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Implementation of Retroreflective Pavement Markers (RPMs) in Rumble Strips as a Method to Enhance Driving Conditions After Snowplow Operations

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16. Abstract
The absence of retroreflective raised pavement markers (RRPMs) due to snowplow operations leads to reduced road safety from lower visibility of the centerline and monetary losses from reinstalling the markers before the end of their service life. Multifunctionalization of rumble strips to serve as both a sensory warning to roadway users who have drifted from their lane and an in-situ roadway casing to protect markers from snowplows is a novel solution to address the loss and damage to markers due to winter operations. This implementation project aimed to validate the results of a previous project (0-5665) by determining the rumble strip depth that can provide adequate protection to the markers while also still being visible to road users. Two marker types, low profile, and regular profile markers, were evaluated at seven sites around Texas. The damage to the markers from regular snowplow operations was observed and a human visibility study was conducted to determine the detection distance of markers embedded in rumble strips. The results show that a critical rumble strip depth, which depends on the marker geometry, exists where the marker is safe from snowplows and visible. The results also show the regular-profile markers exceeded TxDOT minimum visibility requirements for all the visibility tests; whereas variable results were obtained for the low-profile markers. Recommendations for implementation of the marker-rumble strip multifunctionalization approach to ensure marker snowplow resistance and visibility are provided.

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Chapter 1. Introduction

1.1. Introduction

Snowplow use in northern Texas results in the loss of retroreflective pavement markers. The loss of these markers creates unsafe driving conditions during inclement weather and causes monetary losses to TxDOT from the continuous need to replace RPMs after every winter cycle. *TxDOT Research Project 0-6995-Determine Use of Alternative Retroreflective Pavement Markers (RPMs) on Highways with Centerline Rumble Strips and Winter Weather Pavement Marking Improvements* showed that rumble strips can be used in a multi-functional way to provide not only sound awareness but also protect the retroreflective pavement markers from snowplows.

This implementation project builds upon the findings of the original research project to validate the visibility results of the markers to *(i)* confirm the long-term performance of the markers in rumble strips and *(ii)* determine embedded RPM detection at different distances and vehicle speeds.

1.2. Project 0-6995 Findings Summary

The main findings and recommendations from the *Research Project 0-6995-Determine Use of Alternative Retroreflective Pavement Markers (RPMs) on Highways with Centerline Rumble Strips and Winter Weather Pavement Marking Improvements* were:

- Embedding commercially available markers into rumble strips effectively reduced RPM loss and damage during snowplow operations.
- Epoxy and bitumen were suitable adhesives for embedding commercially available markers into rumble strips. However, bitumen adhesive was recommended due to the lower cost, ease of installation, and lesser setup time.
- Quality control of the depth of the rumble strip groove was important as this impacted both the visibility and snowplow resistance.
- Low-profile markers showed a better ability to withstand snowplows as compared to regular-profile markers; however, regular-profile markers exhibited better nighttime visibility than low-profile markers.
- Stimsonite C40 performed best out of the low-profile markers evaluated and 3M 290 performed best out of the regular-profile markers evaluated.

- Simulations showed embedding markers in rumble strips reduced marker visibility by 43-67% compared to surface-mounted markers, however, the retroreflectivity still exceeded minimum visibility requirements as per ASTM D4280 [1].
- The quantitative and qualitative assessments showed that there was still significant retroreflectivity for nighttime centerline delineation under field conditions, with the markers being visible at over 900 feet by the naked eye of a driver.
- Almost all the surface-mounted markers were lost after snowplow operations, whereas the majority of markers embedded in the rumble strips survived after snowplow operations.

In conclusion, it was noted that while there was a loss in retroreflectivity of the markers embedded in rumble strips there was a lesser loss in markers after snowplow activities were conducted when compared to the conventional surface markers. This meant that the markers embedded in the rumble strips were still available to help delineate the centerline albeit with a lower retroreflectivity, whereas the surface markers were entirely lost.

1.3. Goals

The major goals of this research work were to validate the findings of the original *Research Project 0-6995* and provide recommendations to TxDOT on the optimum marker and rumble strip geometry for snowplow resistance. Two aspects were evaluated in this study:

- Snowplow resistance of the markers embedded in the rumble strips by observing their long-term performance in field conditions.
- Visibility verification of the markers embedded in rumble strips by conducting human visibility studies.

Based on these two aspects, a critical value for the rumble strip depth was determined. This critical value is defined as the depth of a rumble strip in which an embedded marker will have a high likelihood of surviving a snowplow event while also fulfilling minimum visibility requirements.

1.4. Scope of Work

This study involves the observation and collection of data from in-service highway sites as well as one research site. Thus, data collection and analysis were subject to material, logistical, financial, and accessibility constraints.

- Snowplow operations are an inexact process with variability arising from weather conditions, operator behavior, etc. Oftentimes, the exact information, such as the number of times snowplow operations were conducted, the type of snowplow used at the test segments, etc., was not recorded by TxDOT. As such, the research team operated on information provided by the receiving agency on how and when the snowplow operations were conducted.
- The optimal rumble strip and marker geometry recommendations are provided based on the data collected from the six highway sites before and after snowplow operations were conducted. At some sites, snowplow operations were not conducted fully, therefore these sites were not included during the data analysis.
- The nighttime visibility of the markers embedded in the rumble strips was evaluated using human participants recruited from among the general public, and individuals from the receiving and performing agencies. All observations were self-reported by the participants.
- As the visibility study was conducted at nighttime and in a remote location in the case of the highway site at US 180, Anson, there were limitations in the rumble strip geometry being evaluated due to participant availability and logistics. This was compensated by conducting a follow-up study at the research site by examining a wider range of rumble strip geometries.

1.5. Report Organization

This report presents the major activities and key findings from this project. It is organized as follows:

- Chapter 2 discusses the sites selected for this project. Four new highway sites were identified, in addition to the two highway sites from the original *Research Project 0-6995*.
- Chapter 3 focuses on the installation of the markers at the sites discussed in Chapter 2. The best-performing markers of each type (low and regular-profile) from the original *Research Project 0-6995* were selected and embedded in rumble strips.
- Chapter 4 presents the results of the site evaluation of the markers embedded in rumble strips at the highway sites. Marker and rumble strip geometries were measured before snowplow operations were conducted to establish a baseline.
- Chapter 5 presents the results of the snowplow resistance of the markers embedded in the rumble strips at the highway sites. The research team visited the highway sites after snowplow operations were conducted. The

condition of the embedded markers was evaluated, and the geometries were verified. Analysis was conducted to determine the minimum rumble strip depth at which the markers had a high survival rate.

- Chapter 6 presents the results of a nighttime visibility study conducted to verify the visibility of the retroreflective pavement markers embedded in rumble strips at the minimum depth for snowplow resistance. Human road users were recruited to participate in the nighttime visibility study to provide their observations on the markers embedded in the rumble strips. Ad additional study was conducted to determine the maximum depth up to which the marker would be visible to road users.
- Chapter 7 presents the summary of the work conducted and the conclusions drawn. Recommendations on the optimum rumble strip depths and marker types for snowplow resistance are also provided.

Chapter 2. Site Selection

2.1. Overview

This chapter presents a summary of the sites used in this implementation study. Four new highway sites were selected along with two highway sites and one research site from the original *Research Project 0-6995*. In total six highway sites and one research site were selected for this implementation study.

2.2. Overview of Project Sites

Six highway sites in North Texas and one site at the Pickle Research Campus were evaluated as part of the study. Of these sites, four of the sites are new highway sites specifically selected for this project (see Figure 2.1a), whereas two of the highway sites were from *Research Project 0-6995* (see Figure 2.1b). In addition, the research field test site at the Performing Agency's Pickle Research Campus (PRC) which was also used in the original project was used to conduct part of the visibility study (see Figure 2.1c). Site II (US 180, Anson) was also part of the visibility study.

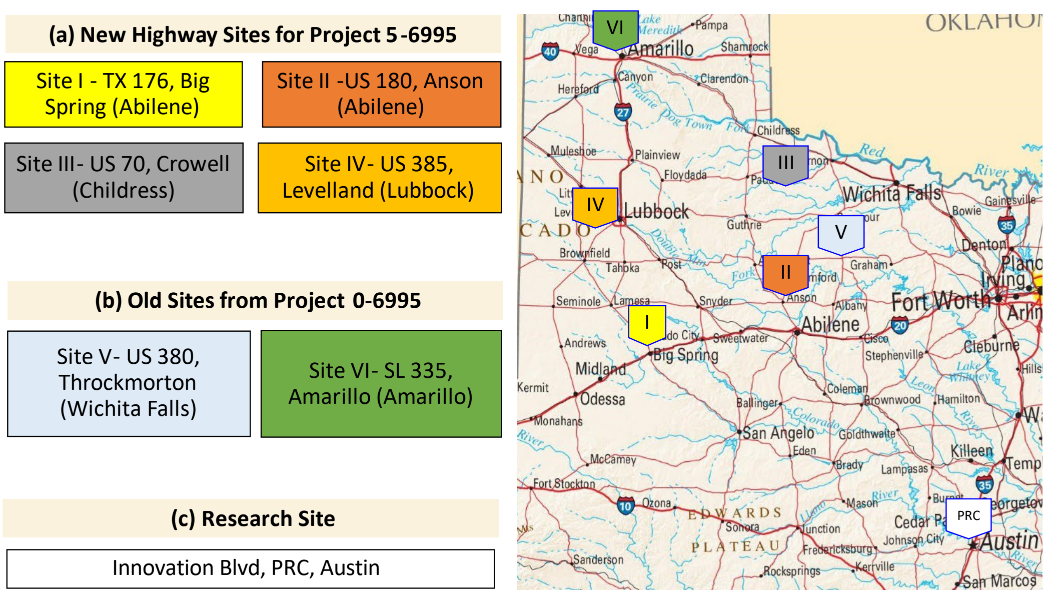


Figure 2.1: Locations of Highway Sites Selected for the Research Project

2.2.1. Identification of New Sites for Project 5-6995

In consultation with the Receiving Agency, four two-lane two-way highway sites were identified (Sites I, II, III, and IV). The sites were selected based on the following selection criteria:

- Location: the site must lie in areas that have a history of snowfall events and have a history of loss and damage to the markers due to snowplow operations.
- The number of lanes: the site must have at least 2 lanes (one lane in each direction) for installation of markers along the centerline.
- Average annual daily traffic (AADT) of 200-8000 with truck traffic was preferred as installation of markers along the centerline of high traffic density areas with truck traffic results in high wear and tear [2]. Medium traffic density areas were selected to observe the effect of snowplow operations on the markers.
- A speed limit of at least 55mph as markers are commonly installed in areas that have higher speed limits which require higher long-range information than at lower speed limits [2].

2.2.1.1. Site I (TX 176, Big Spring)

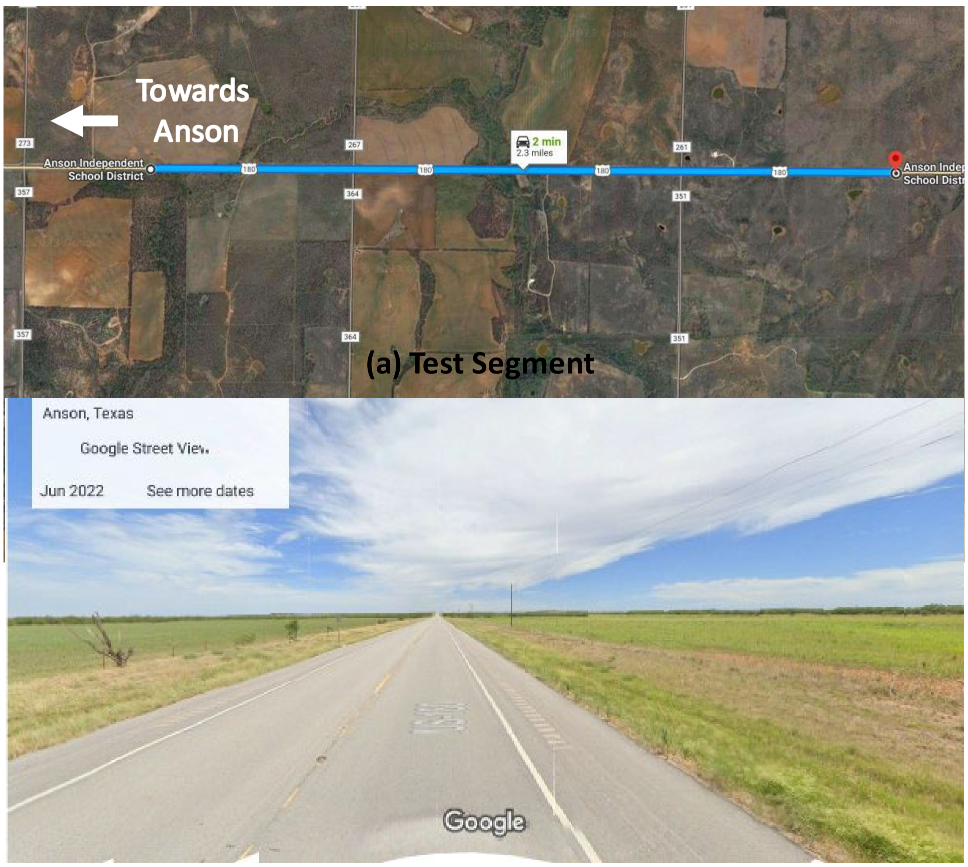
TX 176 is a two-way highway with two lanes located west of Big Spring in the Abilene district (see Figure 2.2a). This site has the highest annual daily traffic of all sites at 3000-5800, with a 25-32% truck population. The site is paved with asphalt and has both solid and broken pavement striping (see Figure 2.2b). As per information received from the receiving agency, this location lost almost 75% of the surface-mounted markers during winter 2021. This district mostly uses a full-scale snowplow with carbide blades and maintainers with steel blades.

(b) Street View

Figure 2.2: Site I at TX 176, Big Spring (Image Source: Google Maps, Accessed 01-07-23)

2.2.1.2. Site II (US 180, Anson)

US 180 is a two-way highway with two lanes located east of Anson in the Abilene district (see Figure 2.3a) with a moderate annual daily traffic of 700-1150 with a 27% truck population. The site is paved with asphalt and has both solid and broken pavement striping (see Figure 2.3b). As per information received from the receiving agency, this location lost almost 75% of the surface-mounted markers during winter 2021. This district mostly uses a full-scale snowplow with carbide blades and maintainers with steel blades.



(b) Street View

Figure 2.3: Site II at US 180, Anson (Image Source: Google Maps, Accessed 01-07-23)

2.2.1.3. Site III (US 70, Crowell)

US 70 is a two-way highway with two lanes located west of Crowell in the Childress district (see Figure 2.4a) with the lowest annual daily traffic of 230-650 with a 46-58% truck population. The site is paved with asphalt and has both solid and broken pavement striping (see Figure 2.4b). This district mostly uses a full-scale snowplow with carbide blades.

(b) Street View

Figure 2.4: Site III at US 70, Crowell (Image Source: Google Maps, Accessed 01-07-23)

2.2.1.4. Site IV (US 385, Levelland)

US 385 is a two-way highway with four lanes located south of Levelland in the Lubbock district (see Figure 2.5a) with moderate annual daily traffic of 1000-2500 and 24-35% truck population. The site is paved with asphalt and has both solid and broken pavement striping (see Figure 2.5b). The pavement at this site was 15 months old and had surface-mounted markers installed. This district mostly uses a full-scale snowplow with steel blades.

(b) Street View

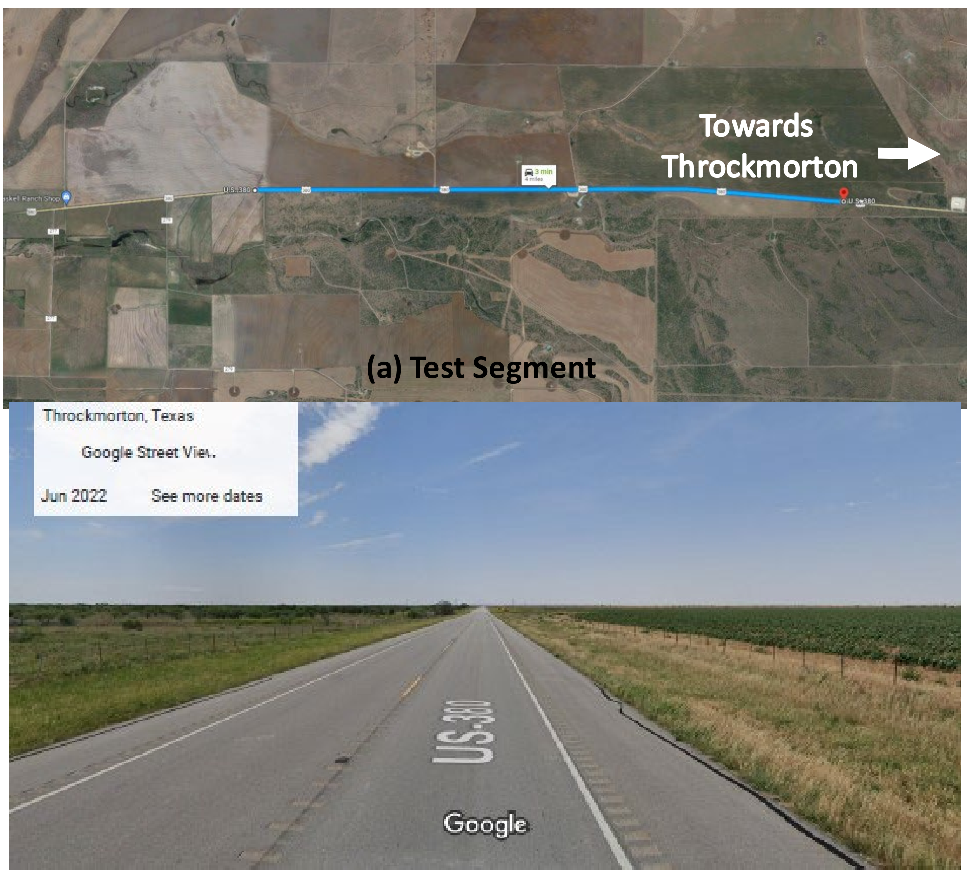
Figure 2.5: Site IV at US 385, Levelland (Image Source: Google Maps, Accessed 01-07-23)

2.2.2. Old Sites from TxDOT Project 0-6995

As part of the original *Research Project 0-6995*, two-lane highway segments were selected for the installation and evaluation of markers embedded in rumble strips. These two sites (Sites V and VI) also continued to be evaluated as part of this project.

2.2.2.1. Site V (US 380, Throckmorton)

US 380 is a two-way highway with two lanes (see Figure 2.6a) located west of Throckmorton in the Wichita Falls district with moderate annual daily traffic of 1078 and 16.9% truck population. The site is paved with asphalt and has both solid and broken pavement striping (see Figure 2.6b). The pavement surface at this site was not recently resurfaced and had deeper rumble strips than specified in TXDOT standard [3]. This site usually uses full-scale snowplows with carbide blades and maintainers with steel blades occasionally.



(b) Street View

Figure 2.6: Site V at US 380, Throckmorton (Image Source: Google Maps, Accessed 01-07-23)

2.2.2.2. Site VI (SL 335, Amarillo)

SL 335 is a two-way highway with two lanes located south of Amarillo in the Amarillo district (see Figure 2.7a) with high annual daily traffic of 8000-26000 and a 6% truck population. The site is paved with asphalt and has both solid and broken pavement striping (see Figure 2.6b). The pavement surface at this site was recently resurfaced before the installation of the rumble strips and thus had shallower rumble strips when compared to the TXDOT standard [3]. This district mainly uses maintainers with steel blades at this location.

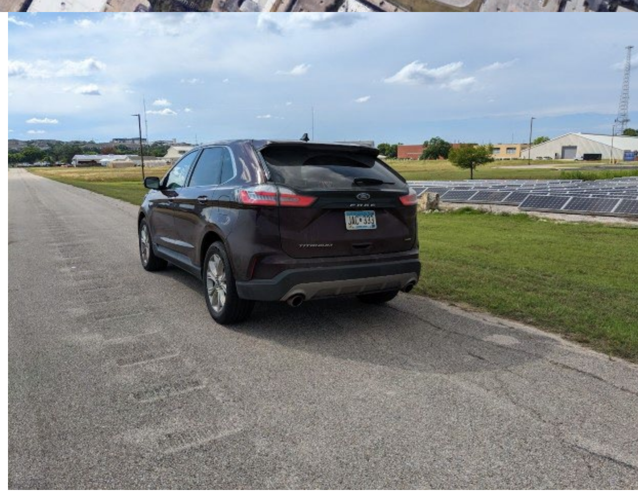
(b) Street View

Figure 2.7: Site VI at SL 335, Amarillo (Image Source: Google Maps, Accessed 01-07-23)

2.2.3. Research Site (PRC, Austin)

The research site is an 800 ft test segment located at Innovation Blvd, Pickle Research Campus, Austin, at the Performing Agency's research campus. As shown in Figure 2.8a, the section lies between a dead-end (Intersection 1) and a 4-way intersection (Intersection 2). The distance between the intersections is 1250 ft. The centerline of the segment has rumble strips cut into it (see Figure 2.8b). This site has no centerline pavement striping.

(a) Test Segment (Image Source: Google Maps, Accessed 01 -07-23)



(b) Photograph of Research Test Segment (Image by Authors)

Figure 2.8: Research Site at Innovation Blvd, Pickle Research Campus, Austin

2.3. Summary

Table 2.1 presents a summary of the sites selected for this study including the new sites (I-IV) selected, old sites (V and VI) from *Research Project 0-6995*, and the research site at PRC, Austin. Site VI is located furthest north while Site I is located furthest south among the highway sites. Site VI has the highest AADT, but the lowest truck traffic, whereas Site III has the lowest AADT, but the highest truck traffic. Most sites use full-scale snow-plows with carbide blades. Carbide blades are harder and have sharper cutting edges than steel or rubber blades and are thus more likely to damage markers. The maintainer-type snowplows have lighter and smaller blades made of steel.

Table 2.1: Summary of Sites Selected for Study

Site	Highway/Location	District	AADT	% Truck	Snowplow
Site I	Tx 176, Big Spring	Abilene	3000 – 5800	25% - 32%	Full-scale with carbide blades
Site II	US 180, Anson	Abilene	700 – 1150	27%	Full-scale with carbide blades
Site III	US 70, Crowell	Childress	230 – 560	46% - 58%	Full-scale with carbide blades
Site IV	US 385, Levelland	Lubbock	1000 – 2500	24% - 33%	Full-scale with steel blades
Site V	US 380, Throckmorton	Wichita Falls	1078	16.9%	Full-scale with carbide blades
Site VI	SL 335, Randall	Amarillo	8000	6%	Maintainer with steel blades
Research Site A*	Innovation Blvd, PRC, Austin	N/A	N/A	N/A	N/A
*This is a test segment located at the performing agency's research campus					

Chapter 3. Installation of Markers

3.1. Overview

This chapter discusses the selection of markers and their embedment in the rumble strips at the new sites selected for *Implementation Project 5-6995-01* (Sites I-IV). A review of the data from the original research project was conducted, and the best-performing markers were selected.

3.2. Selection of Markers

The markers are classified into two general groups, low-profile and regular-profile markers. Low-profile markers are smaller in width, length, and height than regular-profile markers. This allows them to be embedded deeper in the rumble strips providing them with improved safety, but also have lesser visibility than the regular-profile markers. However, the regular-profile markers have a larger bonding area due to their larger size when compared to the low-profile markers. This allows them to have better visibility and better bonding to the pavement surface than the low-profile markers. Three different markers were used in this implementation project, one low-profile-marker (LP1) and two regular-profile markers (RP1 and RP2):

- LP1 is Stimsonite Model C40 markers manufactured by Ennis Flint (see Figure 3.1a) [4].
- RP1 is Model 290 markers manufactured by 3M (see Figure 3.1b) [5].
- RP2 is Stimsonite Model C80 markers manufactured by Ennis Flint (see Figure 3.1c) [6].

LP1 and RP1 were selected for this implementation project based on the market findings of the original *Research Project 0-6995* [7], which showed that these two markers performed the best within their class in terms or retroreflectivity and snow plow resistance. RP2 was used in this study due to scheduling purposes at one of the sites. Table 3.1 summarizes the geometry of the markers. RP2 is slightly longer than RP1 and is taller than RP1 by 2 mm. RP1 is taller than LP1 by 5 mm (see Figure 3.2). As such, for RP1 and RP2 the depth of the rumble strip would need to be deeper than for LP1 to adequately protect them from snowplows. Table 3.1 also provides the retroreflectivity of the markers as measured on the field as per ASTM E1710 [8] in the *Research Project 0-6995* [7]. At 100 ft (30 m), LP1 and RP1 markers have a retroreflectivity of 5.2 and 8.1 mcd/lx respectively. RP1 has a greater retroreflectivity than LP1 which would indicate that it would be easier to detect these markers at night. RP2 does not have a retroreflectivity value as this marker type was not installed on the field during *Research Project 0-6995*.

Table 3.1: Selected Marker Information

Marker	Dimensions			Slope of Lens	Retroreflectivity
	Length	Width	Height		
LP1	3.96 in (10.1 cm)	1.91 in (4.9 cm)	0.48 in (1.1 cm)	35º to base	5.2 mcd/lx at 100 ft (30m)
RP1	4 in (10.2 cm)	3.51in (8.9 cm)	0.625 in (1.6 cm)	30º to base	8.1 mcd/lx at 100 ft (30m)
RP2	4.55 in (11.6 cm)	3.2 in (8.1 cm)	0.66 in (1.8 cm)	35º to base	N/A*

*Measurement was not conducted as this marker was not in the original test plan.

400 markers of both the LP1 and RP1 markers were delivered to the TxDOT offices in Abilene and Mundane from the manufacturers (Ennis Flint and 3M), with the intention that 100 of each marker would be installed at the four highway sites (Sites I-IV). TEnnis Flint delivered the markers in mid-November 2021 and 3M delivered the markers in late November 2021. However, at Site III (US70, Crowell) the annual marker replacement was scheduled for early November by TxDOT which was before the delivery of the preferred markers. As a result, all sites except for Site III (US70, Crowell) had 100 LP1 and 100 RP1 markers installed. At Site III (US70, Crowell) 102 RP2 markers were procured by the contractor.

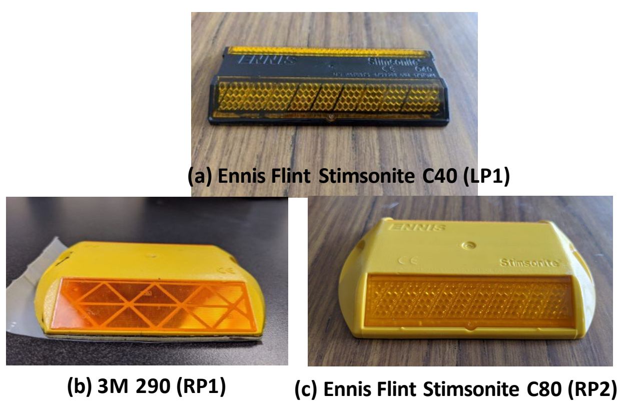


Figure 3.1: Markers Deployed in Project 5-6995

Figure 3.2: Height of Markers

3.3. Embedment of Markers in Rumble Strips

The research team developed an embedded marker installation guide (see Appendix A) and provided it to TxDOT. The installation guide contained information about installation sequence, spacing, and procedures for embedding the markers in rumble strips and was developed to facilitate uniform and consistent embedment of markers in rumble strips across the highway sites. Figure 3.3 shows a schematic of a typical marker after rumble strip embedment in (a) plan and (b) section views. In general, the embedment process consists of placing a bitumen adhesive in a rumble strip, after which the marker is placed on the bitumen and pushed down until the marker bottoms out (the marker sits in the deepest part of the rumble strip).

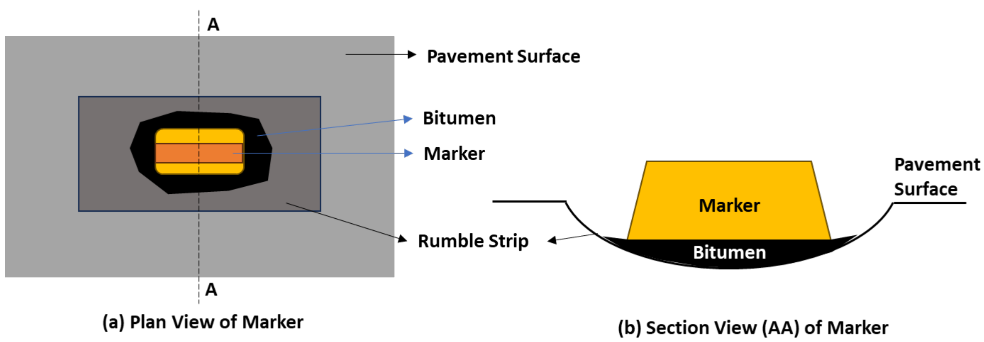


Figure 3.3: Installation of Markers at Highway Sites I-IV by Embedding in Rumble Strips

The markers were installed at the test sites by contractors under the guidance of Abilene District TxDOT Engineers. Around 100 markers each of both types (low and regular-profile) were to be placed according to the installation guide at each of the four sites. LP1 and RP1 markers were installed at Site I (TX 176, Big Spring) in early December 2021, at Site II (US 180, Anson) in late November 2021, and at Site IV (US 385, Levelland) in late December. At Site III (US 70, Crowell) RP2 markers were installed in early November 2021. This was due to the contractor for this district scheduling marker installation before the shipment of the preferred markers arrived at Site III. Thus, only 100 RP2 regular-profile markers were installed at this site. Figure 3.4 shows typical examples of the three marker types evaluated in this study (a) low-profile LP1 marker (b) regular-profile RP1 marker, and (c) regular-profile RP2 markers.

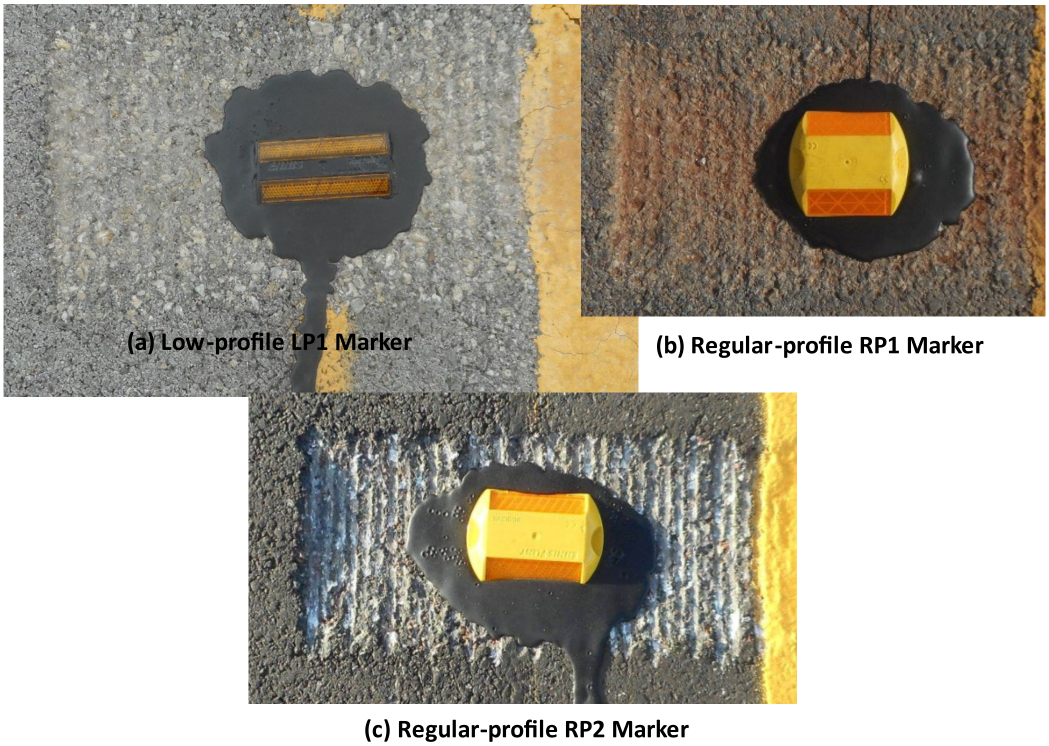


Figure 3.4: Markers Installed at Highway Sites

3.4. Summary

500 markers were installed across the four new implementation sites (I-IV) by embedding them in rumble strips. Two types of markers were installed, low and regular-profile, based on the installation guide provided by the research team. At Sites I, II, and IV, approximately 100 of each type of low-profile LP1 and regular-profile RP1 markers were installed. At Site III, due to contractor constraints, 100 regular-profile RP2 markers were installed. This was done to ensure the uniformity of markers embedded in rumble strips. The installation was done by TxDOT-approved contractors under supervision by TxDOT engineers.

Table 3.2: Summary of Markers Installed at Highway Sites

Site	Orientation of Site	Length of Test Segment	Type of Marker	Number of Markers Installed	Location Coordinates	
					Start	End
Site I – TX 176 (Big Spring in Howard County)	West to East	1.6 miles	LP1	92	32.264334, -101.532124	32.263323, -101.519384
			RP1	95	32.263144, -101.518121	32.261438, -101.505617
Site II – US 180 (Anson in Jones County)	West to East	1 mile	LP1	95	32.750976, -99.776210	32.750944, -99.752288
			RP1	98	32.750782, -99.750626	32.750777, -99.737031
Site III – US 70 (Crowell in Foard County)	East to West	1.6 miles	RP2	102	34.032051, -99.933783	34.040362, -99.948578
Site IV - US 385 (Levelland in Hockley County)	South to North	2 miles	LP1	93	33.497927, -102.375685	33.509721, -102.375539
			RP1	100	33.510923, -102.375537	33.521840, -102.375374
Site V - US 380 (Throckmorton in Wichita Falls County)*	West to East	1.8 miles	LP1	200	33.184022, -99.428574	33.182761, -99.402982
			RP1	100	33.183849, -99.471473	33.183905, -99.445617
Site VI – SL 335 (Amarillo in Randall County)*	West to East	2.9 miles	LP1	97	35.120678, -101.792959	35.120719, -101.792993
			RP1	60	35.126200, -101.757350	35.133432, -101.745807

* Sites from *Research Project 0-6995*

Chapter 4. Site Surveys

4.1. Overview

This chapter discusses the initial evaluation of the markers embedded in the rumble strips at the highway sites. Geometric information on the rumble strips and markers was collected to establish a baseline condition for the markers before undergoing snowplow operations. This was done by visiting the sites after markers were embedded in rumble strips to determine the rumble strip depth and marker protruding height. The initial conditions were established by taking photographs of the markers and conducting a qualitative nighttime visibility assessment under static and dynamic conditions.

4.2. Site Evaluations

Before the markers were exposed to snowplow operations, the research team visited each site after receiving confirmation from TxDOT that the markers were installed. Table 4.1 presents the dates the field surveys were conducted at each site before snowplow operations. Two dates are mentioned for Site IV as inclement weather necessitated the initial site visit to be cancelled mid-trip. Thus, the site was visited again the following month to complete the evaluations. All site visits were conducted with traffic control provided by Barricades Unlimited [9] to ensure the safety of the research team. Traffic control consisted of placing warning signage for motorists before entering the test site area, truck-mounted attenuators at the ends of the test area, a pilot car to guide traffic across the test area, and cones to cordon off the centerline and a lane for the team to conduct research activities.

Table 4.1: Field Visit Dates

Sites	Field Visit Dates
Site I (TX 176, Big)	03/04/2022
Site II (US 180, Anson)	12/17/2021
Site III (US 70, Crowell)	12/16/2021
Site IV (US 385, Levelland)	02/02/2022 and 03/03/2022
Site V (US 380, Throckmorton)	03/11/2021
Site VI (SL 335, Amarillo)	05/06/2021

4.3. Experimental Methods

Research Project 0-6995 findings revealed that the depth of the rumble strips in which the markers were embedded played an important factor in impacting their retroreflectivity and snowplow resistance. Specifically, markers embedded in deeper rumble strips at Site V had a higher survival rate than the markers embedded at Site VI which had shallower rumble strips (see Table 4.2). It was also qualitatively estimated by the research team that the markers at Site VI were more visible during nighttime conditions than the markers at Site V [7].

Table 4.2: Marker Survival Rates at the Original Highway Sites

Site	Rumble Strip Depth	Marker Type	Survival Rate
Site V (US 380, Throckmorton)	16.35 mm	Low-profile LP1	100%
		Regular-profile RP1	95%
Site VI (SL 335, Amarillo)	5.73 mm	Low-profile LP1	83%
		Regular-profile RP1	42%

Armed with these findings, the research team conducted pre-snowplow site evaluations at the highway sites and collected the following information:

- Number and types of markers installed at each site
- Protruding height of the marker embedded in the rumble strip, i.e., the height of the marker above the pavement surface
- Depth of each test rumble strip with an embedded marker
- A photograph of each test marker in a rumble strip was captured to observe:
  - Rumble strip surface and shape
  - Body and lens condition
  - Adhesive conditions
  - Placement of marker in rumble strip
  - The offset of markers from lane markings
- Qualitative nighttime visibility assessment of the markers embedded in rumble strips from a vehicle with a low beam headlight in static and dynamic condition

4.3.1. Marker Protruding Height and Rumble Strip Depth

The protruding height (H_p) of the marker is defined as the height of the marker protruding above the pavement surface, (see Figure 4.1). This protruding region is the part of the marker lens that is visible to a road user[10], however, this is also the region that is most susceptible to being damaged by a snowplow blade going over it. As such, the protruding height is an important factor that can predict the survival rate of a marker undergoing snowplow operations and visibility.

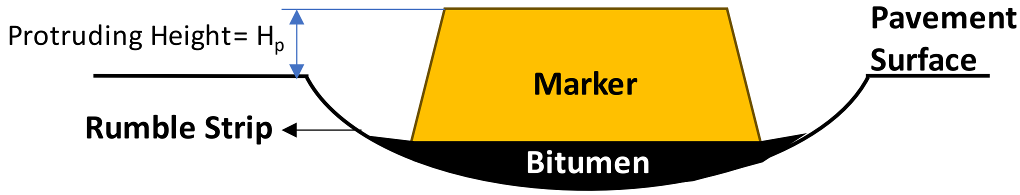


Figure 4.1: Protruding Height of Markers

The protruding height of the marker is dependent on three factors, the depth of the rumble strip in which the marker is embedded, the height of the marker itself, and the bitumen thickness. Of these factors, the height of the marker is fixed for a given type of marker. The thickness of bitumen should be similar across the sites as the installation method selected for this study is the bottoming-out method, i.e., during placement, the markers are pushed all the way down to the bottom of the rumble strip (see Appendix A). Thus, the depth of the rumble strip (D_r) is the critical factor affecting the protruding height and is an effective way of controlling the protruding height of the marker (see Figure 4.3).

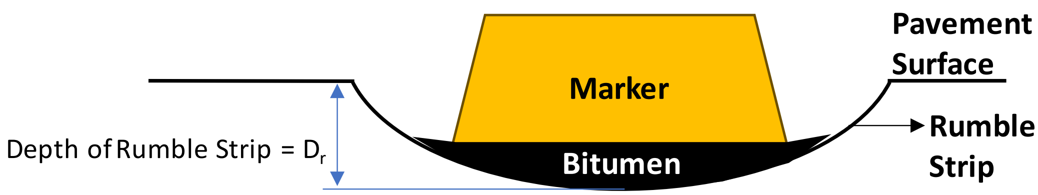


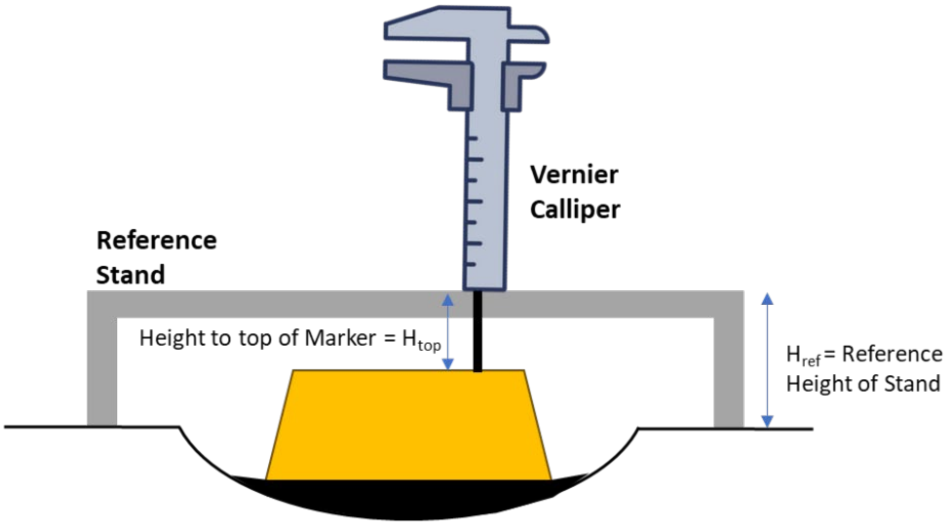
Figure 4.2: Depth of Rumble Strip

4.3.2. Field Measurement

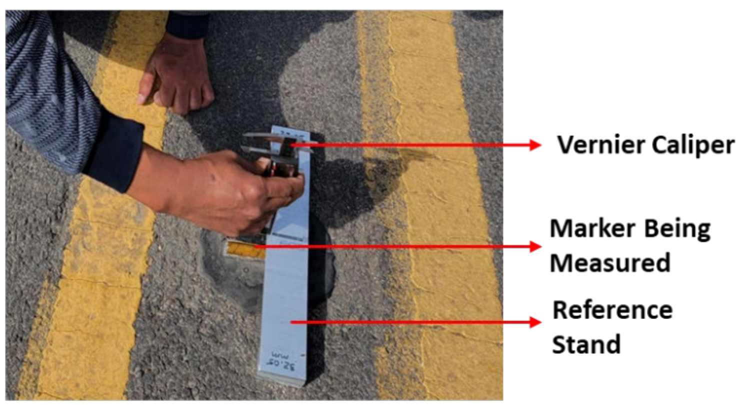
The protruding heights of all the test markers were determined as shown in Figure 4.3. A reference stand with a standard height of 32 mm (H_{ref}) was used at all sites. The reference stand was placed over the embedded rpm so that it straddled each side of the pavement adjacent to the rumble strip. The stem of a vernier caliper was used to measure the depth from the top of the reference stand to the top of the marker (H_{top}) (see Figure 4.3a). The vernier caliper had a resolution of 0.01 mm. Figure 4.3b shows a typical marker being measured at the highway sites. The protruding height was calculated using Equation 4.1.

$$H_p = H_{ref} - H_{top}$$

Equation 4.1



(a) Measuring Protruding Height of Marker



(b) Field Measurement

Figure 4.3: Measurement of Protruding Height of Markers

At all sites, the research team also measured the depth of each rumble strip containing an embedded rpm. A method like the one used to determine the protruding height was followed, except that in this case, the stem of the vernier caliper was used to measure the depth from the top of the reference stand to the bottom of the rumble strip (D_{bot}) next to the bitumen patty (see Figure 4.4a) The depth of the rumble strip was measured on both sides of the marker as shown in Figure 4.4b and Figure 4.4c. The depth of the rumble strip was calculated using Equation 4.2.

$$D_r = H_{ref} - D_{bot}$$

Equation 4.2

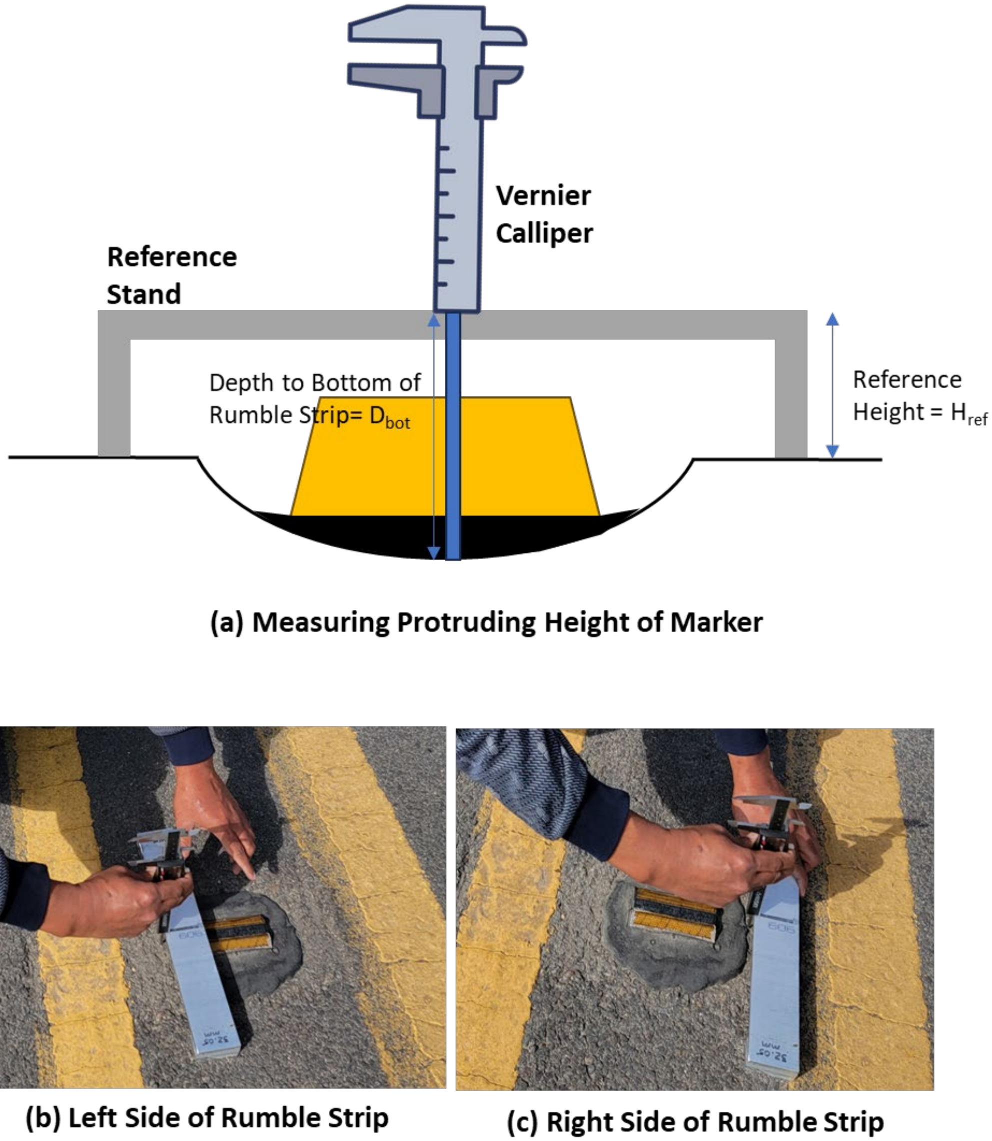


Figure 4.4: Measurement of Depth of Rumble Strip

4.4. Results and Discussions

In this section, the results of the pre-snowplow field visits to the six highway sites are presented. This includes the protruding height of markers, the depth of rumble strips, and the condition assessment of the markers before being snowplowed. This data allowed the research team to establish baseline conditions of the markers at the field sites. The marker height and depth data are depicted using box and whisker plots. An example of a typical box plot showing the rumble strip depth is shown in Figure 4.5. The major points of statistical relevance are described:

- **Minimum and maximum:** These are the smallest and largest values in the dataset depicted by the bottom and top whiskers (i.e., horizontal lines) respectively. For the example shown in Figure 4.5, the minimum and maximum whiskers show that the rumble strip depth ranges between 15 mm and 11 mm.
- **First and third quartile:** These are represented by the bottom and top perimeter of the box. The first quartile represents the 25th percentile and the third quartile represents the 75th percentile. For the example shown in Figure 4.5, the first and third quartiles are at 14 mm and 12 mm respectively. This means that 25% of the rumble strips are deeper than 14 mm and 75% of the rumble strips are deeper than 12 mm.
- **Median:** This is the middle value of the dataset calculated by arranging the data points in ascending or descending order. The median is also known as the second quartile and thus it represents the 50^{th} percentile of the data. For the example shown in Figure 4.5, this means that 50% of the rumble strips are deeper than the median value of 13 mm.
- **Average:** The average of the data is shown by the “x” at 13.07 mm.

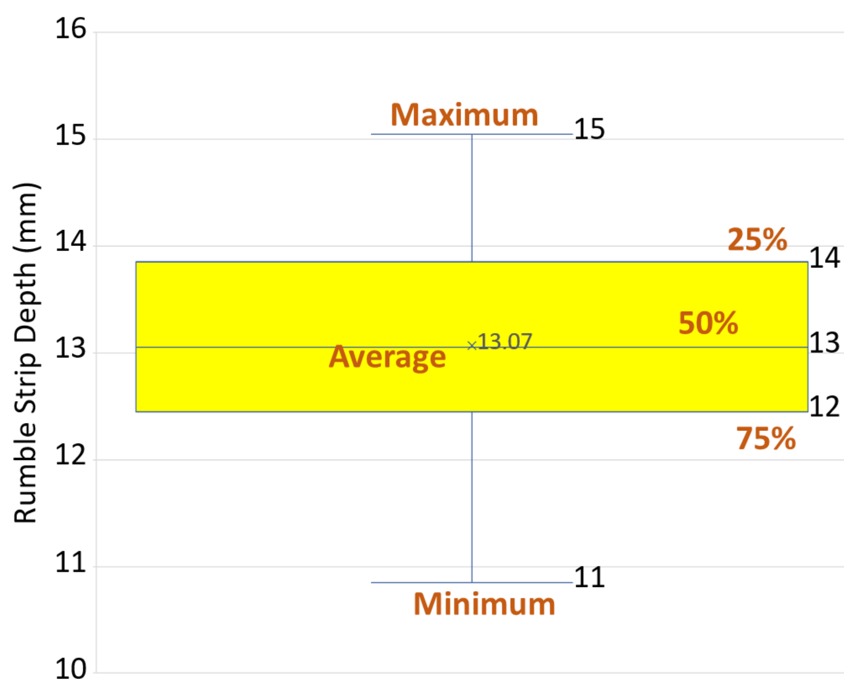


Figure 4.5: Example of a Box and Whisker Plot Showing the Major Points of Statistical Relevance

4.4.1. Protruding Height of Markers

Three marker types were evaluated: low-profile Stimsonite C40 (LP1), regular-profile 3M 290 (RP1), and regular-profile Stimsonite C80 (RP2). The markers vary in height with the LP1 marker being approximately 11 mm tall, and RP1 marker being 16 mm tall, and the RP2 marker being 18 mm tall. Thus, they have different protruding heights when placed in the rumble strips. Figure 4.6 and Figure 4.7 show the protruding height of the low-profile and regular-profile markers respectively. Except for Site III, which has the RP2 markers, all other sites have RP1 markers. The protruding height of the regular-profile markers is higher than the low-profile markers. This leads to the low-profile markers sometimes being below grade, e.g., US 380 where the protruding height is negative (-3.35 mm).

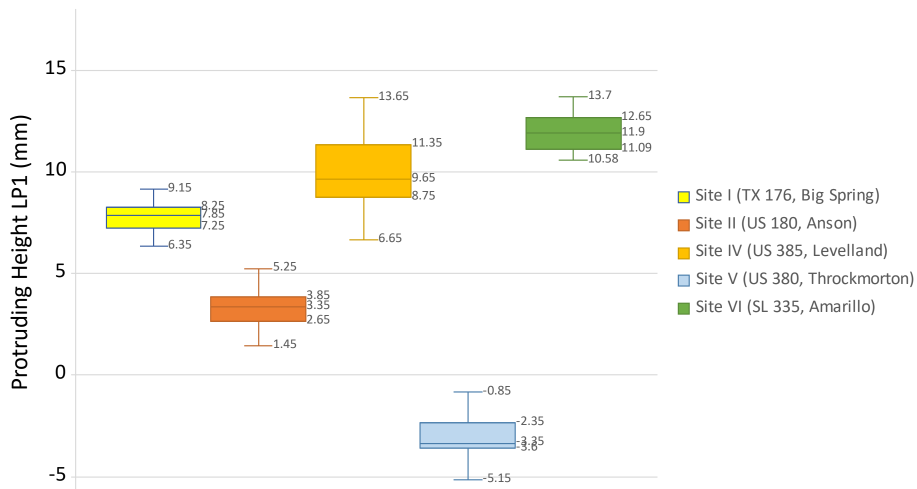


Figure 4.6: Protruding Height of Low-profile LP1 Markers at all Sites

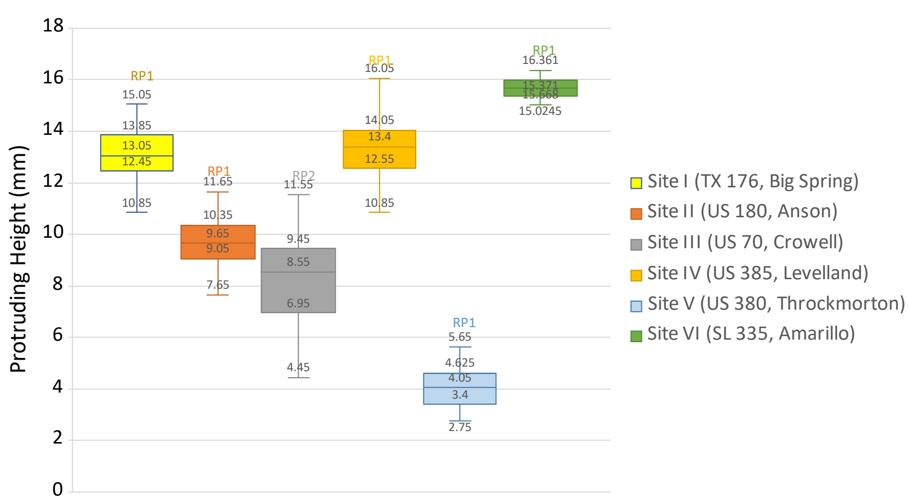


Figure 4.7: Protruding Height of Regular-profile Markers at all Sites

4.4.2. Rumble Strip Depth

Figure 4.8 shows the variation of rumble strip depths across the six highway sites. SL 335 had the shallowest rumble strip depths of all the sites, averaging 6.35 mm. This was followed by TX 176 and US 385 with both sites having an average rumble depth being 8.15 mm. US 380 had the deepest rumble strips, with an average depth being 16.35 mm. The remaining two sites averaged 12.9 and 12.6 mm respectively.

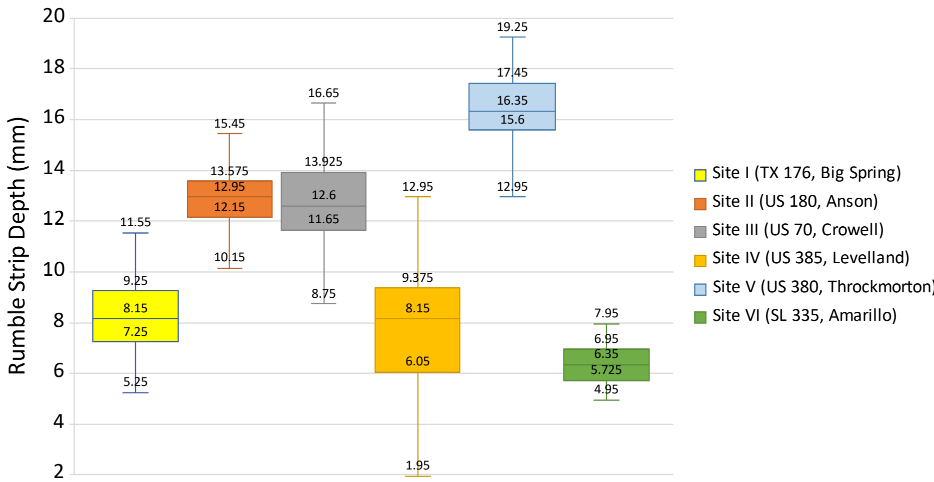


Figure 4.8: Rumble Strip Depths across the Sites

TxDOT standards, however, prescribe rumble strip depth of 1/2"± 1/8" (12 mm ± 3 mm) [3]. Thus, the range of rumble strips should lie between 9 mm and 15 mm. However, from Figure 4.8, it can be seen the depth of the rumble strips varied between 1.95 to 19.25 mm across all the sites. Table 4.3 shows the range of rumble strip depths at each site, calculated by taking the difference between the maximum and minimum rumble strip depth. The average range of rumble strips across the six sites is 6.6 mm. One site (Site IV) had an 11 mm variation between the shallowest and deepest rumble strips. This is of particular importance as the depth of the rumble strip is an important factor influencing the snowplow resistance of markers, as seen in the findings of the original *Research Project 0-6995*[7].

Table 4.3: Range of Rumble Strips Depths Across the Sites

Site	Rumble Depth (mm)			Range (mm)
	Average	Minimum	Maximum	
Site I (TX 176, Big Spring)	8.15	5.25	11.55	6.3
Site II (US 180, Anson)	12.95	10.15	15.45	5.3
Site III (US 70, Crowell)	12.6	8.75	16.65	7.9
Site IV (US 385, Levelland)	8.15	1.95	12.95	11
Site V (US 380, Throckmorton)	16.35	12.95	19.25	6.3
Site VI (SL 335, Amarillo)	5.73	4.95	7.95	3

4.4.3. Protruding Height and Rumble Strip Depth

The protruding height of a marker is related directly to the depth of the rumble strip it is embedded in, as seen in

Figure 4.9. A good correlation between the protruding height of a marker and the depth of the rumble strip the marker is embedded within was observed for all three markers. This is of importance because, during the installation of markers embedded in rumble strips, the depth of the rumble strip depth is the most important element as it effectively controls the protruding height of the marker, i.e., the area of the marker that is exposed to the snowplow blade. During construction, the rumble strip depth can be controlled by calibrating the cutting head, and during the embedment of markers, they can be bottomed out, effectively controlling the protruding height. Thus, in the later part of this study, rumble strip depth is considered the critical element in ensuring snowplow resistance and visibility of the markers.

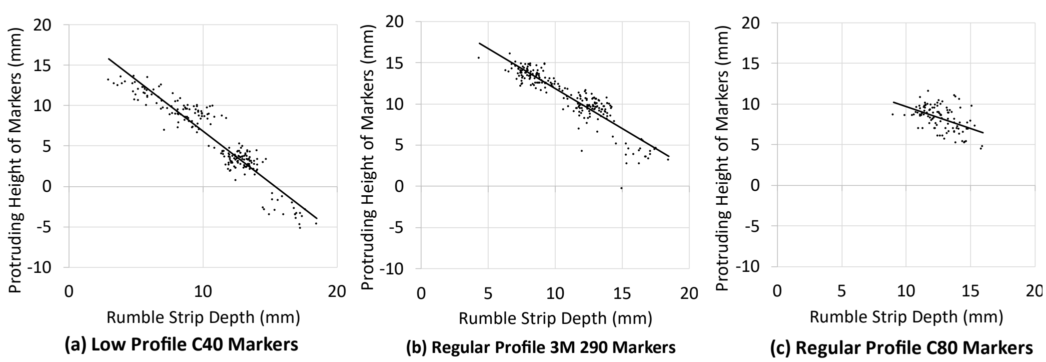


Figure 4.9: Relationship between Protruding Height of Markers and Rumble Strip Depth

4.4.4. Initial Conditions of Markers

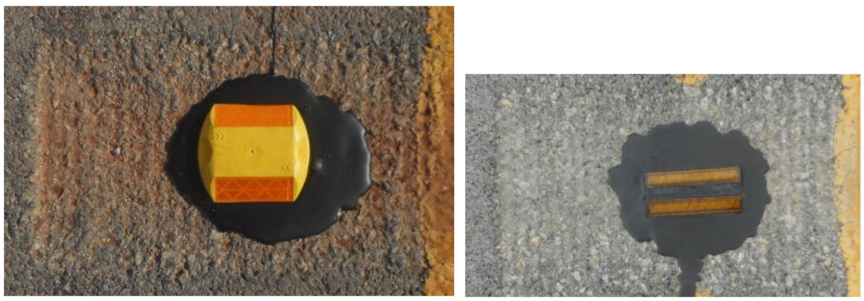
In addition to the marker and rumble strip geometry, the initial conditions of the markers were also recorded. This was done to establish the baseline condition after installation and before snowplow operations were conducted. Numbers and types of markers were collected. This data was used to determine how many markers of each type were installed at each site, so it would be possible to compare how many were lost or damaged after snowplow operations in the subsequent field visits.

Photographs were taken of all test markers to assess the initial conditions of the marker lens and body. Examples of the markers installed at the new highway sites (I-IV) are shown in Figure 4.10. As seen in the figure, the markers are in good condition with no damage to the lenses. The bitumen puddle diameter is between

7-8 inches. Generally, the markers were centered within the bitumen puddle and the marker lens was clear with the adhesive not covering any part of it.

RP1 **LP1**

(a) Site I (TX 176, Big Spring)



RP1 **LP1**

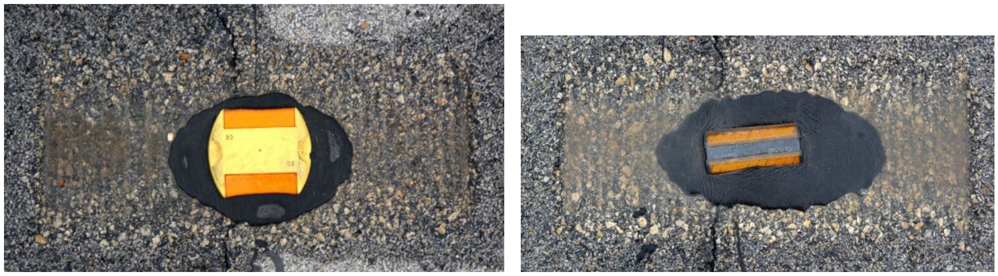
RP2

(c) Site III (US 70, Crowell)

RP1 **LP1**

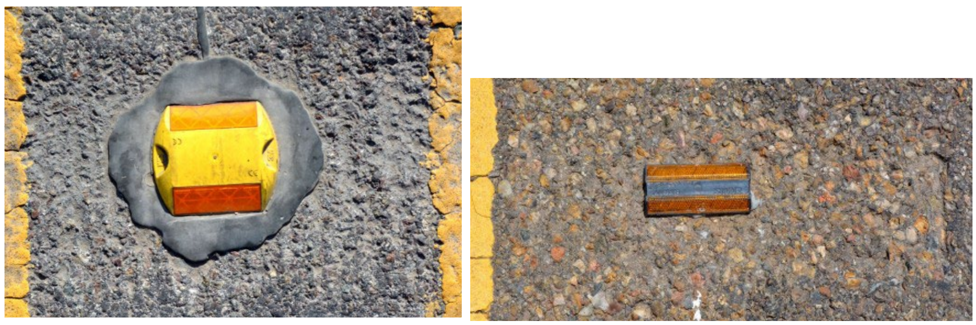
(d) Site IV (US 385, Levelland)

Figure 4.10: Examples of Markers Installed at the New Highway Sites (I-IV)



RP1 LP1

(a) Site V (US 385, Throckmorton)



RP1 LP1

(b) Site VI (SL 335, Amarillo)

Figure 4.11: Examples of Markers Installed at the Old Highway Sites (V and VI)

4.4.5. Preliminary Qualitative Nighttime Visibility of Markers

The research team conducted nighttime qualitative visibility assessments of markers at each test site. This was done to get an idea of the retroreflectivity of the markers embedded in rumble strips and to verify the distance up to which they were visible. The research team qualitatively assessed the visibility distance of markers embedded in the rumble strips by placing a vehicle at a particular point on the roadway and counting the number of visible markers illuminated by the headlights of the vehicle. The counting was done by a researcher in the driver's seat and was repeated with another researcher. The average number of markers seen by these two people is presented in Table 4.4. Since the markers are evenly spaced and the spacing between the markers is known, for example, eight markers visible at 80 ft spacing equates to 640 ft visibility distance as seen in Figure 4.12a and 12 markers visible at 40ft equates to 480 ft visibility distance as seen in Figure 4.12b. This visibility distance is presented in Figure 4.13. At a minimum, the low-profile markers were visible from approximately 1300 ft, whereas the regular-profile markers were visible at approximately 1500 ft. It should be noted, that as the visibility assessments were conducted at different times, the research team used different vehicles for the sites. However, in all cases, a full-size sports utility vehicle (SUV) was the test vehicle. At Site I (TX 176, Big Spring) and Site IV (US 385, Levelland) a 2021 Ford Expedition was used. At Site II (US 180, Anson) and Site III (US 70, Crowell) a 2021 Chevy Tahoe was used. In addition, the team conducted a dynamic visibility assessment of the markers while driving and captured videos of markers illuminated by the headlight. These videos are available for viewing in the data repositories of the performing agency and are available on request.

Table 4.4: Number of Embedded Markers Visible at Nighttime

Field Sites	**Number of Visible Markers**		
	Low-profile LP1 Markers	**Regular-profile RP1 Markers**	**Regular-profile RP2 Markers**
Site I (TX 176, Big Spring)*	28	30	-
Site II (US 180, Anson)+	20	23	-
Site III (US 70, Crowell)+	-	-	17
Site IV (US 385, Levelland)*	26	32	-
Test vehicle sued: *2021 Ford Expedition +2021 Chevy Tahoe			

(a) 80 ft Spacing **(b) 40 ft Spacing**

Figure 4.12: Qualitative Visibility of RP1 Markers Illuminated with Headlights

Figure 4.13: Visibility Distances of Markers Embedded in Rumble Strips at New Highway Sites (I-IV)

At Site V (US 380, Throckmorton) and Site VI (SL 335, Amarillo) quantitative measurements of the retroreflectivity of the embedded markers were conducted using a charged coupled device photometric camera as part of *Research Project 0-6995*. The results of that study are presented in Table 3.1.

4.5. Summary

Site surveys were conducted on the highway sites (I-VI) after the markers were embedded in the rumble strips and before being snowplowed. This allowed the research team to establish a baseline condition for the markers. This included collecting geometrical information on the rumble strips and markers along with pictures of the markers to observe the markers' initial condition. A qualitative assessment of the nighttime visibility of the embedded markers was also conducted under static and dynamic conditions. The following conclusions were drawn:

- The markers were embedded in centerline rumble strips using bituminous adhesives. The initial condition of the markers indicated that they were in good condition concerning the body and lens. The lens was unobstructed by the adhesive.
- The rumble strip depths at the sites varied significantly, with depths ranging from 1.95-19.25 mm. This was beyond the acceptable range of 12 ± 6 mm as per TxDOT standards.
- The preliminary qualitative visibility assessments showed promising results for the nighttime visibility of markers embedded in the rumble strips.

Chapter 5. Snowplow Resistance Evaluation

5.1. Overview

This chapter presents the evaluation of the snowplow resistance of the markers embedded in rumble strips at the highway field sites. *Research Project 0-6995* indicated that the maximum amount of damage to the markers occurred after the first pass of the snowplow [7]. The markers installed during *Research Project 0-6995* were observed over two winter cycles and the newly installed markers on the selected highways were observed over one winter cycle to quantify the degree of damage experienced by the markers after undergoing snowplow activities. The markers were examined before each winter season, i.e., before snowplowing, and in the spring season, i.e., after snowplowing. The results of the pre-snowplow field visits are presented in Section 4.4. This provided insights into the relationship among rumble strip depth, marker protruding height, and damage resistance of the markers.

5.2. Post-snowplow Site Evaluations

Site visits were conducted to the six highway sites (Sites I-VI) after the Receiving Agency informed the research team that snowplow operations were conducted at the sites. During these post-snowplow visits, the rumble strip depth and protruding height of markers were verified, and the damage rating of each marker was captured.

Table 5.1 presents a summary of the field visits. The dates of the field visits as well as the marker types and numbers, snowplow status, average rumble strip depth and marker protruding height, and marker retention status are provided. It is seen that most markers at Sites III (US 70, Crowell), Sites IV (US 385, Levelland), and VI (SL 335, Amarillo) were lost. Site V (US 380, Throckmorton) has an almost 100% survival rate for low-profile LP1 markers and a 90% survival rate for regular-profile RP1 markers.

Based on the site evaluation, the research team believes that the centerline region was not snowplowed at Site I (TX 176, Big Spring) and Site II (US 180, Anson). Due to this uncertainty, the two sites are highlighted in yellow in Table 5.1. This deduction was made because of the following reasons:

Table 5.1: Field Site Information

Site	Field Visit Dates			Centerline Snowplow Status	Average Rumble Strip Depth (mm)	Type and Number of RPMs**	Average Protruding Height (mm)	Marker Retention Status
	Pre-snowplow	Post-snowplow Visit 1	Post-snowplow Visit 2					
Site I – TX 176 (Big Spring in Howard County)	03/04/2022	Not Snowplowed	03/21/2023	No	8.3	LP1 (92)	7.78	100%
						RP1 (95)	13.07	100%
Site II – US 180 (Anson in Jones County)	12/17/2021	06/02/2022	05/24/2023	No	12.8	LP1 (95)	3.28	100%
						RP1 (98)	9.95	100%
Site III – US 70 (Crowell in Foard County)	12/16/2021	06/02/2022	05/23/2023	Yes	12.7	RP2 (102)	8.2	0%
Site IV - US 385 (Levelland in Hockley County)	02/02/2022 and 03/03/2022	Not Snowplowed	03/21/2023	Yes	7.9	LP1 (93)	9.95	54%
						RP1 (100)	13.37	23%
Site V - US 380 (Throckmorton in Wichita Falls County)*	03/11/2021	06/03/2022	05/23/2023	Yes	16.4	LP1 (200)	-3.09	100%
						RP1 (100)	3.9	90%
Site VI – SL 335 (Amarillo in Amarillo County) *	05/06/2021	06/28/2022	No markers	Yes	6.3	LP1 (97)	11.94	4%
						RP1 (60)	15.52	0%

* *Research Project 0-6995* Sites
** Marker Types: LP1- Low-profile Stimsonite C40, RP1 – Regular-profile 3M 290, RP2 - Regular-profile Stimsonite C80
Yellow highlights: Uncertainty in snowplow status of centerline

- The centerline region did not show any signs of snowplow activities being conducted, i.e., very minimal damage to markers.
- Markers embedded at other sites with similar rumble strip depths were lost due to snowplow activities, whereas the markers at Site I and Site II remained. Specifically, Site I (TX 176, Big Spring) and Site IV (US 385, Levelland) both have rumble strips that are approximately 8 mm deep on average. Similarly, Site II (US 180, Anson) and III (US 70, Crowell) both have rumble strips that are approximately 12 mm deep rumble strips. Thus, it is unlikely that the markers at Sites I and II would have survived unscathed.
- At Site II, all surface-mounted markers in the test strip survived (see Figure 5.1).

Figure 5.1: Undamaged LP1 Surface Marker on the Test Strip at Site II (US 180, Anson)

5.2.1. Damage Rating System

The markers show different types of damage after being subjected to snowplow operations. To quantify this damage a damage rating system was developed under *Research Project 0-6995* [7]. Examples of each type of damaged marker are shown in Figure 5.2. The following classifications of markers were observed at the field sites after snowplow operations have been completed:

- **Functional:** These markers are either undamaged or have undamaged lenses and are still capable of being retroreflective. Can be divided into:
  - **Good**: Fully functional with no visible defects on the marker body and lenses (see Figure 5.2a)
  - **FL:** Functional lenses, markers have defects on the body or minor defects on the lenses due to damage from the snowplow blade but have fully functional lenses (see Figure 5.2b)

- **Non-functional:** These markers have either damaged lenses or are missing and cannot provide the required amount of retroreflectivity. Can be divided into:
  - **NFL:** Non-functional lenses, markers have damaged lenses due to snowplow operations (see Figure 5.2c)
  - **MAI:** Missing markers that have debonded at the marker-adhesive interface (see Figure 5.2d). Fragments of missing and/or damaged markers were occasionally found at the edge of the pavement by the research team.
  - **PAI:** Missing markers that have debonded at the pavement adhesive interface (see Figure 5.2e)

(a) Good Condition **(b) Functional Lens**

Functional Markers

(c) Non-functional Lens **(d) Marker Adhesive Interface** **(e) Pavement Adhesive Interface**

Missing Markers

Non-Functional Markers

Figure 5.2: Examples of Damaged Markers

5.2.2. Damage Evaluation of Markers

This section presents the marker retention after undergoing snowplow operations. The different damage types are presented along with the number of markers exhibiting each type of damage. The retention rates of the three marker types are presented in Figure 5.3 (Low-profile LP1 Marker) Figure 5.4 (Regular-profile RP1 Marker), and Figure 5.5 (Regular-profile RP2 Marker). In the figures, the share of functional markers (good condition and damaged markers with functional lenses, FL) at each site are depicted in green while the non-functional markers (missing, MAI, and PAI, and damaged markers with non-functioning lenses, NFL) are depicted in red.

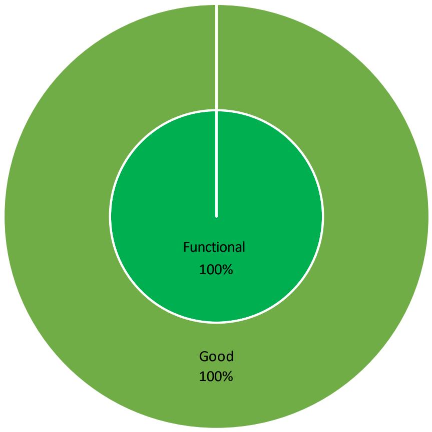
At Sites I (TX 176, Big Spring) and II (US 180, Anson) there was 100% functionality of both marker types (see Figure 5.3a and b, and Figure 5.4a and b). However as discussed in Section 5.2, Sites I and II appear to have not undergone snowplow operations on the centerline. Thus, this data is not considered in the snowplow resistance evaluation.

Site III (US 70, Crowell), the only site with the RP2 markers, lost all markers (see Figure 5.5). Site IV (US 385, Levelland) showed more variation in the types of damages sustained. There were 51% functional LP1 markers and 23% functional RP1 markers (see Figure 5.3c and Figure 5.4c). Site V (US 380, Throckmorton) had undamaged LP1 markers with 100% functionality and 90% functionality RP1 markers (See Figure 5.3d and Figure 5.4d). Site VI (SL 335, Amarillo) was the worst performing site with only 4% LP1 markers and 0% RP1 markers being functional (See Figure 5.3e and Figure 5.4e).

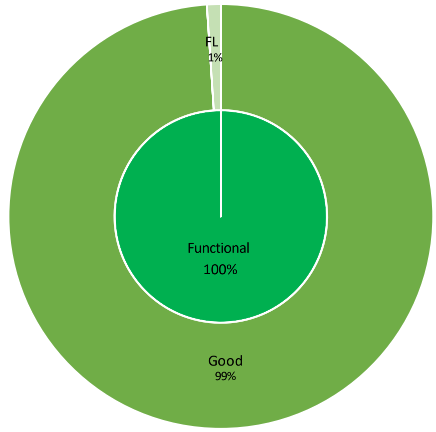
Table 5.2 shows the retention rate of each type of marker. Across Sites III-VI, where markers were subjected to snowplow operations the RP2 marker retention rate was the lowest at 0%. The low-profile LP1 performed better with a 53% retention rate when compared to the regular-profile RP1 markers at 42%.

Table 5.2: Marker Retention Rate

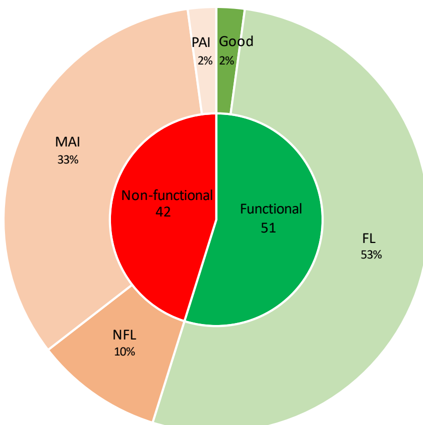
Marker Type	Number of Markers Installed	Number of Functional Markers Remaining after Snowplow Operations	Retention Rate
Low-profile LP1	290	154	53%
Regular-profile RP1	269	112	42%
Regular-profile RP2	102	0	0 %



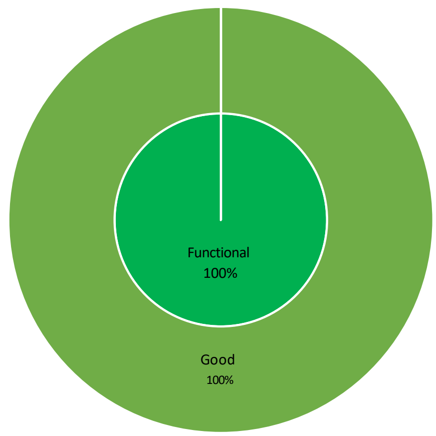
(a) TX 176, Big Spring



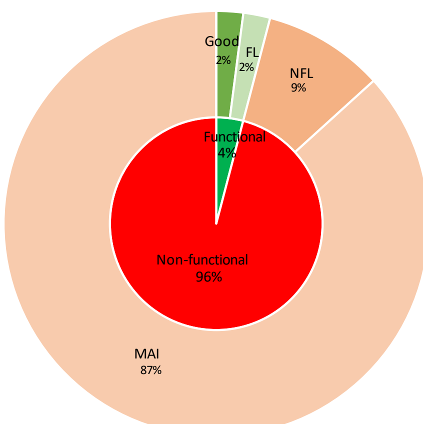
(b) US 180, Anson



(c) US 385, Levelland



(d) US 380, Throckmorton



(e) SL 335, Amarillo

Legend

FL: Functional Lenses

NFL: Non-functional lenses

MAI: Marker Adhesive Interface

PAI: Pavement Adhesive Interface

Figure 5.3: Snowplow Damage of Low-profile Stimsonite LP1 Markers

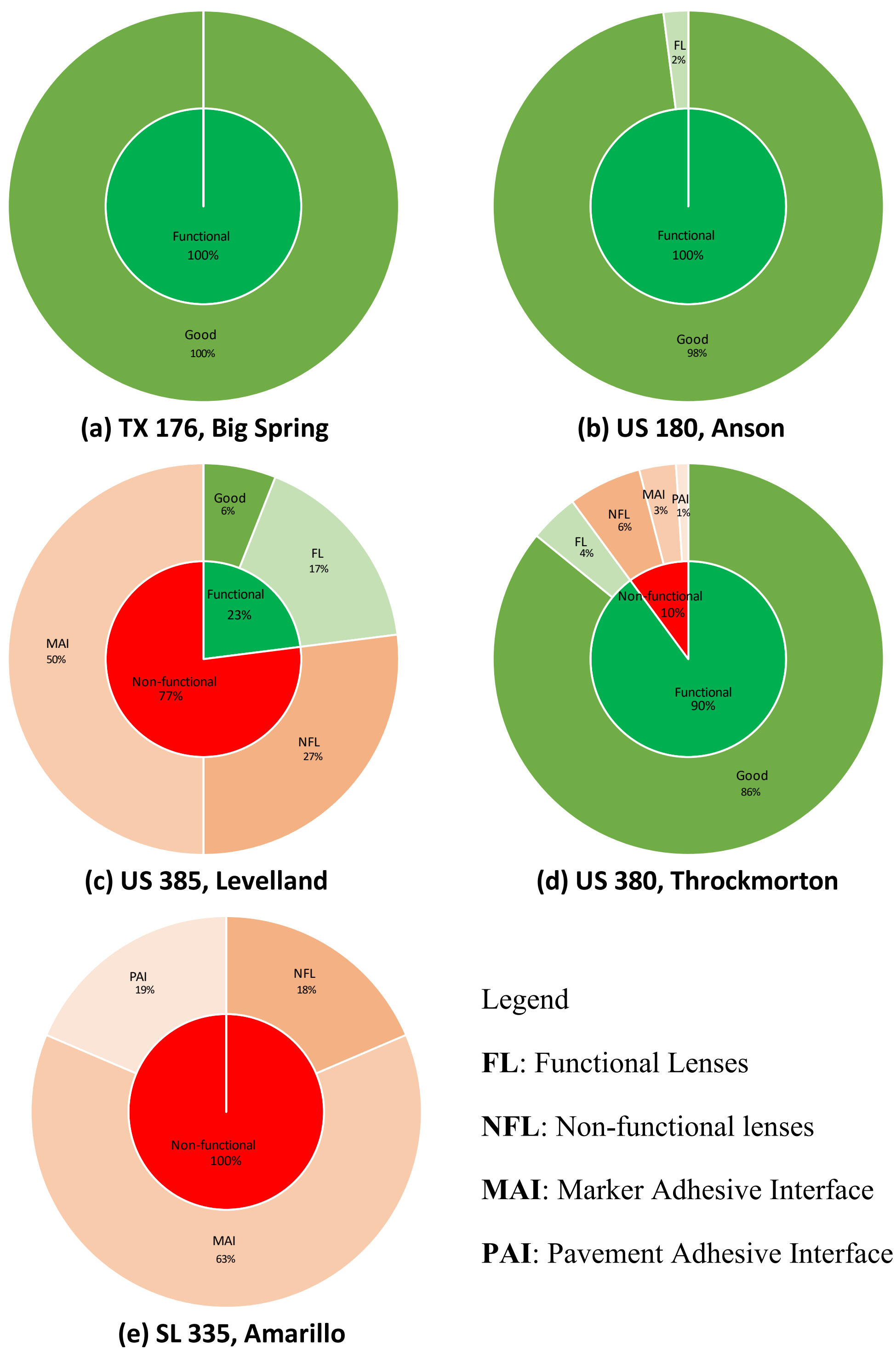
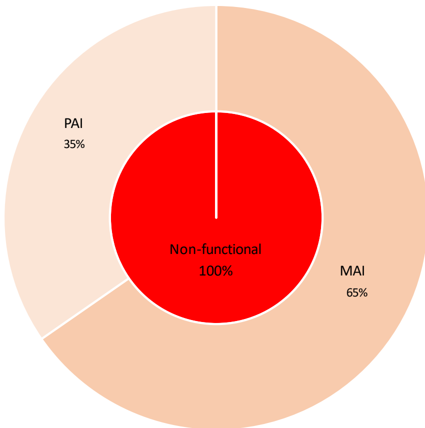


Figure 5.4: Snowplow Damage of Regular-profile RP1 Markers



Legend

FL: Functional Lenses

NFL: Non-functional lenses

MAI: Marker Adhesive Interface

PAI: Pavement Adhesive Interface

Figure 5.5: Snowplow Damage of Regular-profile Stimsonite RP2 Markers at US 70, Crowell

5.2.3. Snowplow Resistance

Table 5.2 showed that the low-profile LP1 marker had a higher retention rate than the regular-profile RP1 marker. However, it must be noted that the RP1 markers are taller than the LP1 markers and thus, protrude higher than the LP1 markers. To truly evaluate the snowplow resistance of each marker type, an analysis of the marker retention rate concerning the protruding height and in turn the rumble strip depth is presented.

5.2.3.1. Retention Rate vs Protruding Height

Figure 5.6 shows the retention rate of the low-profile markers vs the average protruding height of the markers at the different sites. Sites I (TX 176, Big Spring) and II (US 180, Anson) are omitted from the data analysis as the centerline was most likely never plowed. There were no low-profile markers installed at Site III (US 70, Crowell). At Site IV (US 385, Levelland), 55% of markers survived when the protruding height was 9.95 mm. At Site V (US 380, Throckmorton) which had a protruding height of -3.06 mm, the marker retention rate was 100% (note, the negative value indicates that the markers were below grade). Site VI (US 385, Levelland) had the highest protruding height (11.94 mm), and almost all markers were lost. The sites were all snowplowed with either carbide or steel blades, both of which have hard and sharp edges capable of causing loss and damage to the markers.

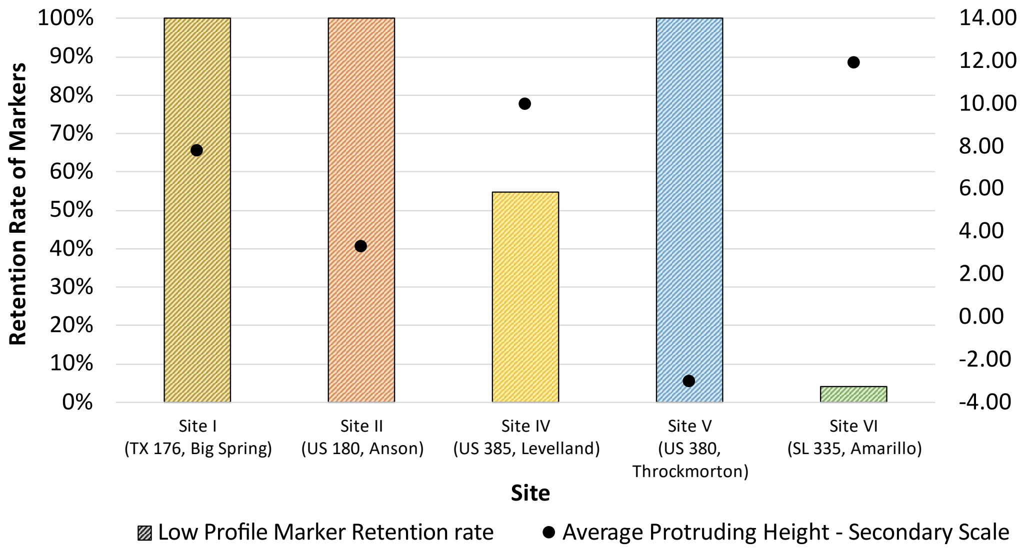


Figure 5.6: Retention Rate vs Average Protruding Height – Low-profile Markers

Figure 5.7 shows the retention rate of the regular-profile markers vs the average protruding height of the markers at the different sites. At Site III (US 70, Crowell) the protruding height was 8.22 mm with the 0% markers surviving. It must be noted that Site III has a different marker type, the RP2 marker which has previously shown poorer performance when compared to the RP1 markers as it is 2 mm taller, which allows it to be damaged at higher rates than the RP1. At Site IV (US 385, Levelland), 23% of markers survived when the protruding height was 13.35 mm. At Site V (US 380, Throckmorton) which had the lowest protruding height, 3.93 mm, the marker retention rate was 90%. At Site VI, all markers were lost at the highest protruding height of 15.52 mm.

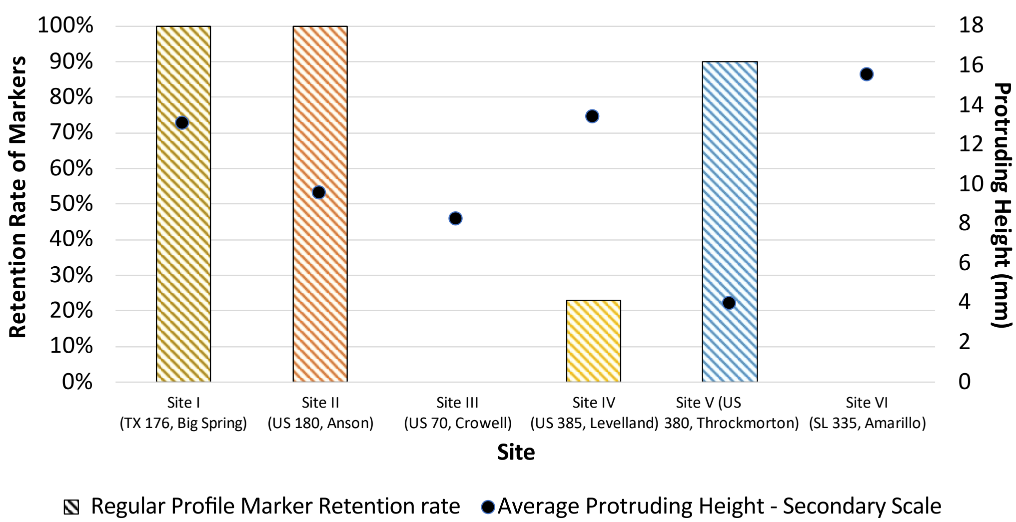


Figure 5.7: Retention Rate vs Average Protruding Height – Regular-profile Markers

Based on the marker retention rates from Sites III-VI, the maximum protruding height for the markers was determined. Figure 5.8 presents a box and whisker plot of the protruding height of the markers. The red plots indicate markers that were non-functional after snowplow operations and the green plots indicate markers that were functional after snowplow operations. Low-profile markers are depicted in solid plots and regular-profile markers in hashed plots. For low-profile markers, 75% of the markers below protruding height of 2.4 mm were functional. Similarly, for low-profile markers, 75% of the markers below protruding height of 4.8 mm were functional. Thus, it can be concluded that the maximum protruding heights for snowplow resistance for both low and regular-profile markers are 2 and 5 mm respectively.

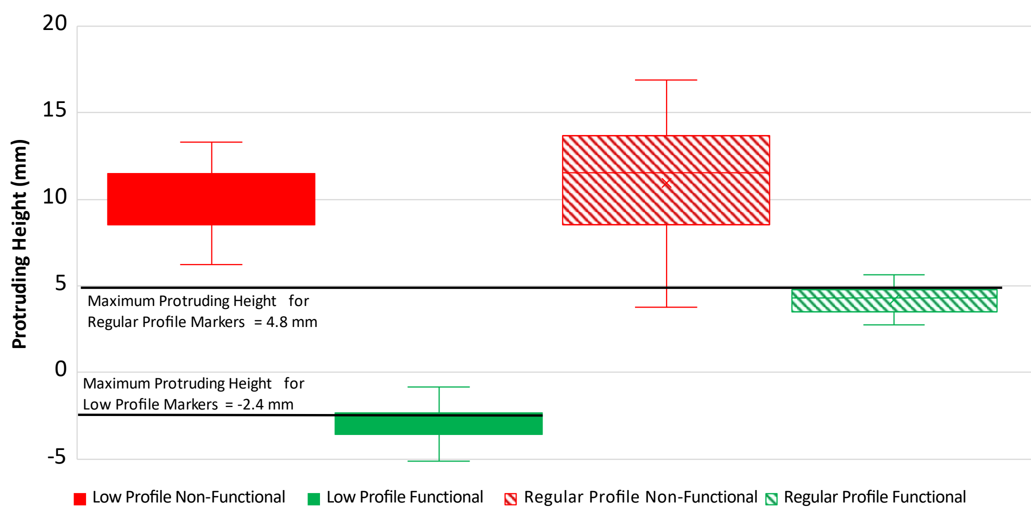


Figure 5.8: Maximum Protruding Height for Marker Retention

5.2.3.2. Retention Rate vs Rumble Strip Depth

Rumble strip depth is the controlling factor for marker retention as deeper rumble strips provide adequate protection to the markers during snowplow operations. Figure 5.9 shows the effect of rumble strip depth on the retention rate of the markers at the different sites. Sites I (TX 176, Big Spring) and II (US 180, Anson) were omitted from the study as the centerline was most likely never plowed.

At Site III (US 70, Crowell) the rumble strip depth was 12.7 mm with 0% markers surviving. It must be noted that Site III has a different marker type, the RP2 marker which has previously shown poorer performance when compared to the RP1 markers. At Site IV (US 385, Levelland), 38% of markers survived when the rumble strip depth was 7.5 mm. At Site V (US 380, Throckmorton) which had the largest rumble strip depth, 16.4 mm, the marker retention rate was 95%. At Site VI

(SL 335, Amarillo), which had the shallowest rumble strips at 6.3 mm, almost all markers were lost with a retention rate of 0.02%.

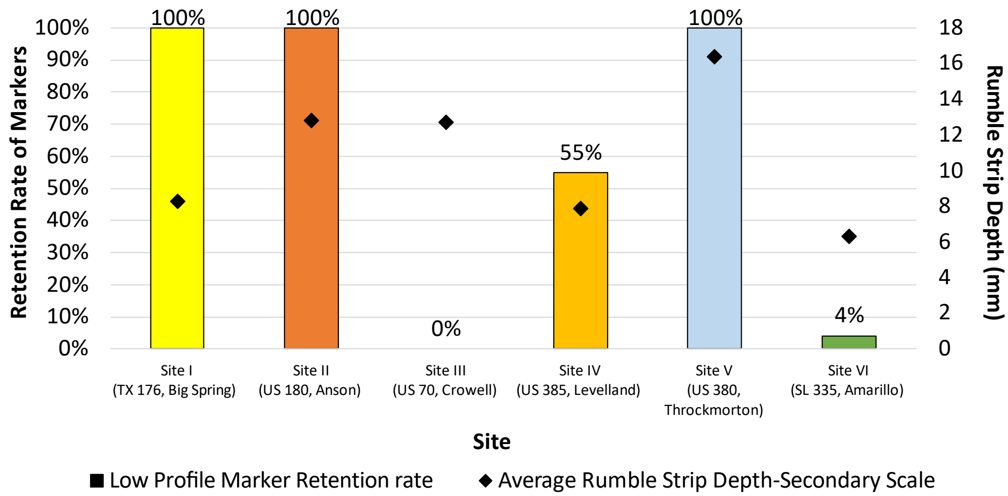


Figure 5.9: Marker Retention Rate vs Rumble Strip Depth

Based on the marker retention rates from Sites III-VI, the minimum rumble strip depth for snowplow resistance for the two marker types was determined. Figure 5.9 presents a box and whisker plot of the rumble strip depths. The red plots indicate rumble strip depths where markers were non-functional after snowplow operations and the green plots indicate rumble strip depths containing functional markers after snowplow operations. Low-profile markers are depicted in solid plots and regular-profile markers are depicted in hashed plots. For low-profile markers, 75% of rumble strips deeper than 12.4 mm had functional markers after snowplow operations. Similarly, for regular-profile markers, 75% of rumble strips deeper than 15.8 mm had functional markers after snowplow operations. Thus, the minimum rumble strip depth for snowplow resistance for low-profile markers is 12 mm, and for regular-profile markers is 16 mm.

Hence it is determined that snowplow-resistant rumble strip depth for a marker installed using the bottom-out method was approximately equivalent to the height of the marker. For the 12 mm high LP1 marker, the rumble depth for snowplow resistance was 12 mm. Similarly, For the 16 mm high LP1 marker, the rumble depth for snowplow resistance was 16 mm. Based on this, the likely snowplow-resistant rumble depth for the RP2 marker installed using the bottom-out would be 18 mm. However, additional field studies will be required to confirm this.

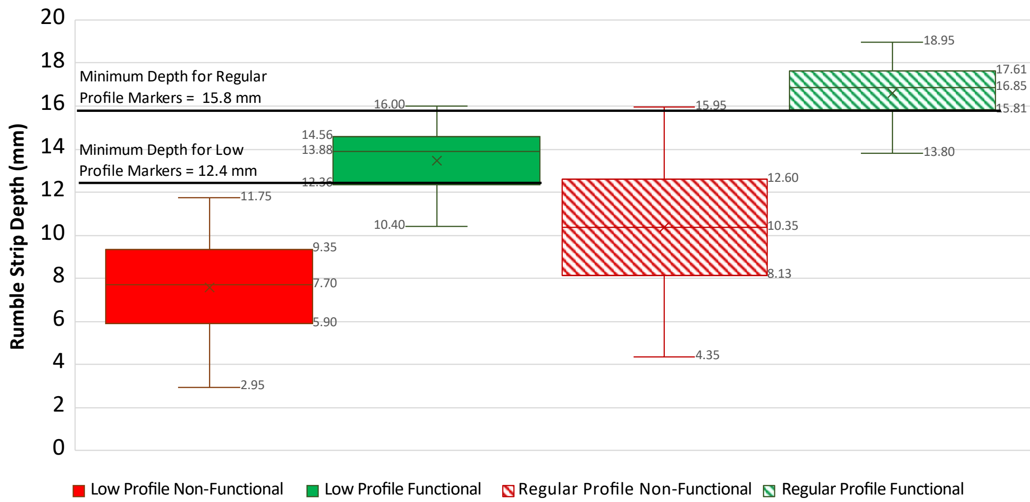


Figure 5.10: Minimum Rumble Strip Depth for Marker Retention

5.2.4. Rate of Survival of Embedded Markers

The minimum rumble strip depth determined in the Section 5.2.3.2 was verified by determining the rate of survival of a marker if it was embedded in a rumble strip. Figure 5.11 compares the marker survival rate versus the rumble strip depth. The relationship between the rate of survival (R_s) and rumble strip depth (D_r) is presented in Equation 5.1 for low-profile markers (LP1) and Equation 5.2 for regular-profile markers (RP1). The relationships are valid for markers in rumble strips with depths between 2-13 mm and 13-17 mm for low and regular-profile markers respectively. Below and above these depths the markers have 0% and 100% rates of survival.

$$Low\ Profile\ R_s = 26.975D_r - 248.16$$

Equation 5.1

$$Regular\ Profile\ R_s = 26.5D_r - 349.42$$

Equation 5.2

At 12 mm rumble strip depth, the rate of marker survival is 75% as per Equation 5.1. Similarly, at 16 mm rumble strip depth, the rate of marker survival is 75% as per Equation 5.2. This aligns with the minimum rumble strip depth at which 75% of the markers survived a snowplow event in Section 5.2.3.2. *Thus, a marker embedded in a* ***snowplow-resistant depth rumble strip*** *has a 75% survival rate.*

It is seen from Figure 5.11 that controlling the depth of the rumble strip is very important to snowplow resistance as reducing the depth by even one millimeter reduces the rate of survival to 40% from 75% in case of low-profile markers and to 20% in case of regular-profile markers.

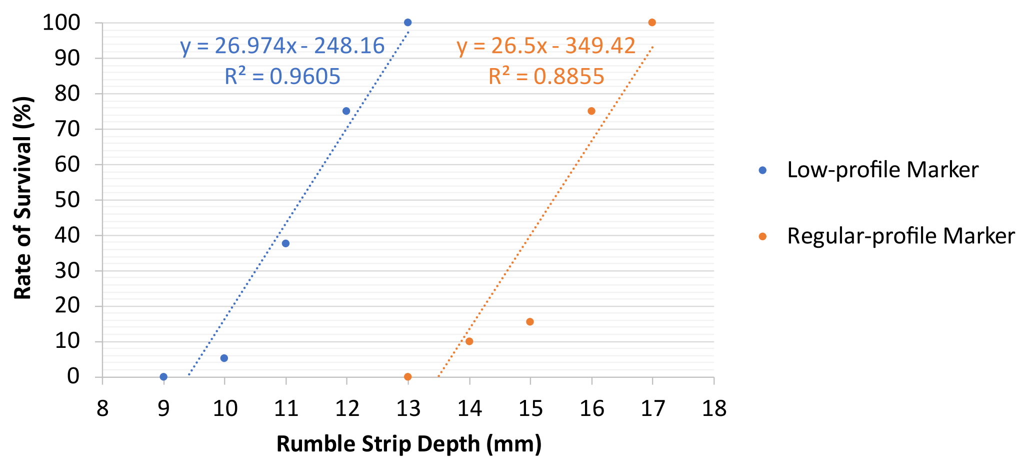


Figure 5.11: Relationship between Marker Survival Rate and Rumble Strip Depth

5.2.5. Cost Analysis

Based on the findings of *Research Project 0-6995* the cost of installing a marker is \$3.50. If 40% of the two-lane rural highways in Northern Texas require retroreflective raised pavement markers to be installed at 80 ft spacing, this would require 784160 markers each year, totaling a cost of \$2.7 million. In the case of surface-mounted markers, there would be a 90% loss of markers resulting in a replacement cost of \$2.5 million annually.

If the markers are embedded in existing rumble strips, there would still be loss and damage to markers, due to them not being in rumble strips that have sufficient depths. The cost of replacing 47% of the LP1 would be \$1.28 million and the cost of replacing 59% of the regular-profile RP1 markers would be \$1.62 million annually. The replacement cost is derived from the survival rate of the markers (see Table 5.2).

If these markers were instead embedded in snowplow-resistant depth rumble strips of 12 mm for low-profile LP1 and 16 mm for regular-profile RP1 markers, the replacement cost would reduce to \$0.6 million. The rate of loss of the markers embedded in snowplow-resistant depth rumble strips is 25%. Thus, it is seen that there is significant savings to TxDOT.

5.3. Summary

Site evaluations before and after snowplow operations were conducted on the six highway sites. It was determined that the centerline at Site I (TX 16, Big Spring) and Site II (US 180, Anson) were not plowed, thus the data collected from these sites were not used to evaluate the snowplow resistance of markers. The following conclusions were drawn from this phase of the research:

- Rumble strip and marker geometry are critical to the snowplow resistance of the retroreflective pavement marker placed in the rumble strips.
- Post snowplow operations markers were found to be functional (good condition or damaged with still functioning lenses) or non-functional (damaged lenses or missing with debonding occurring at either the marker adhesive interface or pavement adhesive interface).
- The retention rate of the markers was dependent on the depths of the rumble strip that the markers were placed in and the marker's protruding height.
- The maximum protruding height, i.e., the height at which the marker survives a snowplow operation, was calculated to be eight mm.
- The minimum rumble strip depth required to provide sufficient protection to the marker installed using the bottom-out approach, i.e., snowplow-resistant depth rumble strip, was determined to be 12 mm for the low-profile markers and 16 mm for the regular-profile markers. This is approximately equal to the height of the marker.
- All RP2 markers in this study were installed in rumble strip depths shallower than the height of the markers and did not have any markers retained after snowplow operations. Thus, the likely snowplow-resistant rumble depth for the RP2 marker installed using the bottom-out would be 18 mm. However, additional field studies will be required to confirm this.
- Controlling rumble strip depth is very important to the snowplow resistance of markers as the probability of survival reduces drastically when the rumble strip depth decreases.
- Embedding markers in snowplow-resistant depth rumble strips can reduce significant replacement costs for TxDOT.

Chapter 6. Human Visibility Survey

6.1. Overview

In *Research Project 0-6995*, visibility assessment studies were conducted and it was found that the markers were illuminated at a distance of 740 ft to 900 ft from the driver [7] which exceeds the minimum required visibility distance of 200 ft per TxDOT standards [11].

During this phase of the project, additional visibility assessment studies were conducted to confirm the night-time visibility of markers embedded in snowplow-resistant depth rumble strips using human participants. Two sites were used for the visibility studies: Research Site A (Innovation Blvd at Pickle Research Campus, Austin) and Highway Site II (US 180, Anson). Visibility assessments were conducted based on two types of tests: dynamic tests to determine the distance at which road users can perceive the markers while in motion, and static tests to determine the distance at which road users can distinguish the markers from a static point were conducted. The results of this task provide insights into the extent to which the embedded markers have sufficient retroreflective visibility to road users.

6.2. IRB Approval

As the study involved human participants the Performing Agency was required to get UT Austin Institutional Review Board (IRB) approval before proceeding with the study [12]. This was to ensure that the research which involved humans applied ethical principles and complied with federal regulatory requirements for protecting the rights and welfare of human participants. As part of this process the study protocol, participant selection criteria, participant compensation information, communications distributed to the participants, etc. were provided to IRB. The study was approved on 01/04/2023 and granted an IRB Protocol Number (STUDY00003391).

6.3. Participant Selection Process

The target participants for the study were road users between the ages of 18-70 with a valid driver's license. The methodology used to recruit participants is described in this section.

6.3.1. Recruitment

For Site A (PRC), two invitation methods were adopted to procure participants. Emails and paper flyers were prepared with project details, compensation information, and the date, time, and venue of the study. Emails were circulated within various academic departments at the Performing Agency and residential communities near the test site location. In addition, flyers were put up in common areas at the Performing Agency and in residential communities. For Site II at US 180, Anson, invitations were sent by email to TxDOT employees and staff at the Abilene District Office. Participants were allotted a participant ID to maintain their confidentiality. In this report, the data will be presented in aggregate form.

6.3.2. Intake Survey and Eligibility Requirements

The invitation emails and flyers contained a link to an automated online survey developed using Qualtrics®. Appendix B provides information on the surveys sent to the participants. This survey collected the contact information and screened out participants who did not fulfill the participation criteria. Participants with a valid driver's license and between the ages of 18-70 years were selected for further participation.

6.3.3. Informed Consent

The eligible participants were asked to provide their informed consent to participate in the study using Qualtrics®. The consent form provided information on the research project, participant duties, compensation information, risks involved, data privacy, and research team contact information.

6.3.4. Background Survey

Participants who consented to participate in the study were directed to provide information on their demographics and driving style (see Appendix B). The survey was designed to collect information about key factors that impact a road user's perception of the retroreflective pavement markers at nighttime [13,14].

6.3.5. Final Selection

The target number of participants for each site was 10 to 20 people. 19 eligible participants applied for Site A (PRC) and 12 eligible participants applied for Site II (US 180, Anson). Thus, for both sites, all eligible and consenting participants were invited to participate in the study and were requested to make themselves available for the nighttime visibility study and provided with the location and time to arrive. One participant at each site did not arrive for the test. Therefore, there were 17 participants at Research Site A and 10 participants at Highway Site II. One participant was involved in the studies at both sites. After completion of the study participants were compensated for their time with Tango-enabled gift cards that were sent by email.

6.4. Participant Characteristics

6.4.1. Demographics

Participants' age ranges were divided into four decades, 18-30 years, 31-40 years, 41-50 years, and 51-70 years with 12, 10, four, and three participants in each decade respectively (see Figure 6.1a). There were 19 male and 10 female participants (see Figure 6.1b). All participants selected their sex assigned at birth with zero intersex participants and none declining to answer.

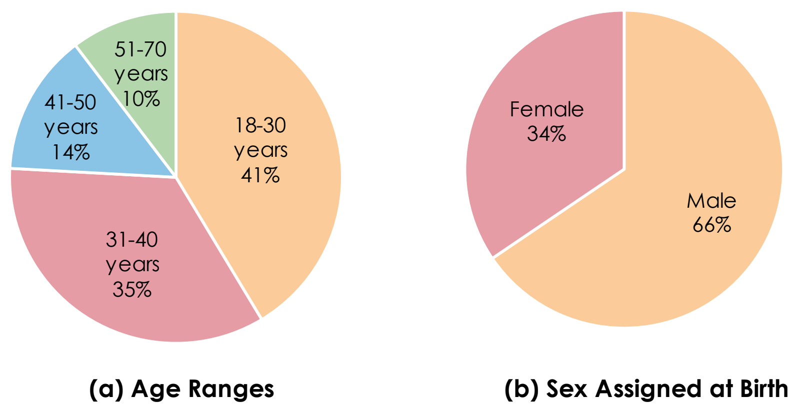


Figure 6.1: Participant Demographics

6.4.2. Driving Experience

All participants had a Class A, B, or C driver's license type with two participants having a Motorcycle license as well. All participants had at least 1 year of driving experience, with six having 1-5 years, five having 5-10 years of experience and 17 having more than 10 years of experience (see Figure 6.2a). Eight participants drove less than 5,000 miles annually, 13 participants drove between 5,000 and 10,000 miles annually, and six drove more than 10,000 miles (see Figure 6.2b).

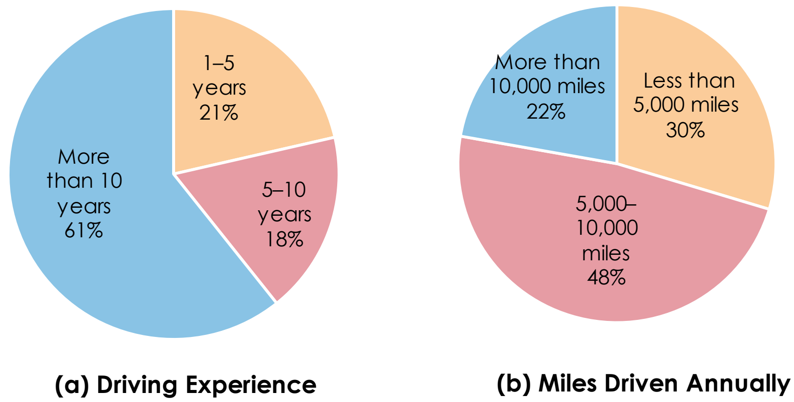


Figure 6.2: Participant Driving Experience

6.4.3. Night Driving

Participants were requested to provide information on their driving experience during nighttime when visibility is lower. All participants reported driving during nighttime at least once per week, with 11 participants driving 1-2 days, 14 participants driving 3-4 days and three participants driving more than 5 days each week in the nighttime (see Figure 6.3a). 25 participants reported driving more cautiously during nighttime and 4 participants claimed that they drove as they would normally do during daytime (see Figure 6.3b). Finally, when asked about the negative impact of headlight glare during nighttime, 11 participants reported having difficulties and three participants reported that they did not face any issues and two were unsure (see Figure 6.3c).

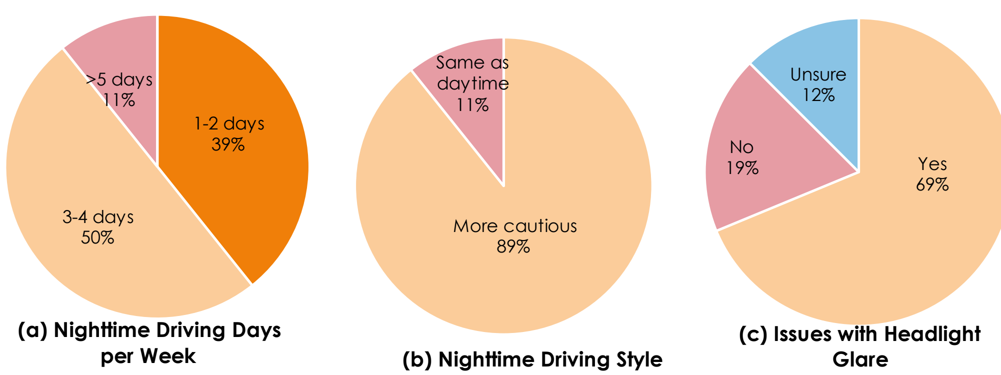


Figure 6.3: Participant Nighttime Driving Style

6.4.4. Safety Awareness

Participants were asked about their awareness of road safety. For example, when asked about how often they drove over the speed limit, four participants reported always, 10 reported sometimes and 14 reported rarely (see Figure 6.4a). All participants reported that they recognized some or all the road delineation markings. Four participants recognized lane markings, three recognized markers, five recognized rumble strips and 16 reported recognizing all of the above (see Figure 6.4b). 21 participants reported that they had no difficulty in perceiving the lane markings at nighttime and six and one participants reported little to moderate difficulty respectively (see Figure 6.4b).

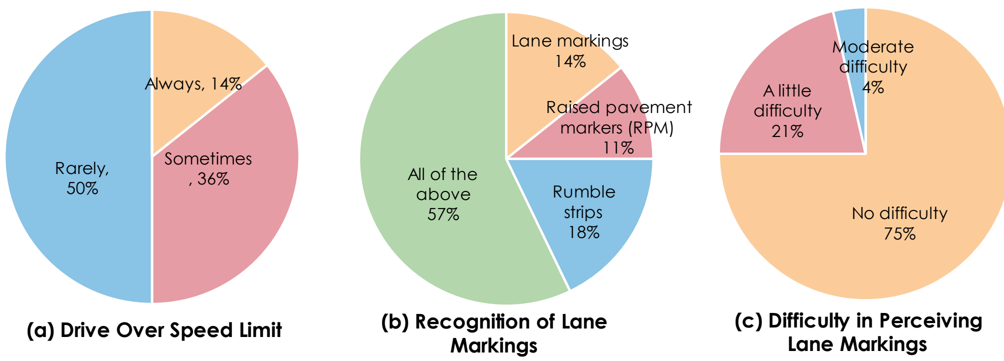


Figure 6.4: Road Safety Awareness in Participants

6.4.5. Visual Acuity

In response to the questions regarding corrective lenses, 12 participants reported they always wore prescriptive lenses, two reported sometimes, and 14 reported never wearing prescriptive lenses (see Figure 6.5a). Of the 14 participants who wore prescriptive lenses, 12 reported they wore single lenses, one reported wearing bifocals, and one reported wearing progressive lenses (see Figure 6.5b). To ensure that their visual ability was accurately captured, the research team also recorded the visual acuity of all participants with a standard eye chart while wearing their prescription lenses on the day of the study. It was found that all participants had the minimum required 20/40 vision for driving (see Figure 6.5c). Four participants had 20/20 vision. 16 participants displayed nearsightedness, i.e., a visual acuity greater than 20/20 (e.g., 20/10 vision). Nine participants displayed farsightedness, i.e., visual acuity less than 20/20 (e.g., 20/40 vision).

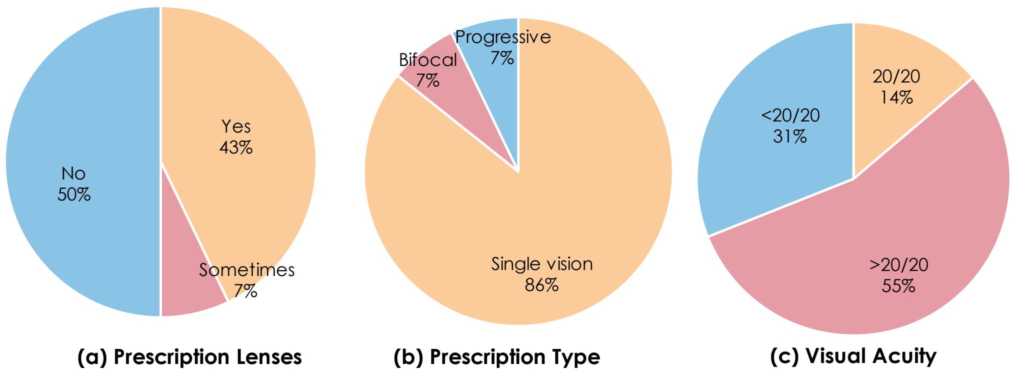


Figure 6.5: Corrective Lenses

6.5. Site A (PRC)-Visibility Study

The main objective of the visibility study conducted at Site A (PRC) was to determine if a marker embedded in a snowplow-resistant depth rumble strip will still be visible to road users under static and dynamic conditions.

6.5.1. Site Description

Site A (PRC) is an 800 ft test segment located at Innovation Blvd, Pickle Research Campus, Austin, at the Performing Agency's research campus (see Figure 6.6). The section lies between a dead-end (Intersection 1 in Figure 6.6) and a four-way intersection (Intersection 2 in Figure 6.6). The distance between the intersections is 1250 ft. The centerline of the segment has rumble strips cut into it and does not have any striping paint.

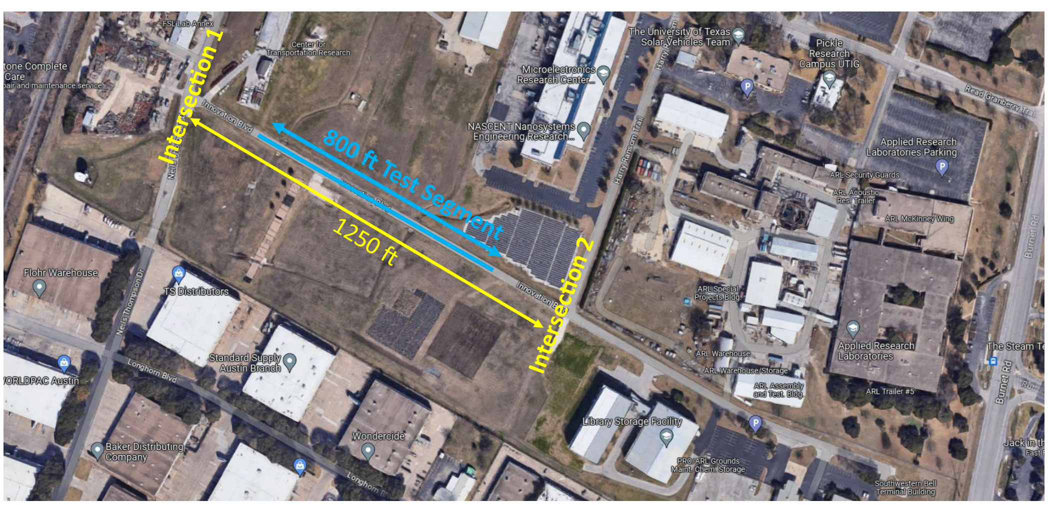


Figure 6.6: Site A (PRC), Test Segmented is Highlighted in Blue

6.5.2. Study Protocol

A full-size sports utility vehicle (SUV), a 2022 Ford Edge was used as the test vehicle at this site. The observations of 18 participants of the markers under static and dynamic conditions were collected. Four to seven different participants were scheduled each day for three days. The testing was conducted after astronomical twilight for two hours. 15 minutes was required to complete the static test and an additional 10 minutes was required to complete the dynamic test per participant. Each participant spent 25 minutes undergoing testing. The protocols for the static and dynamic tests are provided in this section.

6.5.2.1. Static Test

A static test was conducted to determine the minimum visibility distance, i.e., the distance at which a marker embedded in a rumble strip was visible to the participants. The minimum visibility distance for retroreflective pavement markers is 200ft according to TxDOT DMS-4200 [11]. Thus, a key goal was to see whether the markers were visible at this distance when embedded in a snowplow-resistant depth rumble strip. Each marker type (LP1 and RP2) was tested at two rumble strip depths (D_r). The two rumble strip depths were selected based on the snowplow resistance evaluation where it was determined that the snowplow resistant rumble strip depth for LP1 markers was 12 mm and for RP1 markers was 16 mm. As shown in Figure 3.2, LP1 has a lower height than RP1, thus it will sit at a lower protruding height in a rumble strip than RP1 (see Figure 6.7). The following procedure (see Figure 6.8) was followed:

1. Two participants were seated in the front seats of the test vehicle, while the remaining participants waited in the designated waiting area near the test segment. The test vehicle was parked straddling the centerline to enable the same viewing angle for both participants.
2. One LP1 marker was placed in a 12 mm deep rumble strip that was 200 ft from the test vehicle and the headlights were turned on. The passengers were requested to indicate whether they could perceive the marker in the data sheet that was provided to them (see Table 6.1). The headlights were then turned off.
3. The LP1 marker was placed in a 16 mm deep rumble strip and step 2 was repeated.
4. Steps 2 and 3 were repeated for the RP1 marker at the 12 mm and 16 mm rumble depths.
5. Steps 2 -4 were repeated for the remaining distances of 400, 600, and 800 ft.

6. In total each participant observed 16 individual markers and indicated whether they could perceive the marker and their response was recorded on the data sheet.

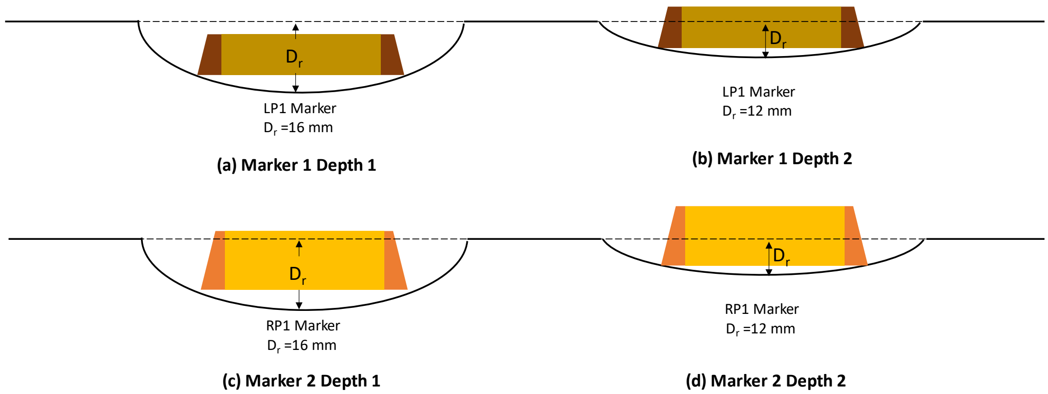


Figure 6.7: Static Test Marker Types and Rumble Strip Depths at Site A (PRC, Austin)

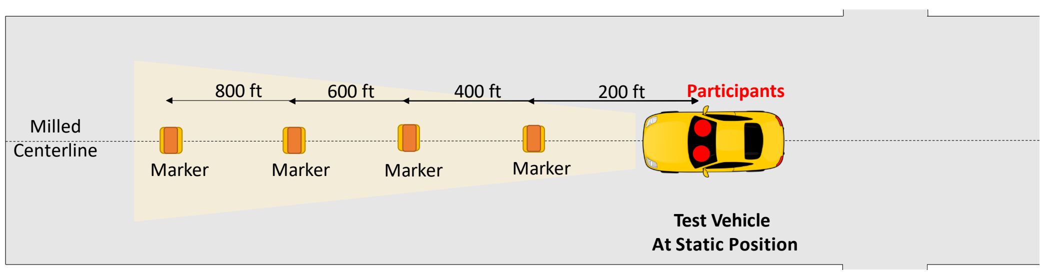


Figure 6.8: Static Test Protocols at Site A (PRC)

Table 6.1: Static Test Data Sheet for Site A (PRC)

Detection Distance	Visible (Yes/No)			
	LP1 Marker		RP1 Marker	
	Rumble Depth 12 mm	Rumble Depth 16 mm	Rumble Depth 12 mm	Rumble Depth 16 mm
200 ft				
400 ft				
600 ft				
800 ft				

6.5.2.2. Dynamic Test

While the static test provided information on the minimum visibility distances, road users tend to observe the markers when they are driving. Dynamic conditions can change the visibility of the markers due to narrowed field of vision that is constantly changing [15–18]. This necessitates quantifying their visibility when the road user is dynamic. The visibility of the two markers was evaluated at their snowplow-resistant rumble strip depths, 12 mm for LP1 markers, and 16 mm for RP1 markers (see Figure 6.9) under dynamic conditions. The following procedure (see Figure 6.10) was followed:

1. LP1 marker was placed in a 12 mm deep rumble strip.
2. One participant was seated on the passenger side of the test vehicle with the headlights on. The remaining participants waited in a designated waiting area.
3. A researcher drove the vehicle at 35 mph from approximately 500ft beyond the test segment to ensure that the marker would come into view at some point during the test.
4. Passengers were requested to verbally announce when they observed the marker and a timer was started by another researcher and stopped when the test vehicle crossed the marker.
5. This time was noted down as the perception time in the data sheet (see Table 6.2) and the perception distance (D_p) was determined from the perception time using Equation 6.1.

$$D_p = \frac{Speed}{Perception\ Time}$$

Equation 6.1

6. Steps 1-4 were repeated for the RP1 marker.

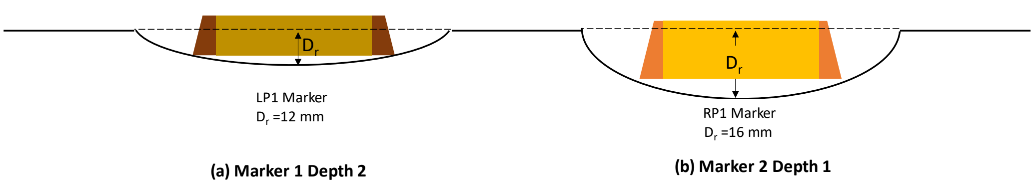


Figure 6.9: Dynamic Test Marker Types and Rumble Strip Depths at Site A (PRC, Austin)

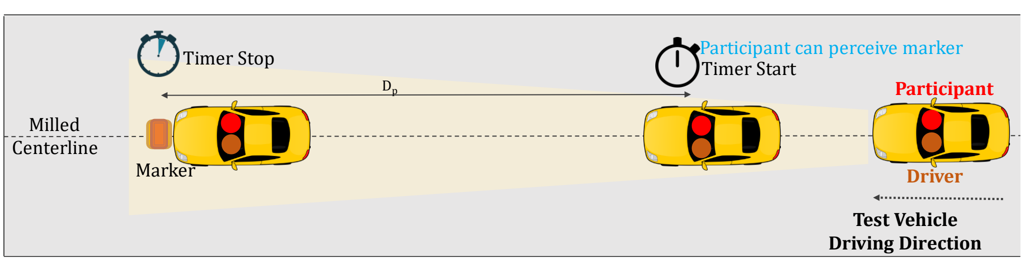


Figure 6.10: Dynamic Test Protocols at Site A (PRC)

Table 6.2: Dynamic Test Data Sheet for Site A (PRC)

Marker Type	Perception Time (s)
LP1 in 12 mm Rumble	
RP1 in 16 mm Rumble	

6.5.3. Results and Discussions

The results of the static and dynamic tests at Site A (PRC Austin) are presented in the following section.

6.5.3.1. Static Test

Figure 6.11 presents the results of the static visibility tests of the LP1 marker. When embedded in a 12 mm deep rumble strip, the marker was visible at 600 ft to 100% of the participants. At 800 ft, 77% of the participants were able to see the marker. 12 mm was the minimum rumble strip depth required for snowplow resistance for the LP1 marker (see Section 5.2.3.2). When embedded at a deeper rumble strip depth, the LP1 marker when embedded in 16 mm rumble strip had very low visibility, even at 200 ft, with only 16% of the participants being able to see it. Interestingly, only one participant could see the marker at 400 ft and zero reported being able to detect the LP1 marker at 600 and 800 ft.

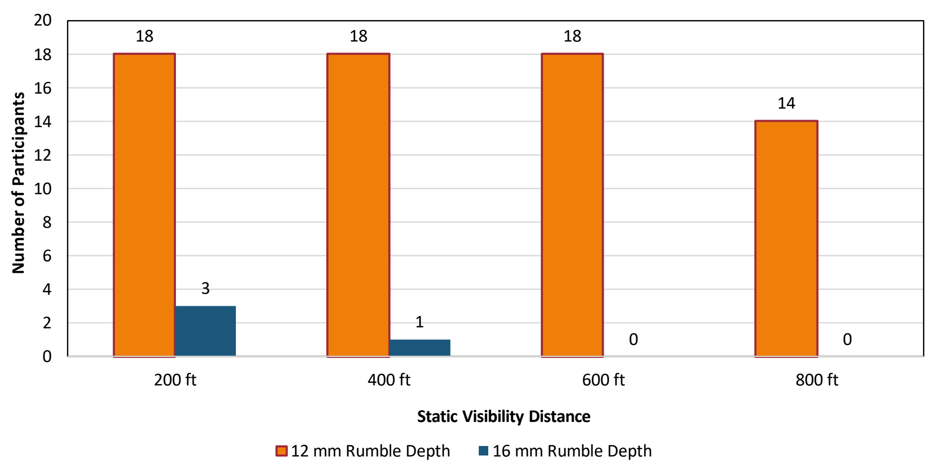


Figure 6.11: Static Visibility Distance of LP1 Markers at Site A (PRC)

Figure 6.12 presents the results of the static visibility tests of the regular-profile RP1 marker. When embedded in a 16 mm deep rumble strip the marker was visible at 600 ft to 100% of the participants. At 800 ft, 44% of the participants were able to see the marker. 16 mm was the minimum rumble strip depth required for snowplow resistance for the RP1 marker (see Section 5.2.3.2). When embedded in a 12 mm rumble strip (shallower than the snowplow-resistant rumble depth) all participants were able to see the markers up to 600 ft. At 800 ft 94% of the participant were able to see the marker. However, it must be noted that an RP1 marker in a 12 mm rumble strip would have a 100% rate of loss from snowplow operations (see Section 5.2.4).

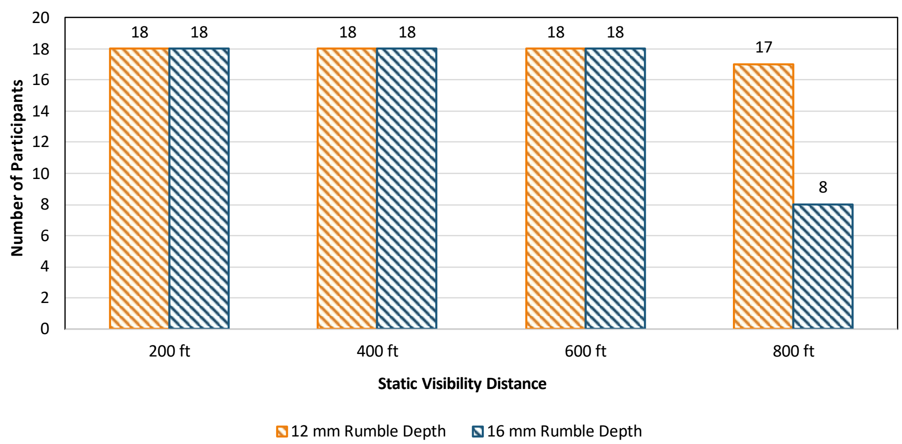


Figure 6.12: Static Visibility Distance of RP1 Markers at Site A (PRC)

Thus, from a static position, the LP1 marker was visible at 600 ft when embedded in a 12 mm deep snowplow-resistant rumble strip and the RP1 marker was visible at 600 ft when embedded in a 16 mm deep snowplow-resistant rumble strip to 100% of the participants. This exceeds the minimum visibility distance according to TxDOT DMS-4200 is 200 ft [11] and KDOT 2206 is 300 ft [19].

6.5.3.2. Dynamic Test

Figure 6.13 presents the visibility distances of the markers under dynamic conditions at their respective snowplow-resistant depth rumble strips. For the low-profile LP1 marker embedded at 12 mm, the visibility distances ranged between 549 ft to 1196 ft. The average distance was 909 ft. For the regular-profile RP1 marker embedded at 16 mm, the visibility distances ranged between 462 ft to 1109 ft. The average distance was 781 ft. The speed of the test vehicle was 35 mph. Based on the FHWA-RD-97-152 report, the minimum visibility distance at 25 mph is 110 ft, and at 55 mph is 250 ft. Based on linear interpolation, this would result in a minimum visibility distance of 163 ft at 35 mph. Thus, when embedded in snowplow-resistant depth rumble strips, both markers were visible under dynamic conditions.

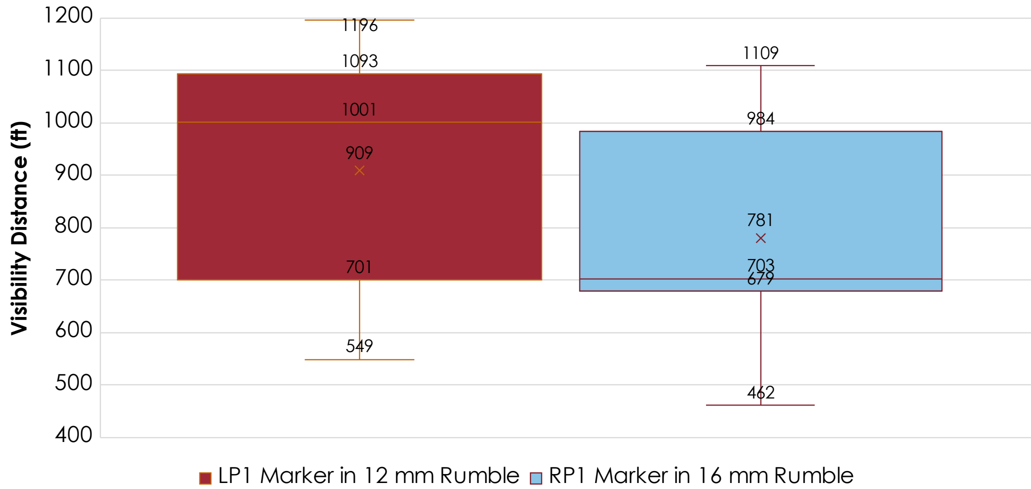


Figure 6.13: Dynamic Visibility Distance of Test Markers at Site A (PRC)

6.6. Site II: US 180, Anson

The main objective of the study conducted at Highway Site II (US 180, Anson) was to verify the visibility results obtained at the research site under field conditions. At the research site, the testing speed was limited to 35 mph, whereas at the highway site, the visibility was evaluated at highway speeds of 55 mph. This allowed the research team to capture the visibility of the markers embedded in rumble strips in realistic driving conditions [20].

6.6.1. Site Description

Site II is a 2.3-mile test highway segment located at US 180, Anson (see Figure 6.14). The segment is a two-way highway with rumble strips along the centerline. The highway slopes from west to east with a small hill on the western portion. 99 RP1 markers were embedded in the rumble strips along the centerline for a length of 1.4 miles. There is a 400 ft gap with no markers followed by 96 Stimsonite LP1 markers which were embedded in the rumble strips along the centerline for a length of 0.8 miles. The average rumble strip depth at this site was 12.95 mm with a maximum of 15.45 mm and a minimum of 10.15 mm. The markers were spaced at either 40 ft in regions with low visibility or 80 ft in areas with good visibility.

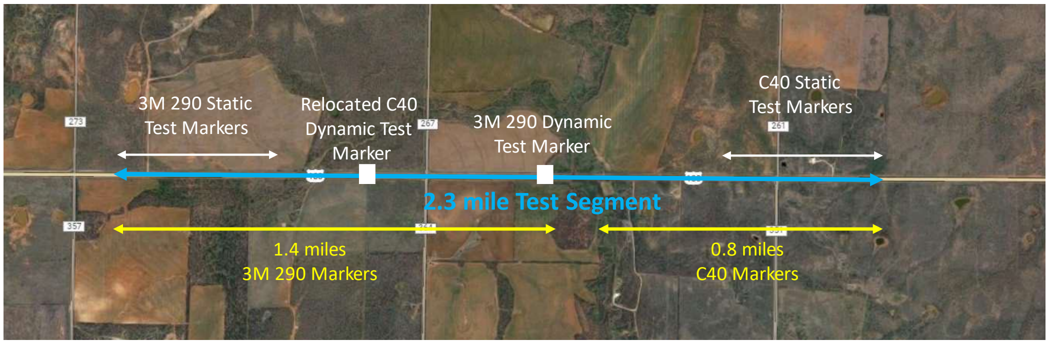


Figure 6.14: Site II ([US 180, Anson]), Test Segmented is Highlighted in Blue

6.6.2. Study Protocol

As this test segment was part of an in-service highway adequate measures were taken to ensure the safety of the researchers and participants. Traffic control was provided for the test segment. One lane of the highway was cordoned off using reflective traffic cones, preventing public traffic from entering the test segment. A pilot car was used to lead the public along the neighboring lane in both directions in an alternating manner. The study was conducted over five hours on one day beginning at 9 PM and ending at 1 AM. The time taken to complete testing for one participant was 20 minutes. A full-size sports utility vehicle (SUV), a 2022 Nissan Murano was used as the test vehicle at this site. The observations of 11 participants of the markers under static and dynamic conditions were collected. The study was conducted over five hours on one day after astronomical twilight, beginning at 9 PM and ending at 1 AM. The time taken to complete testing for one participant was 20 minutes. The protocols for the static and dynamic tests are provided in this section.

6.6.2.1. Static Test

A static test was conducted to determine the maximum visibility distance of the markers embedded in rumble strips under field conditions. This was the maximum distance up to which participants were able to distinguish individual markers. 40 consecutive markers of each type were selected for the static test and all other nearby markers were covered. Two marker types (RP1 and LP1) were evaluated. Participants were seated in the passenger side of the test vehicle and driven to the RP1 marker test segment. The markers in this segment were spaced 80 ft apart. The test vehicle was parked on the right lane facing west and the participant was requested to report the number of markers that were distinctly visible to them (see Figure 6.15a). Then, the participant was then driven to the LP1 markers test segment. The markers in this segment were spaced 40 ft apart. The vehicle was parked in the right lane facing east and the participant was requested to report the number of markers that were distinctly visible to them (see Figure 6.15b). All markers were evaluated for the static test under as-installed conditions. The average rumble strip depth for the LP1 markers was 12.6 mm and for RP1 markers was 12.3 mm. While the LP1 markers were somewhat in snowplow-resistant depth rumble strips (12 mm depth) the RP1 markers were in significantly shallower rumble strips than the snowplow-resistant depths (16 mm). Thus, the RP1 markers were not evaluated at snowplow-resistant depths.

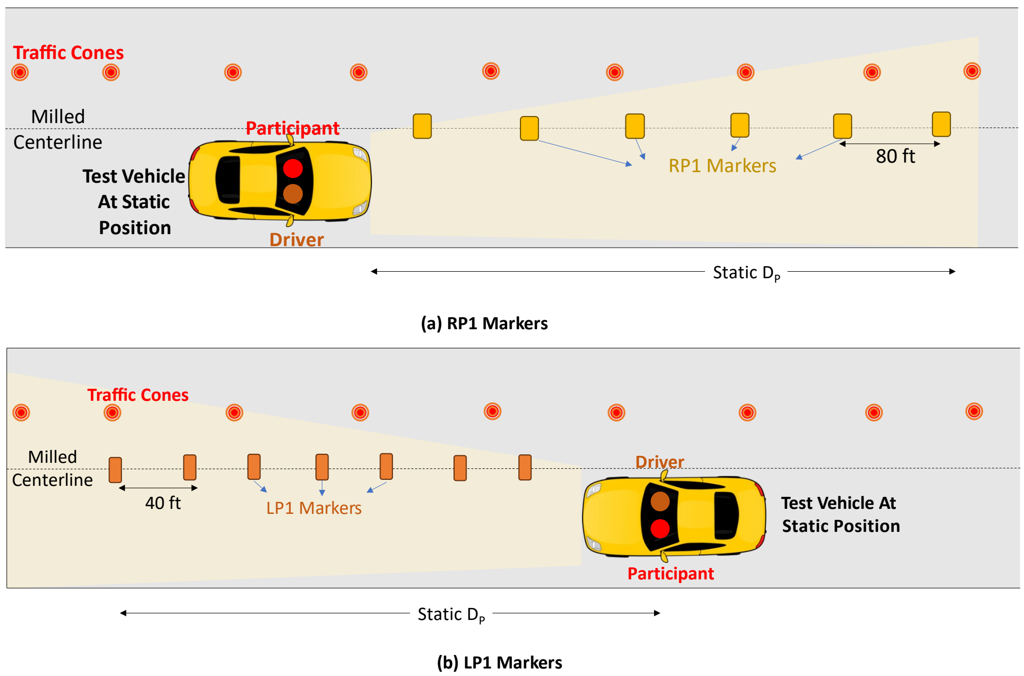


Figure 6.15: Static Test Protocols at Site II (US 180, Anson)

6.6.2.2. Dynamic Test

Like the dynamic test conducted at Research Site A, the perception distance was determined at Highway Site II under dynamic conditions. However, the dynamic test at the highway site was conducted at higher speeds (55 mph) than at the research site (35 mph). It is seen that the speed at which the test vehicle travels is a major factor affecting visibility distance. This necessitates quantifying the visibility of the embedded markers at highway speeds.

For the dynamic test, only one marker of each type was isolated and 30 markers before and after the test marker were covered using sandbags. The visibility of the two marker types (LP1 and RP2) was evaluated at their respective snowplow-resistant depth rumble strips (see Section 5.2.3.2). Two rumble strips were deepened, and the markers were embedded in them, 12 mm for LP1 markers and 16 mm for RP1 markers.

Figure 6.16 presents a schematic representing the dynamic test protocol for both marker types. The RP1 marker was approached from the east and the LP1 marker from the west on the right lane. Participants were seated on the passenger side of the test vehicle with the headlights on. A researcher drove the vehicle at 55 mph from over 2000 ft away to ensure that the marker would come into view at some point during the test. Passengers were requested to indicate when they observed the marker, at which point a researcher (different from the previous one) started a timer. The researcher stopped the timer when the test vehicle crossed the marker. This time was recorded as the perception time. The perception distance (D_p) was determined using Equation 6.1.

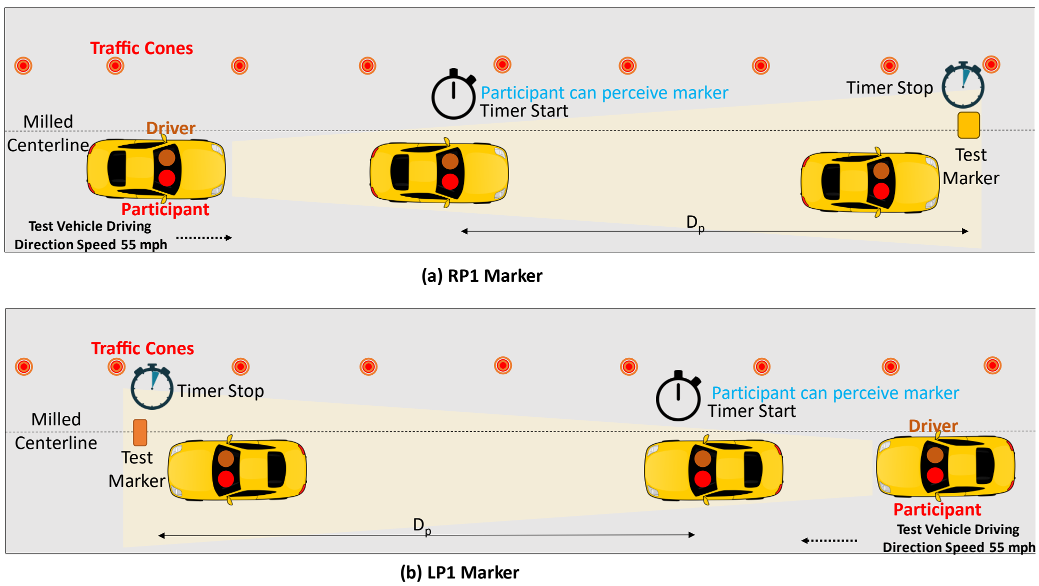


Figure 6.16: Dynamic Test Protocols at Site II (US 180, Anson)

6.6.3. Results and Discussions

The results of the static and dynamic tests at Site II (US 180, Anson) are presented in the following section.

6.6.3.1. Static Test

Figure 6.17 presents the visibility distance of the markers under static conditions. As a reminder, the LP1 markers are spaced 40 ft apart and the average rumble strip depth for these markers in the test segment was 12.6 mm. For the LP1 markers, on average, participants were able to individually count 11 markers, with one participant seeing a maximum of 16 markers. This equates to an average detection distance of 433 feet, with a minimum detection distance for the LP1 marker of 280 ft and a maximum detection distance of 640 feet. From a static position, the low-profile LP1 marker was visible at 433 ft when embedded in a 12.6 mm deep snowplow-resistant rumble strip, which exceeds the minimum visibility distance of 200 ft specified in TxDOT DMS-4200[11]. Whereas for the RP1 markers, they were spaced at 80 ft and the average rumble strip depth for these markers was 12.3 mm. On average, participants were able to individually count 11 markers with one participant seeing a maximum of 15 markers. This equates to an average detection distance of 909 feet, with a minimum detection distance for the RP1 marker of 720 ft and a maximum detection distance of 1200 ft. However, it must be noted that the snowplow-resistant rumble strip depth for the RP1 markers for snowplow resistance is 16 mm, thus, these markers at 12.3 mm will most likely be lost during snowplow operations.

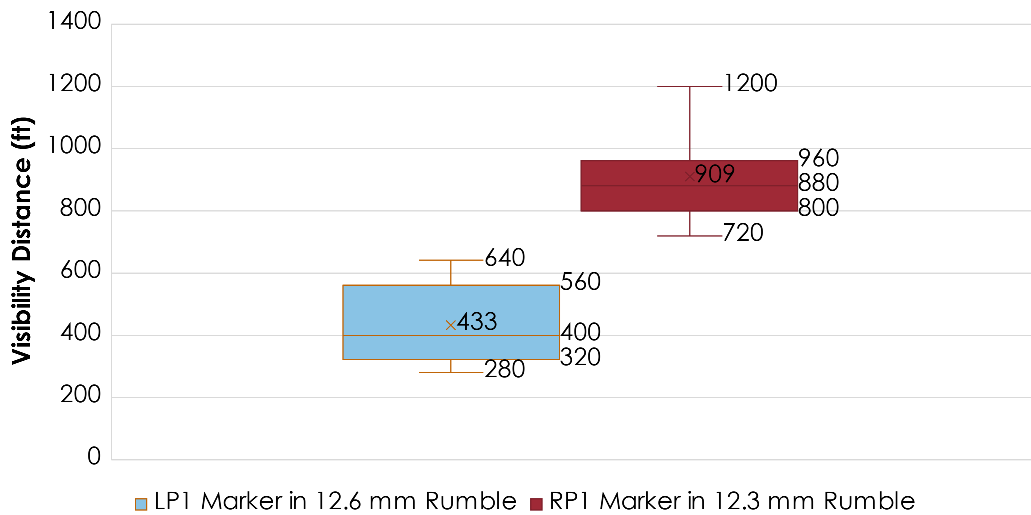


Figure 6.17: Static Visibility Distance of Test Markers at Site II (US 180, Anson)

6.6.3.2. Dynamic Test

Figure 6.18 presents the visibility distances of the markers under dynamic conditions at their respective snowplow-resistant depth rumble strips. For the low-profile LP1 marker embedded at 12 mm, the visibility distances ranged between 0 and 151 ft with only one participant seeing the marker at 441 ft. The average distance was 83 ft. Five of the 11 participants did not see the marker at all. For the regular-profile RP1 marker embedded at 16 mm, the visibility distances ranged between 194 and 605 ft. The average distance was 446 ft.

The speed of the test vehicle was 55 mph. Based on the FHWA standards the minimum visibility distance at 55 mph is 250 ft [21]. Thus, at the snowplow-resistant depth rumble strip, the RP1 marker was visible and the LP1 marker was not visible under dynamic conditions.

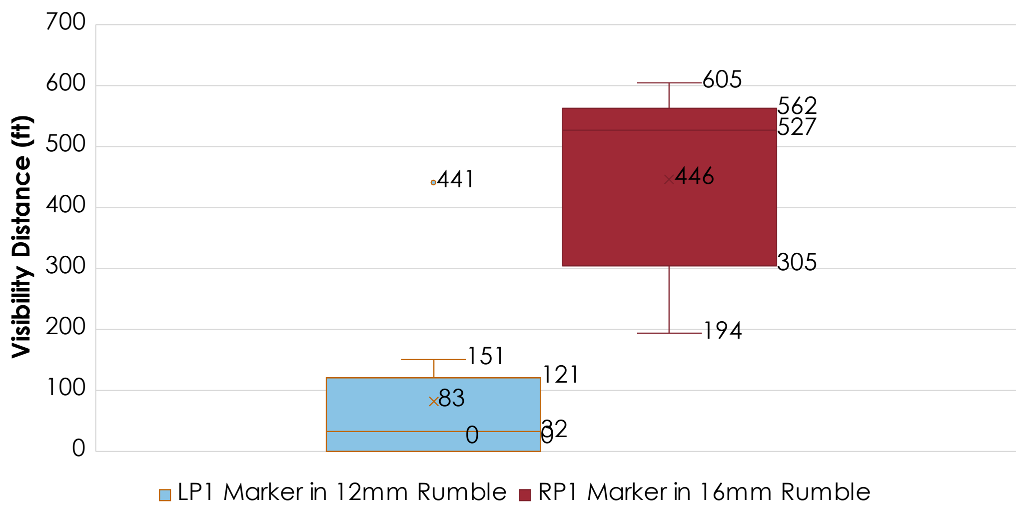


Figure 6.18: Dynamic Visibility Distance of Test Markers at Site II (US 180, Anson)

6.6.3.3. Comparison of the Two Sites

When compared to the dynamic test at Site A (PRC) the visibility distances were lower at Site II (US 180, Anson) as seen in Figure 6.13 and Figure 6.18. There were several differences in the sites:

- Higher test speed at the highway site (55 mph) than at the research site (35 mph) may have resulted in participants spotting the markers at a shorter distance at the highway site than at the research site [22].
- The markers at the highway site were almost 3 years old. They were exposed to wear and tear from traffic, UV radiation, and weather. This can cause reduced retroreflectivity of the marker lenses leading to reduced visibility [20]. In contrast, the markers at the research site were brand new.
- The presence of distractions like reflective lane markings, reflective strips on the traffic cones, and flashing lights from the truck-mounted attenuator (TMA) also may have played a role in reducing the distance at which participants were able to spot the marker (see Figure 6.16). In comparison, at Site A (PRC) there were no lane markings, traffic cones, and TMAs to distract the participant (see Figure 6.10).
- This was of particular importance for the LP1 marker, which had very low visibility distances. The traffic control equipment placed on the roadway was present to comply with highway safety rules, however, they added additional reflective items that could potentially interfere with the visibility of the test marker. For the LP1 markers (see Figure 6.19a), the participants were on a downward slope with the TMA on the eastern side visible with flashing lights at the end of the test site. This was not the case with the RP1

marker as an upward slope towards the hill on the western side blocked the flashing lights from the TMA on the western side (see Figure 6.19b).

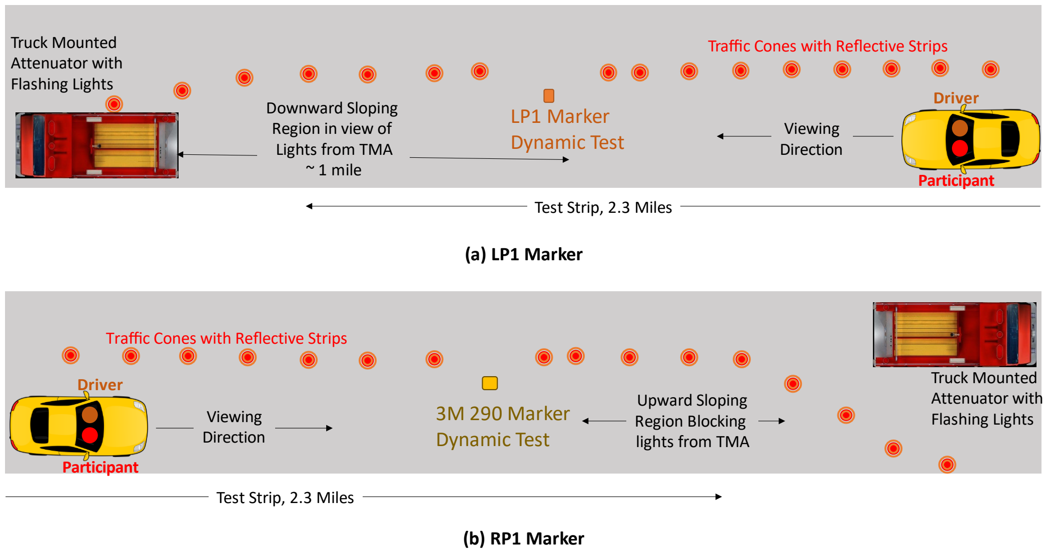


Figure 6.19: Distractions from Reflective Cones and Flashing Lights during Dynamic Test at Site II (US 180, Anson)

6.7. Participant Characteristics and Visibility

The visibility data was analyzed and correlated with the information of the participants which was collected during the intake and background surveys. This analysis provides additional understanding about how participant characteristics like age, sex assigned at birth, driving experience, and driving styles can influence the visibility of the markers [13,14].

For this analysis, the dynamic test data from both Sites A and B were used. As the test protocols at the two sites were the same except for the speed of the test vehicle (35 mph at Site A and 55 mph at Site II), the two visibility distances were merged to create a larger dataset. Since one participant (herein called Participant X[#]) participated in the studies at both sites, this presents a unique opportunity to gain insight into the relationship between speed and visibility at the two test sites. Participant X's visibility distance of the RP1 marker was 562 ft at Site II and 1108 ft at Site A. Thus, the ratio of the visibility distance of Participant X at 55 mph vs 35 mph was 0.51, which means that the RP1 marker was detectable at approximately half the distance at 55 mph than at 35 mph. To further leverage this

[#] Participant X was a female in the 31-40 year age group with normal vision and over 10 years of driving experience.

unique opportunity, a dataset was generated by converting the visibility distances at Highway Site II to Research Site A using Equation 6.2:

$$D_{A,35mph} = 0.51\, D_{II,55mph}$$

Equation 6.2

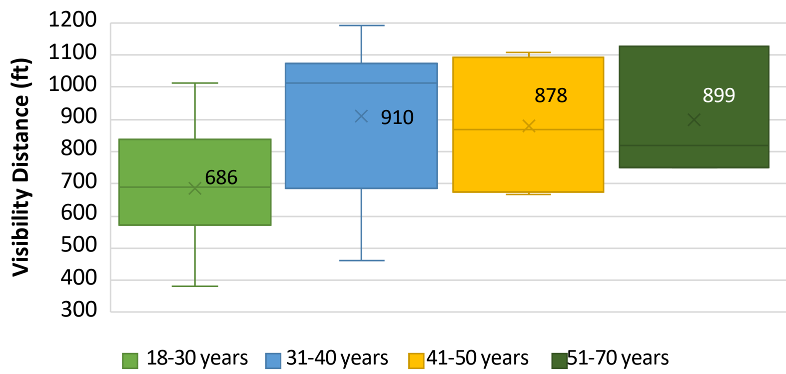
where $D_{II,55mph}$ is the detection distance of a participant at Site II traveling at 55 mph, and $D_{A,35mph}$ represents the participant's estimated marker detection distance if the participant was traveling at 35 mph at Site A. A similar analysis was not performed for the LP1 marker as Participant X was not able to see the marker at Site II and their visibility distance was 0 ft. Thus, the participant characteristics analysis is performed with the visibility data of the RP1 marker.

6.7.1. Role of Age, Sex, and Visual Acuity

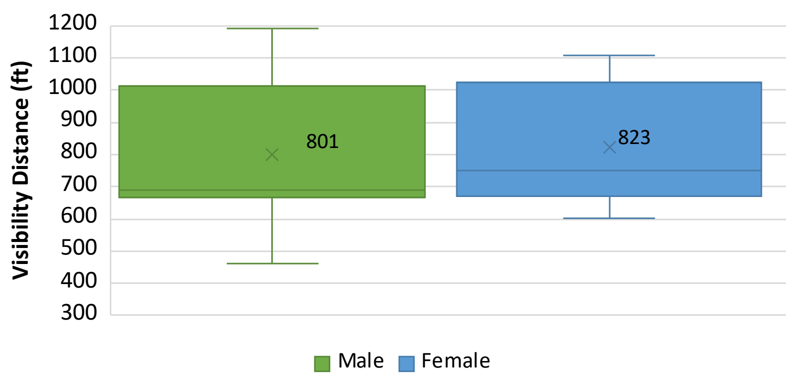
Figure 6.20 shows the influence of age and sex assigned at birth on the visibility detection distance for the RP1 marker when traveling at 35 mph. The dataset comprises the visibility data directly obtained from the participants at Site A (PRC) study and the visibility distances estimated using Equation 6.2 for the participants at Site II (US 180, Anson).

Visual acuity decreases with an increase in age [23], and as shown in Figure 6.20, from 31 to 70 years of age, the visibility detection distance decreased with the age of the participants. The average detection distance was reduced from 910 ft to 899 ft from the 31-40 years age group participants to the 51- 70 years age group participants. However, the participants in the 18-30 year age had the lowest visibility distances of all age groups, which could be due to younger drivers being less prone to fully scan a roadway than more experienced drivers [24] (see Figure 6.20a). However, for all age groups, the detection distance for the RP1 marker exceeded the minimum value of 200 ft per TxDOT standards [11].

Overall, participants assigned female at birth (AFAB) displayed a higher average marker visibility detection distance than the participants assigned male at birth (AMAB). While AMAB humans often display better dynamic visual acuity than AFAB humans [23], AFAB humans generally showed higher sensitivity to contrast under scotopic conditions [25]. Scotopic conditions are environments with low lighting as in the case of this study where participants were required to detect a bright object in a relatively dark environment (see Figure 6.20b). Thus, the slightly higher average detection distance could be due to the scotopic conditions of the test environment.



(a) Effect of Age on Marker Detection Distance



(b) Effect of Sex Assigned at Birth on Marker Detection Distance

Figure 6.20: Effect of Participant Demographics on RP1 Marker Detection Distance

The capacity to detect an object's is highly dependent on one's visual acuity. Figure 6.21 shows how the influence of the participants' visual acuity on the detection distance for all the markers. Participants with eyesight greater than 20/20 (i.e., far-sighted vision) exhibited the highest visibility distances followed by participants with 20/20 vision and then participants with eyesight lower than 20/20 vision. However for all participants with a vision at or better than 20/40, the detection distance for RP1 marker exceeded the minimum value of 200 ft per TxDOT standards [11]. The minimum vision standard as per the Texas Administrative Code for driving is 20/40 with or without corrective lenses [26].

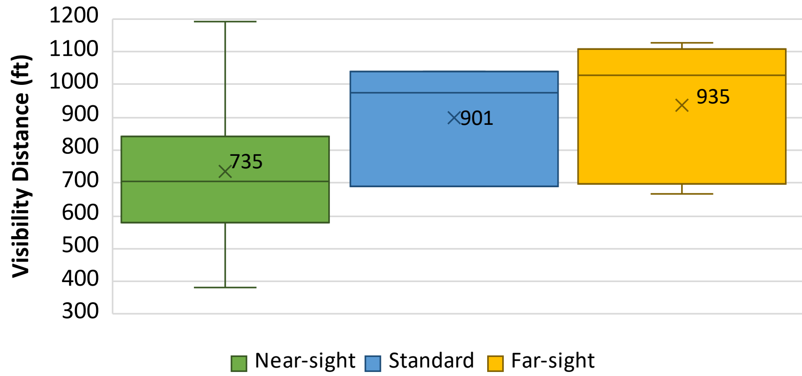


Figure 6.21: Effect of visual acuity on marker detection distance (where 20/20 vision is termed as "standard")

6.7.2. Role of Driving Experience

Figure 6.22 shows the influence of the driving experience of the participants (number of years they have been driving) on the visibility distance. It was seen that on average participants with less driving experience had lower visibility distances than the participants with more driving experience. Studies have shown that experienced drivers tend to have a larger useful field of view and exhibit higher visual attention [27,28].

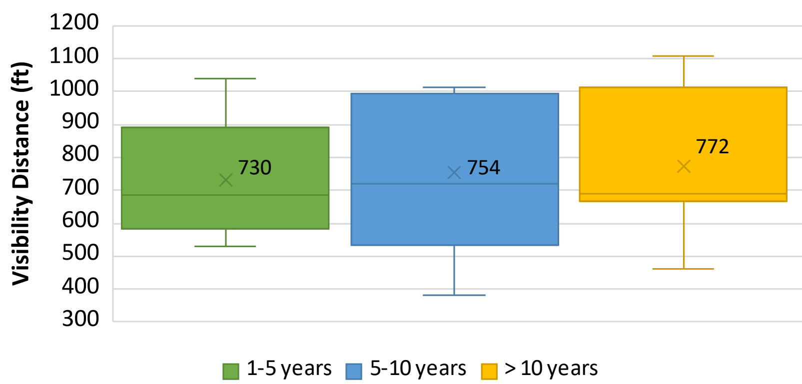
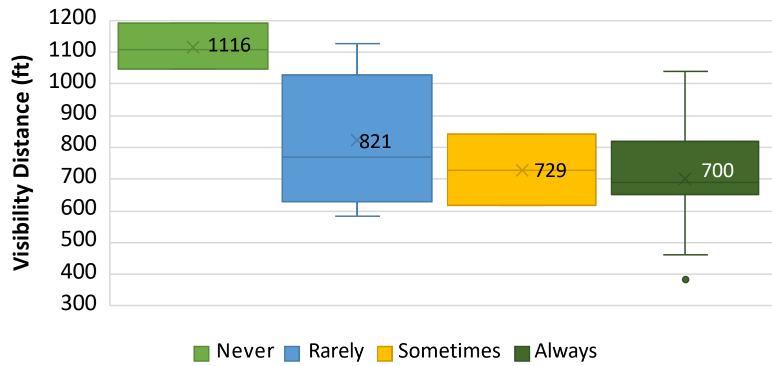


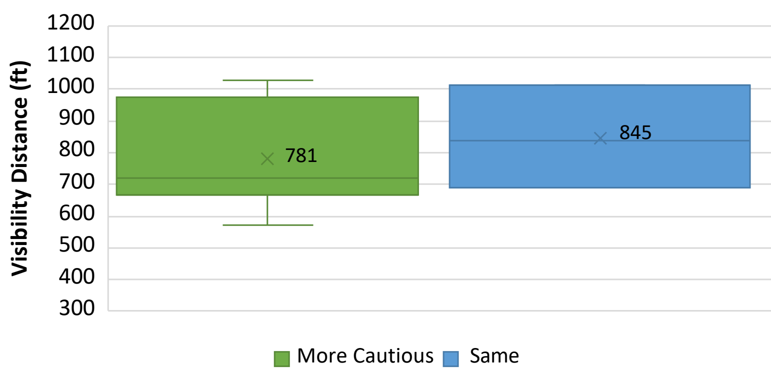
Figure 6.22: Effect of Driving Experience on Marker Detection Distance

6.7.3. Role of Risk Behavior

The psychology of drivers is a well-researched factor influencing the outcomes of driving behavior. Cautious drivers who take fewer risks while driving have lower rates of accidents during driving [29]. However, cautiousness is reported to result in slower perception of information [30]. This is seen in the analysis of visibility distances based on the propensity of a participant to drive at speeds exceeding the speed limit in Figure 6.23a. Participants who are less likely to speed had lower visibility distances than the participants likely to speed more often. Similar trends were seen in the participants who indicated that they drive more cautiously during nighttime conditions than during daylight conditions. Specifically, participants who drive more cautiously during nighttime conditions had a lower marker visibility detection distance than participants who reported driving the same in nighttime and daylight environments (see Figure 6.23b).



(a) Effect of Propensity to Speed on Marker Detection Distance



(b) Effect of Cautiousness While Driving in Nighttime Conditions on Marker Detection Distance

Figure 6.23: Effect of Risk-taking Behavior on Marker Detection Distance

6.8. RPM Perception Survey

After completion of the visibility study participants were asked to complete a survey where they were asked to provide their views on the retroreflective pavement markers (see Appendix B). At Research Site A (PRC) participants were only asked to answer questions about the overall visibility of the markers embedded in rumble strips. At Site II (US 180, Anson) in addition to the overall visibility, participants were also asked to compare the markers to lane markings and rate the utility of the markers in delineating the pavement centerline. Figure 6.24 shows the results of this survey. Most participants reported that the overall visibility of the markers embedded in the rumble strips was “Good” and “Very Good” with only one participant reporting “Fair” and none reporting “Bad” or “Very Bad” (see Figure 6.24a). Most participants also reported that the embedded markers were more visible than the pavement markings at Highway Site II with 1 participant being ambivalent and 2 disagreeing (see Figure 6.24b). All participants also reported that the markers aided them in seeing the centerline with 10 participants claiming that the markers were “Extremely Useful”, one claiming “Somewhat Useful” and none selecting the “Not Useful” options (see Figure 6.24c). Thus, it was seen that the participants in general had positive feedback about the retroreflective pavement markers embedded in the rumble strips.

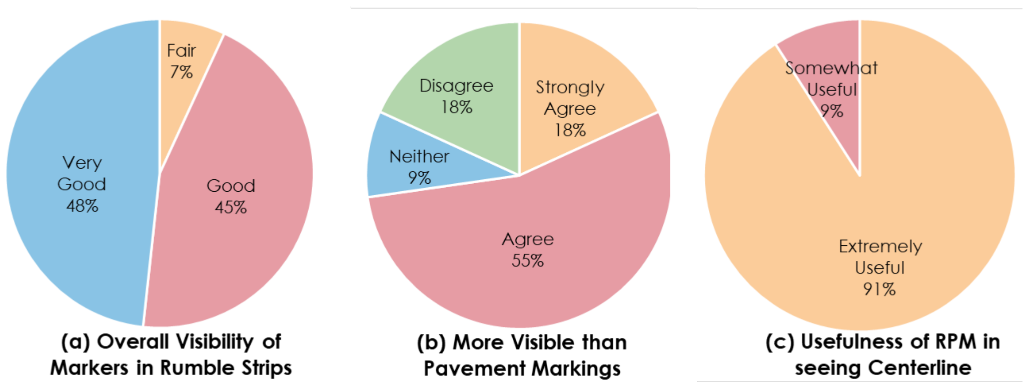


Figure 6.24: Participants’ Perception of Markers Embedded in Rumble Strips

6.9. Maximum Rumble Strip Depth

While it was seen that both marker types passed minimum visibility requirements when embedded in snowplow-resistant depth rumble strips, under field conditions it is not always possible to construct rumble strips at these specific depths due to variations occurring during cutting of the rumble strips.

As such, a follow-up study was conducted to determine the visibility of the markers in rumble strips deeper than the snowplow-resistant depth. This was done to determine the tolerance values for rumble strip depth, i.e., the maximum depth up to which the markers would still be visible to the road user. This study was conducted using a sample size of five participants with a standard sedan-type 2012 Chevrolet Cruze. It must be noted that the visibility tests conducted in the previous sections were done with a standard SUV-type vehicle. The viewing angle in sedans is typically lower than in SUVs, leading to lower visibility distances. The demographic information of the participants is presented in Table 6.3.

Table 6.3: Participant Demographics for Maximum Rumble Strip Depth Evaluation

Participant Number	Age Group	Sex Assigned at Birth	Driving Experience	Visual Acuity
1	31-40 years	Male	>10 years	20/20
2	31-40 years	Female	>10 years	20/20
2	41-50 years	Male	>10 years	20/15
3	41-50 years	Female	>10 years	20/25
4	51-70 years	Male	>10 years	20/15

Table 6.4 presents the visibility distances of markers embedded in rumble strips at different depths. It was seen that at the snowplow-resistant depths, both markers were visible at 600 ft. When the depth was increased by 2 mm, the visibility was reduced to 150 ft and when increased by 4 mm, the visibility decreased further to only 50 ft. Thus, when the rumble strip depth increases to more than the snowplow-resistant depths, the markers do not pass minimum visibility requirements as per TxDOT standards [11]. Thus, the maximum depth for optimal visibility is the same as the snowplow-resistant depth (i.e., *12 mm for LP1 markers and 16 mm for RP1 markers)*.

Table 6.4: Visibility Detection Distance of Low profile (LP1) and Regular profile (RP1) Markers Embedded in Rumble Strips

Marker Type	Depth	Static Visibility Distance	Passes Minimum Visibility
LP1	12 mm*	600ft	Yes
	14 mm	150ft	No
	16 mm	50ft	No
RP1	16 mm*	600ft	Yes
	18 mm	150ft	No
	20 mm	50ft	No
*Minimum rumble strip depth for snowplow resistance			

It must be noted that these visibility distances are for one single marker, whereas under field conditions there will be a continuous line of markers, which are more visible than a single isolated marker. Thus, leeway may be provided during the cutting of rumble strips, and currently, TxDOT guidelines specify rumble strip depts of 12 ± 3 mm (i.e., a three-millimeter tolerance).

Based on the results from the follow-up study, markers were visible at 150 ft when they are installed in rumble strips within 2 mm of the snowplow-resistant depth.

Thus, 2 mm is set as the tolerance. **Hence, the critical rumble strip depth that will enable the markers to have adequate snowplow resistance and visibility is 14 ± 2 mm for the LP1 markers and 16 ± 2 mm for the RP1 markers**.

Since the TxDOT minimum visibility distance is 200 ft, the reduced visibility distances arising from installing the markers in strips deeper than the maximum depth for optimal visibility (which can happen when rumble strips depths are closer to the maximum tolerance depth versus the minimum tolerance depth) may be compensated by appropriately reducing the spacing between the markers embedded in rumble strips. For example, instead of spacing markers 40 feet apart, the markers are spaced 35 feet apart.

6.10. Conclusions

A human visibility study was conducted to evaluate the visibility of the retroreflective pavement markers embedded in rumble strips at snowplow-resistant depths. Two sites were selected for this visibility study, research Site A (PRC, Austin) with 18 participants and highway Site II (US 180, Anson) with 11 participants. Two markers were evaluated, low-profile Stimsonite C40 (LP1) and regular-profile 3M 290 (RP1) at their respective snowplow-resistant rumble depths of 12 mm and 16 mm. The visibility of each marker was evaluated using two tests, static and dynamic, and after testing almost all participants had positive opinions regarding the use of markers embedded in rumble strips to aid in centerline delineation.

The regular-profile marker exceeded minimum visibility requirements as per TxDOT standards under static and dynamic conditions at low and highway speeds. The low-profile marker exceeded minimum visibility requirements as per TxDOT standards under static and dynamic conditions at low speeds but did not meet minimum visibility requirements at highway speeds. This is attributed to the high amounts of visual distractions during the low-profile marker testing, as such, additional visibility studies should be conducted to confirm the low-profile marker data.

The visibility of both marker types reduced drastically when placed in rumble strips deeper than the snowplow-resistant rumble strip depths. Compared to current rumble strip depth guidelines, deeper rumble strips with tighter tolerances are recommended and the reduced visibility distances arising from the deeper rumble strips may be compensated by appropriately reducing the spacing between the markers embedded in rumble strips.

Chapter 7. Conclusions and Recommendations

The loss and damage to retroreflective raised pavement markers due to snowplow operations lead to reduced road safety due to the non-presence of functional markers and monetary losses to TxDOT from having to reinstall the markers before the end of their service life. Rumble strips can be multifunctionalized by embedding markers in them to provide snowplow resistance to the markers while also fulfilling their primary duty of alerting drivers of lane departures during driving.

The study found that controlling depth during the cutting of the rumble strips is crucial for the successful deployment of this approach. Low-profile Stimsonite C40 markers embedded in 14 ± 2 mm deep rumble strips and regular-profile 3M 290 markers embedded in 16 ± 2 mm deep rumble strips are snowplow resistant and visible to road users, albeit with lower visibility distances. The lowered visibility distances may be compensated by appropriately reducing the spacing between markers.

The research work was divided into six tasks. The major conclusions drawn from each task are presented in the following sections, along with the recommendations for better snowplow resistance of the markers.

7.1. Chapter 2: Site Selection

Seven sites were part of this study. Four new highway sites, Site I (TX 176, Big Spring), Site II (US 180, Anson), Site III (US 70, Crowell), and Site IV (US 385, Levelland), were selected for the study. Two sites, Site V (US 380, Throckmorton) and Site VI (SL 335, Amarillo), from the original research project 0-6955 were also evaluated further. In addition, the research Site A at PRC, Austin was used to conduct human visibility studies along with one highway Site II (US 180, Anson).

7.2. Chapter 3: Installation of Markers

Three marker types with differing geometries and reflectivity were evaluated in this study. Low-profile marker Stimsonite C40 (LP1), and regular-profile markers 3M 290 (RP1) and Stimsonite C80 (RP2). Around 100 each of the LP1 and RP1 markers were installed at sites I, II, VI, V, and VI. At Site III only 100 of the RP2 markers were installed and no low-profile markers were installed due to contractor constraints. The markers were embedded in the centerline rumble strips at the highway sites by the receiving agency per the installation guide provided by the performing agency.

7.3. Chapter 4: Site Evaluations

Site surveys were conducted at the highway sites after the markers were embedded in the rumble strips and before being snowplowed to collect geometric information about the markers (protruding height) and rumble strips (depth) and establish a baseline condition for the markers. A preliminary qualitative assessment of the nighttime visibility of the embedded markers was also conducted. The following conclusions were drawn:

- The protruding height of the marker, i.e., the height of the marker protruding above the pavement surface is an important factor that can predict the survival rate of a marker undergoing snowplow operations and visibility. This is the area that can be potentially damaged by a snowplow blade going over it. Similarly, this is the area of the marker lens that is visible to a road user.
- The protruding height of the marker is dependent on three factors: the height of the marker, the thickness of the bitumen adhesive, and the depth of the rumble strip. For a given marker type and bitumen thickness, the protruding height of the marker is largely dependent on the rumble strip depth.
- The rumble strip depths at the sites varied significantly, with depths ranging from 1.95-19.25 mm. This was beyond the specified range of 12 ± 3 mm as per TxDOT standards.
- The nighttime visibility of the embedded markers under static and dynamic conditions showed promising initial results with the low-profile markers being detectable from approximately 1500 ft and regular-profile markers being detectable from approximately 2100 ft.

7.4. Chapter 5: Snowplow Resistance Evaluation

Site evaluations were conducted by the research team after receiving notice from TxDOT district engineers that snowplow operations were conducted at the six highway sites. The following conclusions were drawn:

- The centerline at Site I (TX 16, Big Spring) and Site II (US 180, Anson) were most likely not plowed, thus the data collected from these sites were not used to evaluate the snowplow resistance of markers.
- Rumble strip and marker geometry are critical to the snowplow resistance of the retroreflective pavement marker placed in the rumble strips.
- Post snowplow operations, markers were either found to be functional despite snowplow operations (capable of retroreflectivity) or non-functional due to snowplow operations (incapable of retroreflectivity).

- The retention rate of the markers was dependent on the rumble strip depth as this impacted the protruding height of the marker. The markers were installed in a bottomed-out manner, i.e., the base of the markers was pushed in till it reached the bottom of the rumble strip.
- Based on the research conducted in this project, the minimum snowplow-resistant depth for a given marker when installed using the bottom-out approach can be predicted based on the marker height.
- The probability of a marker surviving a snowplow event when embedded in a rumble strip that was at the snowplow-resistant depth was ~75% for both marker types.
- The probability of survival reduces drastically if the rumble strip depth decreases beyond the snowplow-resistant depths.

7.5. Chapter 6: Human Visibility Study

A human visibility study was conducted to evaluate the visibility of the retroreflective pavement markers embedded in snowplow-resistant depth rumble strips. The low-profile (LP1) and regular-profile (RP1) markers were evaluated under static and dynamic conditions at two sites, research Site A (PRC, Austin) with 18 participants and highway Site II (US 180, Anson) with 11 participants. The background and demographic data were collected from all participants as well. The following results were obtained:

- The RP1 marker exceeded minimum visibility requirements as per TxDOT standards under static and dynamic conditions at low and highway speeds.
- The LP1 marker exceeded minimum visibility requirements as per TxDOT standards under static and dynamic conditions at low speeds but did not meet minimum visibility requirements at highway speeds.
  - This is attributed to the unique field conditions during the testing of these markers and a follow-up test to confirm the data is recommended.
- Participants in general had positive feedback about the retroreflective pavement markers embedded in the rumble strips.
- Increasing the depth of the rumble strip led to drastically reduced visibility distances. However, it is not possible to cut rumble strips to exact dimensions under field conditions. The range of acceptable rumble strip depth is set to 14 ± 2 mm for LP1 and 16 ± 2 mm for RP1 markers. This changes from the current rumble strip depth guidelines of 12 ± 3 mm.
- Deeper rumble strips with tighter tolerances are recommended and the reduced visibility distances arising from the deeper rumble strips may be

compensated by appropriately reducing the spacing between the markers embedded in rumble strips.

7.6. Recommendations

Rumble strip depth is an important factor influencing both the snowplow resistance and visibility of the markers embedded in the rumble strips. The depth of the rumble strips, as well as the tolerance levels, need to be modified for the successful deployment of this approach. Specifically the following is recommended:

- Stricter inspections during the cutting of the rumble strips and markers will still be necessary for the successful implementation of the embedded RPM technique.
- Current rumble strip depth specifications are 12 ± 3 mm (1/2”±1/8”). This specification must be modified based on the type of marker being used:
    - For low-profile LP1 marker: 14 ± 2 mm
    - For regular-profile RP1 marker: 18 ± 2 mm
- At these rumble strip depths, the markers have a 75% survival rate and visibility ranging between 50-600 ft. The reduced visibility distance can be compensated by reducing the spacing between markers.

Two markers were evaluated as part of the study. Both markers had similar survival rates when embedded in rumble strips at the snowplow-resistant depths. However, the RP1 markers show superior visibility performance with the markers having higher retroreflectivity and being visible from larger distances than the LP1 markers when embedded in rumble strips that are 18 ± 2 mm deep per the installation guide provided in Appendix C. The LP1 markers while having lower visibility can be installed in existing 14 ± 2 mm rumble strips per the installation guide provided in Appendix C. This does not necessitate large changes in TxDOT rumble strip standards, which currently specify that rumble strips should be installed at 12 ± 3 mm.

7.7. Future Work

This study involves the evaluation of markers embedded in rumble strips across six TxDOT highways. Of these, two Sites I (TX 176, Big Spring) and II (US 180, Anson) were likely not snowplowed along the centerline. Collecting data from these sites after the centerline undergoes snowplow operations will build a larger dataset for marker conditions post-snowplowing. This will enable the research team to observe markers in a wider range of rumble strip depths and examine if any other factors influence the damage and loss of markers.

The visibility study conducted to determine the maximum rumble strip depth was performed using a sedan vehicle, while the remaining visibility studies were conducted using an SUV. Repeating the maximum rumble strip depth study using an SUV-type vehicle and installing the embedded markers at different spacing and depths will be useful in determining appropriate spacing under field conditions to improve the visibility of markers embedded in rumble strips.

7.8. Dissemination

The research work conducted as part of this study has been published in the following:

- Md Al-Amin, Vivek Turkar, Mike Rung, and Raissa Douglas Ferron, 2023, "*Enhancement of Highway Conditions during Winter Weather Operations through Coupling Raised Pavement Markers with Rumble Strips*" Transportation Research Record: Journal of the Transportation Research Board, Volume: 2677, Issue Number: 1, ISSN: 0361-1981, EISSN: 2169-4052, doi:10.1177/03611981221098658
- In progress – Savitha Sagari Srinivasan, Michael Rung, md Al-Amin, Raissa Douglas Ferron, "*Multifunctionalization of Rumble Strips for Improving Snowplow Resistance of Retroreflective Pavement Markers*"

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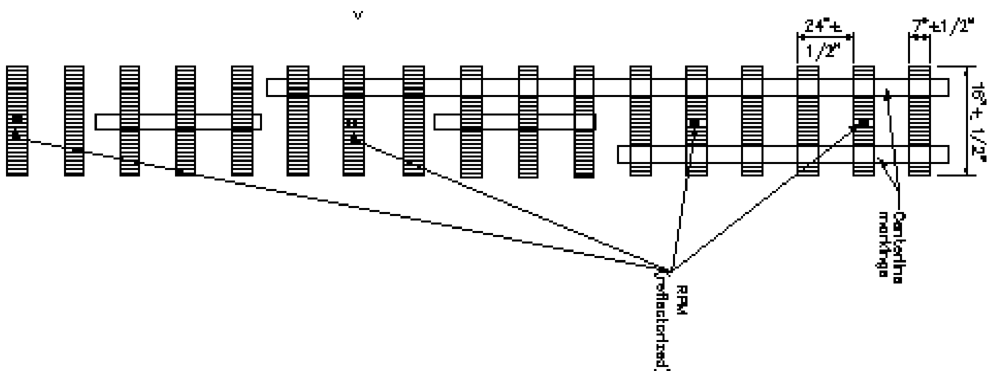
Appendix A –Installation Guide for Test Markers

The installation guide for the markers embedded in rumble strips was prepared and provided to the receiving agency as part of Task 3. This was done to ensure consistency in markers at the highway sites. This involved cutting of rumble strips and embedding markers in the rumble strips.

I. Rumble Strips Specifications and Preparation

Rumble strips for embedment of markers shall be centerline "Milled Rumble Strips" conforming with TxDOT Specifications[3] (i.e., dimensions of 7 inches in the direction of traffic, 16 inches perpendicular to the direction of traffic, and depth of ½ inch (See Figure A. 1)). As per TxDOT Item 533 [31], the depressions must have well-defined edges, a smooth interior finish, and not snag or tear the finished pavement. Any debris shall be cleaned from the rumble strip depression before placing the markers.



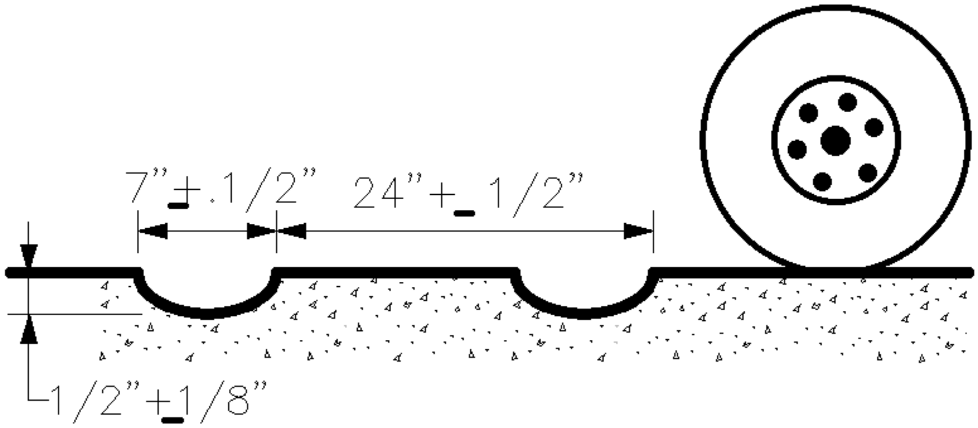


Figure A. 1: Milled Centerline Rumble Strips[3]

II. Marker Installation Sequence

Two types of markers shall be embedded in rumble strips in the test segments at each field implementation site:

- 1. Low-profile – Stimsonite C-40 Two Way Yellow (Ennis Flint)
- 2. Regular-profile – 3M Series 290 Two Way Yellow

The total length of the test segment will be approximately 2 miles and 800 ft long and there shall be no conventional markers (surface-mounted markers) installed in this region. If surface-mounted markers have already been installed, they shall be removed per TxDOT Item 677 [32] or test segments must be selected such that there are no surface-mounted markers within the limits of test segments.

As shown in Figure A. 2, the markers shall be installed according to the following sequence:

- Segment 1: Low-profile markers in rumble strips
  Low-profile markers shall be embedded in rumble strips in the first 1-mile roadway segment. There shall be no surface-mounted markers.
- Segment 2: Blank Space
  No markers (neither markers in rumble strips nor surface-mounted markers) shall be installed in the next 400 ft segment.
- Segment 3: Regular-profile markers in rumble strips
  Regular-profile markers shall be embedded in rumble strips after the 400 ft gap in the next 1-mile segment. There shall be no surface-mounted markers.
- Segment 4: Blank Space

No markers (neither markers in rumble strips nor surface-mounted markers) shall be installed in the next 400 ft segment after the installation of regular-profile markers in rumble strips.

- Segment 5: Regular-profile markers installed conventionally
  Conventional markers (surface-mounted markers) may be placed or remain after a 400 ft segment with no markers.

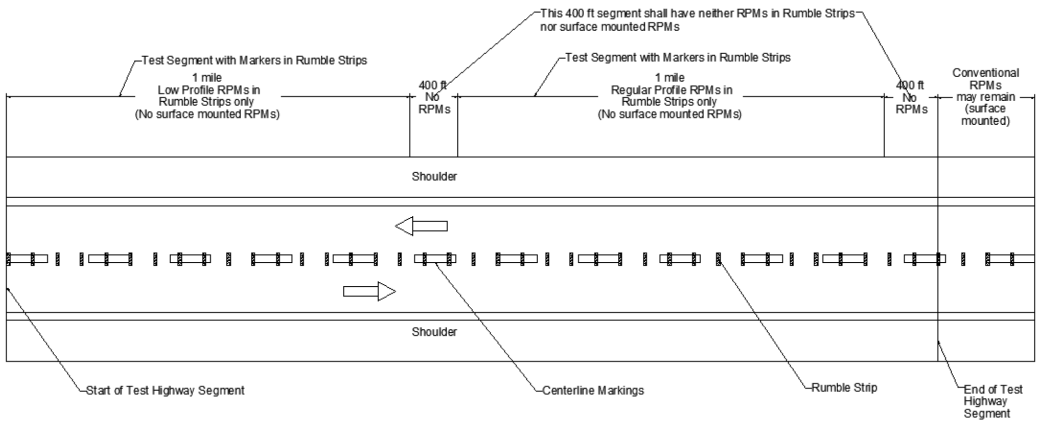


Figure A. 2: Marker Installation Sequence

III. Marker Placement Guidelines

The highway sites can be on roadways with different traffic patterns. In this section, these different scenarios will be considered during placement and the receiving agency will use the appropriate scenario during the placement.

Marker placement in roadways where passing in both directions (i.e., single centerline markings) is allowed markers in rumble strips shall be placed:

1. at 80 ft spacing
2. in line and the gap between skip lines (See Figure A. 3).
3. in the center of the rumble strip, i.e., the center of the marker should be at equidistance from the edges of rumble strips as shown in Details A-A in Figure A. 4.

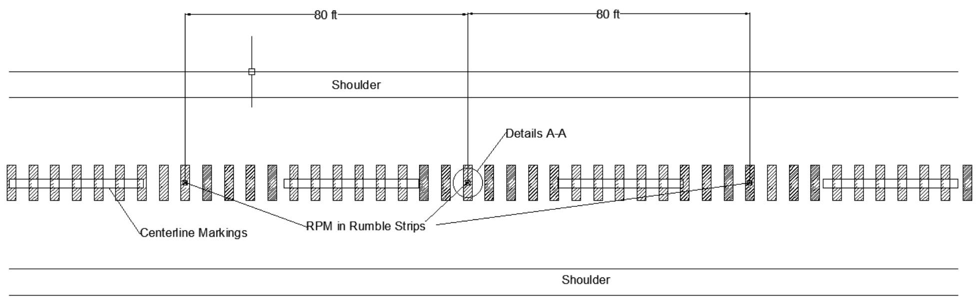


Figure A. 3: Placement of RPMs where Passing in both Directions is Allowed (Single-line Broken Centerline Markings)

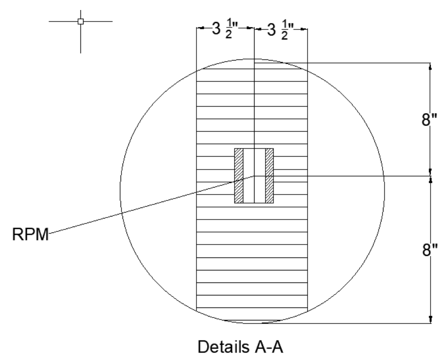


Figure A. 4: Detailed View of Rumble Strip and Marker (AA)

Marker placement in roadways where passing in one direction (i.e., one broken marking line and one solid marking line) is allowed shall be placed:

1. at 40 ft spacing.
2. in rumble strips in the gap between skip lines (See Figure A. 5).
3. at an offset of 2”- 4” from the edge of the solid yellow centerline to avoid painting the marker by error (as shown in Details B-B in Figure A. 6).

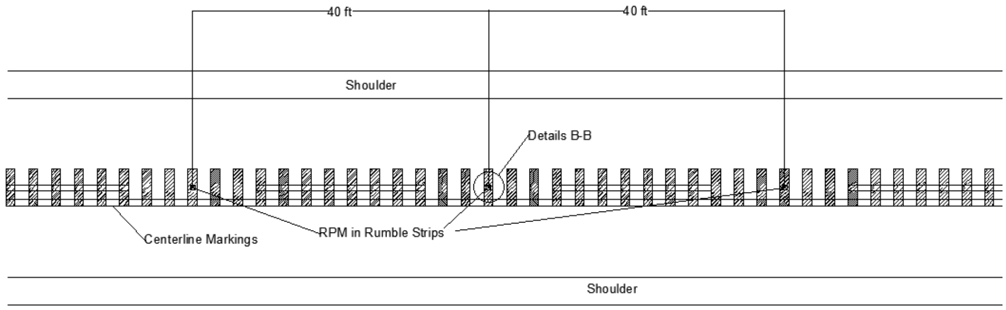


Figure A. 5: Placement of RPMs where Passing in One Direction is Allowed

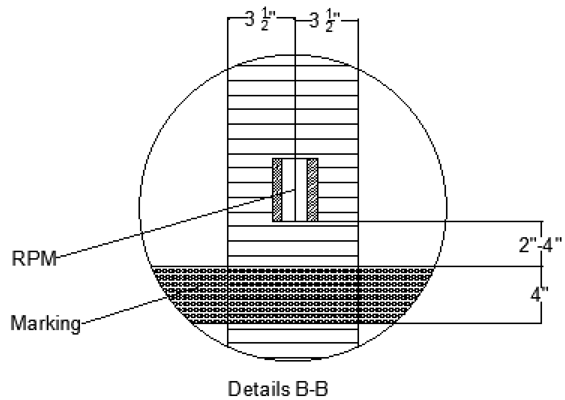


Figure A. 6: Detailed View of the Rumble Strip and Marker (BB)

Marker placement in roadways where passing is not allowed (i.e., double yellow line) shall be placed:

1. between double yellow centerlines at a spacing of 40 ft (See Figure A. 7)
2. offset 2 – 4 inches from the solid yellow lines (as shown in Details C-C in Figure A. 8).

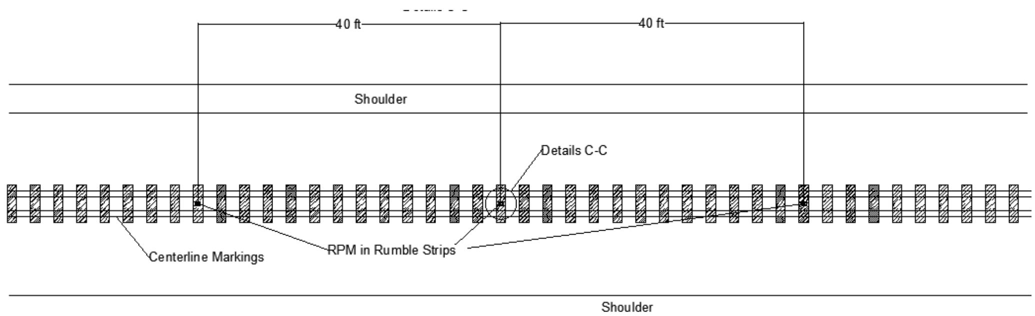
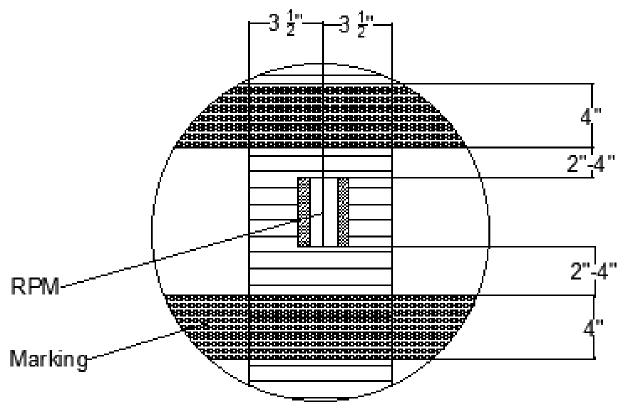


Figure A. 7: Placement of Markers where no Passing is Allowed (Double Yellow Line)



Details C-C
Figure A. 8: Detailed View of Rumble Strip and Marker (CC)

Conventionally installed RPMs (i.e., surface-mounted markers) may be present after the end of Test Segment 4 (See Section II). Marker placement for conventionally installed markers shall be placed per the TxDOT standards [33].

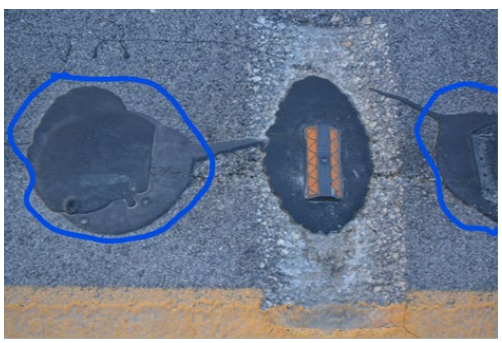
IV. Installations of Markers in Rumble Strips

Markers shall be installed in the rumble strips as follows:

1. Markers in rumble strips shall be installed in regions where residual adhesives from previous markers will not inhibit the visibility of the installed markers. Installing the markers where adhesives from previous markers remain should be avoided (See Figure A. 9a). The remaining adhesive shall be removed around the rumble strips where markers are to be installed **or** rumble strips shall be so selected that there would be no remaining adhesive around them. If the latter is done, this may require

embedding the markers in the rumble strips at distances slightly greater than stated in Section III of this guide. Figure A. 9b shows a desirable embedment of markers in rumble strips.

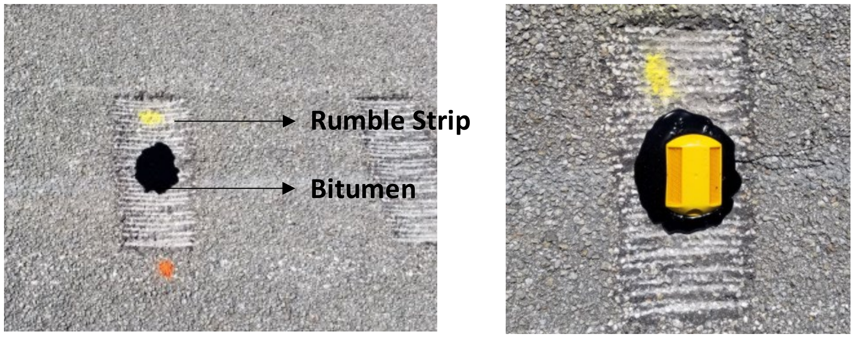
2. The surface of the rumble strip selected for marker embedment shall be prepared so that the bonding surface is free of contaminants and dirt to ensure good bonding [34]. The surface of the rumble strip shall be dry and clean. The pavement surface temperature should be at least 40^0 F (5^0 C) during the embedment of markers.
3. A bitumen applicator shall be placed over the desired rumble strips and a puddle of bitumen shall be dispensed with an adequate amount so that the entire bonding area of the marker is covered (See Figure A. 10a).
4. The marker shall be placed onto the bitumen puddle and pressed down (i.e., bottomed out) so that the marker shall be bonded to the adhesive and contained within the rumble strip. The reflective faces must be perpendicular to traffic. Bitumen shall not flow onto the reflective face (see Figure A. 10b and Figure A. 11).



(a) Bad Installation with Residual Bitumen Close to the Marker Highlighted in Blue

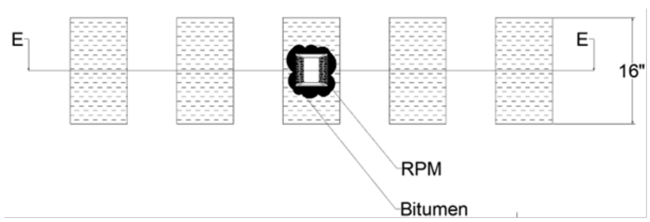
(b) Good Installation with no Residual Bitumen Close to the Marker

Figure A. 9: Examples of Bad and Good Embedment of Markers

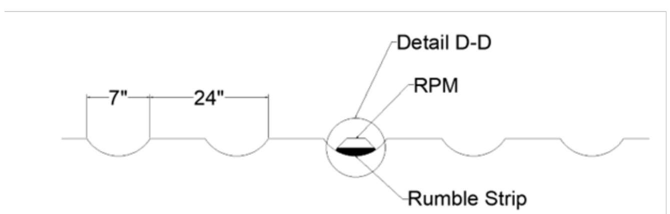


(a) Bitumen Dispensed in Rumble Strip **(b) Marker Placed in Bitumen**

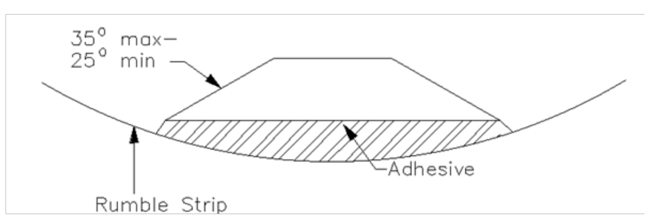
Figure A. 10: Marker Embedded in Rumble Strip



(a) Plan View



(b) Section EE



(c) Detail DD

Figure A. 11: Embedment of Markers in Rumble Strip

Appendix B – Human Participant Surveys

Intake Survey

Name: ___________________

Email Address: _________________

Cell Phone Number: ___________________

Participant ID (Research team will assign an ID):_________________________

1. Are you associated with any of the following?
   1) UT Austin
   2) TxDOT
   3) None of the above
   -
2. Do you have a current valid U.S. driver license?
   1) Yes
   2) No
   -
3. What is your age? (Previous studies have shown that the age of a person is a significant factor affecting the perception of pavement markers):
   1) <18 years
   2) 18 - 30 years
   3) 31 - 40 years
   4) 41 - 50 years
   5) 51 - 60 years
   6) >60 years

Background Survey

1. Please indicate the category of driver's license that you hold (for more information on the categories of driver licenses, please follow the link(Classes of Driver Licenses) :
   1) Class A or Class B
   2) Class C
   3) Class AM or Class BM
   4) Class CM
   5) Class M
   6) Commercial: CDL-A, CDL-B, or CDL-C
   7) Learner permit

8) Other (Please describe): ________________________________

2. How many years have you been driving? (Previous studies have shown that a person's driving experience is a significant factor affecting the perception of pavement markers.)
   1) less than 1 year
   2) 1–5 years
   3) 5–10 years
   4) more than 10 years

3. In a typical week, how many days do you drive when it is dark outside?
   1) 1-2 days
   2) 3–4 days
   3) 5 days or more
   4) I usually do not drive when it's dark

4. Do you have any difficulty driving when headlights from oncoming cars are in your field of vision?
   1) Yes
   2) No
   3) Unsure

5. The picture below shows three different safety devices on a pavement: a pavement lane marking, a raised pavement marker (RPM), and a rumble strip. Which of these safety devices have you noticed when driving? Please check all that apply.

   1) Lane markings
   2) Raised pavement markers (RPM)
   3) Rumble strips
   4) All of the above
   5) None of the above

6. How often do you drive over the speed limit on highways (speed limit $\geq$55)?
   1) Always
   2) Sometimes

3) Rarely
4) Never
5) Don’t know

7. How many miles do you typically drive in a year?
   1) Less than 5,000 miles
   2) 5,000–10,000 miles
   3) More than 10,000 miles

8. Please select which of the following best describes your driving when it is dark outside:
   1) I drive more cautiously when it is dark
   2) I drive the same when it is dark as I do during daylight
   3) I avoid driving in the dark

9. What is your sex assigned at birth? (Previous studies have shown that the assigned sex of a person is a significant factor affecting the perception of road delineation systems.)
   1) Male
   2) Female
   3) Intersex
   4) Prefer not to answer

10. Do you wear prescription glasses or contact lenses while driving?
    1) Yes, always
    2) Yes, sometimes
    3) No

11. Please indicate the type of eyewear prescription that applies to you (for more detail about eye prescriptions, please follow the link: types of eyeglasses):
    1) Single vision
    2) Bifocal
    3) Progressive
    4) Not applicable

12. Please indicate the diopter range of your eyeglasses or contact lenses (this is the optical power of a corrective lens, found in an eye prescription. For more information, please follow the link: how to read an eyeglass prescription):
    1) −4.00 or above
    2) Between −2.25 and −3.75
    3) Between −0.25 and −2.00
    4) Between +0.25 and +2.00
    5) Between +2.25 and +3.75

6) +4.00 or above
7) Do not know
8) Not Applicable

13. Do you have any difficulty seeing the lane markings?
    1) No difficulty
    2) A little difficulty
    3) Moderate difficulty
    4) Extreme difficulty

RPM Perception Survey

1. Overall, how would you rate the visibility of RPMs embedded in rumble strips?
    1) Very poor
    2) Poor
    3) Fair (Neither good nor poor)
    4) Good
    5) Very good

2. Would you agree with the statement, "Generally, RPMs embedded in rumble strips are more visible than pavement markings are at night"?
    1) Strongly agree
    2) Agree
    3) Neither agree nor disagree
    4) Disagree
    5) Strongly disagree

3. Overall, how useful were the RPMs in rumble strips in helping you see the centerline?
    1) Extremely useful
    2) Somewhat useful
    3) Neither useful nor useless
    4) Somewhat useless
    5) Extremely useless

Appendix C –Installation Guide for Snowplow Resistant Markers

This guide provides the changes to be made to the installation procedure to ensure that the embedded markers have sufficient snowplow resistance and meet minimum visibility distance criteria. The marker type to be used is either low-profile Stimsonite C40 or regular-profile 3M 290 markers.

I. Rumble Strips Specifications and Preparation

Rumble strips for embedment of markers shall be centerline "Milled Rumble Strips" conforming with TxDOT Specifications[3] (i.e., dimensions of 7 inches in the direction of traffic, and 16 inches perpendicular to the direction of traffic (See Figure C. 1)). As per TxDOT Item 533 [31], the depressions must have well-defined edges, a smooth interior finish, and not snag or tear the finished pavement. Any debris shall be cleaned from the rumble strip depression before placing the markers.

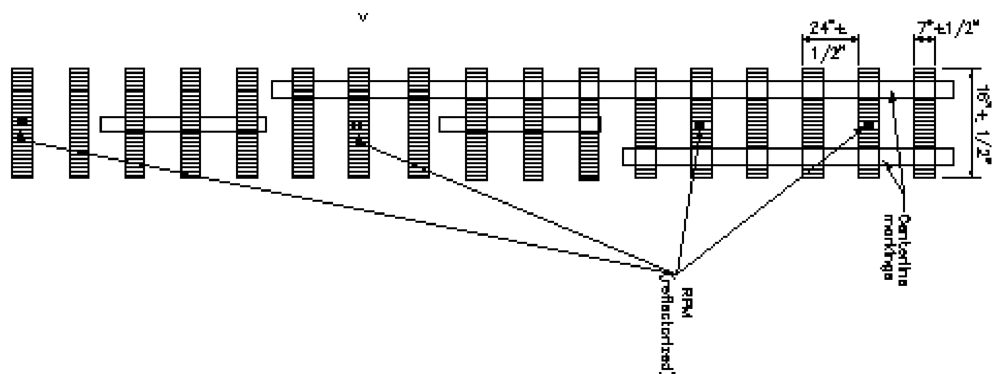


Figure C. 1: Milled Centerline Rumble Strips[3]

The depth shall be modified from 1/2"±1/8" to 7/10"±1/16" or (18 ± 2 mm) if regular-profile markers are used and to 9/16"±1/16" or (14 ± 2 mm) if low-profile markers are used as seen in Figure C. 2. The depth has been increased to accommodate the marker and the tolerance levels have been reduced to ensure adequate visibility.

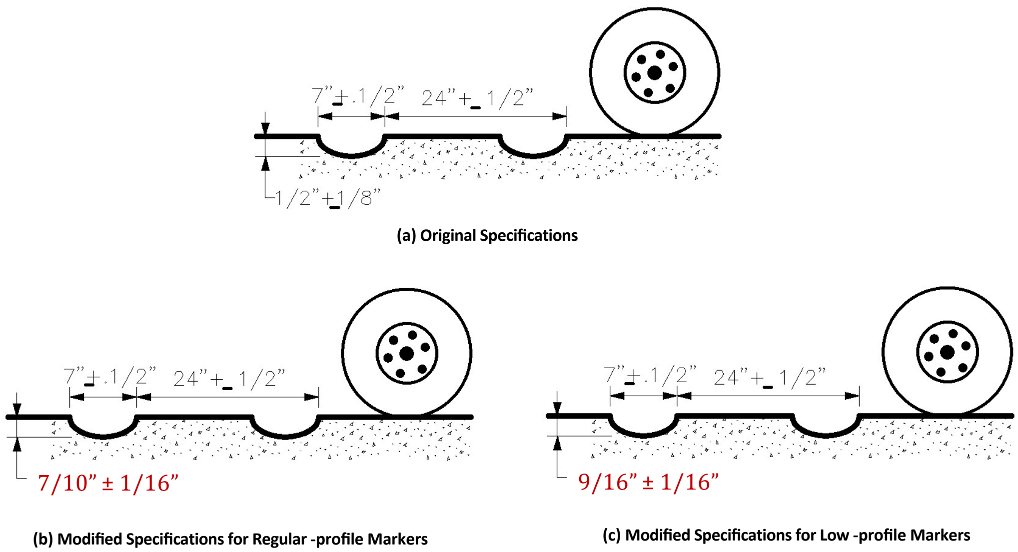
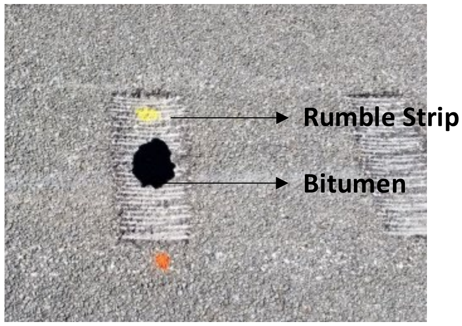


Figure C. 2: Modifications to Rumble Strip Depth

IV. Embedment of Markers in Rumble Strips

Markers placed in the grooves shall adhere to the placement rules for conventional surface-mounted markers per the TxDOT standards [33]. At the current marker spacing of 40 ft for congested areas and 80ft for non-congested areas, the visibility of the markers may not be sufficient at the deeper rumble strip depths. The spacing may need to be modified to compensate for the reduced visibility. Additional research will be required to determine the appropriate spacing. Markers shall be embedded in the rumble strips as follows:

1. Regular-profile 3M 290 or low-profile Stimsonite C40 markers shall be used.
2. The surface of the rumble strip selected for marker embedment shall be prepared so that the bonding surface is free of contaminants and dirt to ensure good bonding [34]. The surface of the rumble strip shall be dry and clean. The pavement surface temperature should be at least 40^0 F (5^0 C) during the embedment of markers.
3. A bitumen applicator shall be placed over the desired rumble strips and a puddle of bitumen shall be dispensed with an adequate amount so that the entire bonding area of the marker is covered (See Figure C. 3a).
4. The marker shall be placed onto the bitumen puddle and pressed down (i.e., bottomed out) so that the marker shall be bonded to the adhesive and contained within the rumble strip. The reflective faces must be perpendicular to traffic. Bitumen shall not flow onto the reflective face (see Figure C. 3b).



(a) Bitumen Dispensed in Rumble Strip

(b) Marker Placed in Bitumen

Figure C. 3: Example of Marker Embedded in Rumble Strip

Appendix D – Value of Research

Introduction

The University of Texas at Austin prepared an estimated value of research corresponding to the research outcome of the project. For the establishment of the VoR, eleven functional comprises of both qualitative and economic areas were identified (see Table D. 1).

Table D. 1: Functional Areas of Project 5-6995-01

Benefit Area	Qualitative	Economic	Both	TxDOT	State	Both
Level of Knowledge	X			X		
Customer Satisfaction	X			X		
System Reliability		X		X		
Increased Service Life		X		X		
Improved Productivity and Work Efficiency		X		X		
Traffic and Congestion Reduction		X			X	
Reduced User Cost		X			X	
Reduced Construction, Operations, and Maintenance Cost		X			X	
Infrastructure Condition		X				X
Engineering Design Improvement			X			X
Safety			X			X

Qualitative Benefits

Four functional areas that contributed to the qualitative benefits of this project were identified and summarised.

- Level of Knowledge
- Customer Satisfaction
- Engineering Design Improvement
- Safety

Level of Knowledge

Project 5-6995 resulted in a significant increase in the "Level of Knowledge" which advanced the understanding and insights of TxDOT infrastructure. The key outcomes derived from the performance of this research comprised the effective multifunctionalization of centerline rumble strips to provide snowplow resistance to commercially available retroreflective raised pavement markers while ensuring their visibility to road users. The project built on the findings of the original *Research Project 0-6995* to provide additional knowledge on the effect of rumble strips and marker geometries on the snowplow resistance and visibility characteristics of the markers embedded in rumble strips. The multifunctionalization approach can be translated into a knowledge base regarding markers embedded in rumble strips as an alternative highway delineation practice. The knowledge of new delineation practices will supplement the knowledge base of the TxDOT winter weather operation practices and maintenance and/or replacement strategies related to pavement markers. The improved level of knowledge will also help TxDOT personnel in making better-informed decisions on highway delineation practices and reduce the uncertainty involved in maintenance and operation resource management and allocations. The level of knowledge in the area of multifunctional rumble strips as an alternative delineation practice will also help TxDOT in maintaining its reputation as the best-in-class DOT in the nation.

Customer Satisfaction

Customers are essential in TxDOT operations and business practices. TxDOT always strides to achieve better customer satisfaction. This project will provide insights into better highway delineation practices which will translate into better infrastructure and better maintenance strategies. These factors will enhance the perception of road users on uniform and safe driving conditions, which in turn increase TxDOT customer satisfaction ratings.

Engineering Design Improvement

The product that stemmed from this research is a snowplow-resistant and cost-effective configuration for highway delineation. Evaluation of the commercially available retroreflective raised pavement markers in rumble strips and their performance enhanced the engineering know-how in the area of alternative highway delineation practices.

Safety

The research outcomes from this project will limit the loss of markers due to winter weather operations and heavy traffic loads, reduce the frequency of maintenance and replacement, and enhance the service life of the markers. However, the main benefit will come from the enhanced delineation of the centerline by markers under low-visibility conditions like darkness, fog, rain, etc., and will reduce head-on collisions. This will result in enhanced safety for road users.

Quantitative Benefits

Economic appraisal corresponding to the project goals and scopes are related to nine functional areas and are identified in the project agreements:

System Reliability – The embedment of markers in rumble strips will withstand winter weather operations, and reduce the frequency of maintenance and replacement. These outcomes will increase the reliability of the centerline delineation of two-lane two-way highways which translates into improved overall highway performance which will result in increased economic efficiency of highway management and operations.

Increased Service Life – The markers embedded in rumble strips will have a longer service life from not getting damaged or lost due to winter weather operations than under the current practice. This increase in service will reduce the cost related to maintenance and replacement, resulting in better economic returns.

Improve productivity and Work Efficiency – Longer service life and reduced replacement rates for the embedded markers when compared to current practice will improve better resource allocations and result in better performance from maintenance teams.

Traffic and Congestion Reduction – The project will reduce the frequency and amount of marker maintenance and replacement which will reduce the traffic slowdown due to work zones. Reduction in traffic congestion will attribute to the economic savings of the overall systems.

Reduced Construction, Operations, and Maintenance – The cost of construction and maintenance will decrease due to a reduction in damage and loss to the markers.

Infrastructure Conditions – Markers embedded in rumble strips will enhance the highways' overall condition and will lead to improvement in general infrastructure assets.

Engineering Design Improvement – The project developed a configuration where RPM and rumble strips work together as an alternative centerline delineation system. This is a major development in engineering design in the area of highway visibility improvement.

Safety –One of the major benefits of the project is a reduction in nighttime head-on crashes and nighttime wet weather crashes. Reduction in the number of crashes will result in greater savings in property damages and fatality, which renders a decrease in cost due to accidents.

Quantitative Analysis of Economic Benefits

The identified economic functional areas such as system reliability, improved productivity and work efficiency, and traffic congestion reduction are correlated with the reduction in maintenance and replacement and increased service life of the markers. The economic benefits of infrastructure conditions are also tied to the increased service life of the markers. Economic benefits for the functional area of safety require extensive analysis of crashes before and after the implementation of projects. However, based on the availability of data for quantitative analysis of economic benefits, this VoR uses a reduction in maintenance and replacement cost and increased service life of markers.

The quantitative analysis of Project 5-6995-01's value as related to the functional area of reduced maintenance and replacement costs and increased service life is shown in Figure D. 1. However, other functional areas are also involved with these two functional areas. The estimated total savings of conducting this project is approximately **$6.7 million,** which equates to a net present value of approximately **$7.7 million**. The payback period is **0.24 years** and the cost-benefit ratio is **18**.

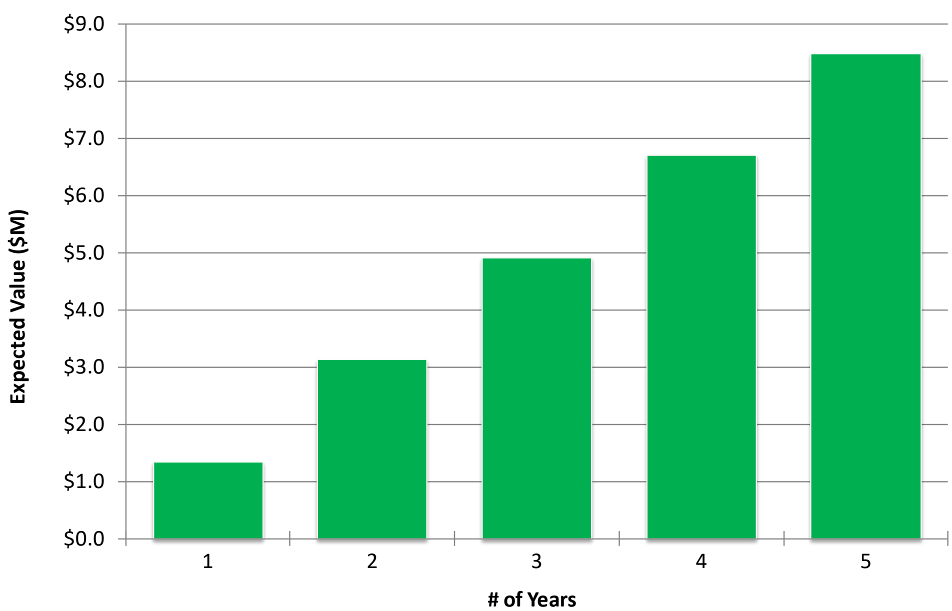


Figure D. 1: Expected Value over Service Life of the Markers

<u>*Explanation of VoR*</u>

Figure D. 2 represents the input and output of the project's value analysis that aided in plotting Figure D. 1. Many of the inputs were dictated by TxDOT or could not be varied as they were based on values from the contract; however, there are two terms, Exp. Value (per Yr) and Expected Value Duration (Yrs), which the research team had full freedom to vary. Therefore, the inputs for these two terms governed the outputs of the economic analysis. Each input term is discussed in detail.

Texas Department of Transportation	Project #	5-6995-01		
	Project Name:	Implementation of Retroreflective Pavement Markers (RPMs) in Rumble Strips as a Method to Enhance Driving Conditions After Snowplow Operations		
	Agency:		Project Budget	$ 439,072
	Project Duration (Yrs)	3.0	Exp. Value (per Yr)	$ 1,783,932
	Expected Value Duration (Yrs)	5	Discount Rate	5%
Economic Value				
Total Savings:	$ 6,696,655		Net Present Value (NPV):	$ 7,723,491
Payback Period (Yrs):	0.246126		Cost Benefit Ratio (CBR, $1 : $___):	$18

Figure D. 2: Value of Research for Project 5-6995-01

<u>*Project Budget:*</u> $439,072 is the total budget of the project. This value is determined by the project's contract.

<u>*Project Duration (Yrs):*</u> The project is initiated on September 1, 2020, and the project will be terminated on August 31, 2023. Therefore, the project duration is 3.0 years was inputted as the project duration.

<u>*Exp. Value (per Year):*</u> A value of $1,783,932 was used as the expected value per year. This value is based on data collected from the original *Research project 0-6995* and information extracted from the available literature. The research team used the following information and assumed the following scenarios to calculate this value.

The project mainly deals with two-lane two-way highways where centerline rumble strips can be used for the embedment of markers. To estimate two-lane two-way highways, the project team first identified TxDOT districts that deal with significant winter weather operations. Based on the findings in the literature 14 districts were identified– Abilene, Atlanta, Amarillo, Brownwood, Bryan, Childress, Dallas, El Paso, Fort Worth, Lubbock, Paris, San Angelo, Waco, and Wichita Falls. Based on the identified districts, TxDOT Roadway Inventory data was used to estimate the two-lane two-way highway miles. The estimated miles of two-lane two-way highways in the districts was 29703 miles. The researchers assumed that 40 percent of these highways may have rumble strips which entailed 11881 miles of road segments. Assuming a typical spacing between markers of 80 feet, the number of required markers per mile is 66. Therefore, in conventional practices, the total number of RPM for 11,881 miles is 784,160. Districts lose about 90% of the conventionally installed marker every year due to winter weather operations and regular traffic operations. The materials and installation cost of replacing a single marker is $2.50 - $3.97. A value of $3.50 was been assumed for VoR estimation. When not impacted by winter weather operations, the typical service life of a marker is 3-5 years. A typical service life of four years was assumed.

Under current installation practices, 90% of the markers are lost or damaged and require replacement, i.e., 704,744 markers would be replaced at $2.5 million annually. Using the recommended installation method of embedding low-profile Stimsonite C40 markers in 14 ± 2 mm deep rumble strips or regular-profile 3M 290 markers in 16 ± 2 mm deep rumble strips will result in only 25% of the markers being lost or damaged, i.e., 187,040 markers would be replaced at $0.7 million annually. The cost savings in this case is $1,783,932 when compared to the conventional installation method. This value has been used in the VoR calculations.

However, if the spacing of the markers will need to be reduced to improve visibility, the cost may increase due to requiring more total number of markers. It must be noted that currently, the extent of reduction in spacing is unknown, thus, the team has presented the presents the replacement costs for a range of possible configurations ranging from best to worst cases in Table D. 2. It is seen that even if the spacing of the markers needs to be reduced to 30 ft, there is still cost savings when compared to the conventional installation method over the typical service life of a marker. Five years is the service life of a marker if it is undamaged from snowplow operations. However, if the spacing needs to be reduced to 20 ft, the cost of replacement becomes higher than conventional surface-mounted markers.

Table D. 2: Cost of Replacing Markers

Configuration	**Markers needed**	**Total number of Markers needed***	**Markers Lost Annually**	**Annual Cost ($)**	**Cost over Five Years**($)**
Conventional installation at 80 ft	66/mile	784,146	705,731	2,470,059	12,350,299
80 ft spacing in rumble strips	66/mile	784,146	196,036	686,127	3,430,638
60 ft spacing in rumble strips	88/mile	1,045,528	261,382	914,837	4,574,185
40 ft spacing in rumble strips	132/mile	1,568,292	392,073	1,372,255	6,861,277
30 ft spacing in rumble strips	176/mile	2,091,056	522,764	1,829,674	9,148,370
20 ft spacing in rumble strips	264/mile	3,136,584	784,146	274,4511	13,722,555
* Based on 11,881 miles **Five years is the service life of a marker if undamaged					

<u>*Expected Value Duration (Yrs):*</u> An expected duration of 5 years was assumed based on the 5-year service life of a marker.

Discount Rate: The 5% discount rate recommended in the University Handbook was used.

Output values

The following terms were determined automatically in the VoR spreadsheet (Figure D. 2): Total Savings, Payback Period (Yrs); Net Present Value (NPV), and Cost-Benefit Ratio (CBR). These terms were determined based on the equations in the University Handbook

Summary

The estimated value of research for Project 5-6995-01 shows that implementation of the markers embedded in the rumble strips method of highway delineation can provide significant cost savings of $1.8 million annually and $8.9 million over five years to TxDOT. The reduced loss and damage to markers can not only reduce monetary losses but also improve highway safety and improve reliability and performance of transportation infrastructure in Texas.