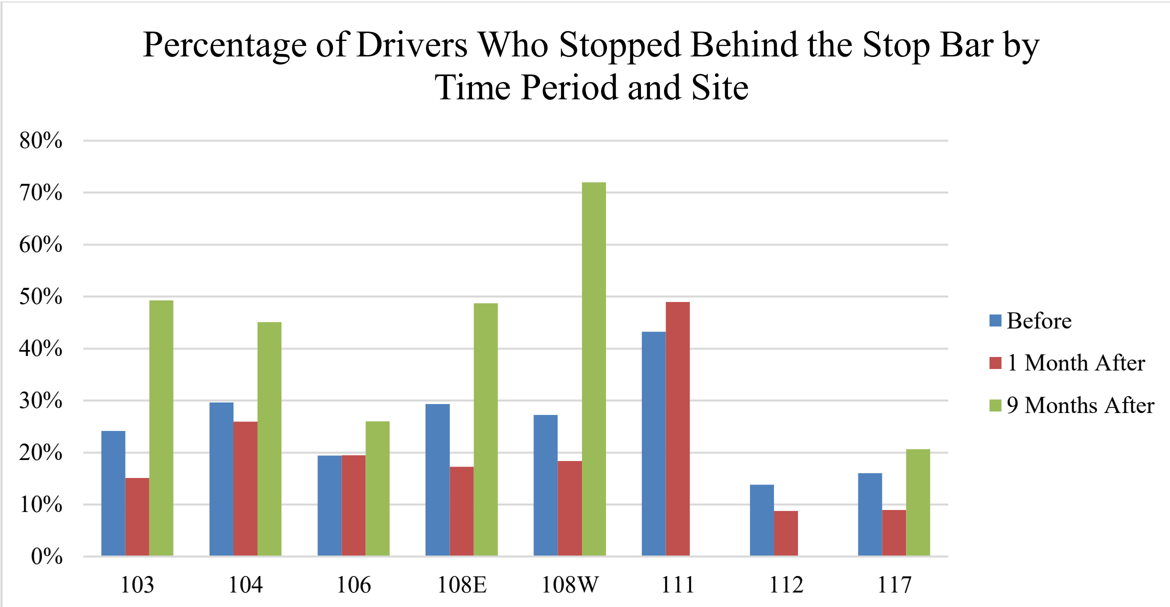


Figure 3-2. Percentage of drivers who stopped behind the stop bar by site and time period

At the 1-month after period, six of the sites experienced a decrease in the percentage of vehicles that stopped behind the stop bar, with values ranging from 3.7% to 12.07%. For instance, at Site 103, 24.17% of vehicles stopped behind the stop bar before installation, while only 15.14% stopped behind the stop bar after installation (a decrease of 9.03%). Site 106 experienced essentially no change, and Site 111 experienced a 5.69% increase in the percentage of vehicles that stopped behind the stop bar.

At the 9-month after period, all of the sites experienced an increase in the percentage of vehicles that stopped behind the stop bar. This ranged from an increase of 4.58% at Site 117 to an increase of 44.74% at Site 108 West. Data were not collected for Site 112, as noted above, due to construction. Additionally, the camera angle at Site 111 in the 9-month after period was positioned such that stop location (i.e., in front of/behind the stop bar) could not be accurately coded, and therefore this metric was not available at this site.

The change from the 1-month after period to the 9-month after period was unexpected since the results are opposite. Drivers may have been preoccupied with crossing the rumble strips immediately after installation and then adjusted their behavior later. It should be noted that stopping location was a somewhat subjective measure due to the camera angles, which may have played a role in the changes seen.

3.6 BRAKING BEHAVIOR

Braking behavior was reduced for a sample of vehicles. The metric used to evaluate braking behavior was the percentage of drivers braking late. A late brake was defined as the driver initiating a brake 290 ft or closer to the intersection, which was based on a safe braking distance for a vehicle traveling 55 mph. All of the sites had a speed limit of 55 mph. Braking was coded when the vehicle's brake lights were visible to the coder. Around 100 traces were coded for each intersection, since reducing this metric was more time consuming than reducing other metrics.

Table 3-6 lists the summary statistics for the percentage of late braking vehicles by time period and site, along with the number of traces that were included. The change in the percentage of late braking vehicles was calculated as a simple arithmetic difference. A decrease in late braking (negative value) was considered to have a positive safety benefit. And is noted in blue in the table. The change in the percentage of drivers who were braking late after TRS installation was evaluated using a two-tailed test of proportions.

Table 3-6. Summary statistics of braking metrics

Site	Time Period	Number of Samples	Percent Late Braking	Change in Percent Late Braking
103	Before	93	4.30%	
	1 Mon After	93	4.30%	0.00%
	9 Mon After	100	8.00%	3.70%
104	Before	95	8.42%	
	1 Mon After	93	10.75%	2.33%
	9 Mon After	100	6.00%	-2.42%
106	Before	100	0.00%	
	After	96	0.00%	0.00%
	9 Mon After	100	3.00%	3.00%
108E	Before	90	11.11%	
	After	98	8.16%	-2.95%
	9 Mon After	99	14.14%	3.03%
108W	Before	94	10.64%	
	After	97	3.09%	**-7.55%***
	9 Mon After	100	7.00%	-3.64%
111	Before	97	2.06%	
	After	96	0.00%	-2.06%
	9 Mon After	100	4.00%	1.94%
112	Before	99	38.38%	
	After	100	28.00%	-10.38%
	9 Mon After	N/A	N/A	N/A
117	Before	97	5.15%	
	After	99	2.02%	-3.13%
	9 Mon After	100	5.00%	-0.15%

*Change is statistically significant at the 95% level of significance.

As shown in Table 3-6, two sites (103 and 106) saw no change in the percentage of late braking drivers in the 1-month after period. Site 104 saw a 2% increase in late braking drivers. The remaining sites experienced a decrease in late braking drivers. The decreases ranged from 2.06% to 10.38%. Most of the decreases were not statistically significant, which is likely due to sample size. Site 112 saw a large portion of drivers braking late. This was likely due to the fact that drivers were traveling slower as they approached the intersection, including at the upstream location, because of the presence of a railroad crossing located approximately 1,000 ft upstream of the intersection. Drivers slowed down to cross the railroad crossing and then did not significantly speed back up after traversing it.

Results were mixed for the period 9 months after installation. Four of the sites experienced an increase in the number of vehicles that braked late, although the increases were small (1.94% to 3.7%). Three sites experienced decreases in the percentage of vehicles that braked late (0.15% to 3.64%). Data were not available at two of the locations, as noted above.

3.7 EVASIVE MANEUVER ANALYSIS

An analysis was conducted to assess the change in the number of drivers making evasive maneuvers in their approach to the intersection. An evasive maneuver was defined as the driver changing course to avoid something; in this case, drivers drove into the opposing lane or toward the shoulder to avoid the rumble strips. Examples of these maneuvers can be seen in Figure 3-3. At sites with a paved shoulder, most of the evasive maneuvers were found to be toward the shoulder. However, when the shoulder was not paved, drivers about half the time shifted toward the opposite lane, often driving over the centerline. Those who moved toward the shoulders in these cases sometimes drove onto the gravel shoulder, but most drove right on the edge line.

Evasive maneuver over center line *Evasive maneuver toward shoulder*

Figure 3-3. Examples of evasive maneuvers

Each of the 250 traces per time period per intersection approach was coded for any evasive maneuvers drivers made. None were found in the before period. However, as seen in Figure 3-4, all intersections saw an increase in evasive maneuvers in the 1-month after period and then a larger increase in the 9-month after period. This was likely due to regular drivers becoming increasingly familiar with the presence of the TRS and choosing to avoid striking them. Sites 103, 104, 108 East, 111, and 117 saw similar numbers of drivers evade the rumble strips in the 9-month after period. It should be noted that the 9-month after data were not able to be collected at Site 112 due to construction.

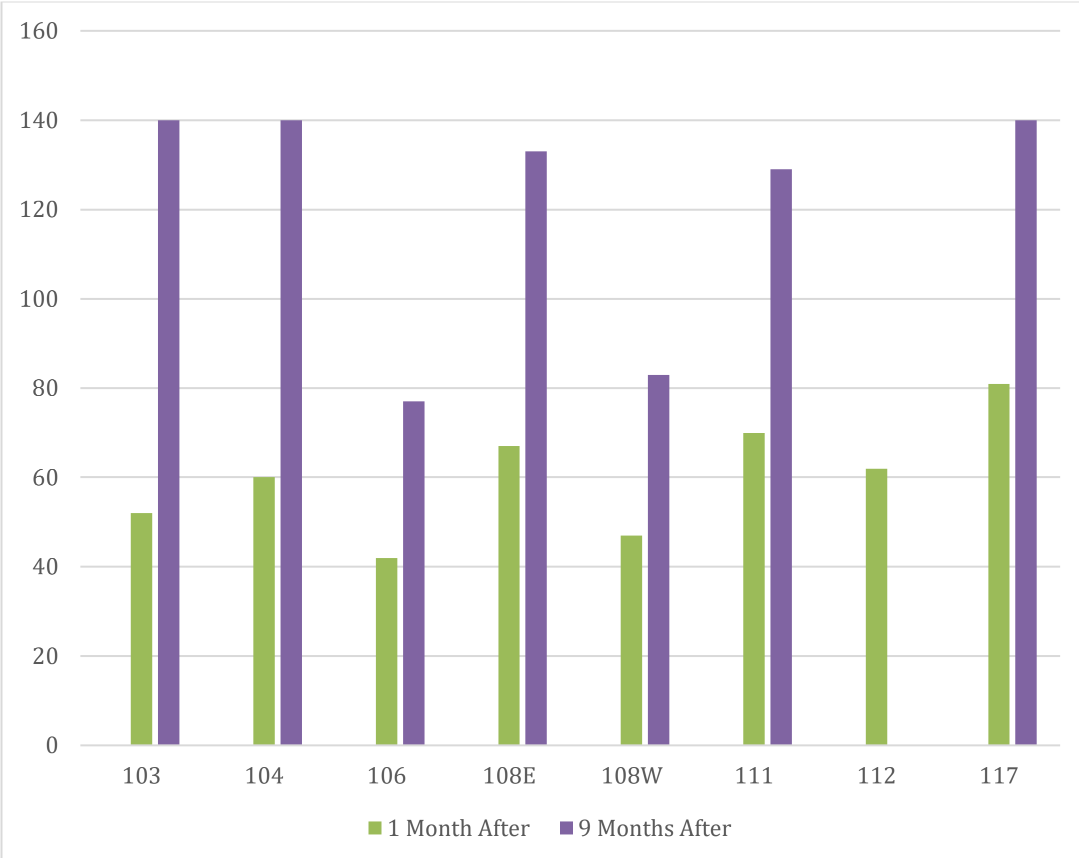


Figure 3-4. Number of evasive maneuvers by time period and site

While these evasive maneuvers resulted in drivers leaving or almost leaving their lane, it does demonstrate that drivers were aware of the rumble strips and chose to purposely avoid them and therefore demonstrates that drivers were aware of the intersection's presence. Additionally, it should be noted that no maneuvers into the opposite lane were seen when other vehicles were present.

3.8 CONCLUSIONS

Two speed analyses, two stopping analyses, one braking analysis, and one evasive maneuver analysis were conducted to evaluate the effectiveness of four TRS patterns installed near eight intersection approaches at rural intersections in northern Minnesota. Since only two sites were available for each pattern, it was not possible to conduct statistical comparisons to determine whether one design was more effective than another. Instead, a quantitative analysis was used for comparison.

Table 3-7 highlights the sites, patterns, and a subjective measure of improvements in safety metrics after the TRS were in place for 1 month. The following color-coding system and symbols were used to show how each site performed by metric:

- Difference was not relevant, with a value of less than 1 mph or 1% (✔ and yellow shading)

- Moderate improvement was noticed, with an improvement value between 1 and 5 mph or between 1% and 10% (**+** and light green shading)
- Major improvement was noticed, with an improvement value greater than or equal to 5 mph or 10% (**++** and dark green shading)
- Minor decrease was noticed, with a decrease value between 1 and 5 mph or between 1% and 10% (**-** and light red shading)
- Major decrease was noticed, with a decrease value greater than or equal to 5 mph or 10% (**--** and dark red shading)
- Difference was statistically significant (*)

Table 3-7. Summary of analyses by site and TRS pattern 1 month after installation

Site ID	TRS Pattern Installed	Reduction in Avg Speed	Decrease in Percent over 45 mph	Change in Speed Upstream to Downstream	Increase in Full/Rolling Stops	Increase in Stops behind Stop Bar	Decrease in Late Braking
106	2 panels/ 6 strips	+*	+*	+*	-*	✓	✓
112	2 panels/ 6 strips	-*	-	+	✓	-	++
103	2 panels/ 12 strips	✓*	✓	✓	+	-*	✓
111	2 panels/ 12 strips	+*	+*	+*	+*	+*	+
108W	3 panels/ 6 strips	✓	-*	+*	++*	-*	+*
104	3 panels/ 12 strips	✓	+*	+*	-	-	-
108E	3 panels/ 12 strips	+*	+*	+*	+	--*	+
117	3 panels/ 12 strips	+	+	+*	+*	-*	+

As the table shows, Sites 108 East (3 panels/12 rumble strips), 117 (3 panels/12 rumble strips), and 111 (2 panels/12 rumble strips) had the highest number of metrics with positive improvements, with improvements in four to six cells. Sites 106 (2 panels/6 rumble strips) and Site 108 West (3 panels/6 rumble strips) had improvements in three cells. All other sites had improvements in two or fewer cells. Site 103 in particular had improvements only in full/rolling stops.

Table 3-8 shows the metrics collated for the 9-month after period, with shading and symbols similar to those used in Table 3-7. Site 112 was undergoing construction during the data collection period and could not be included. Several metrics for other sites were not able to be collected, as noted in the sections above on the individual metrics. Site 117 (3 panels/12 rumble strips) performed the best overall, with improvements in five of the six metrics and three of the metrics showing significant increases, as noted by the dark green shading and ++ symbols. Site 108 West (3 panels/6 rumble strips) performed the second best, with improvements in five of the six metrics, but most metrics showed moderate improvements. Site 106 was next, with improvements in three metrics, but the site also saw decreases in key metrics.

Table 3-8. Summary of analyses by site and TRS pattern 9 months after installation

Site ID	TRS Pattern Installed	Reduction in Avg Speed	Decrease in Percent over 45 mph	Change in Speed Upstream to Downstream	Increase in Full/Rolling Stops	Increase in Stops behind Stop Bar	Decrease in Late Braking
106	2 panels/ 6 strips	++*	++*	-*	--*	-	-
112	2 panels/ 6 strips	NA	NA	NA	NA	NA	NA
103	2 panels/ 12 strips	✓*	✓	-*	+	++*	-
111	2 panels/ 12 strips	✓	✓	-*	+	NA	-
108W	3 panels/ 6 strips	+*	+*	✓	+*	++*	+
104	3 panels/ 12 strips	✓*	✓	-*	✓	++*	+
108E	3 panels/ 12 strips	✓*	✓	NA	++*	++*	-
117	3 panels/ 12 strips	++*	++*	++*	+	+	✓

In order to conduct a quantitative comparison, the metrics that the research team felt were most likely to show an actual safety improvement were compared. **Reduction in average speed** and **reduction in drivers traveling over 45 mph** were considered important because drivers may be less likely to stop if they are traveling faster than appropriate as they approach the intersection. **Increases in full/rolling stops** was also considered an important metric. **Decreases in the number of drivers who brake late** was considered important because the metric indicates that drivers are more likely to begin braking at an appropriate location upstream of the stop sign.

Change in speed from the upstream to downstream location did not show much improvement overall. This may be due to the fact that drivers began slowing sooner upstream because they were aware the rumble strips were in place. As a result, it was difficult to determine the importance of this metric. Similarly, the location where drivers stopped (at/before or after the stop bar) was included as a metric. However, as long as drivers stop, the location of the stop may not be that important.

A qualitative analysis was conducted that assigned a score for improvements. The four metrics (bolded above) that were determined by the team to be the most important metrics were scored. The scoring was used to compare the metrics across designs for the 1-month before and 9-month after periods using the following criteria:

- 1 point given for a moderate improvement in the metric
- 2 points given for a major improvement in the metric
- 0 points given for no change in the metric
- 0 points given when the metric worsened

It was assumed that a metric that worsened was likely to involve factors other than the rumble strips. As a result, metrics that worsened were assigned a 0 rather than a negative value. When a metric was not collected for a particular time period, the cell was not included in the count.

Table 3-9 shows the results of scoring using the point system. As noted above, a numeric scoring system was used to quantify performance across the four metrics the research team determined were most important (average speed, percent of drivers over 45 mph, type of stop, and percent of late braking drivers).

Table 3-9. Quantitative summary of performance by type of design

Design	2 Panels/6 Strips	2 Panels/12 Strips	3 Panels/6 Strips	3 Panels/12 Strips
Score	0.67	0.44	0.88	1.33

The score for each design was summed for all sites with that design for the 1-month and 9-month after periods. These total scores were then divided by the total number of cells, excluding those with values of NA. For instance, for the design with 2 panels and 6 rumble strips, the score would have been calculated as follows:

- Site 106: (1 + 2 + 0 + 0) at 1 month and (2 + 2 + 0 + 0) at 9 months
- Site 112: (0 + 0 + 0 + 2) at 1 month (data not collected at 9 months)
- Total = 9
- Number of cells = 12
- Value = 0.75

As the tables show, the 3-panel, 12-rumble strip design had the highest score (1.33). This design included three sites, and even with one of the sites not performing as well as the others (Site 104), this design ranked at the top. The 3-panel, 6-rumble strip design had the second highest score for both counts (0.88). However, this design only included one site that performed well overall, so the results should be used with caution. The 2-panel design with 6 rumble strips performed the next best (0.67), with the 2-panel design with 12 rumble strips having the lowest score (0.44).

A review of Tables 3-7 and 3-9 indicates that the 3-panel, 12-rumble strip design performed well. This was reinforced by the results of the scoring, which showed significantly higher scores for this design than for others.

CHAPTER 4: NOISE ANALYSIS

Noise analyses were conducted to assess the impact of different TRS designs on both external and in-vehicle noise. Each analysis is described in the following sections.

4.1 EXTERNAL NOISE ANALYSIS

External noise is a concern for surrounding homes and businesses, as discussed in Chapter 1. External noise was evaluated to determine differences among the different TRS designs in terms of the external noise produced. All other things being equal, a design that produces less external noise would be more desirable.

4.1.1 External Noise Analysis Method

The rumble strip designs evaluated in this analysis included two types of panels, one with 6 rumble strips and one with 12 rumble strips (with both panel types having the same spacing and depth). The panels were spaced sufficiently apart that noise was not expected to be additive between panels. As a result, noise was tested for one panel for each design. The 12-rumble strip pattern was tested at Site 108 East, and the 6-rumble strip pattern was tested at Site 108 West.

Noise generated on the roadway is a function of traffic characteristics (e.g., speed, volume, vehicle type, tire characteristics) and roadway characteristics (e.g., type of pavement, pavement condition). Since only one vehicle can cross the rumble strips at time, it was not necessary to collect the noise generated by multiple vehicles. A single test passenger vehicle, a 2021 Dodge Charger, was used to traverse the rumble strips so that speed could be controlled over multiple passes. The vehicle's tires were inflated to 37 psi, except for the rear driver's side tire, which was inflated to 36 psi.

External noises were collected following the FHWA *Noise Measurement Handbook* (RSG et al. 2017). This was done using a Class 2 digital sound meter, the ennoLogic Decibel Meter (Figure 4-1), which sampled within a range of 30 to 130 dB with an accuracy of ±1.5 dB. It had the ability to collect the maximum noise level every second based on samples taken every 125 milliseconds and allowed for A or C frequency rating. The noise meters were tested in the laboratory before being used in the field.

ennoLogic

Figure 4-1. External noise meter

Noise meters were set up on the side of the road 14.5 ft from the lane line and 4 ft from the ground near the middle set of test rumble strips at each site. It was hoped to set the meters near the recommended 50 ft from the center of the lane; however, the available roadsides did not provide space for this, and therefore the meters were placed at a consistent distance as far as possible given the roadside (14.5 ft). The meters were placed at a height of 4 ft from the roadway surface instead of the recommended 5 ft in order to place the meters further from the rumble strips where the roadside began to slope. The in-field data collection setup is shown in Figure 4-2.

Figure 4-2. External noise meter setup in field

The air temperature during the testing was 55 degrees Fahrenheit with a wind speed of 5 mph from the west. Ten runs were made for each site, with vehicle speed being held constant at around 45 mph. This speed was selected because drivers should have slowed to this speed when crossing the pattern. Data were collected from 6 seconds before the vehicle crossed the rumble strips to 6 seconds after (approximately 400 ft).

4.1.2 External Noise Analysis Results

Data were plotted using a smoothing algorithm as shown in Figures 4-3 to 4-5. Data at the rumble strip panel are shown in the center of each graph. Figure 4-3 illustrates the noise pattern at Site 108 West, which had a 6-rumble strip panel. The greatest noise measures for each run ranged from 81.7 to 101.6 dB (with a standard deviation of 5.9). Figure 4-4 shows the noise pattern for Site 108 East, which had a 12-rumble strip panel. Sound levels ranged from 78.3 to 99.8 dB, with an average of 83.8 dB (and a standard deviation of 6.9). Noise levels were similar for both sites, with the 6-rumble strip pattern having a slightly lower standard deviation. As Figure 4-5 shows, external noise is reasonably consistent between the two patterns.

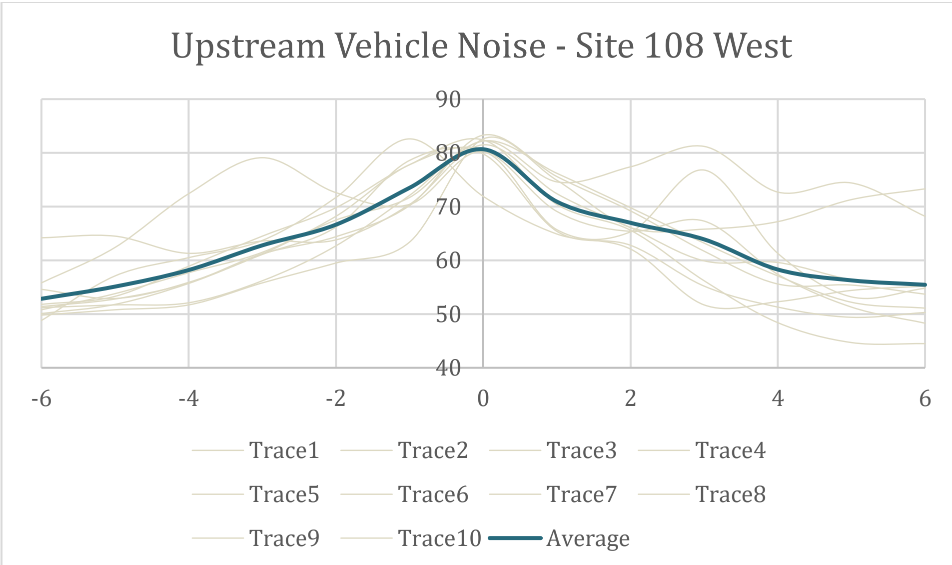


Figure 4-3. Noise pattern for Site 108 West (6-rumble strip panel)

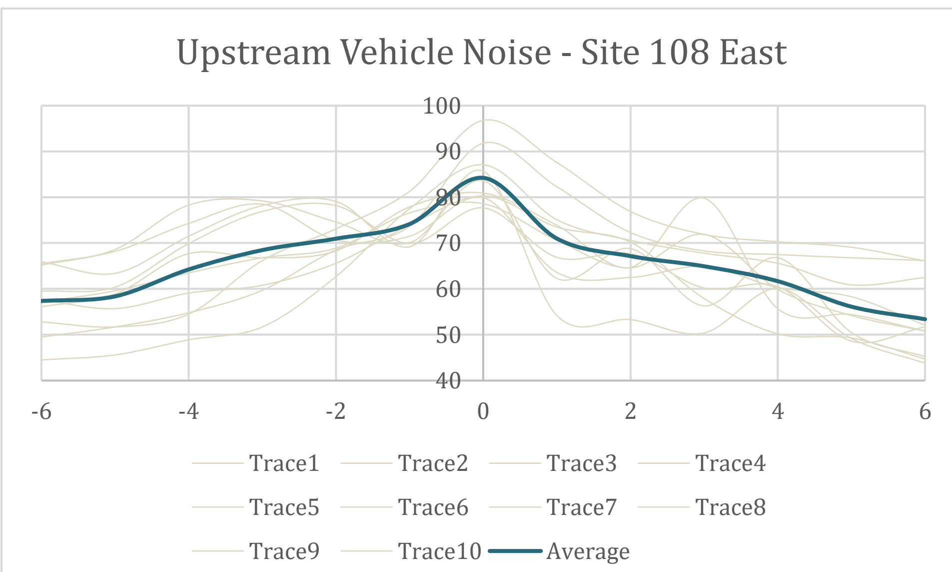


Figure 4-4. Noise pattern for Site 108 East (12-rumble strip panel)

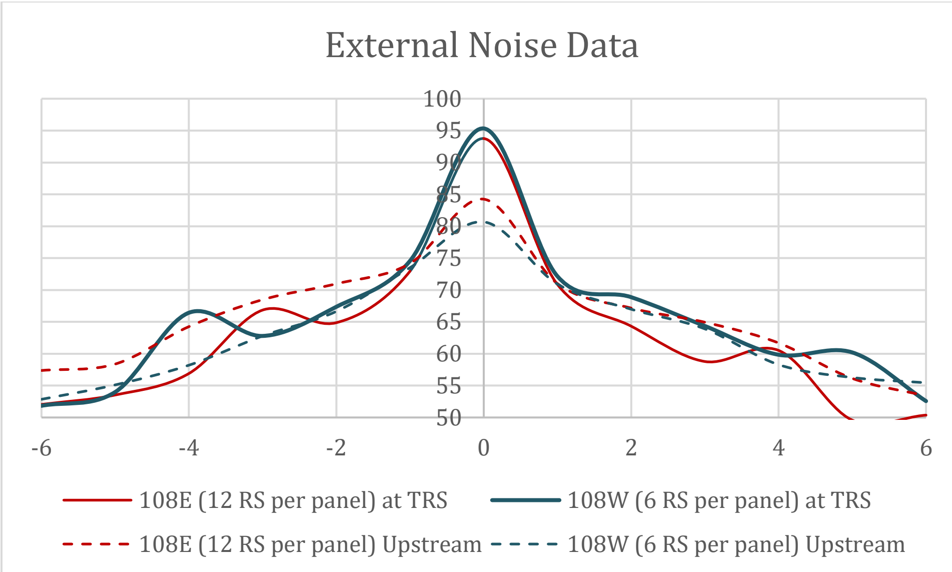


Figure 4-5. Noise pattern combined for both sites

For reference, a list of common sounds with noise levels similar to those recorded in this analysis is shown in Table 4-1. As the table shows, 100 dB corresponds to a car horn. In general, each increase in 10 dB doubles in loudness. As a result, an increase from 80 to 90 dB would be twice as loud. Noise at the level of 80 to 100 dB is considered high, and long-term exposure should be avoided. However, these levels are common along the side of roadways without rumble strips. Additionally sound levels drop off quickly as the distance from the source increases. As a result, the sound levels generated correspond to a point right next to the rumble strips. There is no reason to suggest that the noise generated by either pattern cannot be addressed through FHWA guidance on placement of rumble strips.

Table 4-1. Reference noise levels

Source	Sound Level
Motorcycle	100 dB
Car horn	100 dB
Concert	100 dB
Alarm clock	80 dB
Typical traffic	70 dB
Normal conversations	60 dB
Soft whisper from 5 ft	40 dB

In general, no significant differences were noted between 6-rumble strip panels versus 12-rumble strip panels. As a result, there is no reason to select one or the other due to noise concerns. In terms of the use of 2 panels versus 3 panels, panels are expected to be far enough apart that the additive noise from multiple panels is expected to be minimal. Even if noise levels are additive, two 100 dB sound levels would be expected to produce a sound level of 103 dB, not 200 dB (Noise Monitoring Services 2021).

4.2 INTERNAL NOISE ANALYSIS

Internal noise is one element of rumble strips that is designed to get a driver's attention. Sufficient noise and vibration levels inside a vehicle are necessary to alert the driver when the vehicle crosses a rumble strip (FHWA 2015). Human perception of a sound depends on its level and intensity compared to other background sounds (Terhaar et al. 2016). The amount of noise needed for rumble strips to be effective has not been well quantified. However, FHWA (2015) notes that a distracted driver will likely react to a noise about 3 dB louder than ambient in-vehicle noise levels. A 6 dB increase is needed to alert drowsy drivers. Internal noise and vibration depend on the vehicle's type, size, age, suspension, and speed.

4.2.1 Internal Noise Analysis Method

The critical factors noted above help ascertain the effectiveness of rumble strips and are typically measured using equipment that is placed inside the vehicle near the driver's seat. For this test, the ennoLogic Decibel Meter was strapped to the passenger seat (Figure 4-6) of a 2020 Dodge Journey (Figure 4-7). During the test, the radio was off, the fan was set to 3 to simulate interior noise, and the tires were inflated to 40 psi for the front tires, 41 for the rear driver's side tire, and 37 for the rear passenger's side tire. This was similar to the method used by Hurwitz et al. (2019).

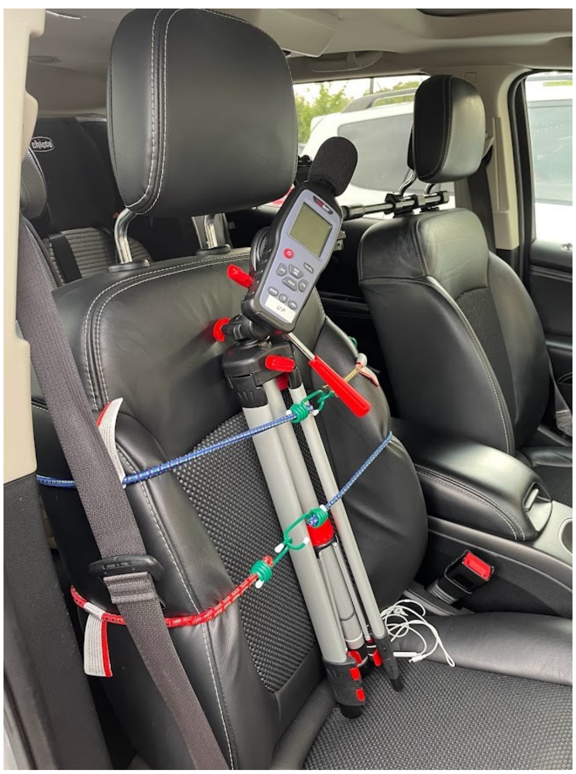


Figure 4-6. Interior noise test setup

Figure 4-7. Interior noise test vehicle

For the test, 10 runs over each type of rumble strip panel were completed traveling at 55 mph. The maximum interior noise was collected for the 3 seconds before and after striking the first set of rumble strips.

4.2.2 Internal Noise Analysis Results

Figure 4-8 shows internal noise readings. As the figure shows, the average interior noise for the panel with 6 rumble strips was 72 dB, and the maximum for the 12-rumble strip panel was 78 dB. The average upstream (control) level was 56 to 58 dB. The 6-rumble strip pattern was approximately 15 dB higher, and the 12-rumble strip pattern was about 26 dB higher than the measured road noise. Both were higher than the suggested 6 dB for alerting a drowsy driver. As a result, no preference would be given to either rumble strip pattern to ensure that sufficient noise levels are present inside the vehicle. The noise levels reflect levels inside passenger vehicles. Levels would be lower for a heavy truck. As a result, anecdotally the 12-rumble strip pattern may be better for larger vehicles.

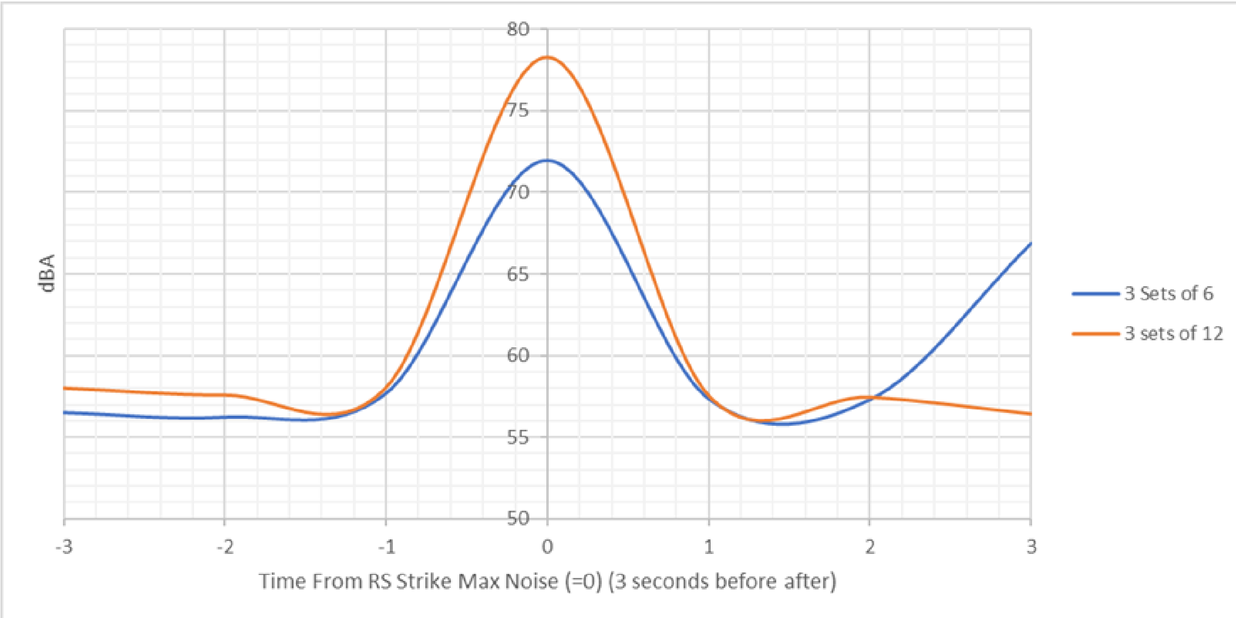


Figure 4-8. Internal noise patterns

CHAPTER 5: SUMMARY AND DISCUSSION

5.1 SUMMARY

This project evaluated the effectiveness of different transverse rumble strip patterns at rural stop-controlled intersections. The patterns used by other states were evaluated and a set of proposed test patterns were developed. A set of test locations was identified in St. Louis County, Minnesota. The locations were selected because they had been identified as having an issue with stopping behavior. Locations were filtered by suitability for data collection and eight final locations were selected.

Data collection devices were placed several weeks before TRS installation and included two video trailers that collected speed/volume and video. Data were also collected at 1 month and 9 months after TRS installation. The TRS patterns were milled in by a contractor. Originally, two sites were intended for each of four configurations. However, issues occurred during milling at one location, and the pattern at that location needed to be changed. This resulted in the following configurations being tested:

- Two sites with 2 panels with 6 rumble strips
- Two sites with 2 panels with 12 rumble strips
- One site with 3 panels with 6 rumble strips
- Three sites with 3 panels with 12 rumble strips

The following metrics were used to assess the effectiveness of the different TRS patterns:

- Change in average speeds on the approach near the intersection
- Change in speeds from upstream (before the TRS) to downstream (near the intersection)
- Change in percentage of vehicles engaging in full/rolling stop
- Change in percentage of vehicles stopping before the stop bar
- Change in percentage of vehicles braking late

Exterior noise was also collected to assess the impact of panel designs with 6 versus 12 rumble strips. All other things being equal, a design that produces less external noise would be more desirable. In general, no significant differences were noted between the 6-rumble strip and the 12-rumble strip designs. As a result, there is no reason to select one or the other due to noise concerns.

Internal noise was also collected to test whether sufficient vibration was produced by 6 versus 12 rumble strips to alert drivers. In both cases, the in-vehicle noise increase was more than the suggested 6 dB that FHWA (2015) notes as necessary to alert a drowsy driver. As a result, no preference would be given to either rumble-strip pattern to ensure sufficient noise levels are produced inside the vehicle.

5.2 DISCUSSION OF EFFECTIVENESS OF THE DIFFERENT TRS PATTERNS

Key findings for each metric were provided in Chapter 3. The most important metric was change in percentage of vehicles engaging in a full/rolling stop. At 1 month after installation, the following resulted:

- Three sites experienced no change or decreases in full/rolling stops (Sites 106 and 112, which had 2 panels and 6 rumble strips, and Site 104, which had 3 panels and 12 rumble strips).
- Five sites experienced improvements (Sites 103 and 111, which had 2 panels and 12 rumble strips; Site 108 West, which had 3 panels and 6 rumble strips; and Sites 108 East and 117, which had 3 panels and 12 rumble strips).

At 9 months after installation, the following resulted:

- Two sites experienced no change or decreases in full/rolling stops (Site 106, which had 2 panels and 6 rumble strips, and Site 104, which had 3 panels and 12 rumble strips).
- Five sites experienced improvements (Sites 103 and 111, which had 2 panels and 12 rumble strips; Site 108 West which had 3 panels and 6 rumble strips; and Sites 108 East and 117, which had 3 panels and 12 rumble strips).
- Data were not collected at one site due to construction.

To conduct a quantitative comparison, the metrics that the research team felt were most likely to show an actual safety improvement were compared. **Reduction in average speed** and **reduction in drivers traveling over 45 mph** were considered important because drivers may be less likely to stop if they are traveling faster than appropriate as they approach the intersection. **Increases in full/rolling stops** was also considered an important metric. **Decreases in the number of drivers who brake late** was considered important because the metric indicates that drivers are more likely to begin braking at an appropriate location upstream of the stop sign.

Change in speed from the upstream to downstream location did not show much improvement overall. This could be because drivers began slowing sooner upstream once they were aware the rumble strips were in place. As a result, it was difficult to determine the importance of this metric. Similarly, the location where drivers stopped (at/before or after the stop bar) was included as a metric. However, as long as drivers stop, the location of the stop may not be that important.

A qualitative analysis was conducted that assigned a score for improvements. The four metrics (bolded above) that were determined by the team to be the most important metrics were scored. The scoring was used to compare the metrics across designs for the 1-month before and 9-month after periods using the following criteria:

- 1 point given for a moderate improvement in the metric
- 2 points given for a major improvement in the metric
- 0 points given for no change in the metric
- 0 points given when the metric worsened

It was assumed that a metric that worsened was likely to involve factors other than the rumble strips. As a result, metrics that worsened were assigned a 0 rather than a negative value. When a metric was not collected for a particular time period, the cell was not included in the count.

The 3-panel, 12-rumble strip design had the highest score (1.33). This design included three sites, and even with one of the sites not performing as well as the others (Site 104), this design ranked at the top. The 3-panel, 6-rumble strip design had the second highest score for both counts (0.88). However, this design only included one site that performed well overall, so the results should be used with caution. The 2-panel design with 6 rumble strips performed the next best (0.67), with the 2-panel design with 12 rumble strips having the lowest score (0.44).

A review of the various metrics indicated that the 3-panel, 12-rumble strip design performed well. This was reinforced by the results of the scoring, which showed significantly higher scores for this design than for the others.

Based on these findings and lessons learned, the following recommendations/conclusions are provided:

- The 3-panel, 12-rumble strip design performed best based on several quantitative comparisons.
- All designs showed improvements in several of the metrics, suggesting that the presence of transverse rumble strips in general provides a safety benefit.
- While all designs showed some improvements in the metrics evaluated, it is recommended that agencies select a design and apply that design consistently.
- External noise was similar for both the 6- and 12-rumble strip designs. As a result, one design will not necessarily result in less external noise than the other.
- Internal noise for both the 6- and 12-rumble strip designs was above the levels needed to alert a drowsy driver.
- A conflict analysis indicated that some drivers move to the left or right to avoid the rumble strips. This is not necessarily a safety issue, since it indicates that drivers are aware of the rumble strips, and the act of shifting left or right may have some speed management benefit. However, placement of wheel path rumble strips should account for drivers shifting from those paths.

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