Rumble Stripe: Evaluation of Retroreflectivity and Installation Practices

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16. Abstract (Limit: 250 words)

This research effort provided the Minnesota Department of Transportation (MnDOT) with field data on the performance of pavement marking materials when used as rumble stripes on MnDOT roadways. These field efforts provide a perspective on the impact that both wear and winter maintenance practices have on retroreflectivity.

Given that these markings were installed by a variety of MnDOT contractors and at different times and roadways, this report also serves to document the range of retroreflectivity provided to drivers at any given time on similar two-lane MnDOT roadways under the installation practice guidelines at the time of installation (2012 to 2013). More specifically, these measurements consider the difference in retroreflectivity provided by direction of travel (e.g., for the same marking, what is the retroreflectivity while driving northbound versus southbound?) and by roadway.

The long-term evaluation collected field measurements both initially and after two winters (18 months) for centerline rumble stripes only and on seven segments over three different roadways.

The in-service evaluation included new centerline and profile rumble stripEs, all of which were installed as part of the 2013 mill and overlay projects on bituminous surfaces within District 4 on two-lane MnDOT roadways. The retroreflectivity data were collected one winter (approximately 12 months) after installation with no initial measurement data being available. This effort included measuring the centerline rumble stripe performance over eight segments on four different roadways and the profile rumble stripe performance over 18 segments on 10 different roadways.

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Rumble Stripe: Evaluation of Retroreflectivity and Installation Practices

Final Report

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Executive Summary

This research effort provides field data for MnDOT staff specific to the performance of pavement marking materials when used as rumble stripEs on MnDOT roadways. These field efforts provide a perspective on the impact that both wear and winter maintenance practices have on retroreflectivity.

Given that these markings were installed by a variety of MnDOT contractors and at different times and roadways, this report also serves to document the range of retroreflectivity provided to drivers at any given time on similar two-lane MnDOT roadways under the installation practice guidelines at the time of installation (2012 to 2013). More specifically, these measurements consider the difference in retroreflectivity provided by direction of travel (e.g., for the same marking, what is the retroreflectivity while driving northbound versus southbound?) and by roadway.

Based on guidance from the project technical advisory panel, this limited field data collection effort was organized into two sections, long-term and in-service.

The long-term evaluation collected field measurements both initially and after two winters (18 months) for centerline rumble stripEs only and on seven segments over three different roadways.

The in-service evaluation included both centerline and profile rumble stripEs on two-lane MnDOT roadways. The retroreflectivity data were collected one winter (approximately 12 months) after installation with no initial measurement data being available. This effort included measuring the centerline rumble stripe performance over eight segments on four different roadways and the profile rumble stripe performance over 18 segments on 10 different roadways.

Long-Term Evaluation

A comparison of the initial (2012) versus long-term (2014) retroreflectivity measurements yielded the following observations:

- Consistent retroreflectivity by direction of travel – The amount of retroreflectivity provided by direction of travel for the same centerline marking varied considerably. This variation is a result of rumble stripE installation practices and, more specifically, bead distribution and embedment.

- Consistent retroreflectivity by roadway – A comparison of retroreflectivity after 18 months showed considerable variation among the three roadways measured.

In-Service Evaluation

The in-service evaluation included new centerline and profile rumble stripEs, all of which were installed as part of the 2013 mill and overlay projects on bituminous surfaces and included adding new rumbles and rumble stripEs within District 4 on two-lane MnDOT roadways.

- Consistent retroreflectivity by direction of travel – The amount of retroreflectivity provided by direction of travel for the same centerline marking varied considerably for both the centerline and the profile marking. It is especially critical for the centerline marking to be consistent in providing similar retroreflectivity regardless of the direction traveled.

- Consistent retroreflectivity by roadway – Retroreflectivity, 12 months after installation, was found to vary considerably between the different roadways measured for both yellow centerline markings and white profile markings.

- Overall, after one season of service, nine of the 14 roadways had more than 90 percent of their retroreflectivity readings measuring in excess of the arbitrary benchmark that was set for performance.

Chapter 1. Introduction

Both traditional pavement markings and rumble strips are used to decrease lane departure crashes. Following the lead of other states, the Minnesota Department of Transportation (MnDOT) experimented with combining traditional pavement markings and rumble strips into a rumble stripe, where the pavement marking is installed in the rumble strip. MnDOT issued guidance for the use of edgeline rumble stripEs as part of Technical Memorandum No. 11-02-T-02.

This study supports MnDOT in their effort to provide centerline rumble stripEs on all rural trunk highways to reduce lane-departure crashes, to provide increased centerline visibility during rainy conditions, and to guide motorists during snowy conditions when striping visibility is poor.

Definitions

- Shoulder rumble strips: A rumble strip outside of the edgeline.
- Rumble stripEs: A rumble strip that contains a pavement-marking stripe. These will be referred to as either edgeline rumble stripEs, centerline rumble stripEs, or profile rumble stripEs.
- Profile rumble stripE: A wider (8-inch) edgeline rumble stripE.
- Initial retroreflectivity: Measurements made within the same season at installation and prior to any winter operations.

Research Description

This research effort provides field data for MnDOT specific to the performance of pavement marking materials when used as a rumble stripEs on MnDOT roadways. The project tasks were as follows:

- Literature Review
- Coordinate Collection of Initial Retroreflectivity
- Long Term Field Evaluation (after 2 years)
- In-Service Data Collection and Analysis (after 1 year)
- Final Report

Chapter 2. Literature Review

The main cause of roadway departure crashes is driver drowsiness and inattention, which are sometimes compounded by driving too fast. Alcohol and drugs can contribute to both fatigue and speed. Driver fatigue also is induced by highway hypnosis, which occurs when the lines and stripes on long, monotonous stretches of highway reduce driver concentration.

Rumble strips are an effective countermeasure for preventing roadway departure crashes. The noise and vibration produced by rumble strips alert drivers when they leave the traveled way. Rumble strips are also helpful in alerting drivers to the lane limits when conditions such as rain, fog, snow, or dust reduce driver visibility.

A newer application of rumble strips is called rumble stripes and is a little different in the placement of the rumble strip (closer to the traveled way) and includes retroreflective pavement marking applied over the rumble strip to increase the visibility of the pavement edge at night and during inclement weather conditions.

This Chapter provides an overview of rumble strips and rumble stripes.

Rumble Strips

There are two main applications of rumble strips:

- Centerline Rumble Strips − an effective countermeasure to prevent head-on collisions and opposite-direction sideswipes, often referred to as cross-over or cross-centerline crashes. Primarily used to warn drivers whose vehicles are crossing centerlines of two-lane, two-way roadways. Examples are shown in Figure 1.

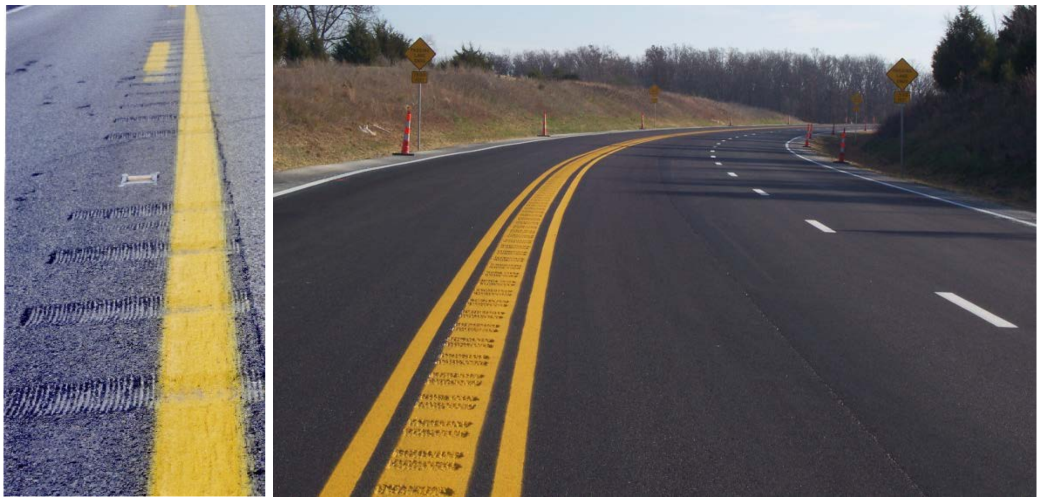


Figure 1. Centerline Rumble Strips

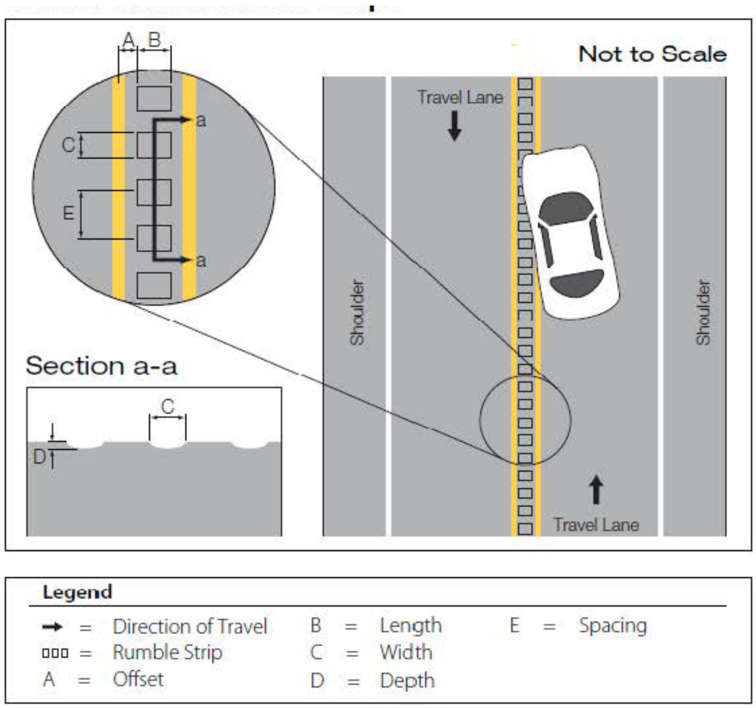
- Shoulder Rumble Strips − an effective means of preventing run-off-the-road crashes. They are primarily used to warn drivers they have drifted from their lane. A variation on this is the edgeline rumble stripe, which places the pavement marking within the rumble strip, improving the visibility of the marking. This is more commonly used on roads with narrow shoulders. Examples are shown in Figure 2.

Figure 2. Shoulder Rumble Strips

Centerline Rumble Strips

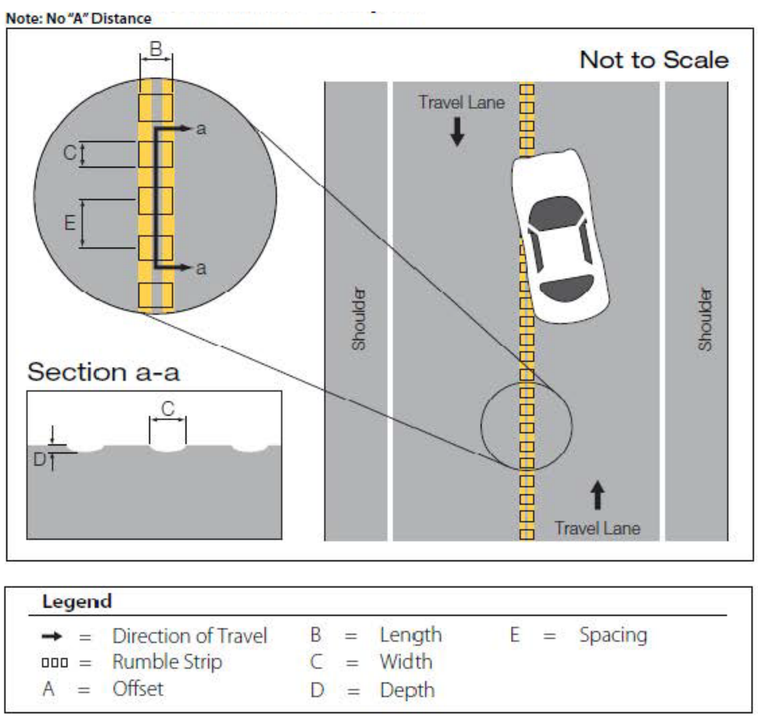
The most common type of centerline (CL) rumble strip is the milled rumble strip (FHWA 2011a). Milled rumble strips can be installed in asphalt or concrete and the installation can be performed anytime. Other types of CL rumble strips include rolled-in rumble strips (rolled into freshly laid asphalt or concrete) and raised rumble strips, typically formed with pavement-marking material and used exclusively in southern climates where there are no snow-plow activities.

According to the Federal Highway Administration (FHWA), the optimum dimension for milled CL rumble strips depends on operating conditions, cross-sectional characteristics, and potential road users. Two key dimensions are the depth and width as shown in Figure 3 and Figure 4.



FHWA 2011a

Figure 3. Centerline Rumble Strips



FHWA 2011a

Figure 4. Centerline Rumble Stripes

Centerline rumble strips are commonly 7 inches wide (C in the figures) and 16 inches long (B in the figures) with a depth of 0.5 inch ± 0.125 inch (D in the figures). A listing of state DOT rumble strip dimensions is included Appendix A and a summary is provided in Figure 5.

Rumble Strip Minimum Dimensions (inches)

State	Type	Offset	Longitudinal Width	Transverse Width	Depth	Center to Center
Colorado	corrugated formed in PC conc shlds	5.9	2.4	17.7	0.5	3.9
New York	corrugated formed in PC conc shlds	11.8	4.9	23.6	1.0	4.9
South Dakota	corrugated formed in PC conc shlds				1.0	5.9
Tennessee	corrugated formed in PC conc shlds	11.8	2.2	36.0	1.0	4.5
Utah	corrugated formed in PC conc shlds	47.2	2.4	70.9	0.8	4.5
Kentucky	cut into cured PC conc shlds	11.8	3.9	47.2	0.5	11.8
Kentucky	formed in PC conc shlds	11.8	2.2	11.8	1.0	4.5
Montana	formed in PC conc shlds	5.9	2.0	11.8	1.0	4.5
Wyoming	formed in PC conc shlds	11.8	2.3		1.0	4.5
Colorado	milled	5.9	5.9	17.7	0.5	11.8
Connecticut	milled		7.1	15.7	0.5	11.8
Florida	milled	15.7	7.1	15.7	0.5	11.8
Michigan	milled		7.1	15.7	0.6	11.8
Montana	milled	5.9		11.8	0.5	11.8
New Jersey	milled	3.9	7.1	15.7	0.5	11.8
New Mexico	milled	11.8	6.9	15.7	0.5	11.8
New York	milled		7.1	15.7	0.5	11.8
Pennsylvania	milled		7.1	15.7	0.5	11.8
South Carolina	milled	9.8	7.0	16.0	0.5	12.0
Tennessee	milled	15.7	5.9	15.7	0.3	11.8
Washington	milled	5.9	7.1	15.7	0.5	11.8
Wyoming	milled	5.9	6.9	15.7	0.5	11.8
Florida	milled: transverse cut	15.7	7.1	15.7	0.5	11.8
New York	narrow formed in PC conc shlds	11.8	6.7	15.7	0.5	23.6
Florida	raised: asphalt		2.0		0.5	11.8
Florida	raised: thermoplastic		3.9		0.5	59.1
Alabama	rolled	5.9	1.0	36.0	0.5	7.9
Arizona	rolled	11.8	2.4	23.6	1.2	7.9
California	rolled	11.8	2.0	35.4	1.0	7.9
Colorado	rolled	5.9		17.7	0.5	7.9
Kentucky	rolled	11.8	1.6	23.6	0.8	9.1
New York	rolled		2.6	17.7	0.7	7.9
South Dakota	rolled	7.9	2.4	36.0	1.2	7.9
Utah	rolled	11.8	1.5	23.6	1.0	7.9
Kentucky	sawed	11.8	5.1	23.6	0.6	59.1

Source: http://safety.fhwa.dot.gov/roadway_dept/pavement/rumble_strips/rumble_types/docs/dimensions.pdf

	Offset	Longitudinal Width	Transverse Width	Depth	Center to Center
avg	11.3	4.5	22.3	0.7	12.4
min	3.9	1.0	11.8	0.3	3.9
max	47.2	7.1	70.9	1.2	59.1

Data source: safety.fhwa.dot.gov/roadway_dept/pavement/rumble_strips/rumble_types/docs/dimensions.pdf

Figure 5. Summary of State DOT Rumble Strip Practices

Centerline rumble strips are typically placed at the center of 2-lane or 4-lane undivided roads and may lap across a longitudinal pavement joint. A few agencies have design details to avoid cutting the strip across the joint—typically by narrowing the rumble strip and placing the strip on each side of the joint, if the remaining pavement width is adequate. Where pavement width is available, this may provide a small amount of additional buffer between vehicles moving in opposite directions.

To maximize the effectiveness of this countermeasure in a given corridor, it is desirable for the rumble strips to be installed on as much of the roadway length as feasible. Therefore, most centerline rumble strips are installed without any breaks or gaps except at intersections and major commercial driveways. Many agencies use centerline rumble strips in passing zones and there has been no indication that this inhibits passing activities among vehicles, including motorcycles (Carlson et al. 2007).

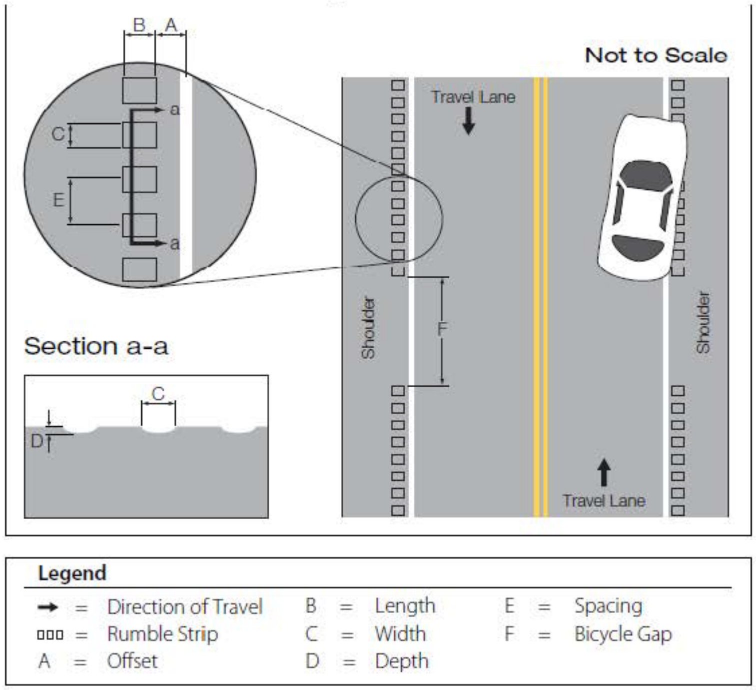
Shoulder Rumble Strips

According to the FHWA, a shoulder rumble strip is a longitudinal safety feature installed on a paved roadway shoulder near the outside edge of the travel lane (FHWA 2011b). The rumble strip is made of a series of milled or raised elements intended to alert inattentive drivers (through vibration and sound) that their vehicles have left the travel lane.

An edgeline rumble strip is a special type of shoulder rumble strip placed directly at the edge of the travel lane with the edgeline pavement marking placed through the line of rumble strips. It is sometimes referred to as an edgeline rumble stripe.

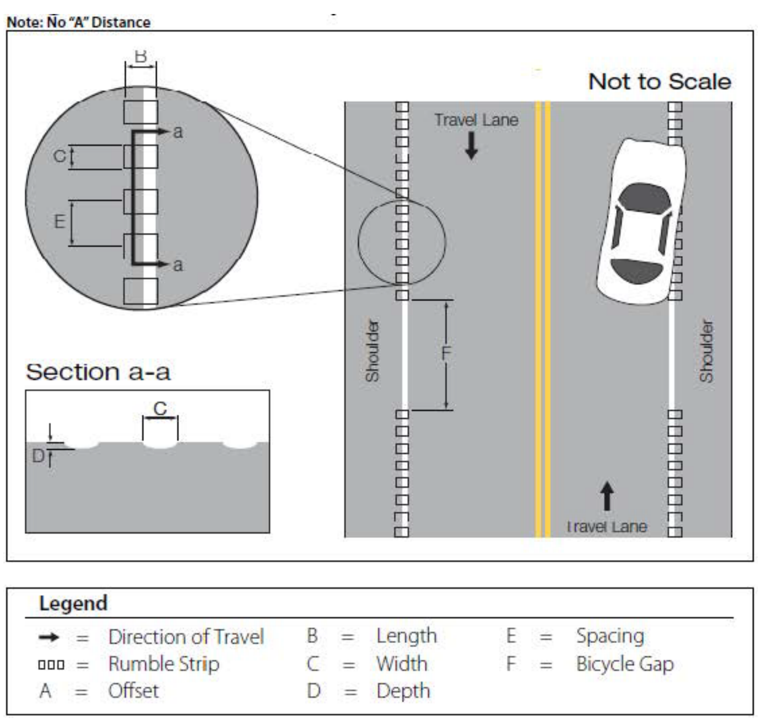
There are four basic rumble strip designs or types: milled-in, raised, rolled-in, and formed. Milled rumble strips produce significantly more vibration and noise inside the vehicle than rolled rumbles. In addition, rolled rumbles lose their effectiveness over time. The key design parameter related to the effectiveness of rumble strips is their dimensions, which tend to be easier to control with milled-in rather than rolled-in or formed rumbles. Profiled markings and other forms of raised rumble strips are sometimes used in climates where snow plowing does not occur.

Optimum dimensions for milled rumble strips depend on operating conditions, cross-sectional characteristics, and potential road users. Two key dimensions that have the most effect on the alerting sound and vibration of rumble strips are depth (D in the following figures) and width longitudinal to the road (C in the following figures) as shown in Figure 6 and Figure 7.



FHWA 2011b

Figure 6. Shoulder Rumble Strips



FHWA 2011b

Figure 7. Edgeline Rumble Stripes

Most research has evaluated shoulder or edgeline rumble strips of 7 inches wide (C in the figures) by 16 inches long (B in the figures) with a depth of 0.625 inches ± 0.125 inch (D in the figures).

Edgeline rumble stripes or shoulder rumble strips with a narrow offset (A in the figures) from the edgeline have been shown to be most effective, because drivers are alerted sooner and the treatment provides a slightly larger recovery area after alerting the driver. Effectiveness is supported by research showing a statistically significant higher reduction in crashes on rural freeways for rumble strips with narrow or no offset, as opposed to those with 9 inches or more offset. For rural two-lane roads, research on the impacts of narrowing the offset distance is inconclusive.

Most agencies also take the location of the pavement joint into account to avoid cutting the strip across or immediately adjacent to the joint. In super-elevated sections where the shoulder slopes in the opposite direction from the roadway, consideration should be given to placing the rumble strips on the super-elevated side so that the driver is warned prior to crossing the slope break.

Where the paved shoulder exists beyond the rumble strip and bicycles are allowed to ride, recurring short gaps should be designed in the continuous rumble-strip pattern to allow for ease of movement of bicyclists from one side of the rumble to the other. A typical pattern is gaps of 10 to 12 feet between groups of the milled-in elements at 40 to 60 feet.

Additional Information

In the last couple of decades, there has been no shortage of research reports and informational guides related to rumble strips and, more recently, rumble stripes. Some of the more comprehensive sources are the National Cooperative Highway Research Program (NCHRP) Report 641, which includes a summary of rumble strip practices and policies as of 2005, and NCHRP Synthesis Report 339, which is focused on centerline rumble strips.

In late 2011, the FHWA released two Technical Advisories related to Shoulder and Centerline Rumble Strips. These are great sources of information and were used heavily herein. Each Technical Advisory includes additional references. The FHWA also maintains a web page on Rumble Strips and Stripes at safety.fhwa.dot.gov/roadway_dept/pavement/rumble_strips/.

Pavement Markings and Rumble Stripes

Rumble stripes and profiled markings both achieve the effects of a rumble strip while serving a dual purpose of marking the traveled way. For southern states without snow plowing activities, profiled markings are common. However, states where snow plowing is frequent, or even a possibility, usually rely on rumble stripes rather than profiled markings. This section of the report describes the experiences and observations regarding rumble stripes, with particular attention regarding the pavement markings used on rumble stripes.

Rumble stripes can include centerlines and edgelines. Some experiments have been conducted using rumble stripes on lane lines, but the application has not been used widely outside of research.

The pavement markings used in rumble stripes are not any different than what are typically used. For instance, if a northern state DOT is mostly a paint state, there is no need to do anything different for a rumble stripe as far as the pavement marking binder is concerned. Paint, epoxy, and thermoplastic are common pavement marking binder materials used in milled rumble stripes. The pavement marking binder used is usually dictated by the familiarity of the agency.

Installation of pavement marking materials on rumble stripes requires some simple preparation. The loose debris from the rumble needs to be cleared and compressed air is typically the most common way of removing the debris. The application of the binder is essentially the same as it is for a flat line, except that contractors typically modify their carriage so that the guiding wheels are outside the rumble stripe patterns. In addition, it is not uncommon to use a slightly higher bead rate on rumble stripes compared to flat lines. Some fanning of the binder material does occur on the lowest sections of the rumble stripe, but it is not noticeable from a driver's perspective.

Reapplication of pavement marking materials to rumble stripes is not any different than a traditional restripe contract. The only slight complication is when an agency specifies epoxy and includes the phrase "remove and replace" in the initial or performance-based requirements, because there appears to be no practical way to remove epoxy from a rumble stripe. Paint and thermoplastic, on the other hand, can be removed with high-pressure water.

A common reason to use rumble stripes is their added visibility benefits over a traditional flat pavement marking. Most of the added benefits are associated with wet-night retroreflectivity, but sometimes even daytime visibility of pavement markings can be improved with the added structure.

The visibility benefits to be gained via rumble stripes depend on a variety of factors. For milled rumble stripes, the quality of the milling process is important to the retroreflective performance of markings. In addition, the pavement marking contractor workmanship is even more critical on a rumble stripe job compared to a traditional flat line job.

Many contractors add a second bead gun and aim it at a diverging angle when striping rumble stripes. This technique helps ensure that beads get embedded on both sides of the rumble. This is particularly important on centerline rumble strips where good retroreflective performance is needed in both directions and not just the direction of application (like edgelines).

One of the most common concerns regarding rumble stripes is the perceived inability to accurately measure their retroreflective performance (see Figure 8).

Figure 8. Measuring Rumble Strip Retroreflectivity

Regardless of the type of pavement marking material used, the debris on the roadway can cause a completely good line to measure poorly. It is usually excess debris on the markings and held within the rumble that causes poor measurements of rumble stripes.

A paper was released that assessed retroreflective measurements on profile markings and rumble stripes. It also compared measurements on rumble stripes made with hand-held retroreflectometers and mobile retroreflectometers (Pike et al. 2011). The study resulted in the following conclusions:

- Retroreflectivity data should be collected along the entire length of a marking segment and averaged. For a retroreflectometer with an 8-inch measurement field, a minimum of three longitudinally adjacent readings should be taken spanning two marking segments for rumble stripe markings with 12-inch spacing. Using a stepping distance shorter than a retroreflectometer's measurement field is not needed.
- Hand-leveling of a handheld retroreflectometer by an experienced user on profiled or rumble stripe pavement markings is a suitable means to maintain the instrument in the plane defined by the tops of the pavement-marking profiles.
- The vertical structure of rumble stripe pavement markings did not appear to increase the dry retroreflectivity measurements of the markings tested.

- The use of a properly calibrated mobile retroreflectometer operated by an experienced user will result in practically the same dry retroreflectivity measurements as handheld retroreflectometer measurements measured in accordance with ASTM E1710 (ASTM International 2011).

Durability

Pavement and shoulder deterioration are common safety concerns regardless of the presence of rumble strips. No strong evidence has surfaced that rumble strips cause premature deterioration. The FHWA (FHWA 2011b) states the following:

- Rumble strips may be placed a few inches away from joints to reduce potential of accelerated pavement deterioration, and an asphalt fog seal can be applied to milled-in strips for protection.
- Shoulder preventive maintenance treatments such as chip seal, ultra-thin hot-mix asphalt, and micro-surface, can be compatible with rumble strips.
- Experience has shown that traffic flow near the rumble keeps water from accumulating in the strip.
- The practice of striping within the rumble can increase the longevity of pavement markings by protecting them from normal wear due to tires and plowing.

MnDOT Guidance

MnDOT provided guidance on the use of Rumble Strips and StripEs on rural trunk highways through Technical Memorandum 11-02-T-02 at the time of the team's initial literature review for this project. Appendix B of this report includes the updated Technical Memorandum (14-97-T-01), which is current at this time.

This policy applied to all projects on rural trunk highways (defined as roadway segments that have minimal residential or commercial development, with little or no further development anticipated in the future) where the posted speed limit is 55 mph or higher.

The purpose of this policy was as follows:

- Provide centerline rumble stripEs and/or shoulder rumble strips on all rural trunk highways
- Reduce lane departure crashes
- Provide increased centerline visibility during rainy conditions
- Guide motorists during snowy conditions when striping visibility is poor

The policy outlined requirements for shoulder rumble strips, centerline rumble stripEs, provided conditions for exceptions, and outlined rumble dimensions. Selected portions follow:

Shoulder Rumble Strips

Shoulder rumble strips *shall* be placed on all rural highway projects where shoulders are constructed, reconstructed, or overlaid and where the posted speed limit is 55 mph or greater, and the *paved shoulder width is 4 feet or greater*. Shoulder rumble strips may also be placed on rural trunk highways on shoulders less than 4 feet in width.

Exception - In all cases, edgeline rumble stripEs may be substituted for shoulder rumble strips and still meet the standards within this Technical Memorandum.

Centerline Rumble StripEs

Centerline rumble stripEs *shall* be placed on all rural highway construction and maintenance projects where bituminous pavement is constructed, reconstructed, or overlaid and where the posted speed limit is 55 mph or greater. This applied to both multi-lane undivided and two-lane undivided highways.

Exceptions

On rural highways where the paved shoulder width is 2 feet or less, shoulder rumble strips or edgeline rumble stripEs may be placed on both sides of the road in lieu of a centerline rumble stripE.

Width of Rumble Strips

The Memorandum said rumble strips are usually 12 inches wide and the width could be reduced to within the range of 8 to 12 inches when the paved roadway width is limited. It also said a 16 inch rumble was required on freeway segments and any design of rumble strips that were less than 8 inches wide or that deviated from the 12-inch corrugation cycle shall require approval by the State Traffic Engineer.

The standard width of rumble strips for centerline rumble stripEs was 16 inches. Any reduction from this shall require approval by the State Traffic Engineer.

Finally, all rumble strips shall meet any and all specifications for Milled Rumble Strips in the MnDOT Standard Specifications for Construction or Special Provisions. This included a requirement that rumble strips be milled in bituminous pavement, and not rolled.

Chapter 3. Coordinate Collection of Initial Retroreflectivity

The research team worked with the project technical advisory panel (TAP) to prepare for measuring a number of rumble stripE projects scheduled for the fall of 2012. Given the variability of striping schedules, this required coordination with district staff as well as a primer and striping subcontractor. The primary activities included identifying potential project locations, completing the field measurements of initial retroreflectivity, and documenting the results. Highlights from these activities follow.

District and Contractor Coordination

Preparations for measuring initial retroreflectivity on new rumble stripE projects began with a request to each MnDOT district to identify potential projects. The information requested from each district included the following:

MnDOT project identification - SP Number
Roadway - Trunk Highway on which the rumble stripE markings would be installed
Location - Begin and end reference points of installation
Line type - Centerline rumble stripE, edgeline rumble stripE, or both
Marking materials - latex, epoxy, standard, or wet reflective media

Figure 9 shows the list of potential measurement locations based on district staff input.

District	Roadway	From	To	SP Number	Line Type
1	TH 169	287.667	290.115	SP 0106-29	Centerline Rumble StripEs
1	TH 200	167.027	175.181	SP 0106-29	Centerline Rumble StripEs
1	TH 200	175.895	190.551	SP 0106-29	Centerline Rumble StripEs
1	TH 200	191.949	201.253	SP 0106-29	Centerline Rumble StripEs
1	TH 61	31.14	33.643	SP 8821-153	Centerline Rumble StripEs
1	TH 61	40.556	42.53	SP 8821-153	Centerline Rumble StripEs
1	TH 61	46.177	51.22	SP 8821-153	Centerline Rumble StripEs
4	TH104	25.198	40.059	SP6110-19	Profile Rumble StripE
4	TH113	15.321	27.252	SP4405.26	Profile Rumble StripE
4	TH12	27.12	42.27	SP 8824-24	Profile Rumble StripE
4	TH12	42.86	59.66	SP 8824-24	Profile Rumble StripE
4	TH210	45.6	66.42	SP8824-24	Profile Rumble StripE
4	TH27	24.11	40.59	SP 8824.24	Profile Rumble StripE
4	TH28	77.79	92.592	SP-6104-11	Intermittent in shoulder
4	TH 29	65.05	75.5	SP2102-54	Centerline/intermittent in shoulder
4	TH29	34.742	54.354	SP 6105-20	Profile Rumble StripE
4	TH32	15.93	34.476	SP1403-24	Profile Rumble StripE
4	TH55	31.87	39.03	SP8824-24	Centerline Rumble StripEs
4	TH59	136.01	144.48	SP8824-24	Profile Rumble StripE
4	TH59	173.59	178.71	SP8824-24	Profile Rumble StripE
4	TH59	153.411	168.063	SP7505-21	Profile Rumble StripE
4	TH59	241.293	254.554	SP5618-26	Intermittent in shoulder
4	TH78	0.15	21.54	SP8824-24	Profile Rumble StripE
7	TH109	0	11.83	SP-2212-28	Alt bid, if Concrete will not have CL
7	TH15	59.462	76.56	SP 5204-112	Centerline Rumble StripEs
7	TH30	121.98	130.54	SP 0705-19	Centerline Rumble StripEs
8	TH68	16+00.246	26+00.417	S.P.4106-21	Centerline Rumble StripEs
8	TH68	27+00.029	37+00.987	S.P.4210-40	Centerline Rumble StripEs

Figure 9. Potential Rumble StripE Measurement Locations for 2012

The research team contacted each district to confirm each project timeline, use of rumble stripEs, marking materials to be used, and contractor details. Roadway annual average daily traffic volumes (AADTs) were reviewed and added to the project information.

The majority of identified projects were found to be either postponed, already completed, or not valid candidates (did not include rumble stripEs). As a result, Figure 10 shows the three 2012 rumble stripE installations project locations measured.

District	Roadway	From	To	SP	Surface Type	AADT	Material	Marking
8	TH68	27+00.029	37+00.987	S.P.4210-40	UltraThin Bonded	2,000	Latex WR	CL rumble stripE
7	TH109	0	11.83	SP-2212-28	Bituminous	780	Epoxy	CL rumble stripE
4	TH55	31.87	39.03	SP8824-24	Bituminous	20,000	Latex	CL rumble stripE

Figure 10. Final Rumble StripE Measurement Locations for 2012

In addition, the installation dates on these three projects were so fluid that the measurements were not able to be scheduled until the installations were complete.

Measuring Initial Retroreflectivity

This section presents the findings specific to the measurement of initial pavement marking retroreflectivity.

Sampling Methodology

The frequency of measurements along each roadway segment followed a previously developed MnDOT protocol (Smadi and Hawkins 2012) for sampling pavement marking retroreflectivity using a handheld device. A summary of this guidance follows:

- Calibrate the handheld instrument according to the manufacturers' recommendations.
- Locate the field sampling locations using milepost markers, if applicable. Select areas that are typical of the marking section, and avoid areas that have paint tracking or other visible contamination.
- On the centerline of undivided highways, measurements were made in both directions of travel. Where two center marking lines existed, alternate measurements were taken between each line and by travel direction.
- On edgelines, 20 equally spaced readings were taken within a 400-foot sampling area regardless of the condition of the line. On lane lines, two readings were taken on each skip for 10 consecutive skips.

Measurement Methodology

Measuring retroreflectivity on each rumble stripE followed the suggested guidance found in the literature (Pike et al. 2011), as highlighted in the Literature Review Chapter, and again, as follows:

- Retroreflectivity data should be collected along the entire length of a marking segment and averaged. For a retroreflectometer with an 8-inch measurement field, a minimum of three longitudinally adjacent readings should be taken spanning twp marking segments for rumble stripe markings with 12-inch spacing. Using a stepping distance shorter than a retroreflectometer's measurement field is not needed.
- Hand-leveling of a handheld retroreflectometer by an experienced user on profiled or rumble stripe pavement markings is a suitable means to maintain the instrument in the plane defined by the tops of the pavement marking profiles.
- The vertical structure of rumble stripe pavement markings did not appear to increase the dry retroreflectivity measurements of the markings tested.
- The use of a properly calibrated mobile retroreflectometer operated by an experienced user will result in practically the same dry retroreflectivity measurements as handheld retroreflectometer measurements measured in accordance with ASTM E 1710 (ASTM International 2011).

Roadway Details and Measurement Sections

Figure 11 notes the in-place conditions observed for each roadway.

Roadway:	TH 68	TH 109	TH 55
Surface Type:	UltraThin Bonded Wear Coarse	Bituminous	Bituminous
Rumble Pattern:	16" x 7"	2@ 8" x 7" with 4" gap*	16" x 7"
Paint Width:	4 inches	4 inches	4 inches
Striping Material:	Latex with wet reflective media	Epoxy with std media	Latex with std media
Line Measured:	Yellow centerline rumble stripE	Yellow centerline rumble stripE	Yellow centerline rumble stripE
Measured Sections:	2 labelled (A, B)	3 labelled (A, B, C)	2 labelled (A, B)
Measured Date:	November 8th, 2012	November 8th, 2012	November 27th, 2012

*Centerline rumble strips had a 4-inch gap between them and the patterns were offset by direction.

Figure 11. Roadway Conditions by Study Location

A location map, showing measurement locations and images, are provided in Figure 12 (for TH 68), Figure 13 (for TH 109), and Figure 14 (for TH 55).

District	Roadway	From	To	SP	Surface Type	AADT	Striping Material	Line Type
8	TH 68	27+00.029	37+00.987	S.P.4210-40	UltraThin Bonded Wear Coarse	2,000	Latex WR	Centerline rumble stripE

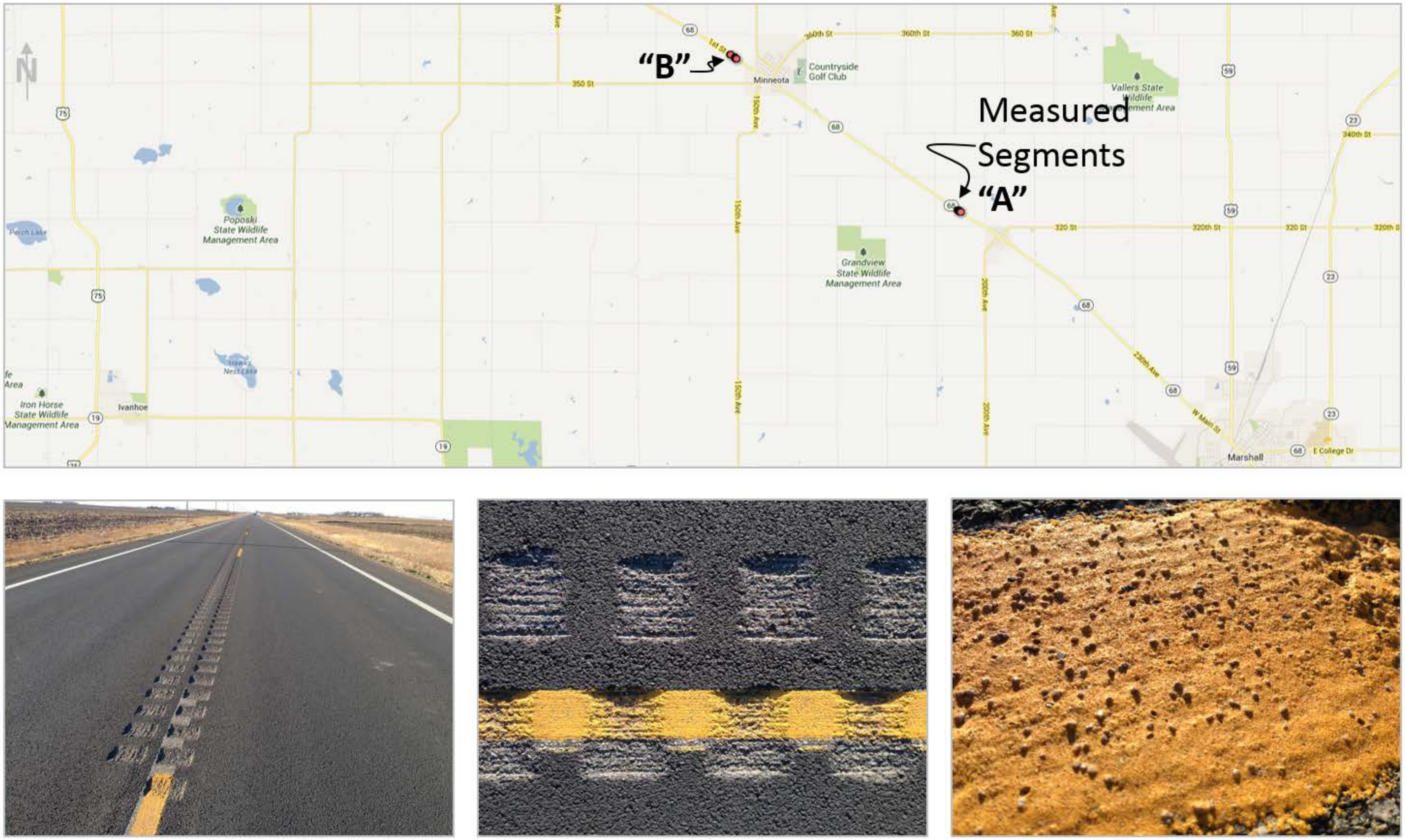


Figure 12. TH 68 Location

District	Roadway	From	To	SP	Surface Type	AADT	Striping Material	Line Type
7	TH 109	0	11.83	SP-2212-28	Bituminous	780	Epoxy	Centerline rumble stripE

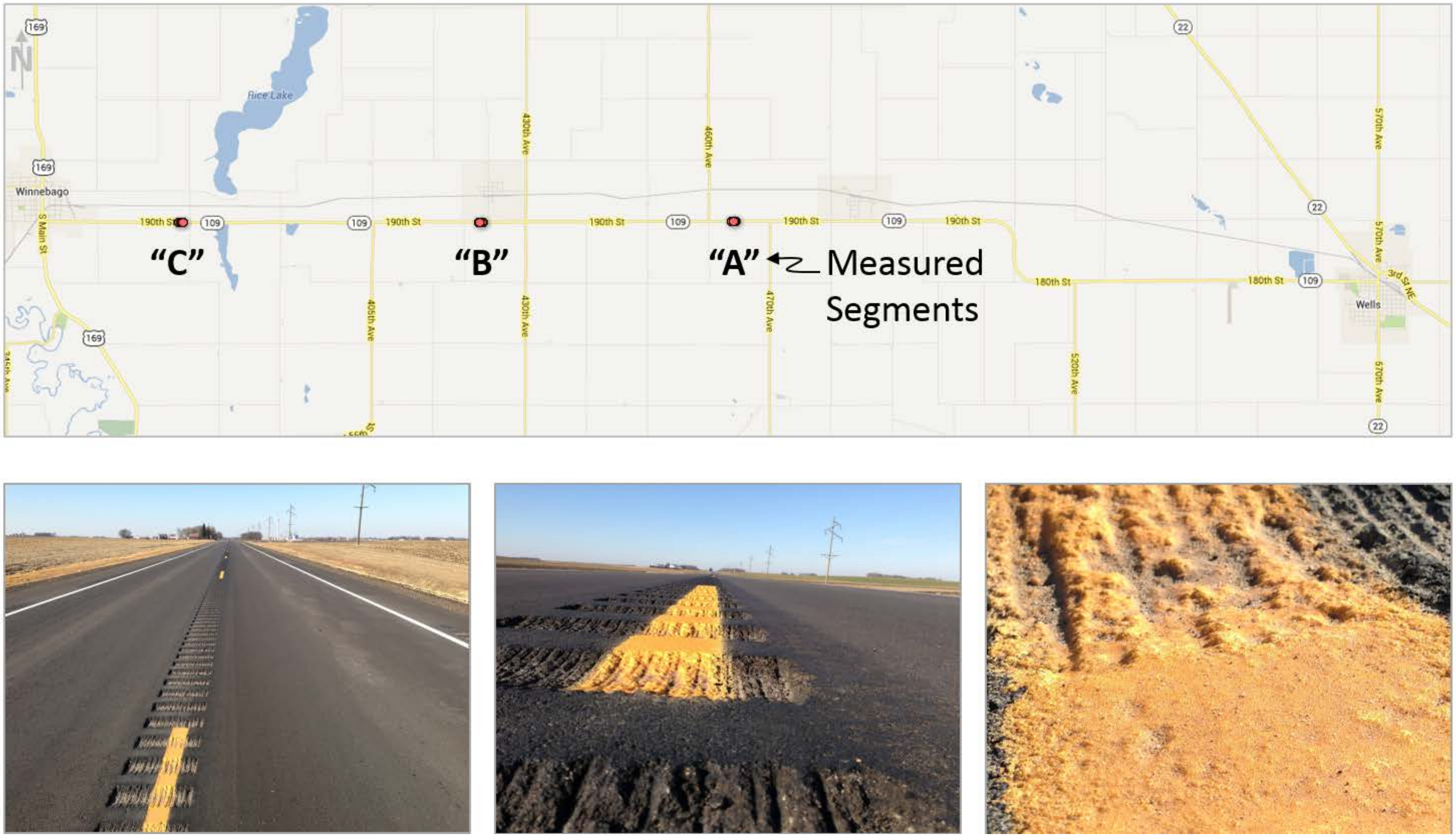


Figure 13. TH 109 Location

District	Roadway	From	To	SP	Surface Type	AADT	Material	Marking
4	TH55	31.87	39.03	SP8824-24	Bituminous	20,000	Latex	Centerline rumble stripE

Figure 14. TH 55 Location

Findings

Measurement results by roadway, measured segment, and travel direction are shown in Figure 15.

Roadway	Rumble StripE	Marking Color	Measured Segment	Retroreflectivity (mcd) by Travel Direction			
				R_L	Dir.	R_L	Dir.
TH 68	Centerline	Yellow	A	237	WB	230	EB
			B	276	WB	225	EB
TH 109	Centerline	Yellow	A	141	WB	163	EB
			B	105	WB	125	EB
			C	117	WB	156	EB
TH 55	Centerline	Yellow	A	135	WB	119	EB
			B	128	WB	141	EB

Note: Values are an average of 16 readings with exception to TH 55 segment B. Based on observed brine contamination, these values reflect an average of 7 readings (E-W Location B), and 13 readings (W-E location B).

Figure 15. Initial Retroreflectivity Measurements by Location and Line Type

Comparison by Roadway

A relative comparison between roadway, segment, and measured direction is shown in Figure 16.

Roadway	Rumble StripE	Marking Color	Measured Segment	Absolute Difference R_L (mcd)	Absolute Difference Percent
TH 68	Centerline	Yellow	A	7	3%
			B	51	20%
TH 109	Centerline	Yellow	A	22	14%
			B	20	17%
			C	39	29%
TH 55	Centerline	Yellow	A	16	13%
			B	13	10%

Figure 16. Relative Comparison of Measurement Results

Overall Summary Initial Measurements

When comparing the three roadway segments, the following observations can be made: The relative difference in retroreflectivity by travel direction is from 3 percent (7 mcd) to 29 percent (39 mcd). The relative difference in retroreflectivity between measurement sections is from 2 percent (5 mcd) and 29 percent (36 mcd).

Chapter 4. Long-Term Evaluation

The research team conducted a long-term evaluation of the same rumble stripEs installed on three roadways in 2012. Given that the initial measurements were conducted in November of 2012, follow-up measurements in April of 2014 provide a perspective of the impact of wear and winter maintenance on retroreflectivity after two winters (18 months).

Findings

Initial and 18-Month Comparison

Figure 17 compares both the initial and 18-month retroreflectivity measurements by roadway segment and direction measured.

Roadway	Rumble StripE	Marking Color	Measured Segment	2012 Retro (mcd) by Travel Direction				2014 Retro (mcd) by Travel Direction			
				R_L	Dir.	R_L	Dir.	R_L	Dir.	R_L	Dir.
TH 68	Centerline	Yellow	A	237	WB	230	EB	109	WB	123	EB
			B	276	WB	225	EB	100	WB	152	EB
TH 109	Centerline	Yellow	A	141	WB	163	EB	92	WB	94	EB
			B	105	WB	125	EB	71	WB	49	EB
			C	117	WB	156	EB	90	WB	117	EB
TH 55	Centerline	Yellow	A	135	WB	119	EB	43	WB	53	EB
			B	128	WB	141	EB	58	WB	66	EB

Figure 17. Retroreflectivity over Time

Figure 18 shows the 18 month comparison of retroreflectivity by direction measured.

- Variation by travel direction – Figure 18 shows the relative difference in retroreflectivity, by travel direction, which ranged between 2 percent no difference (2 mcd on TH 109, Segment A) to 42 percent (52 mcd difference by direction on TH 68, Segment B). This variation is important to understand, especially for these centerline rumble stripEs, given that the position of the marking is in the center of the two-lane roadway and motorist's safety depends on acceptable retroreflectivity from a single marking in both directions.

Roadway	Rumble StripE	Marking Color	Segment	Absolute Difference R_L (mcd)	Absolute Difference Percent
TH 68	Centerline	Yellow	A	14	12%
			B	52	42%
TH 109	Centerline	Yellow	A	2	2%
			B	21	36%
			C	27	26%
TH 55	Centerline	Yellow	A	11	22%
			B	8	13%

Figure 18. Relative Comparison of Retroreflectivity by Direction Measured

Figure 19 shows the relative comparison of 18 month measurements by segment, minimum/average/maximum retroreflectivity, and percent loss.

Variation by retroreflectivity - As shown, after two winters, all sections experienced a considerable loss in retroreflectivity ranging from 24 to 62 percent. The epoxy sections of TH 109 showed the least combined percent loss (37 percent) when compared to the latex sections of TH 68 and TH 55 (53 percent), however, this observation is inconclusive given that the roadway experiences far less traffic at 780 vehicles per day, as compared to 2,000 vpd on TH 68 and 20,000 vpd on TH 55.

			Retroreflectivity (mcd)			Difference in Averages	Difference in Percent
Roadway	Segment	Year	Min	Average	Max		
TH 68	A	2012	133	234	318		
TH 68	A	2014	68	116	164	-118	-50%
TH 68	B	2012	133	234	318		
TH 68	B	2014	59	126	226	-108	-46%
TH 109	A	2012	111	152	183		
TH 109	A	2014	39	93	162	-59	-39%
TH 109	B	2012	88	115	152		
TH 109	B	2014	17	60	140	-55	-48%
TH 109	C	2012	88	136	187		
TH 109	C	2014	33	103	201	-33	-24%
TH 55	A	2012	90	127	158		
TH 55	A	2014	25	48	83	-79	-62%
TH 55	B	2012	38	130	165		
TH 55	B	2014	30	62	158	-68	-52%

Figure 19. Comparison of 18 month retroreflectivity by Roadway Section

Overall Comparison

A comparison of the initial (2012) versus long-term (2014) retroreflectivity measurements yields the following:

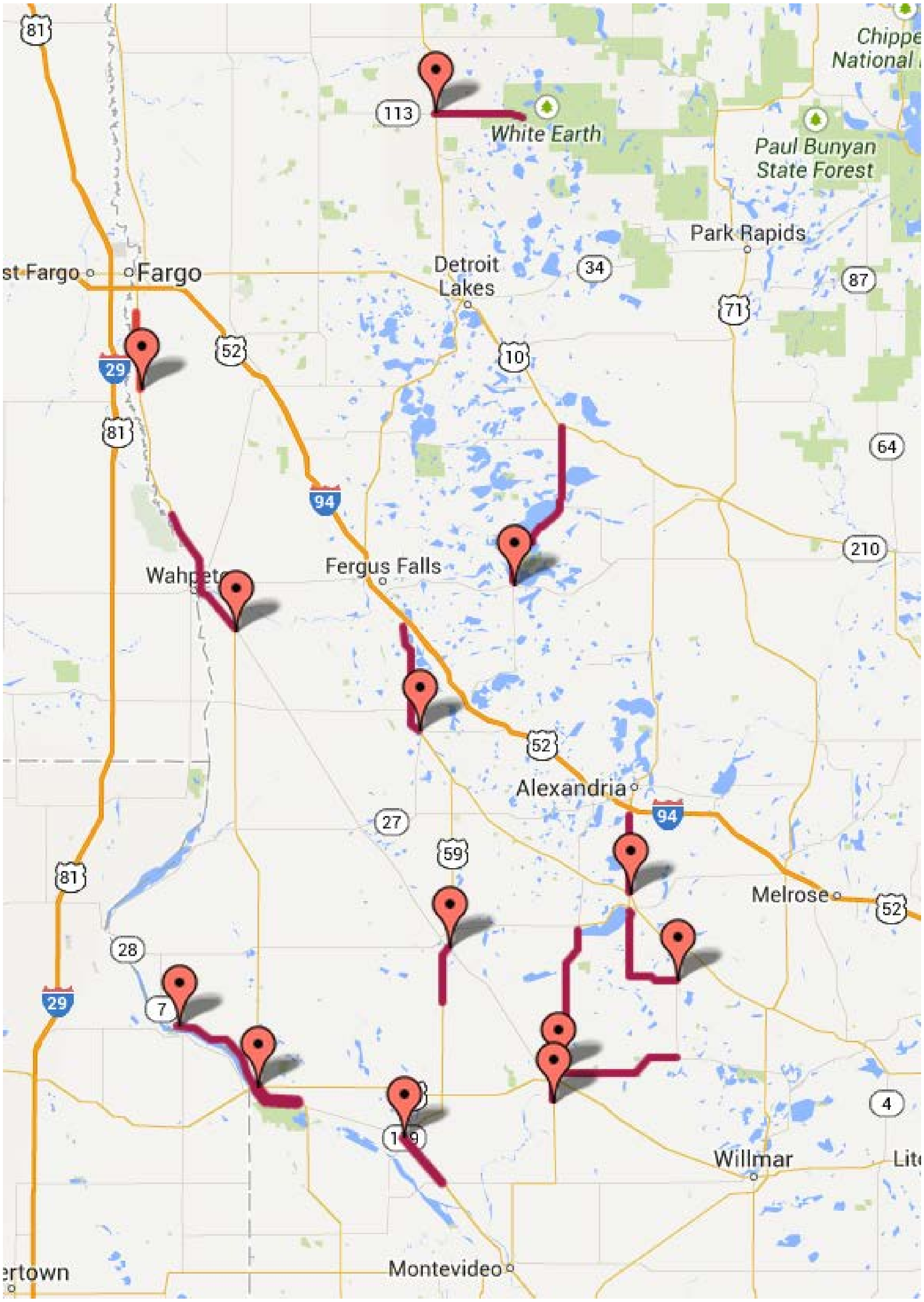
- Consistent retroreflectivity by direction of travel - The amount of retroreflectivity provided by direction of travel for the same centerline marking varied considerably (from 2 percent up to a 40 percent difference depending on the direction of travel). This variation is a result of rumble stripE installation practices and more specifically bead distribution and embedment.
- Consistent retroreflectivity by roadway - A comparison of retroreflectivity after 18 months shows considerable variability from a high of 121 mcd (TH 68) to a midpoint of 86 mcd (TH 109) and a low of 55 mcd (TH 55).

Chapter 5. In-Service Evaluation

The “In Service” evaluation includes both centerline and profile rumble stripEs on two-lane MnDOT roadways. The retroreflectivity data were collected one winter (approximately 12 months) after installation with no initial measurement data being available. This effort included measuring the centerline rumble stripe performance over 8 segments on 4 different roadways and the profile rumble stripe performance over 18 segments on 10 different roadways.

Roadway Locations

A total of 14 roadways were identified for evaluation. These locations all fell within MnDOT District 4 and resulted from recently completed (2013) mill and overlay projects on bituminous surfaces, which included adding new rumbles and rumble stripEs. Figure 20 shows these locations (red pin) along with the length of roadway covered (solid red line) by the construction activity.



Map: ©Google 2015

Figure 20. In-Service Data Collection Locations

Additional descriptive information for each site is included in Figure 21.

District	Roadway	County (s)	AADT	Marking Material	Wet Reflective	Rumble StripE	
						Centerline	Profile
4	TH 7	Swift/Chippewa	1,400	Latex	X	X	
4	TH 29	Pope/Douglas	6,500	Latex	X	X	
4	TH 59	Otter Tail/Grant	1,160	Epoxy	X	X	
4	TH 78	Otter Tail	5,600	Epoxy	X	X	X
4	TH 113	Mahnomen	1,850	Latex	X		X
4	TH 75	Big Stone	500	Epoxy	X		X
4	TH 75	Clay	1,750	Latex	X		X
4	TH 9	Swift	1,350	Latex	X		X
4	TH 7	Big Stone	395	Latex	X		X
4	TH 75	Wilkin	1,750	Latex	X		X
4	TH 29	Swift/Pope	2,050	Latex	X		X
4	TH 104	Pope	1,050	Epoxy	X		X
4	TH 59	Swift/Stevens	1,150	Epoxy	X		X

Figure 21. In-Service Location Details

Details for each study location are provided in Figure 22 through Figure 34 including a location map, images, and locations measured.

District	Roadway	County (s)	SP	Surface Type	AADT	Marking Material	Wet Reflective	Rumble StripE	
								Centerline	Profile
4	TH 7	Swift/Chippewa	SP 7601-17/1201-31	Bituminous	1,400	Latex	X	X	

Figure 22. Swift and Chippewa County TH 7

District	Roadway	County (s)	SP	Surface Type	AADT	Marking Material	Wet Reflective	Rumble StripE	
								Centerline	Profile
4	TH 29	Pope/Douglas	SP 6106-21/2102-54	Bituminous	6,500	Latex	X	X	

Figure 23. Pope and Douglas County TH 29

District	Roadway	County (s)	SP	Surface Type	AADT	Marking Material	Wet Reflective	Rumble StripE	
								Centerline	Profile
4	TH 59	Otter Tail/Grant	SP 2611-16/5616-07	Bituminous	1,160	Epoxy	X	X	

Figure 24. Otter Tail and Grant County TH 59

District	Roadway	County (s)	SP	Surface Type	AADT	Marking Material	Wet Reflective	Rumble StripE	
								Centerline	Profile
4	TH 78	Otter Tail	SP 5620-24/5621-23	Bituminous	5,600	Epoxy	X	X	X

Figure 25. Otter Tail County TH 78

District	Roadway	County (s)	SP	Surface Type	AADT	Marking Material	Wet Reflective	Rumble StripE	
								Centerline	Profile
4	TH 113	Mahnomen	SP 0607-20	Bituminous	1,850	Latex	X		X

Figure 26. Mahnomen County TH 113

						Marking Material	Wet Reflective	Rumble StripE	
District	Roadway	County (s)	SP	Surface Type	AADT			Centerline	Profile
4	TH 75	Big Stone	SP 4405-26	Bituminous	500	Epoxy	X		X

Figure 27. Big Stone County TH 75

						Marking Material	Wet Reflective	Rumble StripE	
District	Roadway	County (s)	SP	Surface Type	AADT			Centerline	Profile
4	TH 75	Clay	SP 1406-67	Bituminous	1,750	Latex	X		X

Figure 28. Clay County TH 75

District	Roadway	County (s)	SP	Surface Type	AADT	Marking Material	Wet Reflective	Rumble StripE	
								Centerline	Profile
4	TH 9	Swift	SP 7606-26	Bituminous	1,350	Latex	X		X

Figure 29. Swift County TH 9

District	Roadway	County (s)	SP	Surface Type	AADT	Marking Material	Wet Reflective	Rumble StripE	
								Centerline	Profile
4	TH 7	Big Stone	SP 0609-29/0602-25	Bituminous	395	Latex	X		X

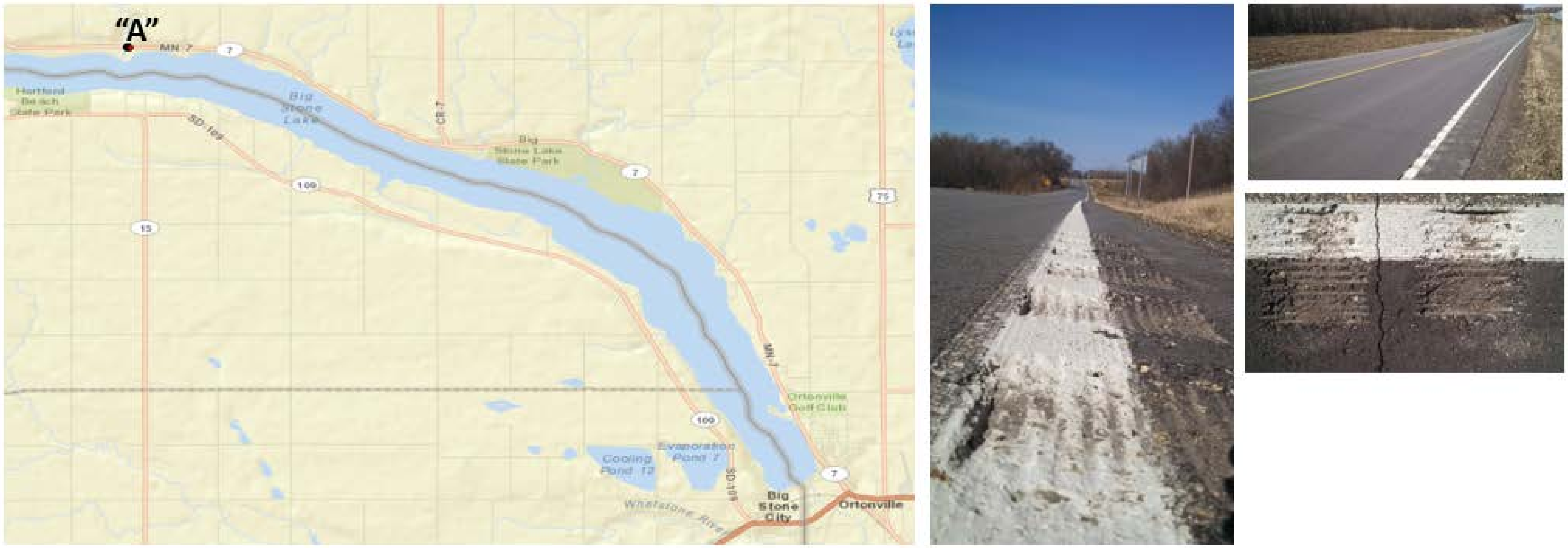


Figure 30. Big Stone County TH 7

District	Roadway	County (s)	SP	Surface Type	AADT	Marking Material	Wet Reflective	Rumble StripE	
								Centerline	Profile
4	TH 75	Wilkin	SP 8407-37/8408-55	Bituminous	1,750	Latex	X		X

Figure 31. Wilkin County TH 75

District	Roadway	County (s)	SP	Surface Type	AADT	Marking Material	Wet Reflective	Rumble StripE	
								Centerline	Profile
4	TH 29	Swift/Pope	SP 7608-18/6105-20	Bituminous	2,050	Latex	X		X

Figure 32. Swift and Pope County TH 29

						Marking Material	Wet Reflective	Rumble StripE	
District	Roadway	County (s)	SP	Surface Type	AADT			Centerline	Profile
4	TH 104	Pope	SP 6110-19	Bituminous	1,050	Epoxy	X		X

Figure 33. Pope County TH 104

District	Roadway	County (s)	SP	Surface Type	AADT	Marking Material	Wet Reflective	Rumble StripE	
								Centerline	Profile
4	TH 59	Swift/Stevens	SP 7505-21	Bituminous	1,150	Epoxy	X		X

Figure 34. Swift and Stevens County TH 59

Findings

The field retroreflectivity measurement findings are sub-divided by pavement marking line type (yellow centerline and white edgeline (which are referred to as a profile marking).

Centerline Rumble StripE

Measurement results for locations with centerline rumble stripEs by roadway and direction measured are shown in Figure 35.

Roadway County(s)	Rumble StripE	Marking Color	Measured Segment	Retroreflectivity (mcd) by Travel Direction			
				R_L	Dir.	R_L	Dir.
TH 7 Swift/Chippewa	Centerline	Yellow	A	141	NB	168	SB
			B	139	NB	164	SB
TH 29 Pope/Douglas	Centerline	Yellow	A	66	NB	88	SB
			B	66	NB	66	SB
TH 59 Otter Tail/Grant	Centerline	Yellow	A	137	NB	163	SB
			B	123	NB	139	SB
			C	126	NB	153	SB
TH 78 Otter Tail	Centerline	Yellow	A	61	NB	85	SB

Figure 35. Centerline Rumble StripE Measurement Results by Location

A relative comparison of measured retroreflectivity by direction of travel is shown in Figure 36.

Roadway County(s)	Rumble StripE	Marking Color	Measured Segment	Absolute Difference R_L (mcd)	Absolute Difference Percent
TH 7 Swift/Chippewa	Centerline	Yellow	A	27	17%
			B	26	17%
TH 29 Pope/Douglas	Centerline	Yellow	A	22	28%
			B	0	0%
TH 59 Otter Tail/Grant	Centerline	Yellow	A	26	17%
			B	16	13%
			C	27	19%
TH 78 Otter Tail	Centerline	Yellow	A	23	32%

Figure 36. Centerline Rumble StripE Relative Comparison by Direction of Travel

When comparing the four roadways where the centerline rumble stripEs were measured, the following observations can be made:

- Variation by travel direction - The relative difference in retroreflectivity, by travel direction, ranged between 0 percent no difference (0 mcd on TH 29 Pope/Douglas, Segment B) to 32 percent (23 mcd on TH 78 Otter Tail, Segment A). This variation is important to understand, especially for these centerline rumble stripEs, given that the position of the marking is in the center of the two-lane roadway and motorist's safety depends on acceptable retroreflectivity from a single marking in both directions.
- Variation by retroreflectivity - The average resulting retroreflectivity, after 1 season, was found to vary considerably among the 4 roadways. TH 7 and TH 59 averaged 153 and 140 mcd respectively in contrast to TH 29 and TH 78 which averaged 72 and 73 mcd respectively. This significant variation leads to questioning what was different between these roadways. Once consideration is that the poorer performing roadways TH 29 and TH 78 carry roughly 5 and 6 times more traffic than TH 7 and TH 59. The pavement marking materials could also impact performance, however no clear trend is evident as TH 7 was a latex installation and TH 78 was epoxy.

Profile Rumble StripE

Retroreflectivity measurement findings for each roadway, by direction measured, for the profiled (edgeline) rumble stripEs are shown in Figure 37.

Roadway County(s)	Rumble StripE	Marking Color	Measured Segment	Retroreflectivity (mcd) by Travel Direction			
				R_L	Dir.	R_L	Dir.
TH 78 Otter Tail	Profile	White	B	72	NB	92	SB
TH 113 Mahnomen	Profile	White	A	195	WB	222	EB
TH 75 Big Stone	Profile	White	A	152	WB	209	EB
			B	191	WB	195	EB
TH 75 Clay	Profile	White	A	454	NB	381	SB
			B	326	NB	304	SB
TH 9 Swift	Profile	White	A	282	WB	369	EB
			B	264	WB	274	EB
TH 7 Big Stone	Profile	White	A	238	WB	259	EB
TH 75 Wilkin	Profile	White	A	159	NB	63	SB
			B	164	NB	154	SB
TH 29 Swift/Pope	Profile	White	A	235	NB	127	SB
			B	206	NB	146	SB
			C	211	NB	210	SB
TH 104 Pope	Profile	White	A	175	WB	216	EB
			B	170	WB	217	EB
TH 59 Stevens	Profile	White	A	108	NB	159	SB
			B	123	NB	115	SB

Figure 37. Profile Rumble StripE Measurement Results by Location

A relative comparison of measured retroreflectivity by direction of travel is shown in Figure 38.

Roadway County(s)	Rumble StripE	Marking Color	Measured Segment	Absolute Difference R_L (mcd)	Absolute Difference Percent
TH 78 Otter Tail	Profile	White	B	20	25%
TH 113 Mahnomen	Profile	White	A	27	13%
TH 75 Big Stone	Profile	White	A	58	32%
			B	4	2%
TH 75 Clay	Profile	White	A	73	18%
			B	22	7%
TH 9 Swift	Profile	White	A	88	27%
			B	10	4%
TH 7 Big Stone	Profile	White	A	21	8%
TH 75 Wilkin	Profile	White	A	95	86%
			B	10	6%
TH 29 Swift/Pope	Profile	White	A	108	60%
			B	60	34%
			C	1	0%
TH 104 Pope	Profile	White	A	41	21%
			B	47	24%
TH 59 Stevens	Profile	White	A	51	38%
			B	8	6%

Figure 38. Profile Rumble StripE Relative Comparison by Direction of Travel

The following observations were made for the profile rumble stripE at the ten locations evaluated:

- Variation by travel direction - The difference in retroreflectivity, by travel direction, ranged between 0 percent no difference (1 mcd on TH 29 Swift/Pope, Segment C) to 86 percent (95 mcd on TH 75 Wilkin, Segment A). Although less critical than on centerline, this bi-directional variation is considerable and should be considered when addressing rumble stripe installation practices and overall bead distribution and embedment. The bi-directional retroreflectivity varied by greater than 30 percent for five out of the 18 measured sections.

- Variation by retroreflectivity - The average resulting retroreflectivity, after 1 season, was found to vary considerably among the 10 roadways from an averaged high of 366 mcd (TH 75 Clay to a low of 82 mcd (TH 78 Otter Tail). As with the centerline findings, the significant variation leads to questioning what was different between these installations and for these roadways.

Consideration of AADT

Figure 39 shows the list of sampled roadways sorted by AADT from high to low with the averaged retroreflectivity measurements noted for both centerline and profile markings.

District	Roadway	County (s)	AADT	Marking Material	Wet Reflective	Avg. Retroreflectivity (mcd)	
						Centerline	Profile
4	TH 29	Pope/Douglas	6,500	Latex	X	72	
4	TH 78	Otter Tail	5,600	Epoxy	X	73	82
4	TH 29	Swift/Pope	2,050	Latex	X		189
4	TH 113	Mahnomen	1,850	Latex	X		209
4	TH 75	Clay	1,750	Latex	X		366
4	TH 75	Wilkin	1,750	Latex	X		135
4	TH 7	Swift/Chippewa	1,400	Latex	X	153	
4	TH 9	Swift	1,350	Latex	X		297
4	TH 59	Otter Tail/Grant	1,160	Epoxy	X	140	
4	TH 59	Swift/Stevens	1,150	Epoxy	X		126
4	TH 104	Pope	1,050	Epoxy	X		195
4	TH 75	Big Stone	500	Epoxy	X		187
4	TH 7	Big Stone	395	Latex	X		249

Figure 39. Comparison of AADT and Performance

This information is also graphed in Figure 40.

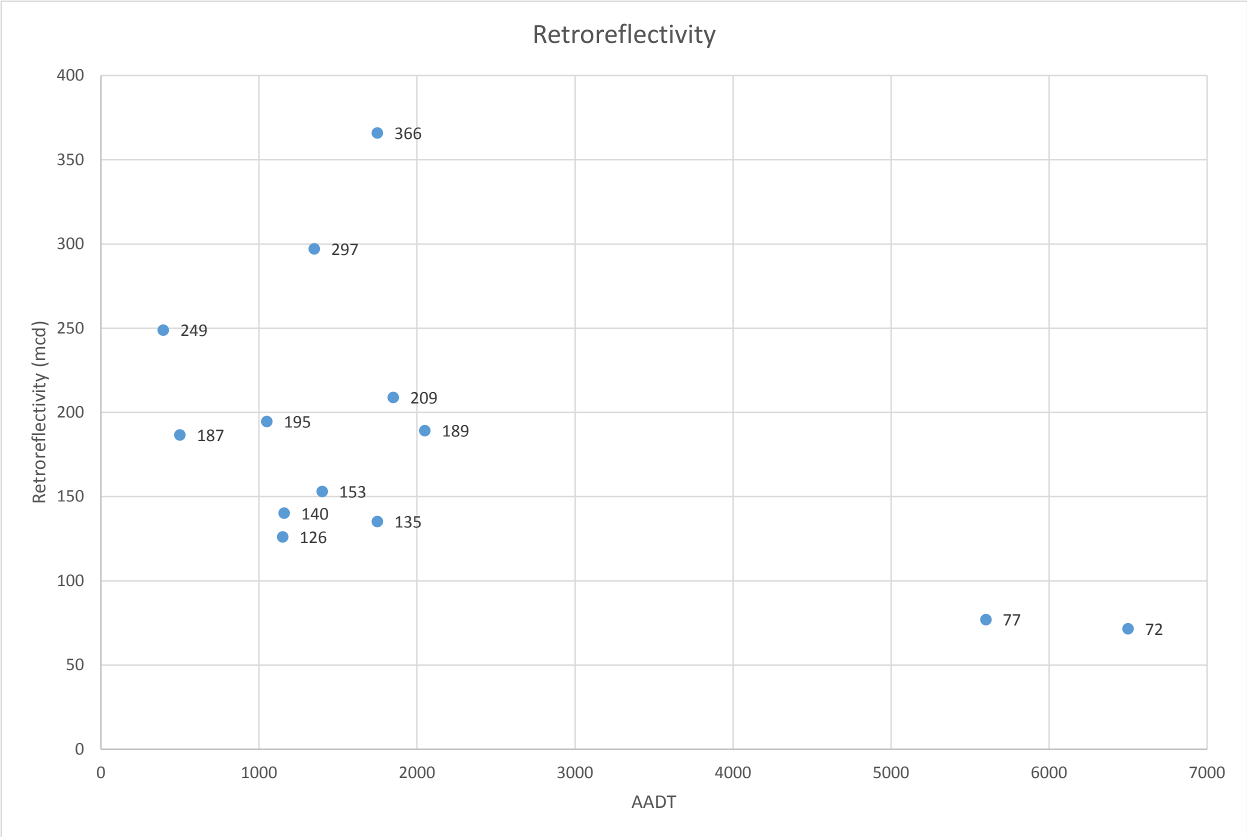


Figure 40. Retroreflectivity by AADT

Since installation in 2013, the performance of these rumble stripEs (in 2014) appears to have some influence from AADT (the lowest measurements observed were on the highest AADT road segments). However, a much larger sample would be required to further refine and statistically quantify this observation. The majority of measurements were found to fall between 126 and 209 mcd within an AADT range of 395 to 2,050.

Overall Comparison After One Year of Service

Figure 41 provides additional measurement information by roadway (all directions of travel) and by line type. As shown, the retroreflectivity readings ranged from a low of 14 to a high of 576 mcd. The highest average retroreflectivity was 366 mcd (TH 75 Clay) and the lowest was 72 mcd (TH 29 Pope). The standard deviation ranged from 22 to 87 mcd. Overall, after one season of service, and using 100 mcd as an arbitrary benchmark for performance, nine out of the 14 roadways had over 90 percent of the retroreflectivity readings in excess of 100 mcd.

Location	RumbleStripe	#Readings	Retroreflectivity (mcd) Min	Max	Average	Std Dev	% of Values >100 mcd
TH7 Swift/Chippewa	Centerline	80	66	218	153	36	93%
TH29 Pope	Centerline	80	22	140	72	30	21%
TH59 Otter Tail/Grant	Centerline	120	97	199	140	22	98%
TH78 Otter Tail	Centerline	40	14	121	73	28	15%
TH78 Otter Tail	Profile	40	35	173	82	30	20%
TH113 Mahnomen	Profile	40	82	319	209	53	95%
TH75 Big Stone	Profile	80	123	259	187	29	100%
TH75 Clay	Profile	80	211	576	366	87	100%
TH9 Swift	Profile	80	166	482	297	71	100%
TH7 Big Stone	Profile	40	176	333	249	46	100%
TH75 Wilkin	Profile	80	46	200	135	47	74%
TH29 Swift/Pope	Profile	120	24	329	189	57	91%
TH104 Pope	Profile	80	56	370	195	67	90%
TH59 Stevens	Profile	80	54	208	126	32	78%

Figure 41. Summary of In-Service Field Measurements

Chapter 6. Conclusions

This research effort provides field data for MnDOT staff specific to the performance of pavement marking materials when used as rumble stripEs on MnDOT roadways. These field efforts provide a perspective on the impact that both wear and winter maintenance practices have on retroreflectivity.

Given that these markings were installed by a variety of MnDOT contractors and at different times and roadways, this report also serves to document the range of retroreflectivity provided to drivers at any given time on similar two-lane MnDOT roadways under the installation practice guidelines at the time of installation (2012 to 2013). More specifically, these measurements consider the difference in retroreflectivity provided by direction of travel (e.g., for the same marking, what is the retroreflectivity while driving northbound versus southbound?) and by roadway.

Based on guidance from the project TAP, this limited field data collection effort was organized into two sections, long-term and in-service.

The long-term evaluation collected field measurements both initially and after two winters (18 months) for centerline rumble stripEs only and on seven segments over three different roadways.

The in-service evaluation included both centerline and profile rumble stripEs on two-lane MnDOT roadways. The retroreflectivity data were collected one winter (approximately 12 months) after installation with no initial measurement data being available. These locations all fell within MnDOT District 4 and resulted from recently completed (2013) mill and overlay projects on bituminous surfaces, which included adding new rumbles and rumble stripEs. This effort included measuring the centerline rumble stripe performance over eight segments on four different roadways and the profile rumble stripe performance over 18 segments on 10 different roadways.

The conclusions for both evaluations follow.

Long-Term Evaluation

A comparison of the initial (2012) versus long-term (2014) retroreflectivity measurements yielded the following observations:

- Consistent retroreflectivity by direction of travel – The amount of retroreflectivity provided by direction of travel for the same centerline marking varied considerably (from 2 percent up to a 40 percent difference depending on the direction of travel). This variation is a result of rumble stripE installation practices and, more specifically, bead distribution and embedment.

- Consistent retroreflectivity by roadway – A comparison of retroreflectivity after 18 months showed considerable variation among the three roadways measured, from a high of 121 mcd (TH 68), to a midpoint of 86 mcd (TH 109), and a low of 55 mcd (TH 55).

In-Service Evaluation

The in-service evaluation included new centerline and profile rumble stripEs, all of which were installed as part of the 2013 mill and overlay projects within District 4 on two-lane MnDOT roadways.

- Consistent retroreflectivity by direction of travel – The amount of retroreflectivity provided by direction of travel for the same centerline marking varied considerably for both the centerline (0 percent up to 32 percent difference) and the profile marking (0 percent up to 86 percent difference). It is especially critical for the centerline marking to be consistent in providing similar retroreflectivity regardless of the direction traveled.

- Consistent retroreflectivity by roadway – Retroreflectivity, 12 months after installation, was found to vary considerably between the different roadways measured. The yellow centerline markings showed two roadways measuring in the mid 150 mcd range and the remaining two measured at roughly half, in the 70 mcd range (TH 7 and TH 59 averaged 153 and 140 mcd, respectively, in contrast to TH 29 and TH 78, which averaged 72 and 73 mcd, respectively). The white profile markings' highest average retroreflectivity was 366 mcd (TH 75 Clay) and the lowest was 72 mcd (TH 29 Pope). The standard deviation ranged from 22 to 87 mcd.

- Overall, after one season of service, and using 100 mcd as an arbitrary benchmark for performance, nine of the 14 roadways had over 90 percent of the retroreflectivity readings measuring in excess of 100 mcd. The percent of measurements exceeding this 100 mcd benchmark for the remaining five roadways were 15, 20, 21, 74, and 78 percent.

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Appendix A. Rumble Strip Dimensions from State DOTs

All dimensions (mm) unless otherwise noted.

		Offset				Longitudinal Width			Transverse Width		Depth			Center to Center			
State	Type	Low	Left Sh	Right Sh	±	Low	High	±	Low	High	Low	High	±	Low	High	±	Comments
Colorado	milled	150				150	200		450	610	13	16		300			may be older standard
Connecticut	milled		150	300		180			400		13			300		13	
Florida	milled	400				180		13	400		12	16		300		25	Skip array is standard; 2100 mm of milled groves with 1500 mm of skip.
Florida	milled: transverse cut	400				180		13	400	700	13	16		300		25	Transverse is 150 mm slope down/up. Skip array 2100 mm of milled groves with 1500 mm of skip.
Kentucky	cut into cured PC conc shlds	300				100			1200		13			300			Set of 6 grooves every 18m O.C.
Kentucky	sawed	300				130		15	600		15		5	1500		50	Used to correct rolled or as option of contractor
Michigan	milled					180			400		15			300			
Montana	milled	150							300	400	13	19		300			Longitudinal cut with 300 radius milling head
New Jersey	milled	100				180			400		13			300			
New Mexico	milled	300				175		15	400		13	16		300			
New York	milled		100	250		180			400		12			300			
Pennsylvania	milled		300	460	13	180			400	430	13	16		300			
South Carolina	milled	250				177		12	406		12	16		305		25	
Tennessee	milled	400				150		13	400		7	10		300			
Washington	milled	150				180		13	400		13	16		300			
Wyoming	milled	150				175			400		13	16		300			
Alabama	rolled	150				25			915		13			200			
Arizona	rolled	300				60			600		30			200			
California	rolled	300				50			900		25			200			
Colorado	rolled	150							450	610	13	25		200	250		may be older standard
Kentucky	rolled	300				40		10	600		20		5	230		25	
New York	rolled		150	300		65			450		19			200	300		Offset for right shoulder 150 to 300mm. Transverse width 150 sloped, 700 total width mm
South Dakota	rolled	200				60			915		30			200			
Utah	rolled	300				38			600		25		3	200	230		
Colorado	corrugated formed in PC conc shlds	150				60			450	610	13	25		100			may be older standard
Kentucky	formed in PC conc shlds	300				57			300		25			114			1800 mm of corrugations 18m & 23 m O.C.
Montana	formed in PC conc shlds	150				50			300	400	25			114			continuous pattern
New York	narrow formed in PC conc shlds	300				170	190		400		12	19		600			
New York	corrugated formed in PC conc shlds	300				125			600		25			125			5 depressions in 600 to 625 mm spaced at 500 to 1000 mm intervals
South Dakota	corrugated formed in PC conc shlds										25			150			7 depressions in 1300 mm spaced at 12 m intervals
Tennessee	corrugated formed in PC conc shlds	300				57			915		25			115			depressions in 1940 mm spaced at center point of conc shld slab
Utah	corrugated formed in PC conc shlds	1200				60			1800		20			115			depressions in 1800 mm spaced at 15 m intervals
Wyoming	formed in PC conc shlds	300				58				1200	25			115			Transverse width varies, allow 1200 bicycle traffic. Intermittent/continuous contractor choice
Florida	raised: thermoplastic	0				100					12			1500			for structures approach with narrow shlds
Florida	raised: asphalt	0				50					13			300			for structures approach with narrow shlds

Source: http://safety.fhwa.dot.gov/roadway_dept/pavement/rumble_strips/rumble_types/docs/dimensions.pdf

Data source: safety.fhwa.dot.gov/roadway_dept/pavement/rumble_strips/rumble_types/docs/dimensions.pdf

Appendix B. MnDOT Technical Memorandum 14-07-T-01

MINNESOTA DEPARTMENT OF TRANSPORTATION
Engineering Services Division
Technical Memorandum No. 14-07-T-01
May 21, 2014

To: Electronic Distribution Recipients

From: Susan M. Mulvihill, P.E.
Deputy Commissioner / Chief Engineer

Subject: Rumble Strips and Stripes on Rural Trunk Highways

Expiration
This Technical Memorandum supersedes No. 11-02-T-02 (Rumble Strips and Stripes on Rural Trunk Highways) and shall remain in effect until May 21, 2017 unless superseded prior to this date or incorporated into the MnDOT Standard Plans, the Road Design Manual, and/or Traffic Engineering Manual.

Implementation
This policy shall be in effect for all programmed rural highway projects where the paved surface is constructed, reconstructed, or overlaid. This does not include preventive maintenance projects such as chip seals and microsurfacing; however, preventive maintenance projects on surfaces that have existing rumble strips or stripes shall ensure that these are perpetuated in accordance with the standards within this Technical Memorandum, particularly with respect to depth. Any paving constructed by MnDOT forces is exempt from the requirements of this Technical Memorandum.

This policy applies to all projects on Rural Trunk Highways where the posted speed limit is 55 mph or higher. For the purpose of this technical memorandum a Rural Trunk Highway is defined in the Definitions section. Districts may implement this policy on Urban Trunk Highways

While this policy provides for standards that will require an increased use of rumble strips and stripes, it also provides for more flexibility and discretion on the part of the District. Notably, the District has the discretion for the preferred lateral placement and width of the shoulder rumble strip in order to abate noise concerns, accommodate bicyclists, acknowledge pedestrian use, and manage pavement conditions.

The guidelines contained in this Technical Memorandum apply to all Rural Trunk Highways. However, other road authorities are encouraged to evaluate their needs accordingly.

Introduction
Detailed crash analysis has shown that lane departure crashes, such as run off the road, sideswipe and head-on crashes, on rural two-lane two-way highways in Minnesota result in an over represented number of fatalities and serious injuries.

Both traditional pavement markings and rumble strips are used to decrease the number of lane departure crashes. Following the lead of other states, MnDOT experimented with combining traditional pavement markings and rumble strips into a "rumble stripe," where the pavement marking is installed on the rumble strip.

The NCHRP Report 641 shows that the use of rumble strips both on the shoulder and beneath the centerline result in a significant reduction of targeted crashes. This report can be found at the following URL: http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_641.pdf.

-MORE-

Additionally, numerous states in the region have enacted systematic policies to require rumble strips and rumble stripes on their trunkline roadways. Michigan, Missouri, and North Dakota have policies requiring centerline rumble stripes, plus edgeline rumble stripes or shoulder rumble strips, on most of their rural trunkline roadways

Studies have shown that the ambient noise decibel level generated by a vehicle driving over a properly constructed rumble strip is comparable to that of a truck passing by on a standard, non-rumbled surface. The noise from rumble strips may be more noticeable as the public is more accustomed to truck traffic, the frequency of the sound is different, and rumble hits tend to be more of an impulse noise. Due to these noise concerns, the District Traffic Engineer, based on engineering judgment, may gap centerline rumble stripe locations near residential homes.

Purpose
To provide centerline rumble stripes and/or shoulder rumble strips on all Rural Trunk Highways to reduce lane departure crashes, to provide increased centerline visibility during rainy conditions, and to guide motorists during weather conditions when striping visibility is poor.

Definitions

Shoulder Rumble Strips
These are defined as rumble strips outside of the edgeline.

Rumble Stripes
Rumble stripes are defined as a rumble strip that contains a pavement marking stripe. These will be referred to as either **edgeline rumble stripes** or **centerline rumble stripes.**

Rural Trunk Highway
This is defined as a roadway segment that has minimal residential or commercial development, with little or no further development anticipated in the future. Officially, rural segments will be defined by language in Chapter 2 of the MnDOT Access Management Manual. (Refer to the attached Reference 1, which shows the rural definition on page 10 in Chapter 2 of the MnDOT Access Management Manual.)

Requirements

Shoulder Rumble Strips
Shoulder rumble strips shall be placed on all rural highway construction and maintenance projects where shoulders are constructed, reconstructed, or overlaid and where the posted speed limit is 55 mph or greater, and the paved shoulder width is 4 feet or greater. Shoulder rumble strips may also be placed on rural trunk highways on shoulders less than 4 feet in width.

The location of the shoulder rumble strip will depend upon the width of the shoulder – see Figure 1 (Two-Way Bituminous Roadway with Paved Shoulder – Section View), Figure 2 (Two-Way Concrete Roadway with Paved Shoulder – Section View) and Figure 3 (Shoulder Rumble Strip on Divided Roadways) for typical dimensions. The District has the discretion for the lateral placement of the shoulder rumble strip in order to abate noise concerns and to accommodate bicyclists.

Shoulder rumble strips shall also be placed on the left shoulder of multi-lane divided roads.

Centerline Rumble Stripes
Centerline rumble stripes shall be placed on all rural highway construction and maintenance projects where pavement is constructed, reconstructed, or overlaid and where the posted speed limit is 55 mph or greater. This applies to both multi-lane undivided and two-lane undivided highways.

-MORE-

Exceptions
Based on engineering judgment, the District Traffic Engineer may gap centerline rumble stripes near residential homes, particularly in passing zone areas and curvilinear alignments. Appropriate gaps for driveway entrances can be found on Figure 10. If the gapping causes centerline rumble installation to be less than 1/8 mile (660 feet), the centerline rumble may be omitted for this segment.

Based on engineering judgment, the District Traffic Engineer may gap shoulder rumbles on the inside of a horizontal curve with nearby residences if a Safety Edge or wider shoulder is installed.

On rural highways where the lane width is 11 feet or less, or the paved shoulder width is 2 feet or less, shoulder rumble strips or edgeline rumble stripes may be placed on both sides of the road in lieu of a centerline rumble stripe.

In all cases, edgeline rumble stripes may be substituted for shoulder rumble strips and still meet the standards within this Technical Memorandum.

Shoulder rumble strips are not required in areas where there is a bus shoulder. However, it is assumed that bus shoulders will usually be installed in areas that are NOT defined as rural trunk highways in the Access Management Guide.

Shoulder rumble strips are not required in locations with guardrail or cable barrier implemented.

Even in cases where shoulder rumble strips are not required due to a narrow paved shoulder width, their installation, or the installation of an edgeline rumble stripe, is encouraged for proactive safety reasons.

Districts shall consider placing centerline rumble stripes and shoulder rumble strips on in-place shoulders at locations on which no construction, reconstruction, or overlay projects are scheduled in the near future as a systematic proactive safety measure. The District Materials Engineer should make recommendations regarding the structural adequacy of the in-place roadway and/or shoulder to receive rumble strips.

Width of rumble strips
Rumble strips are usually 12" in width. The width of the rumble strip can be reduced to within the range of 8"-12" when paved roadway width is limited. A 16" rumble is required on freeway segments. Any design of rumble strips that are smaller than 8" in width, or that deviate from the rumble cycle of 12" called for in Figures 4-8 shall require approval by the State Traffic Engineer.

The standard width of centerline rumble stripes is 16" of total rumble. The 16" may be continuous or split into two 8" rumbles which straddle the centerline pavement joint (each rumble typically 2" away from the joint, creating a 4" gap between rumbles). Any design of centerline rumble stripes that are smaller than 16" of total rumble width or that deviate from the corrugation cycle detailed in Figures 6 through 8 shall require approval by the State Traffic Engineer.

All rumble strips shall meet any and all specifications for Milled Rumble Strips in the MnDOT Standard Specifications for Construction or Special Provisions. This includes a requirement that rumble strips be milled in bituminous pavement, and not rolled.

The placement of shoulder rumble strips and edgeline rumble stripes with respect to the traveled lane shown in Figures can be deviated from at the discretion of the District.

-MORE-

Modifications for concrete pavement
On concrete paved roadway surfaces, there are two options for how to install shoulder rumble strips. They include:

- Installing 3' long structural rumble strips on alternating panels, and also shoulder rumble strips on the adjacent paved bituminous shoulder. (Refer to Figures 3C, 3D, & 7.)
- Milling in either continuous or intermittent shoulder rumble strips outside the edgeline, but on the concrete surface. (Refer to Figures 3C, 3D and 8.)

The recommended practice for placing centerline rumble stripes on concrete pavement is to install two 8" rumbles on either side of the centerline joint, each 2" away from the joint.

Shoulder rumble strips on Figure 8 and the rumble strips beneath the centerline marking in Figures 7 and 8 may be hand formed in construction, so long as the final dimensions conform to the depth and pattern in the typical drawing of Section B-B in Figure 8, and the appropriate respective width called out in this Technical Memorandum.

Bicycle travel on shoulders
Shoulder widths that provide less than 4 feet of clear space with rumble strips are not considered adequate to accommodate bicyclists. Where practical and feasible, Districts are encouraged to provide a minimum of a 6 foot paved shoulder where shoulder rumble strips will be placed on trunk highways with existing or potentially significant bicycle travel.

In order to meet the needs of bicyclists, flexibility has been built in to this Tech Memo. As stated above and reflected in the attachments, rumble strips as narrow as 8" as well as edgeline rumble stripes may be used at the discretion of the District. Also, while the dimensions in Figures 1 through 4 indicate the typical lateral placement of the shoulder rumble strip, the District has the discretion to deviate from this configuration with input from the State Bicycle Coordinator. Quality control of the lateral placement of rumble strips on these sections must be ensured.

The longitudinal rumble strip pattern for shoulder rumble strips and edgeline rumble stripes on non-freeway segments is to include a 12' gap in each 60' cycle. Refer to Figures 4B and 5B. This remains a standard from the previous two Technical Memoranda that are being combined. Districts may increase the gap from 12' in downhill sections with the approval of the State Traffic Engineer.

Questions
Any questions regarding the technical provisions of this Technical Memorandum can be addressed to the following:

- **Ken Johnson,** State Work Zone and Pavement Marking Engineer, at **(651) 234-7386**

Any questions regarding publication of this Technical Memorandum should be referred to the Design Standards Unit, DesignStandards.DOT@state.mn.us. A link to all active and historical Technical Memoranda can be found at http://techmemos.dot.state.mn.us/techmemo.aspx.

To add, remove, or change your name on the Technical Memoranda mailing list, please visit the web page http://techmemos.dot.state.mn.us/subscribe.aspx

Attachments:
Reference 1
Figures 1-10

-END-

REFERENCE 1: Rural Definition from the MnDOT Access Management Manual

Mn/DOT Access Management Manual

Subcategory A – Rural

This subcategory is intended for trunk highway segments that extend through agricultural, open, or forested areas with limited development. It is also assigned to areas planned for long-term, low-density development, characterized by scattered, large-lot residential development and limited commercial or industrial use. Highway segments outside municipalities are generally designated as Rural (Subcategory A), unless the area is undergoing or planned for urban-scale development. Highways in this subcategory are generally expected to operate at speeds of 50 mph or more; however, in areas lacking a complete supporting local road network, these highways will also be required to provide direct access to adjacent property.

Special attention should be given to transition areas on the fringe of growing municipalities where local zoning may permit urban-type development without corresponding requirements for streets and utilities. Since the private access allowance in Rural (Subcategory A) areas is more permissive than in Urbanizing (Subcategory B) areas, it is important to appropriately categorize these transition areas in order to maintain long-term safety and mobility goals for the corridor.

In some geographically-large municipalities, full urbanization may not be anticipated within the next 20 (or more) years. Highway segments extending through areas of municipalities planned to remain rural in character are designated Rural (Subcategory A).

Figure 2.3 illustrates a municipal area with both a Rural (Subcategory A) segment that extends into an area that is not planned for development and an Urbanizing (Subcategory B) segment that extends into a transition area outside the city's boundary.

Figure 2.3: Category Assignments in a City

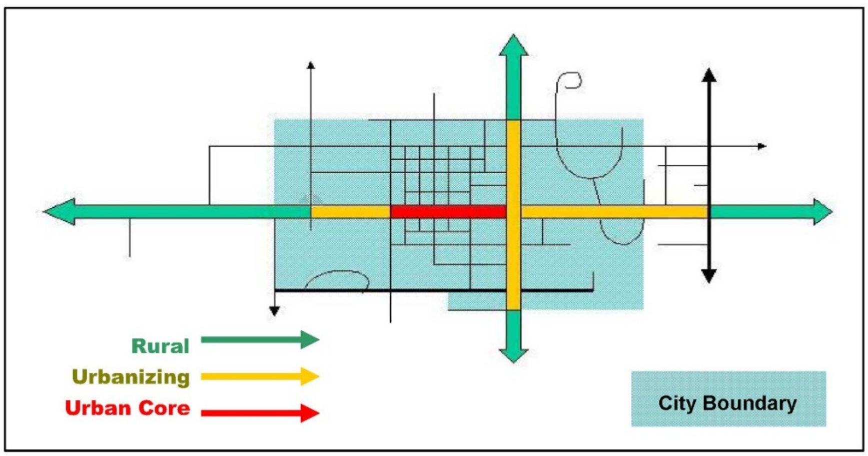
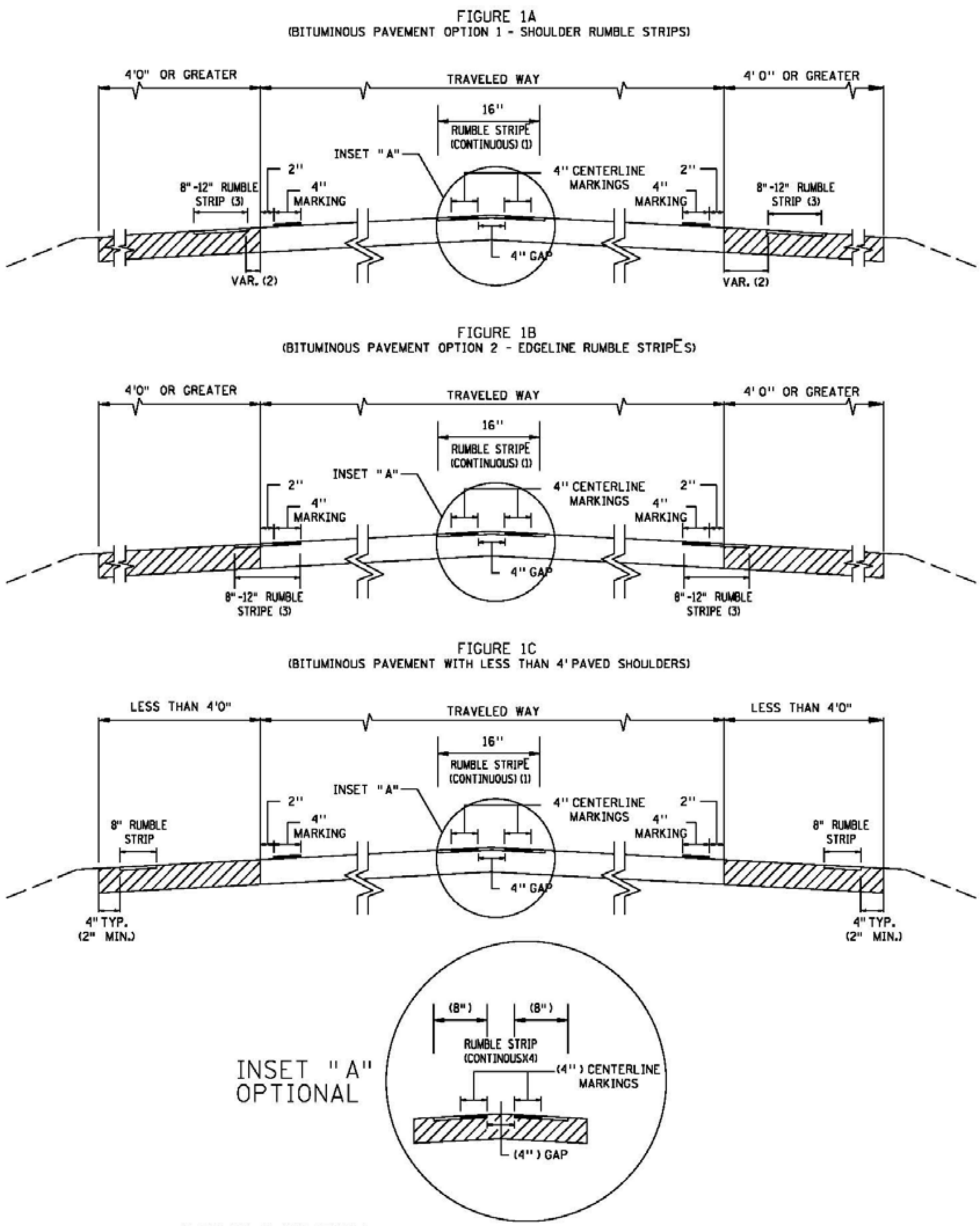


FIGURE 1 - TWO-WAY BITUMINOUS ROADWAY WITH PAVED SHOULDER - SECTION VIEW



(1) SEE FIG. 6A FOR DETAILS.
(2) 2" WHERE SHOULDER WIDTH IS LESS THAN 6'; 12" WHERE SHOULDER WIDTH IS 6' OR GREATER.
(3) INTERMITTENT PATTERN. USE 8" RUMBLE STRIP/STRIPE WHERE SHOULDER WIDTH IS LESS THAN 6'.
(4) SEE FIG. 6B FOR DETAILS.

FIGURE 2 - TWO-WAY CONCRETE ROADWAY WITH PAVED SHOULDER - SECTION VIEW

FIGURE 2A
(CONCRETE PAVEMENT OPTION 1 - STRUCTURAL EDGELINE AND SHOULDER RUMBLE STRIPS)

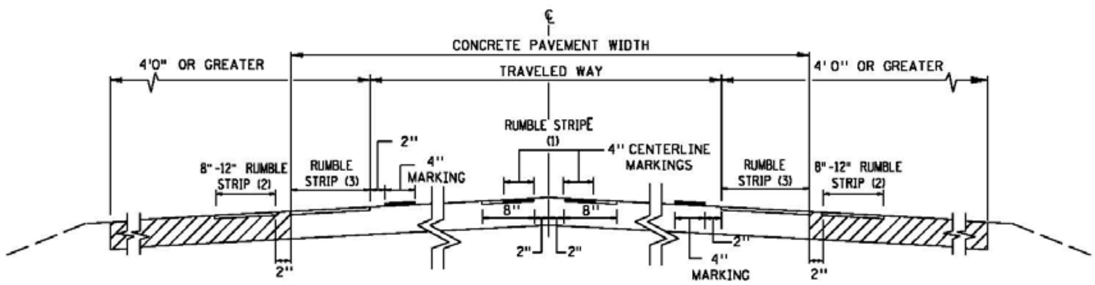


FIGURE 2B
(CONCRETE PAVEMENT OPTION 2 - EDGELINE RUMBLE STRIPEs)

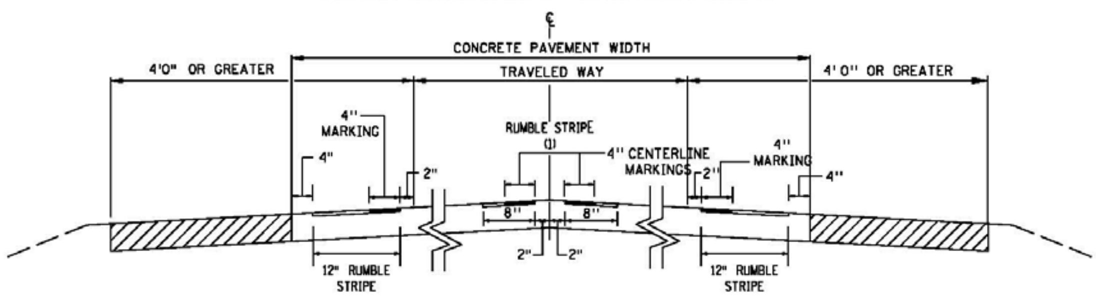
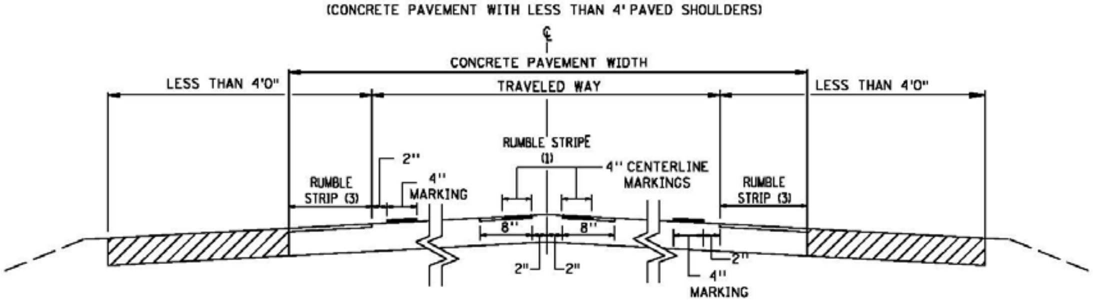


FIGURE 2C
(CONCRETE PAVEMENT WITH LESS THAN 4' PAVED SHOULDERS)



(1) SEE FIGS. 7 AND 8 FOR DETAILS.

(2) USE 8" INTERMITTENT WHERE SHOULDER WIDTH IS EQUAL TO OR GREATER THAN 6' AND LESS THAN 8'.
USE 12" INTERMITTENT WHERE SHOULDER WIDTH IS 8' OR GREATER.
NOT NECESSARY WHERE SHOULDER WIDTH IS LESS THAN 6'.

(3) WHERE SHOULDER WIDTH IS LESS THAN 6' USE GROUND-IN INTERMITTENT OPTION.
STRUCTURAL RUMBLES MAY BE USED IN ALL OTHER CASES.
SEE FIG. 7 AND 8 FOR RUMBLE STRIP OPTIONS, PLACEMENT, AND DIMENSIONS.

FIGURE 3 - SHOULDER RUMBLE STRIP ON DIVIDED ROADWAYS - SECTION VIEW

FIGURE 3A
BITUMINOUS FREEWAY (ONE ROADWAY SHOWN)

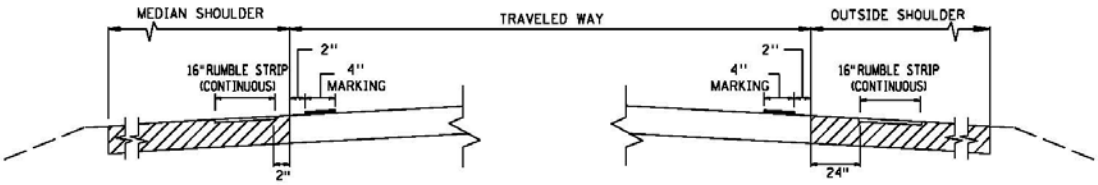


FIGURE 3B
BITUMINOUS MULTI-LANE (ONE ROADWAY SHOWN)

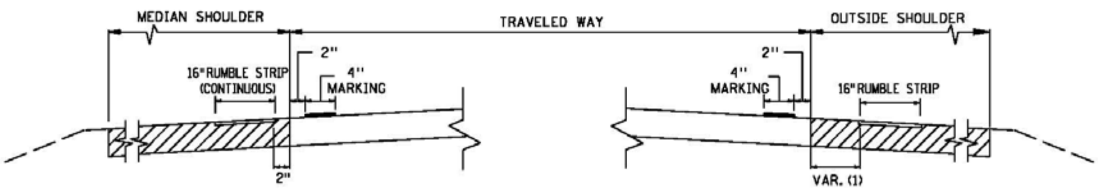


FIGURE 3C
CONCRETE FREEWAY/MULTI-LANE OPTION A (ONE ROADWAY SHOWN)

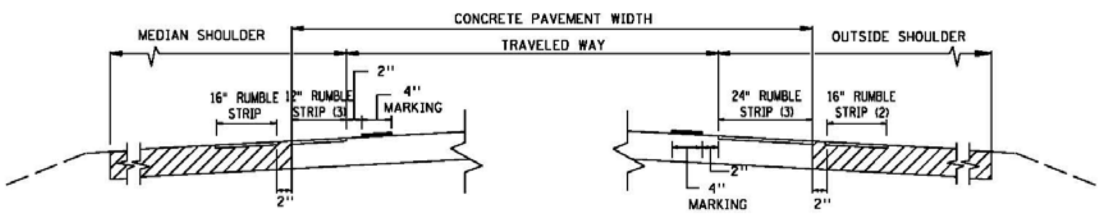
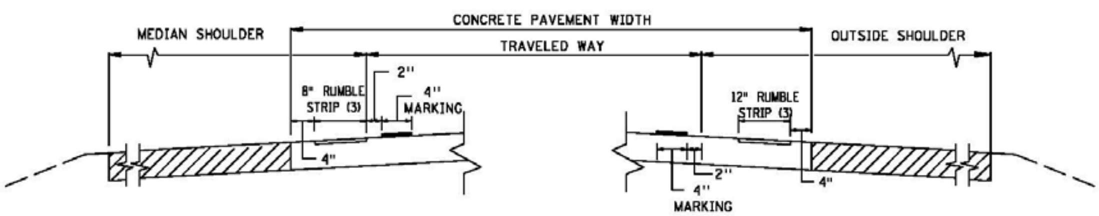


FIGURE 3D
CONCRETE FREEWAY/MULTI-LANE OPTION B (ONE ROADWAY SHOWN)

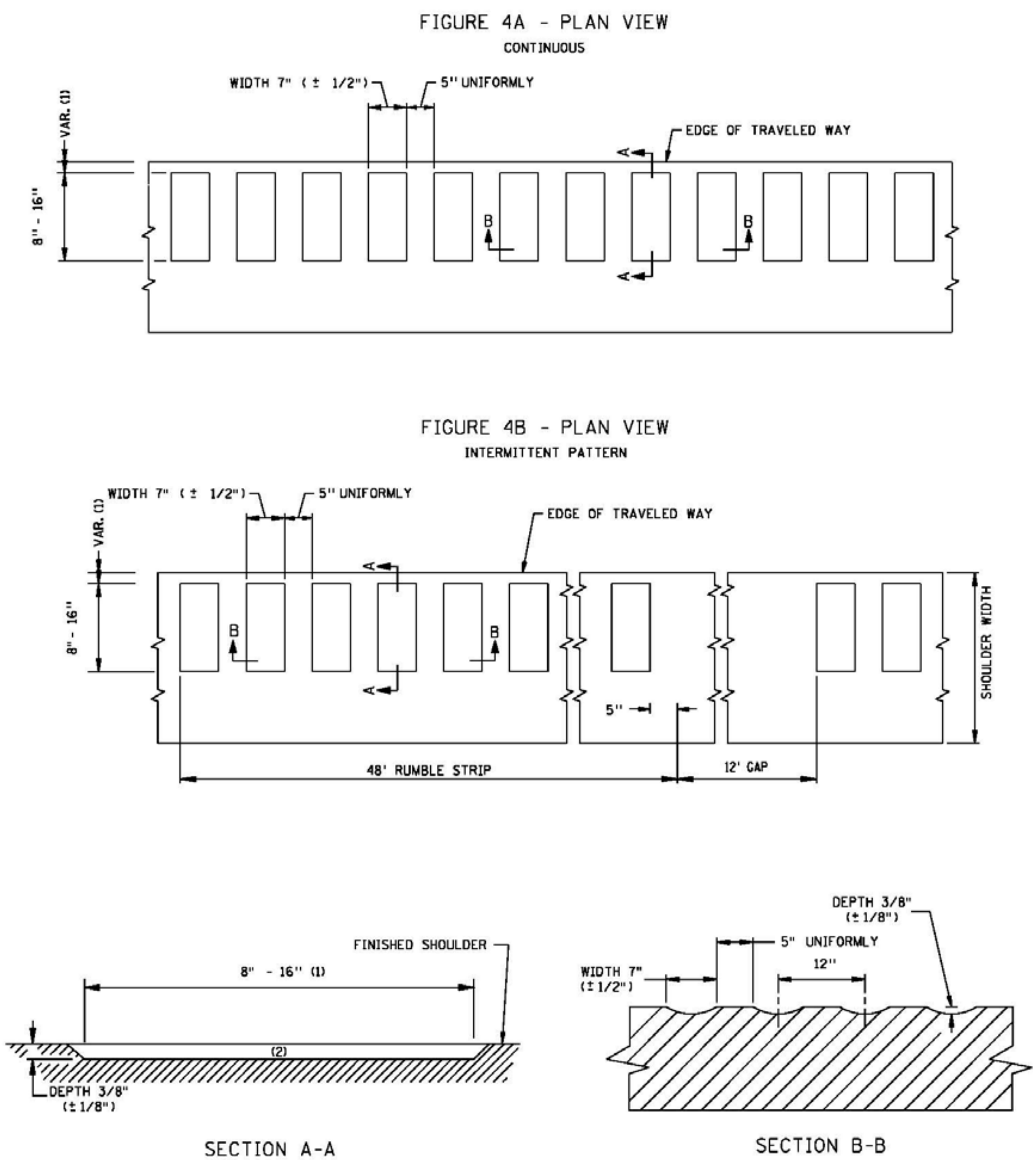


(1) 2" WHERE SHOULDER WIDTH IS LESS THAN 6'; 12" WHERE SHOULDER WIDTH IS 6' OR GREATER.

(2) USE 8" INTERMITTENT WHERE SHOULDER WIDTH IS EQUAL TO OR GREATER THAN 6' AND LESS THAN 8'.
USE 12" INTERMITTENT WHERE SHOULDER WIDTH IS 8' OR GREATER.
USE 16" CONTINUOUS ON FREEWAY.
NOT NECESSARY WHERE SHOULDER WIDTH IS LESS THAN 6'.

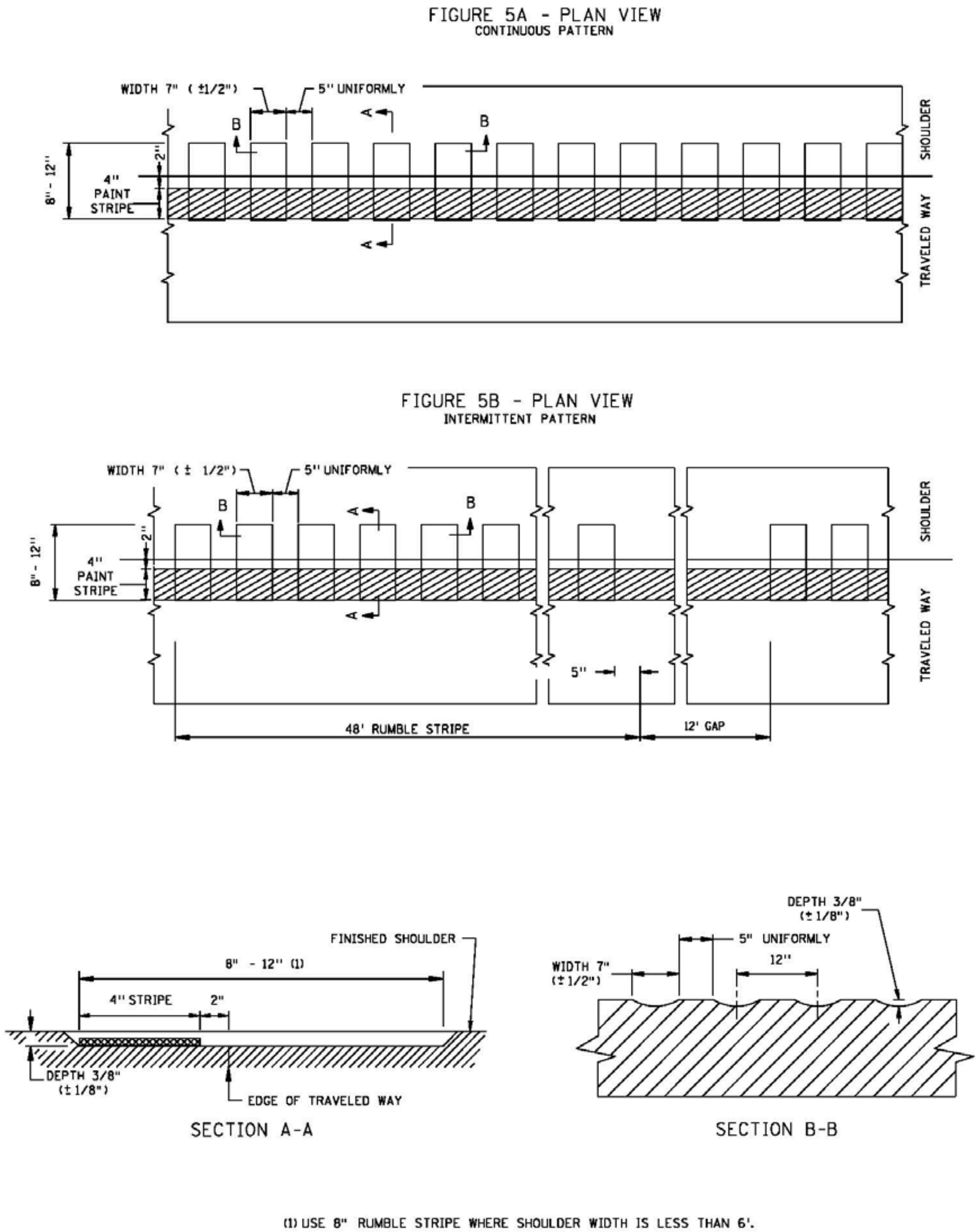
(3) SEE FIG. 7 AND 8 FOR RUMBLE STRIP OPTIONS, PLACEMENT, AND DIMENSIONS.

FIGURE 4 - BITUMINOUS SHOULDER RUMBLE STRIP



(1) REFER TO FIGURES 1 AND 3 FOR SPECIFIC APPLICATIONS.
(2) DEPTH OF RUMBLE SHALL BE UNIFORM.

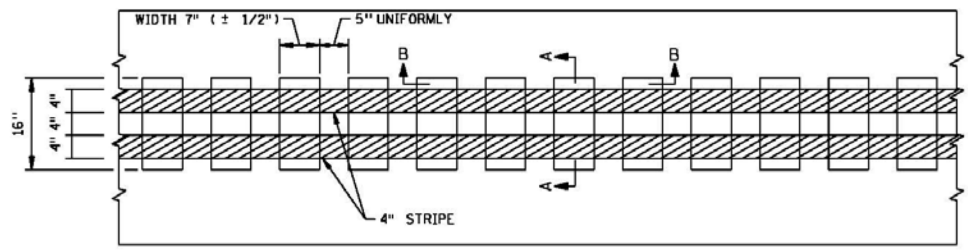
FIGURE 5 - BITUMINOUS EDGELINE RUMBLE STRIPE

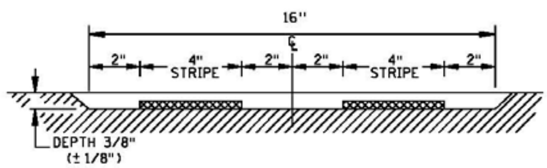


BITUMINOUS CENTERLINE RUMBLE STRIPE - PLAN VIEW

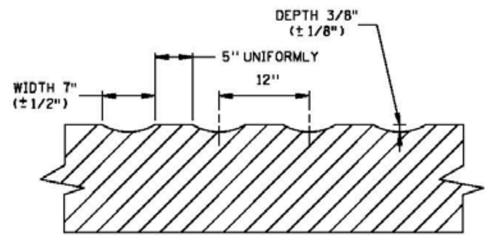
FIGURE 6A

16"





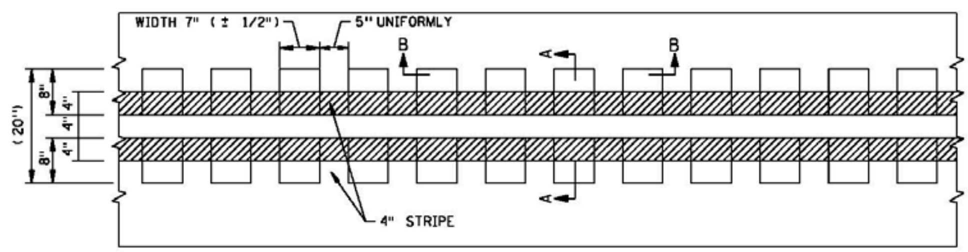
SECTION A-A

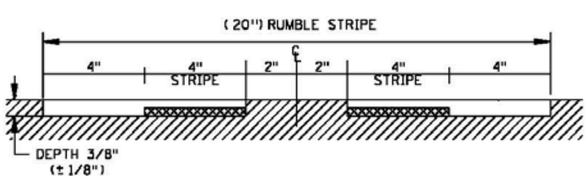


SECTION B-B

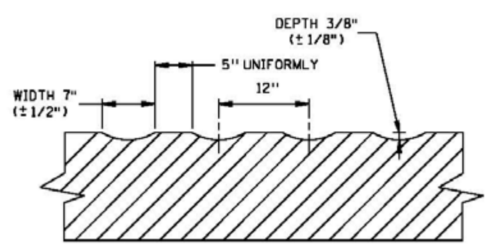
FIGURE 6 B

20"



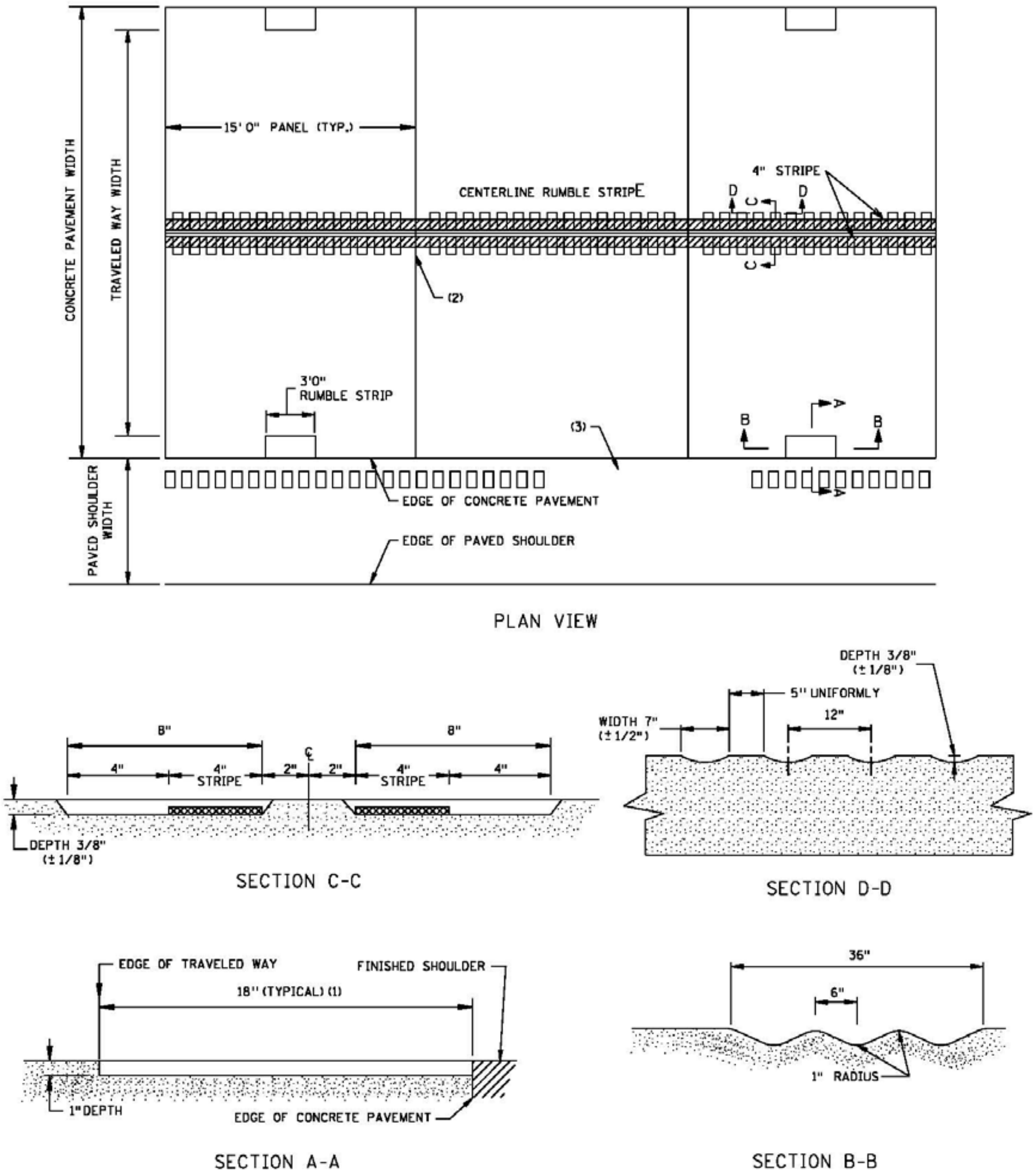


SECTION A-A



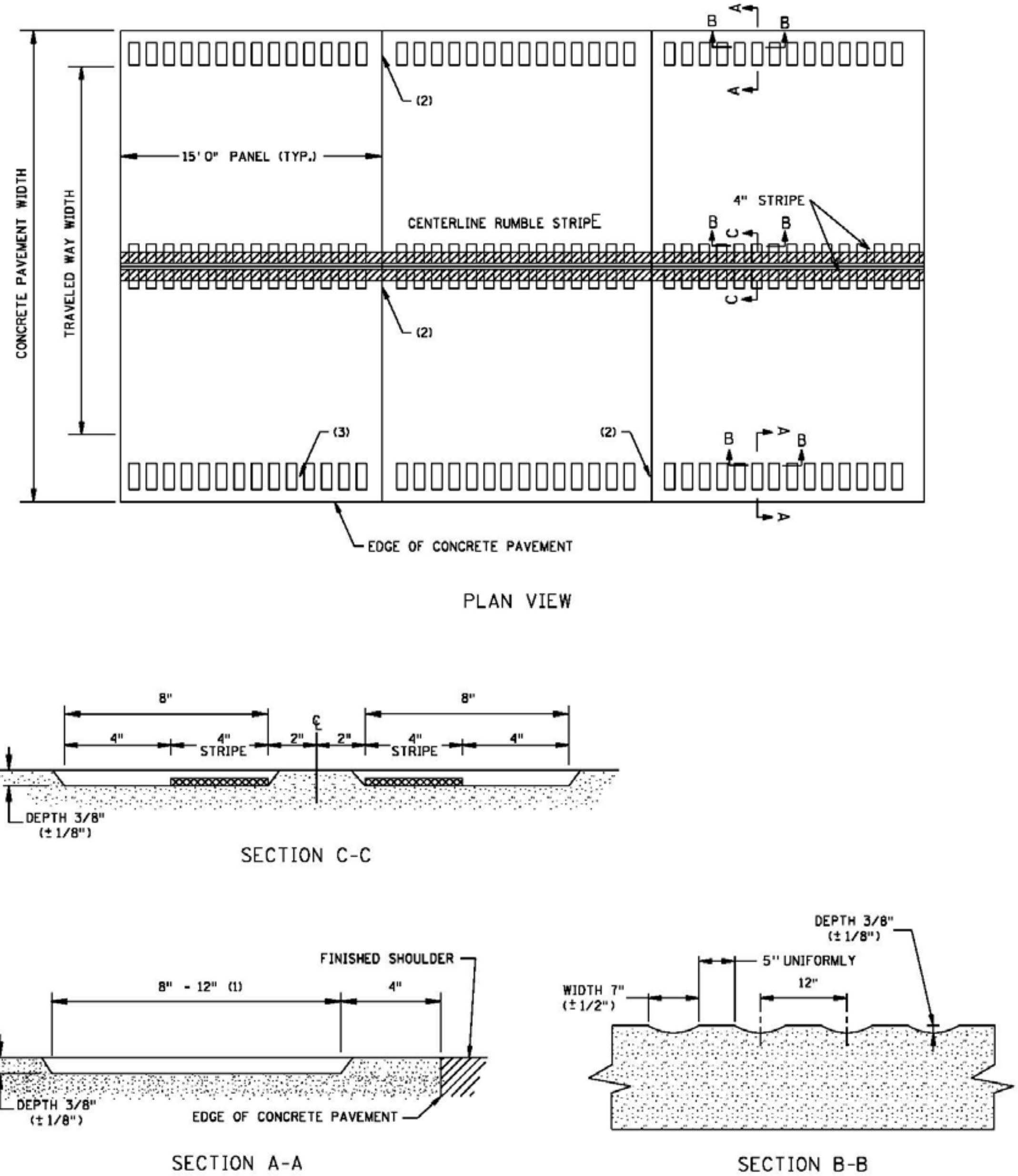
SECTION B-B

FIGURE 7 - CONCRETE PAVEMENT OPTION A - STRUCTURAL RUMBLE STRIP



(1) FOR DIVIDED ROADWAYS USE 1'0" ON INSIDE LANE AND 2'0" ON OUTSIDE LANE.
(2) OMIT ONE CORRUGATION SO THAT THERE IS AT LEAST 6" CLEARANCE ON EITHER SIDE OF TRANSVERSE JOINT.
(3) INTERMITTENT DESIGN SHOWN FOR ILLUSTRATION PURPOSES. REFER TO FIGURE 4B FOR INTERMITTENT PATTERN.

FIGURE 8 - CONCRETE PAVEMENT OPTION B - CONCRETE RUMBLE STRIP



(1) REFER TO FIGURES 2 AND 3 FOR SPECIFIC APPLICATIONS.
(2) OMIT ONE CORRUGATION SO THAT THERE IS AT LEAST 6" CLEARANCE ON EITHER SIDE OF TRANSVERSE JOINT.
(3) CONTINUOUS DESIGN SHOWN FOR ILLUSTRATION PURPOSES. REFER TO FIGURE 4B FOR INTERMITTENT PATTERN.

FIGURE 9 - SHOULDER RUMBLE STRIP - APPROPRIATE BREAKS

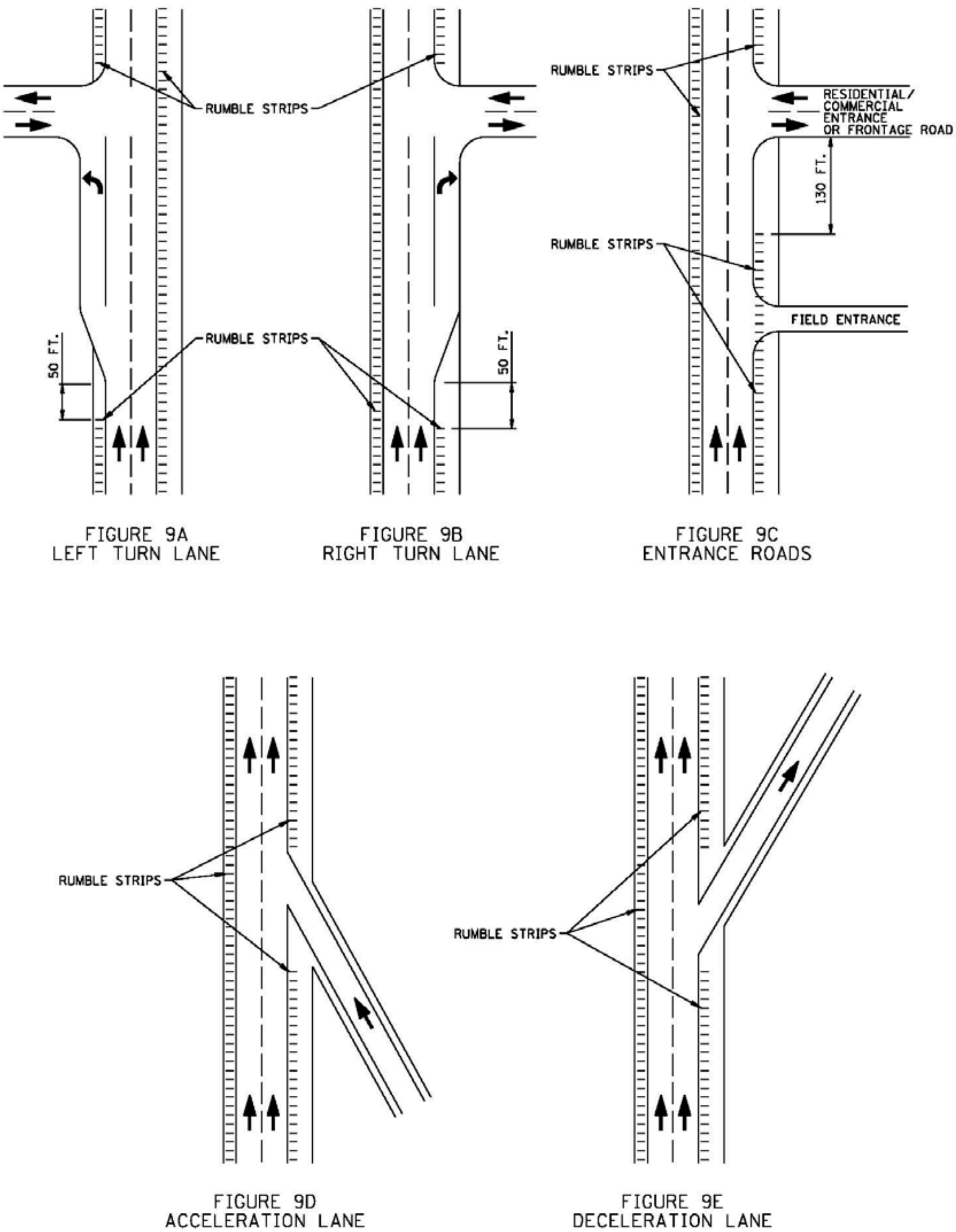
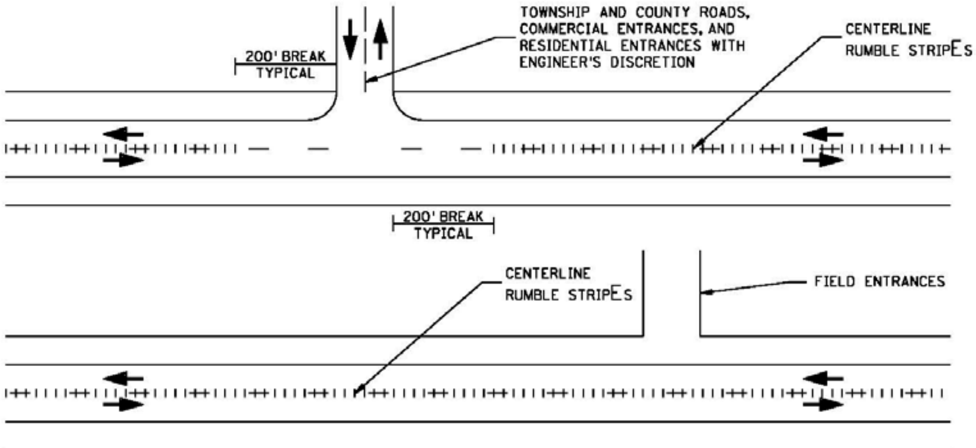


FIGURE 10 - CENTERLINE RUMBLE STRIPE - APPROPRIATE BREAKS (1)



(1) PAVEMENT MARKINGS AND STRIPING SHALL BE COMPLIANT WITH THE CURRENT TRAFFIC ENGINEERING MANUAL (TEM) AND THE CURRENT MINNESOTA MANUAL OF UNIFORM TRAFFIC CONTROL DEVICES (MN/MUTCD)