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CENTER FOR TRANSPORTATION RESEARCH

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Determining Use of Alternative Retroreflective Pavement Markers (RPMs) on Highways with Centerline Rumble Strips and Winter Weather Pavement Marking Improvements

Raissa Ferron
Michael Rung
Md Al Amin
Vivek Turkar
Amit Bhasin
David Fowler

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16. Abstract

The use of snowplows in northern Texas frequently results in the loss of retroreflective pavement markers (RPMs). The loss of RPMs is not only costly but also creates unsafe driving conditions during inclement weather. Pavement sections in these districts often use a centerline rumble strip for safety. Traditionally, these rumble strips have precluded the use of metal-encased RPMs (i.e., snowplowable RPMs). This project is focused on determining the efficacy of inserting RPMs into the trough regions of the rumble strips. The report explores use of existing commercially available RPMs as well as RPM design adjustments to accommodate retroreflection requirements while preventing loss of RPMs due to snowplows. In addition, the project also explores the concept of innovative flexible memory markers as a snowplowable configuration, providing an alternative delineation practice. The results show that embedment of RPMs can be an extremely effective way to reduce losses and damages to RPMs during snowplow operations. Successful implementation of this project results will result in millions of dollars of savings for Departments of Transportation and increased roadway safety.

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Center for Transportation Research
The University of Texas at Austin
3925 W. Braker Lane, 4th floor
Austin, TX 78759

https://ctr.utexas.edu/

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Chapter 1. Introduction

This chapter discusses the motivation behind the work and the key objectives, as well as scope.

1.1. Motivation

Centerline delineation of roadways is used to prevent head-on collision caused by lane departure by users. Retroreflective pavement markers (RPMs) provide a means to not only delineate roadways but to increase the nighttime visibility of roadways. They were patented in 1934 and since that time have been used extensively throughout the world to increase roadway safety. When light is projected on retroreflective pavement markers by a source (e.g., vehicle) the retroreflective pavement markers operate by reflecting light to the source. Retroreflectivity can be provided through a variety of methods, such as through the use of glass beads, wet reflective optics, and prismatic cube-corner retroreflection (Ceifetz, et al., 2017). Raised non-snowplowable markers are critical for nighttime delineation in rainy conditions where the pavement markings perform poorly.

Most of the Texas Department of Transportation (TxDOT) districts in Texas use raised retroreflective non-snowplowable markers. However, during winter operation conditions, these RPMS are dislodged by snowplow operations. This is a particular concern for the northern regions in Texas since these regions are prone to snowfall during the winter months (see Appendix 1). A survey was conducted as a part of this research where 17 out of 25 TxDOT districts responded. Districts in the northern regions of Texas—Amarillo (AMA), Childress (CHS), Wichita Falls (WFS), and Lubbock (LBB), shown in Figure 1-1—reported more than 70% of the RPMs are damaged each year; as much of 90% of this loss is attributed to the winter weather operations. Dislodgement of the RPMs results in unsafe driving conditions and increases the cost of road maintenance since the RPMs need to be replaced annually.

Snowplowable RPMs are also used in regions of high snowfall. Snowplowable markers have a system in which the retroreflective marker body is put inside a metal casing to protect it from the snowplow. However, even these markers have some issues such as fracture and dislodgement. This dislodgement causes the marker to become a projectile, causing safety concerns, damage to the pavement, a jump of the snowplow blade (which results in unplowed segments), and increased maintenance needs. Out of 17 TxDOT districts that responded to the survey, only 3 districts—Amarillo (AMA), Childress (CHS), and El Paso (ELP)—reported the use of snowplowable RPMs. However, it should be noted that even though the El

Paso District uses snowplowable markers, more than 70% of the installed markers are lost during the winter months (see Appendix 1).

Figure 1-1 TxDOT Districts (41)

A rumble strip is another approach to delineating roadways. It provides road users with a warning upon crossing the centerline, creating sound and vibration. A study in Michigan revealed that rumble strips prevented 51% of fatal crashes caused when cars departed their lanes and crossed over the centerline *(11)*. As per National Cooperative Highway Research Program (NCHRP) Report 641, centerline milled rumble strips have prevented 38 to 50% of crashes associated with vehicles approaching from opposite directions for rural two-lane roads and 37 to 91% for urban two-lane roads *(21)*.

1.2. Goal and Objective

The goal of the project was to assess the use of existing commercially available RPMs within the trough regions of rumble strips (referred to as rumble inserts) to achieve cost-effective and snowplowable configurations by taking advantage of the pre-installed rumble strip.

This study of pavement markers embedded in the groove of the rumble strip is the first of its kind to be reported in the literature, to the knowledge of the authors.

While embedding the RPMs into the rumble strip may protect the RPMs from the force exerted on them by snowplows, this positioning creates is a key challenge of maintaining adequate retroreflectivity, since the groove edge of the rumble strip can block light to the marker. As a result, this embedment would reduce the marker's ability to reflect the light to the driver's eyes. ***Therefore, the primary objective of the study was to estimate the optimum installation depth such that the markers are protected from the snowplow without compromising the retroreflective performance of the system.***

1.3. Scope

For recessed markers, ASTM D4383-18 *(39)* suggests a minimum groove length of 42 in. (1.1 m) from the edge of the marker to the groove edge measured in the direction of traffic. It was discussed in the 2017 Annual National Transportation Research Evaluation Program (NTPEP) RPM Technical Committee Meeting *(44)* that the shortest length of the groove (in the direction of traffic) to accommodate the RPMs with a plastic housing is 6 ft for a single marker and 9 ft for a pair of markers placed side by side in a single groove. This allows enough light to hit the marker and be reflected sufficiently to attract drivers' attention. However, cutting the groove with that dimension is costly, which hinders the alteration in the groove geometry of the rumble strip in which the markers are supposed to be installed. Thus, this project focused on ways to use existing rumble strip grooves (length in direction of traffic is 7 inches) and did not investigate approaches involving expanding the length of the groove. With respect to rumble strips, the scope is focused on milled rumble strips as opposed to other types (e.g., raised, formed, rolled).

Retroreflective paints and coatings have been used in conjunction with the retroreflective strip to create a rumble stripe. A retroreflective rumble stripe consists of three major components: rumble strip, matrix phase (e.g., paint or coating), and retroreflective inclusions (e.g., retroreflective beads). The matrix phase is painted on top of the rumble strip, after which the inclusion is applied to the matrix phase. Based on feedback from the TxDOT research team, the scope of the work focused on the use of RPMs since RPMs are more retroreflective than a single painted rumble stripe. However, information about rumble stripes is provided in Chapter 2 of this report.

In addition to the commercially available RPMs, the project also incorporated design and configuration of innovative flexible memory markers as rumble inserts.

Chapter 2. Literature Review

This chapter presents an overview of relevant previous research pertaining to the performance in snowy conditions of reflective pavement markers and striping materials.

2.1. Rumble Strip

Texas Manual on Uniform Traffic Control Devices (TMUCTD) *(34)* defines a rumble strip as “a series of intermittent, narrow, transverse areas of rough-textured, slightly raised, or depressed road surface that extends across the travel lane to alert road users to unusual traffic conditions or are located along the shoulder, along the roadway centerline, or within islands formed by pavement markings to alert road users that they are leaving the travel lanes.”

Looking at the shape, size, and installation method, rumble strips can be divided into four most common types:

1. Rolled
2. Formed
3. Raised
4. Milled

Rolled rumble strips are formed by pressing the hot asphalt pavement in the shape of rounded or V-shaped grooves. Formed rumbles strips are created on the fresh concrete surface; the grooves are created by pressing the forms into fresh concrete. Raised rumble strips are created by placing the markers or the strips on the pavement. Profiled thermoplastic pavement markings also fall into this category. It is used in warmer regions or where the milled rumble strips are not feasible such as pavements with a thin asphalt surface course layer. Milled rumble strips are formed by grinding the pavement surface and are ideal for the colder regions. Milled rumble strips are the focus of this work. For milled rumble strips, it is specified that the thickness of the asphalt surface course is not less than 2 inches and less than 3 years old *(36)*.

TxDOT standard milled rumble strip dimensions are as follows *(20)*:

- Depth: 0.5 ± 0.125 inch (maximum)
- Width: 7 ± 0.5 inches along the traffic direction
- Length: 16 ± 0.5 inch perpendicular to the traffic direction

- Separation of the adjacent grooves: 17 ± 0.5 inch (edge to edge distance between adjacent grooves) (see Figure 2-1 and 2-2)

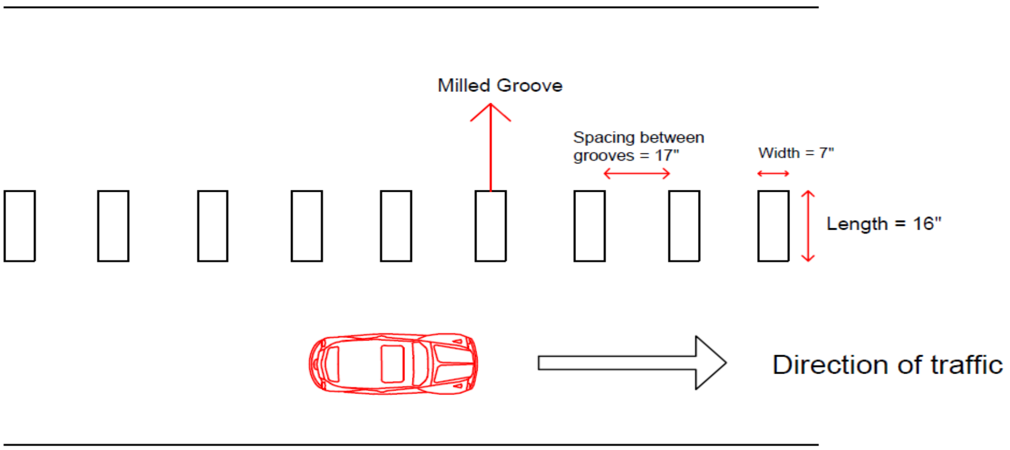


Figure 2-1 Milled centerline rumble strips - plan view

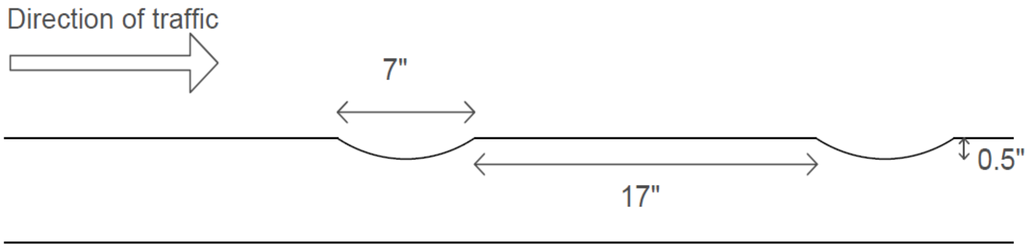


Figure 2-2 Milled centerline rumble strips - profile view

2.2. Retroreflective Pavement Markers (RPMs)

Pavement markers have emerged as an alternative to pavement markings since most of the pavement markings have poor performance in inclement weather conditions. Pavement markers provide better visibility than pavement markings in adverse conditions such as rainy, foggy nights due to the retroreflective element that is extended above the surface.

As per the Roadway Delineation Practices Handbook, FHWA, an ideal RPM should meet three requirements:

- Provide both day and night minimum visibility equivalent to retroreflective painted stripe
- Be highly visible under wet night conditions

- Neither be damaged by snowplow nor cause damage to snowplow blade

A typical RPM consists of 2 retroreflective lenses, body, and bottom sticking to the pavement surface usually by epoxy or bitumen (see Figure 2-3). The lens consists of trihedral angled mirror geometry widely known as corner-cube. These mirrors are arranged perpendicular to each other. The light hits one of the mirrors then getting reflected to second and eventually to the third mirror which eventually reflects light to the opposite direction of entered light *(19)*. Conventional RPMs get dislodged easily by snowplows; therefore, these are usually not suitable for regions that see frequent snowplow operations. The cost associated with these failures led to the development of snowplowable markers.

Figure 2-3 Typical raised pavement marker: 3M-290 marker

2.2.1. Snowplowable Raised Pavement Markers (SRPMs)

A snowplowable raised pavement marker consists of a retroreflector unit that is protected by a metal casing (see Figure 2-4). These are installed into long grooves that accommodate the base of the marker, filled with adhesive to bond with the pavement surface. The casing is supposed to prevent damage to the retroreflective unit and snowplow blade.

Figure 2-4 3M-190 Pavement marker in steel casting

However, studies have shown that a show a significant jump of a snowplow blade can occur when it contacts a snowplowable marker *(14,27)*. This occurs irrespective of the design of the marker and proper installation. A possible reason for this excessive plow blade jump could be that the speed of the snowplow was more than optimum. However, even the snowplow can become dented from the metal causing damage to the plow blade *(14)*. But perhaps the most concern is that even these markers can be dislodged from the pavement and turned into a projectile by the force exerted by the snowplows. This typically occurs in deteriorating pavement in the vicinity of marker, or the marker installed near the pavement joint *(28)*. Furthermore, dislodgement of the RPMS can compromise the integrity and overall life of the pavement. Pavement patches created by marker removal can create potholes and can further cause pavement deterioration *(27,28)*. Ceifetz et al. suggested using lightweight snowplowable markers to prevent markers from getting dislodged and becoming a projectile as these markers would be more prone to breaking into pieces than dislodgement *(10)*.

Pigman & Agent *(14)* showed that Stimsonite 96 and Dura-Brite RPMS were able to provide delineation while withstanding the impact of the snowplow but caused damage to the snowplow blade. The test period was 16 months and 6 to 8 snowplow passes occurred. Further research on snowplowable markers with steel casting has been conducted which recommended the use of these markers with proper installation and maintenance *(28)*. Another study showed poor installation as a major factor for a marker's failure and recommended yearly replacement of markers on high traffic interstates should take place *(8)*.

A study by Shepard revealed that 55% of the total markers (Stimsonite Type T99) installed were damaged by the action of snowplows, with markers placed on a bituminous surface exhibiting more damage than markers placed on a portland cement concrete (PCC) surface. This could be due to stripped aggregates in the bituminous surface *(2)*. Shephard's study occurred over the course of 2 winters Stellfox tested several snowplowable markers installed on both PCC and hot mix asphalt (HMA) surfaces. The markers remained intact after 24 snowplow passes and showed significant improvement in retroreflectivity after removing dirt from the lens *(15)*.

2.2.2. Recessed Marker

Recessed markers are RPMs that are placed into a groove to protect them from the snowplow blade. This arrangement also prevents damage to snowplow blades *(14)*. Moody *(1)* in 1975 performed a study assessing the feasibility of installing low-profile markers into a ¼" depth groove. These grooves were 5 ft long in the direction of traffic (compared to the TxDOT rumple strips which are 7 inches long length in the direction of traffic). The markers were bonded with epoxy. The results showed that the reflected light from the marker makes a small solid angle making it visible only when viewed from the line of installed markers.

Another study by Shepard *(2,3)* in Virginia incorporated placing the corner-cube RPMs into ½" deep grooves held under normal traffic for over 20 months including 2 winters (total snowfall of 90 inches). These grooves were 5 ft long in the direction of traffic and the marker was installed at one edge of the groove. Recessed markers escaped the damage due to snowplow, but showed surface cracking due to the impact of normal traffic.

Pigman and Agent *(14)* evaluated recessed markers installed in a 0.75" deep groove at 3/4th depth and recommended recessing markers as "most functional and cost-effective." These grooves were 40 inches long in the direction of traffic and the marker was installed at the mid-length of the groove. The marker recessed in the groove was a regular raised RPM Stimsonite 911 marker. Since the recessed marker was sitting below the road surface, it did not interfere with the snowplow and the damage done to marker was only due to the normal traffic. After 16 months in the field it had the retroreflectivity of 2.5 cd/fc (233 mcd/lx) at 0^{o} entrance and 0.2^{o} observation angle where the minimum retroreflectivity requirements for new markers was 2.7 cd/fc for the silver-white lens.

Bryden et al. evaluated the performance of recessed reflectors *(29)*. For the evaluation of wet-night visibility, markers were placed on the abandoned pavement with 44 different combinations of groove geometry, the best patterns were then installed on highways exposed to traffic. 105 recessed reflectors were placed on a highway with varying pavement types, roadway geometry, reflector depth, and groove geometry. The system consists longitudinal grooves of the sinusoidal cross-section of 4-inch total width and length of 5 ft (aligning the direction of traffic) and ½ depth, along with recess of dimension 2” by 4” and ½” deep into which corner-cube reflector (Stimsonite Model 99 Type L2) was installed with epoxy. Further, the groove dimension was optimized to prevent the obstruction provided by groove peaks to the light path. This amount of obstruction depends on viewing distance, the curvature of the road (vertical and horizontal), reflector mounting depth, and the shape of the groove. Even after one year of traffic and winter maintenance operation in between all the markers were still functioning while the sight distance varied between 480 ft to 40 ft. The subjective delineation ratings were found to be varied between excellent to poor by governing factors such as roadway geometry, recess depth, dirt buildup, and drainage of the water.

2.3. Flexible Memory Marker

A flexible memory marker is an innovative pavement marker consisting of a body that is flexible, elastic, and strongly anchored to the pavement. The flexibility of the body material facilitates it to bend under the forces exerted by the snowplow, while the elasticity of the material accounts for the marker to regain its initial position when exerted force is removed. The major issues with earlier discussed snowplowable markers were:

- Dislodgement of the marker
- Damage to the snowplow blade

Flexible memory marker tackles both issues associated with snowplowable markers. Because of the flexible body, the marker would experience high strain and low stress leading to less stress developed at the anchorage system, therefore, it can be installed even on aging pavements with greater confidence. Further, the body of this marker is lightweight and flexible, hence damage to the snowplow blade would also be eliminated. Greater elevation of the retroreflective element from the road surface would result in better visibility of the marker.

The “cat’s eye” marker, invented by Percy Shaw *(46)* in the 1930s, was the first of its kind (see Figure 2-5). It consists of a flexible dome mounted in a metal housing, that accommodates four retroreflective reflectors—two on each side. Though it serves its purpose for retroreflection, there are issues with the dislodgement of the marker housing by vehicles. Several designs for flexible markers have been invented, named ‘Retractable Traffic Delineator’ (*30)*, ‘Flexible Raised Pavement Markers’ (*31)*, and ‘Raised Depressible Pavement Marker’ *(32)*.

Figure 2-5 Cat's eye pavement marker (45)

A retractable traffic delineator is another type of flexible marker and it consists of the following major components: cylindrical hollow housing (closed at the bottom, open at the top), watertight membrane, light-reflecting member, and holder for the light-reflecting member. The components make an arrangement such that the light reflecting member can be lowered upon the activation of an external force (horizontal or vertical) and upon removal of the external force, as a result of biasing action, the light reflecting member regains its initial position *(30)*.

Murphy *(31)* invented a flexible raised pavement marker (see Figure 2-6) incorporating the following major components: a cylindrical hollow housing (closed at the bottom, open at the top), dome of the cross-section of an approximate sine wave, ribs projecting from the surface to protect reflector unit that is attached to the dome. The material of construction is an elastomer with maximum glass transition temperature -50 °C (preferably polyurethane compound with a lubricating polymer, such as silicone). The material is said to resist high strain rates even at low temperatures (0 °C to -30 °C) making it suitable for the regions that experience high snowfall.

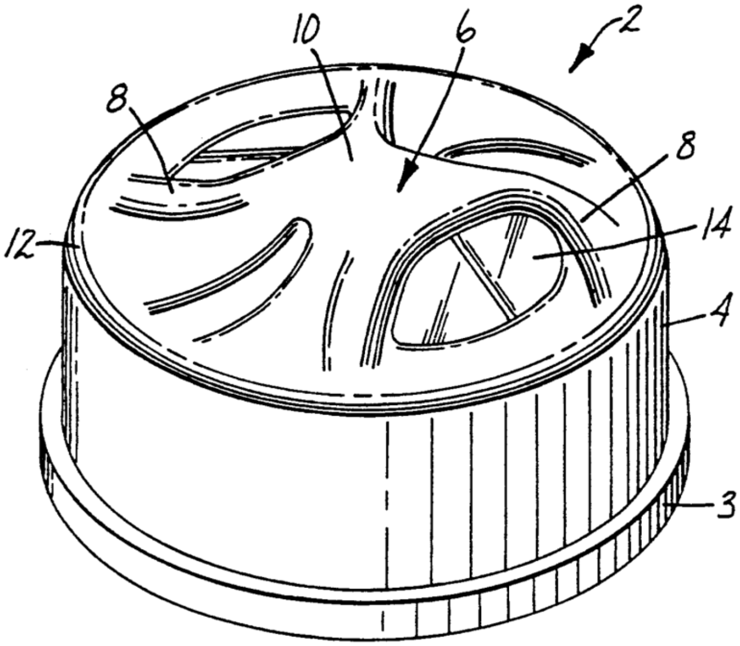


Figure 2-6 Flexible raised pavement marker design by Murphy (31)

The design of Paulos *(32)* (see Figure 2-7) consists of a base container, a piston assembly including a reflector, and a resilient, compressible, watertight body. By the action of the external force, the reflector can be lowered and gets back to its initial position with the help of piston when the external force is removed. This marker incorporates a high-profile 3M™ reflective lens. The commercial design of this technology has been developed, more details of this can be found at HIGHWAY BEACON® *(33)*.

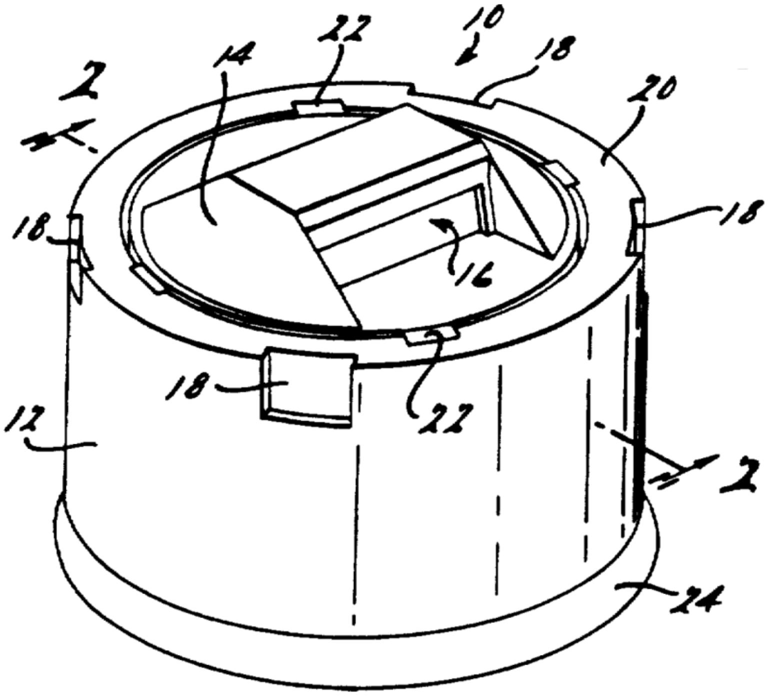


Figure 2-7 Design of raised depressible pavement marker by Paulos (32)

All of these markers require a groove much deeper than the groove of the rumble strips, hence these cannot be installed in the existing groove without any alteration to the groove. These designs are based on depressing the lens body below the road surface when the external load is applied. It was discussed in the update meeting of this project with TxDOT that since the aforementioned marker designs require a certain minimum groove depth these markers are not the ideal solution for this project's goal since they will require coring the road and replacement at each surface preparation which will excessively increase the cost associated with the marker.

2.4. Retroreflective Pavement Marking

The purpose of the retroreflective pavement marking is to guide the light emitted by the vehicle headlamps to the driver's eyes. This kind of marking has two components: (i) retroreflecting material (glass beads), (ii) binder that holds the retroreflecting material, pigment, and solvent.

An exhaustive study of pavement markings has been covered in 'Roadway Delineation Practice Handbook' *(19)*, the relevant findings are discussed below:

Most of the pavement marking incorporates glass beads to add retroreflectivity (see Figure 2-8). Glass beads are small rounded glass used to make the pavement markings retroreflective. There are 3 ways to apply glass beads to pavement markings: (i) by spraying or dropping the beads on the wet binder, (ii) premixing with the binder and (iii) portion of glass beads can be dropped on the premixed wet glass beads and binder. The key requirements for glass beads are transparency and roundness, which can be supported by understanding the optics of glass beads.

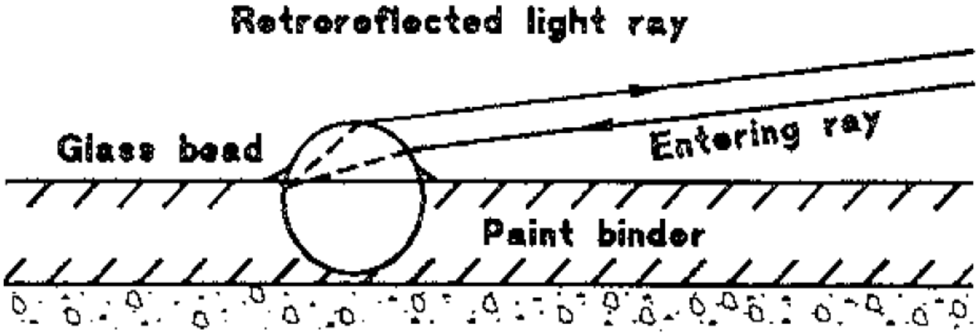


Figure 2-8 Retroreflection mechanism of glass beads (19)

The light emitted by the vehicle headlamps enters the glass bead (refraction) and gets reflected by the bead surface that is in contact with the binder on the opposite side. That amount of light reflected towards the driver depends on the refractive index (RI) of the glass beads, bead characteristics (shape, size, and surface), and the number of beads exposed to the light. Due to the optics of the bead, retroreflectivity is at about 55 to 60% of the embedment in the binder.

The pavement markings can be judged upon two criteria durability and visibility. The performance of the pavement markings is guided by three major factors: roadway surface, traffic, and environmental factors. Typically, the failure of the marking system can be defined by three mechanisms:

- Abrasive wear of upper surface
- Cohesive failure of the paint
- Adhesive failure of marking-pavement surface interface

Failure of the marking cannot be associated with only one type of stress rather it is the combination of the stresses caused by three mechanisms stated earlier. When abrasive wear is a predominant cause of failure, increasing the thickness of the marking can alleviate the performance but for later two types of failure increasing the marking thickness further exacerbate the marking's performance.

Apart from this, pretreatment of the pavement surface accounts for better adhesion. Lower roughness of the surface on which marking is applied leads to less durable and less retroreflective marking. The performance of the repainted markings is found better than the that is applied on bare pavement. The pretreatment of the PCC could also enhance the durability of the markings.

The weather/climate condition is equally responsible for the performance of the pavement marking. Ranging from air temperature/pavement temperature, humidity to wind velocity, and surface moisture, all have a significant impact on the performance of marking. Heavy snowfall creates adverse conditions for markings due to heavy abrasion because of snowplow action and increased brittleness of marking material causing the fracture and debonding from the pavement surface (23).

Several types of marking materials and their characteristics are discussed below:

2.4.1. Pavement Marking Materials

1. Paints: Paints are the oldest most widely used material for pavement marking. TxDOT has been using paints frequently classifying it as Type II pavement marking, but now the shift is towards thermoplastics. It consists of pigment, binder, and glass beads to introduce retroreflectivity. Solvent-based paints have been disallowed in Texas due to environmental considerations and only water-based paints are in use (23). Paints are not as durable as other marking materials but turn out to be a cost-effective solution for roadways with low traffic volume.

2. Thermoplastic: Thermoplastic is classified by TxDOT as a Type I pavement marking *(23)*. Typically, thermoplastic consists of 15 to 35% binder, 14 to 33% glass beads, 8 to 12% titanium dioxide, and 48 to 50% of filler materials. Although thermoplastic can be more expensive than other marking materials, it has better durability and visibility. A single thermoplastic might be equivalent to 20 repaintings of paints; in terms of cost-effectiveness, thermoplastic is expected to function for at least 3 to 6 years *(19)*. Carlson et al. found sprayed thermoplastic, along with raised RPMs, to be the most cost-effective solution overall *(4)*.

   At the time of the application, at high temperature, the binder of the thermoplastic makes a thermal bond with the asphalt while in the case of concrete surface this kind of bonding is not possible rather liquid thermoplastic accommodates in the pores of the concrete forming a mechanical interlock *(23)*. Due to weak bonding with concrete thermoplastic and is not used often on concrete pavements situated in areas that experience high snowfall. Along with this, a profiled thermoplastic could be an alternate solution to rumble stripe but is not acceptable in snowplow operating states *(10)*. A primer-sealer is recommended before the application of thermoplastic on PCC *(19)*. When ice laid on the pavement bonds with the thermoplastic marking, the snowplow removes ice along with the marking.

3. Epoxy: Epoxy is known for good adhesion with both asphalt and concrete surfaces along with abrasion resistance. It takes more time to dry as compared to other marking materials and quick-drying epoxies are even more expensive.

4. Methyl Methacrylate (MMA): “Methyl methacrylate has been introduced and publicized as a nonhazardous, field-reacted, two-component, cold-curing material.” It is also resistant to common chemicals found on roads such as oils, antifreeze, etc. *(19)*. MMA has shown very good performance in cold weather *(23)*.

   Lu and Barter *(5)* inferred from their study that MMA was the best performer in cold regions of Alaska and other northern states competing with preformed tapes, thermoplastics, MMA, and traffic paints. It can be applied at a temperature as low as -1℃. MMA also provided the greatest reflectivity even on wet surfaces. The retroreflectivity results collected in Alaska between October 1994 and April 1995 showed the reflectivity drop of 65%, 8%, and 21% for yellow preformed tapes, MMA, and traffic paints respectively & the drop of 69%, 13%, and 62% for white preformed tapes, MMA, and traffic paints respectively. In Idaho, the reflectivity of preformed tapes dropped faster than MMA for the first three years, although, both had satisfactory retroreflectivity for the first four years.

5. Preformed Tape: Preformed tapes do not require heat for the application on the pavement. It is highly durable, abrasions resistant, and requires high installation cost, therefore these are suitable on roadways with high traffic volume.

   There are two methods of installation of preformed tapes inlay method and the overlay method. In the inlay method, the tape is rolled and pressed by drum roller on the newly constructed top layer of the asphalt pavement (still warm up to 130 ºF) creating exceptional thermal bond retracting moisture. In the overlay method, the tape is applied to the existing pavement with the help of adhesive creating the bond weaker in comparison with the inlay method *(23)*. Results revealed by 3M describes the comparative performance of these two methods. The study shows adhesive failure due to the action of snowplows. Less than 0.01% of tape installed by the inlay method was damaged in comparison with the overlay method which had seen more than 2% damage. The inlaid tape remained intact without any visible damage even after 3 winters *(17)*.

6. Polyurea: Polyurea markings are sprayed, two-component durable pavement marking but are relatively new in the market. It requires a special stripping apparatus, thus limits the number of contractors available *(23)*. It can be applied on all pavement surfaces even at freezing temperatures. On the PCC pavements, polyurea performs better than thermoplastic and could be used in the lieu of thermoplastics *(4)*. Polyurea markings outperform waterborne paint as well with Benefit-Cost Ratio more than one for the state of Michigan *(10)*.

Table 2-1 shows the estimated cost in terms of the pavement surface and annual average daily traffic (AADT) for the pavement marking materials discussed above:

Table 2-1 Estimated cost of pavement markings, 2004 data (23)

	Estimated Cost of Pavement Marking per year of service life per lf ($)								
	Asphalt			Concrete			Surface Treatments		
AADT →	< 1K	1K to 10K	> 10K	< 10K	10K to 50K	> 50K	< 1K	1K to 10K	> 10K
Paints	0.08		NS	0.08		NS	0.08		NS
Thermoplastic	0.05	0.05	0.07	0.07	0.09	NS	0.05	0.05	0.07
Epoxy	0.1	0.1	0.13	0.1	0.1	0.13	0.1	0.1	0.13
MMA	0.5			0.5			0.5		
Preformed Tape	NS*	0.43		NS	0.43		NS		
Polyurea	0.25	0.25	0.33	0.25	0.25	0.33	0.25	0.25	0.33

*NS=Not suitable

An issue with the pavement markings installed on a flat road surface is their performance in wet night conditions. In the case of wet markings, the light emitted by the vehicle headlamps does not reach the glass bead for retroreflection and gets reflected by the water surface covering the glass bead (see Figure 2-9). Markings incorporating larger bead sizes perform better in such conditions (see Figure 2-10). The use of larger Type III beads increases the wet-night detection distance for waterborne paints and thermoplastics. To extend the service life of the larger glass beads, they should be used with a durable binder *(12)*. The method of distribution of glass beads on markings also has an impact on the reflectivity of markings. The retroreflectivity of the markings using glass beads for retroreflection was greater when measured in the direction of glass beads application than that when measured against the direction of application. Several works of literature have noted such inconsistent retroreflectivity in terms of the direction of measurement (25,26,27).

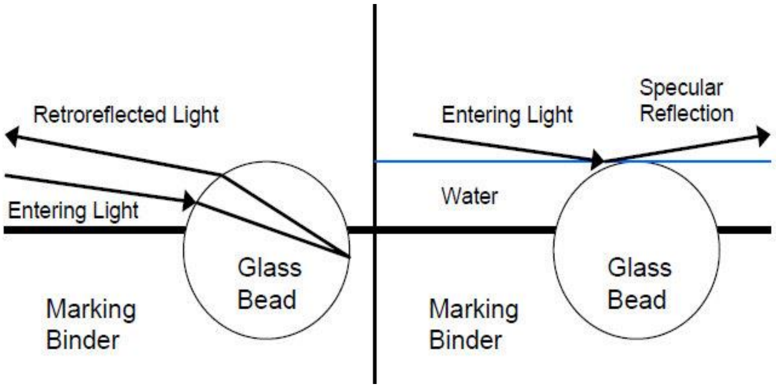


Figure 2-9. Glass bead optics under dry and wet condition (24)

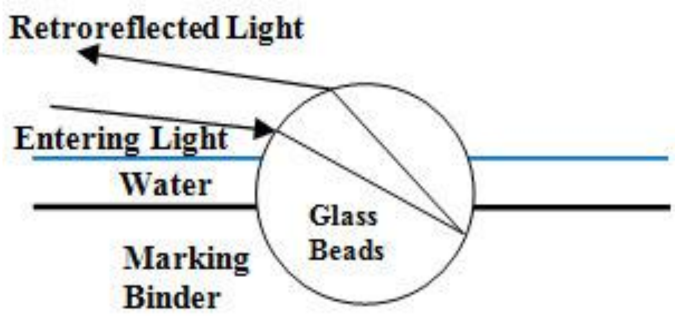


Figure 2-10. Optics of larger beads in wet condition (24)

2.4.2. Rumble Stripe

A rumble stripe is a rumble strip that has been painted with a strip across its length in the direction of traffic. The grooves in the rumble stripe not only protect the marking from abrasion but are useful on a rainy night. Water runs off the inclined groove surface, eliminating the possibility of water to reflect light. However, extruded thermoplastic had better retroreflectivity when installed on the surface than on grooves due to the ability of surface-installed thermoplastic to drain the water off the surface *(24)*.

In the areas where the snow removal activity takes place, grooving the pavement marking enhances the durability along with better retroreflective performance *(18)*. Indented markings improve the service life of the material including winter operations, although, this does not apply to waterborne and sprayable thermoplastics *(13)*. Gibbons and Williams also indicated the benefit of recessed markings in terms of protection from snowplows and concluded that excluding the cost of cutting the groove, rumble stripe was most cost-effective *(7)*.

In terms of the type of glass beads, rumble stripe performed better in wet-night conditions using Type II beads with a thermoplastic binder, although no significant improvement was observed in terms of detection distance when using larger Type III beads *(4)*.

Hawkins et al. evaluated the performance of rumble stripes *(25)*. Arbitrarily, a minimum of 100 mcd has been taken as acceptable. After one season in service, out of 14 roadways, 9 roadways had 90% of the retroreflectivity reading more than 100 mcd.

Because of poor retention of raised pavement markers on aged pavements, Abbas and Sarker evaluated markings to better delineate rumble strips *(24)*. 3M All Weather Paint lost wet retroreflectivity even if installed on a rumble strip exposed to the first winter. On the surface, 3M 380WR ES durable tape also lost wet retroreflectivity during the first and second winter making it expensive in comparison with raised pavement markers. Since 3M 380WR ES durable tape was deteriorated by snowplow, placement in the groove was recommended. Overall, the markings installed in the groove were less deteriorated in comparison with the same marking installed on the surface.

A similar study in Indiana evaluates the centerline rumble stripes as an alternative to raised pavement markers that were being damaged by the action of snowplows or heavy vehicles *(27)*. The results showed that centerline rumble stipes had better retroreflectivity than standard painted lines and cost less than raised pavement markers making it a cost-effective solution. Measurement of retroreflectivity even after two winters exceeded the FHWA threshold for repainting. The research suggested a drop of 54% and 38% in installation cost for centerline delineation when using centerline rumble stripe instead of RPMs with 40ft and 80ft spacing respectively further, 63% and 52% reduction in life cycle cost for 40ft and 80ft spacing of RPMs respectively.

2.5. National Transportation Product Evaluation Program (NTPEP)

NTPEP reports the performance of several SRPMs submitted by the manufacturers for evaluation. The SRPMs were installed on a test section with the following attributes:

- Average annual daily traffic (AADT) over 20,000
- Speed limit between 50 to 75 mph
- A minimum average snowfall of 25 inches

The lens and steel castings of the SRPMs were observed biannually for 2 years. The detection distance of RPMs was 122 meters (400 feet for the nighttime visibility tests) using a typical automobile with a low-beam headlight. The condition of the housing, lens, and the nighttime visibility of the SRPMs was defined on a 0 to 5 rating scale as follows:

Housing:

5 = Excellent, Completely intact, in "like new" condition, good adhesion
4 = Good, Minor scrapes/scratches visible on close examination of surfaces
3 = Fair, Some cuts but none larger than 10 mm
2 = Poor, Some cuts larger than 10 mm
1 = Very Poor, showing significant wear, no longer protecting reflector
0 = Missing or damaged beyond use

Lens:

5 = Excellent, Completely intact, in "like new" condition
4 = Good, Minor scrapes/scratches visible on close examination of surfaces
3 = Fair, Some abrasion, none greater than 5 mm
2 = Poor, Some large cuts/cracks/chips greater than 5 mm
1 = Very Poor, Showing significant wear, significant discoloration
0 = Missing or damaged beyond use

Night Visibility:

5 = Excellent, Completely intact, Bright, in "like new" condition
4 = Good, Clearly visible from greater than 100 m (328 ft)
3 = Fair, Some loss in reflectivity, barely visible from 100 m (328 ft)
2 = Poor, Significant loss of reflectivity, visible from 50 m (165 ft)
1 = Very Poor, Significant loss of reflectivity, barely visible, discoloration
0 = Missing or totally nonreflective

There were two such programs. The results indicate the superior retroreflectivity performance of the 3M 190 and Stimsonite C40 lens over Rayolite series model 2004 lens when these are installed in their respective castings. Also, the C40 lens incurred more damage than did the 3M 190 when installed in their respective castings. Further, all the markers held more retroreflectivity in the concrete pavements in comparison to asphalt pavements. A summary of the results of the two testing programs is reported in Table 2-2.

Table 2-2 NTPEP results for selected snowplowable RPMs

National Transportation Evaluation Program: Laboratory and Field Evaluations of Snow Plowable Raised Pavement Markers (Report 2008 NTPEP 5008.2) *(43)*

Section				Coefficient of Luminous Intensity Cleaned Condition (mCd/lx)					Coefficient of Luminous Intensity Uncleaned Condition (mCd/lx)				Casting (0 - 5) Rating					Lens (0 - 5) Rating					Nighttime visibility (0 - 5) Rating					
	Age (months) →			0	6.5	12.5	18.5	24	0	6.5	12.5	18.5	24	0	6.5	12.5	18.5	24	0	6.5	12.5	18.5	24	0	6.5	12.5	18.5	24
	Manufacturer	Casting	Lens	Average					Average				Average of 15 markers					Average of 15 markers					Average of 30 markers (Group of 10)					
Asphalt	Ray-O-Lite, Div. of Pac Tech Inc.	Snow-lite 100	Model 2004	816	290	95	40	16		204	56	26	8	5	5	5	5	5	5	4.5	2.7	2.1	1.5	5	4.3	4	3.8	3.7
	Nightline Markers Inc.	Night-line R-100	3M 190	335	197	3	3	e		112	3	3	2	5	5	5	5	5	5	5	3.9	3.8	3.5	4	3.3	3.2	3.2	4
	Ennis Faint, Stimsonite	96LP	C40	458	150	7	4	9		112	8	4	7	5	5	5	5	5	5	4.7	3.8	3.8	3.3	4.7	3.8	3.3	3.5	3.3
	Ray-O-Lite, Div. of Pac Tech Inc	Snow-lite 150	Model 2004	770	298	67	22	11		234	54	23	10	5	5	5	5	5	5	4.5	3.3	2.9	2.5	5	4.2	3.7	4	3.3
Concrete	Ray-O-Lite, Div. of Pac Tech Inc	Snow-lite 100	Model 2004	770	343	131	88	34		307	106	84	29	5	5	5	5	5	5	3.7	3	2.9	2.3	5	3.8	4	3.8	3.7
	Ennis Faint, Stimsonite	96LP	C40	457	201	7	6	12		178	10	7	10	5	5	5	5	5	5	4.3	3.7	3.7	3.1	5	3.7	4	3.8	3.7
	Ray-O-Lite, Div. of Pac Tech Inc	Snow-lite 150	Model 2004	795	396	103	64	30		375	87	75	29	5	5	5	5	5	5	4.1	3.4	3.4	2.8	5	3.7	3.8	3.8	4

National Transportation Evaluation Program: Laboratory and Field Evaluations of Snow Plowable Raised Pavement Markers (Report 2007 NTPEP 5007.2) *(42)*

Section				Coefficient of Luminous Intensity Cleaned Condition (mCd/lx)					Coefficient of Luminous Intensity Uncleaned Condition (mCd/lx)				Casting (0 – 5) Rating					Lens (0 - 5) Rating					Nighttime visibility (0 - 5) Rating					
	Age (days) →			7	218	386	580	764	7	218	386	580	764	7	218	386	580	764	7	218	386	580	764	7	218	386	580	764
	Manufacturer	Casting	Lens	Average					Average				Average of 15 markers					Average of 15 markers					Average of 30 markers (Group of 10)					
Asphalt	Ennis Faint, Stimsonite	Model 101	C40	1253	188	73	69	14		123	40	25	7	5	5	5	5	5	5	3.3	2.3	2.3	2.2	5	4	4	3.5	3
	Ennis Faint, Stimsonite	Model 101LP	C40	1270	223	80	58	6		158	57	42	5	5	5	5	5	5	5	3.7	2.6	2.6	2.8	5	4	3.3	3	2.3
	Hallen Products	Model H 1010	3M 190	197	118	92	59	3		103	75	38	5	5	5	5	5	5	5	4.9	3.9	3.9	3.9	4	3	2	2	1.3
Concrete	Ennis Faint, Stimsonite	Model 101	C40	1099	280	167	151	49		219	124	107	27	5	5	5	5	5	5	4.3	3.1	2.9	2.8	5	4	4	4	3.7
	Ennis Faint, Stimsonite	Model 101LP	C40	1116	257	161	129	20		244	134	117	20	5	5	5	5	5	5	3.9	3.1	3	2.9	5	4	4	3.5	3
	Hallen Products	Model H 1010	3M 190	230	138	123	124	7		136	108	116	10	5	5	5	5	5	5	5	4	3.9	3.9	3.5	3	3	2	2.7

Chapter 3. TxDOT Districts Survey

To augment the literature review, a survey was conducted to gain a better understanding of pavement marker performance in wintery conditions across the state of Texas. This chapter discusses the results of the survey.

3.1. Survey Questions

The survey consisted of the following questions:

- Contact Information
    - Name
    - Agency
    - State
    - District
    - Email
    - Phone

- Do you install centerline rumble strips in your area?

- If yes, list the types of roadways where you implement milled centerline rumble strips. (e.g. highways, rural non-freeways)

- What is the centerline rumble strip profile?

- What are the dimensions of the milled centerline rumble strips?

- What type of pavement markers are you using for centerline roadway delineation? Select all applicable options.
    - ➢ Raised non-snowplowable markers
    - ➢ Recessed markers
    - ➢ Raised snowplowable markers

- What is the installation (anchorage) method for pavement marker? Select all applicable options.
    - ➢ Adhesive
    - ➢ Mechanical

- If you are using recessed markers, what is the size and shape of the groove where the markers are installed? Briefly mention the performance issues.

- Have you attempted to install the pavement markers in the trough of rumble strips?

- Please share your experience of installing pavement markers in the through of rumble strips.

- On average, what percentage of pavement markers are lost yearly?
    - Total Loss
    - Loss attributed to snowplow operation

- What are the approximate per unit and installation costs for markers used in your area?
    - Raised non-snowplowable markers
    - Recessed markers
    - Raised snowplowable markers

- What are the materials you are using for rumble stripes? Please mention the following for the material:
    - Installation/application method
    - Service life
    - Cost (per linear foot)

- What is the annual maintenance budget for rumble stripe markings?

- What percentage of the marking maintenance budget is attributed to snowplow damage?

- What is the estimated annual cost savings to the users after the implementation of centerline rumble strips?

3.2. Survey Analysis

Of the 25 TxDOT Districts, personnel from 17 responded to the survey (see Figure 3-1).

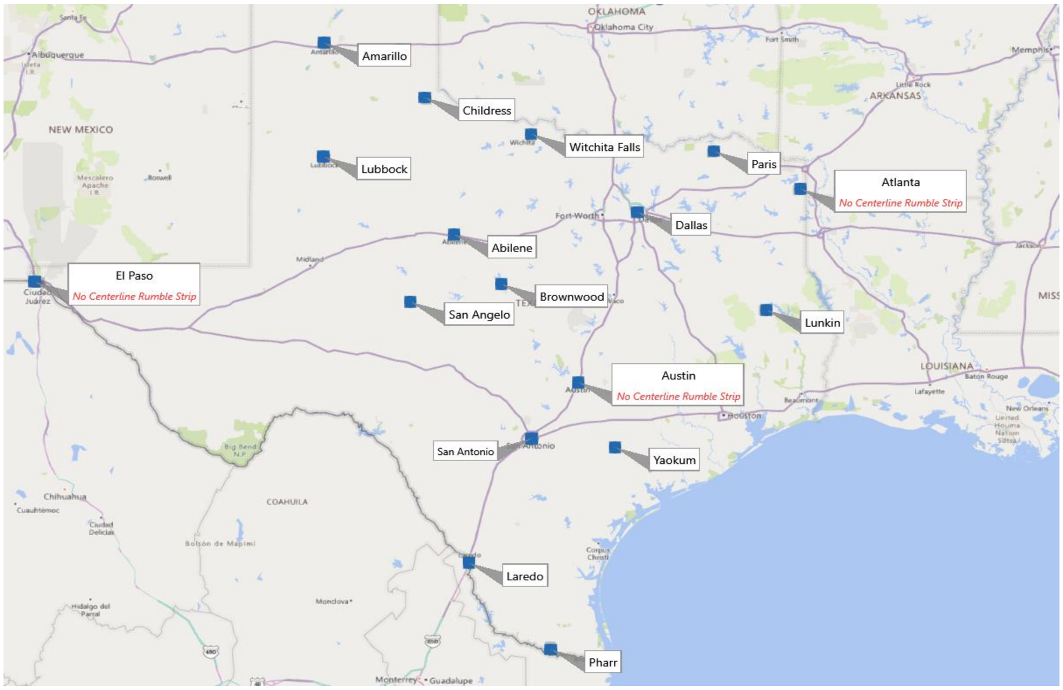


Figure 3-1 TxDOT districts that responded to the survey

Based on the results of the survey, the following can be concluded:

<u>System used:</u>

- Rumble strips are installed as per the requirements and on the pavement with more than 2 inches thick asphalt layer. The dimension of the centerline rumble strip was consistent all over the state (7” x 16” x 0.5”), except Pharr, TX where the groove dimension perpendicular to the direction of the traffic was reported to be 8” instead of 16” with same remaining dimensions.

- Three districts—Atlanta, Austin, and El Paso—do not install the centerline rumble strip (Figure 3-1 provides the locations of these districts).

- The wide use of raised non-snowplowable markers is seen in the survey results. Three districts, El Paso, Amarillo, and Childress install the snowplowable RPMs along with conventional RPMs.

- TxDOT is yet to install the RPMs in any type of groove. As for pavement marking, thermoplastic is widely used in the state of Texas.

<u>Performance:</u>

- A vast majority of the pavement markers are lost during the snowplow operation. Where the pavement markings have a service life of 2 to 5 years, a large number of RPMs get damaged and even dislodge in a yearly manner (see Figure 3-2).

- Some districts do not see that much snowfall thus the damage to the RPMs is only attributed to the normal traffic.

- Some districts use the profile stripes instead of the rumble stripes. The rumble strips cost less than the profile stripes and last longer, but it damages the seal coat resulting in loss of rumblings.

<u>Cost/Budget:</u>

- The cost of thermoplastic striping ranges from \$0.25/lf to \$0.85/lf and for the non-snowplowable RPMs it falls in the range of \$2.17 to \$3.97 per unit.

- As for the marking maintenance budget, it ranges from \$25,000 to \$3.5 million with up to 50% of the maintenance budget attributed to the damage due to the snowplow run.

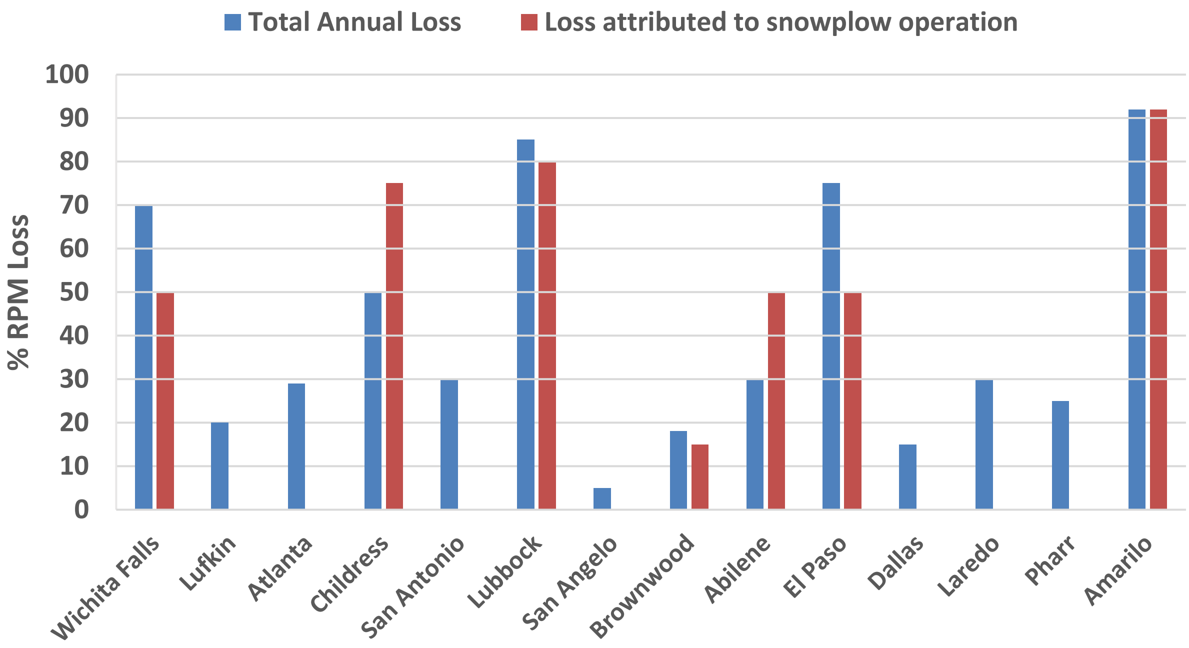


Figure 3-2 RPM loss in the state of Texas

Damage to the RPMs during the winter operations is a big issue in Texas. This is even more prominent in the districts with much lower winter temperatures than the rest of Texas (see Appendix 1). The Wichita Falls, Childress, Lubbock, El Paso, and Amarillo Districts lose more than half of the RPMs installed on the roadway where most of the damage is associated with the winter operations. However, for the districts with relatively warmer winter the percentage of RPM lost is less than 30% and most of the damage is associated with the normal traffic. As per the reported groove dimensions by the TxDOT districts, the groove dimensions of 7” x 16” x 0.5” were chosen for this research.

Chapter 4. Laboratory Retroreflectivity Testing

Screening studies were performed to evaluate the feasibility of installing RPMs into rumble strip grooves. Since the project deals with the centerline delineation of the roadway, only the RPMs incorporation yellow color lens were evaluated. The purpose of the screening studies was to gain insight into the critical depth for which the RPMs should be installed in the groove of the rumble strips for the in-field evaluation. This chapter discusses the results of these screening studies.

4.1. Key Definitions

To explain the retroreflection of the RPMs, it is necessary to touch upon some key terminologies. The ASTM standard E808–01 *(37)* provides key definitions of relevant parameters:

- ***Illuminance(E):*** quantity of light or luminance flux falling on a unit area of a surface

  $E = \frac{d\Phi}{dA}$; Unit: lumen per meter square (lm/m^2) or lux

- ***Luminous intensity (I):*** flux per unit solid angle. It is the amount of flux from a point source contained in a small angular volume.

  Unit: Candela (cd=lumen/steradian)

- ***Coefficient of luminous intensity (R_I):*** the ratio of the luminous intensity (I) of the retroreflector in the direction of observation to the illuminance ($E_\perp$) at the retroreflector on a plane perpendicular to the direction of the incident light, expressed in candelas per lux or

  $R_I = I/E_\perp$; Unit: ($\text{cd}\cdot\text{lx}^{-1}$) or cd/fc

- ***Coefficient of retroreflection (R_A):*** of a plane retroreflecting surface, the ratio of the coefficient of luminous intensity (R_I) to the area (A) Unit: candelas per lux per square meter ($\text{cd}\cdot\text{lx}^{-1}\cdot\text{m}^{-2}$)

  $R_A = R_I/A$, where A is the surface area of the sample

Similarly, relevant vectors, axes, planes, and angles are defined as follows (see Figure 4-1):

- Retroreflector Center: the point on or near a retroreflector that is designated to be the location of the RPM.

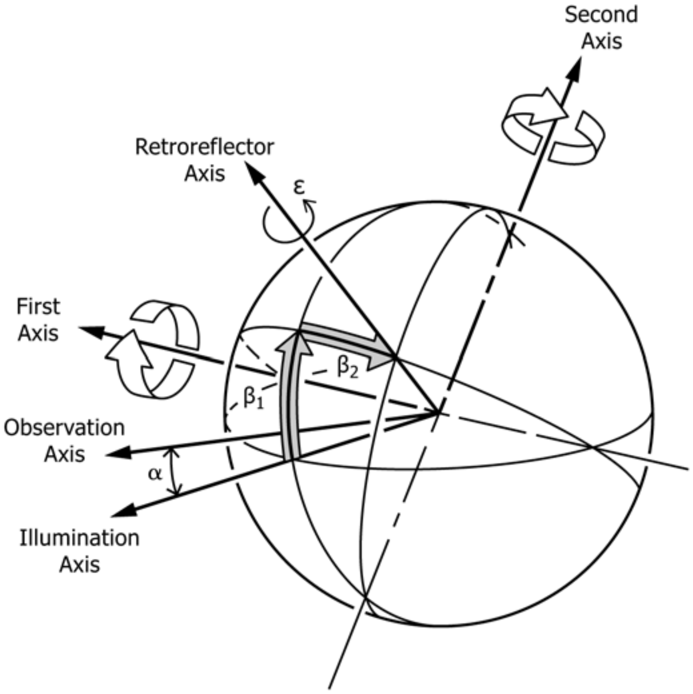


Figure 4-1 CIE (goniometer) system for measuring retroreflectors (37)

- Illumination Axis ($\vec{\boldsymbol{\imath}}$): the half-line from the retroreflector (RPM) center through the source point (lamp).
- Observation Axis ($\vec{\boldsymbol{o}}$): the half-line from the retroreflector (RPM) center through the observation point (receiver).
- Retroreflector Axis ($\vec{\boldsymbol{r}}$): a designated half-line from the retroreflector center.
- Datum Axis ($\vec{\boldsymbol{t}}$): a designated half-line from the retroreflector center perpendicular to the retroreflector axis.
- First Axis ($\vec{\boldsymbol{f}}$): the axis through the retroreflector center and perpendicular to the observation half-plane. It can be defined as:

$$\vec{\mathbf{f}} = \vec{\mathbf{i}} \ \mathbf{x} \ \vec{\mathbf{o}}$$

- Observation Half Plane: the half-plane that originates on the line of the illumination axis and contains the observation axis. First Axis, $\vec{\boldsymbol{f}}$ can be defined as the normal vector to observation half-plane.
- Entrance Half Plane: the half-plane that originates on the line of illumination axis and contains the retroreflector axis.
- Observation Angle (α): the angle between the illumination axis and the observation axis. It can be defined as:

$$\alpha = \cos^{-1}\left(\frac{\vec{\boldsymbol{i}} \cdot \vec{\boldsymbol{o}}}{|\vec{\boldsymbol{i}}| \times |\vec{\boldsymbol{o}}|}\right)$$

- Entrance Angle (β): the angle between the illumination axis and the retroreflector axis.

- Entrance Angle Component (β1): the angle from the illumination axis to the plane containing the retroreflector axis and the first axis. It ranges as $-180^0 < \beta_1 \leq 180^0$.

$$\beta_1 = \frac{\pi}{2} - \cos^{-1}\left(\frac{\vec{\boldsymbol{i}} \cdot (\vec{\boldsymbol{r}} \times \vec{\boldsymbol{f}})}{|\vec{\boldsymbol{i}}| \times |\vec{\boldsymbol{r}} \times \vec{\boldsymbol{f}}|}\right)$$

- Entrance Angle Component (β2): the angle from the plane containing the observation half-plane to the retroreflector axis. It ranges as $-90^0 < \beta_2 \leq 90^0$.

$$\beta_2 = \cos^{-1}\left(\frac{\vec{\boldsymbol{f}} \cdot \vec{\boldsymbol{r}}}{|\vec{\boldsymbol{f}}| \times |\vec{\boldsymbol{r}}|}\right)$$

- Rotation Angle (ε): the angle in the plane perpendicular to the retroreflector axis from the observation half-plane to the datum axis, measured counterclockwise from a viewpoint on the retroreflector axis. It ranges as $-180^0 < \varepsilon \leq 180^0$.

$$\varepsilon = \frac{\pi}{2} - \cos^{-1}\left(\frac{\vec{\boldsymbol{t}} \cdot \vec{\boldsymbol{f}}}{|\vec{\boldsymbol{t}}| \times |\vec{\boldsymbol{f}}|}\right)$$

4.2. Test Setup

The laboratory test of the RPMs was performed at TxDOT Cedar Park campus. The test setup consisted of 15 m photometric range with a CCD (Charged-Coupled Device) camera comprised of multiple sensors that facilitate the area retroreflectivity measurement of the marker. The goniometer can be controlled by the software feeding the input angle sets, i.e., observation angle (α), entrance angle component (β_1), entrance angle component (β_2), and the rotation angle (ε). The multi-sensor CCD camera was able to evaluate the R_A value by taking into account the illuminated area of the marker which could not be done by the single sensor camera. Given the fact that the recessed markers have reduced area exposed to the vehicle headlight while the remaining retroreflective surface being ineffective, the coefficient of retroreflection, R_A is a vital measurement for this study. Once the photograph of the lit RPM was captured with the CCD photometer camera, the ‘area of interest' could be selected manually. This area of interest is the supposed area lit by the vehicle headlight in the field. Similarly, the effective coefficient of luminous intensity, R_I can be measured by the multiplication of R_A value and the selected area.

$$Coefficient\ of\ retroreflection, R_A = \left(\frac{I}{E_{\perp}A}\right); Unit: (cd \cdot lx^{-1} \cdot m^{-2})$$

Description: R_A of a plane retroreflecting surface is the ratio of the coefficient of luminous intensity, R_I to the area, A.

$$Coefficient\ of\ luminous\ intensity, R_I = R_A \cdot A_{selected}\ Unit: (cd \cdot lx^{-1})$$

Description: —R_I ratio of the luminous intensity, I of the retroreflector in the direction of observation to the illuminance, $E_{\perp}$ at the retroreflector on a plane perpendicular to the direction of the incident light.

The light source was calibrated to the CIE Standard Source A with the correlated color temperature of 2856 ± 20 K before the measurements. The angles can be defined in the software as input parameters. The test setup (see Figures 4-2 and 4-3) represents a configuration in which α, β_1, β_2, and ε can be specified, which provides the opportunity to simulate the infield geometry in the darkroom.

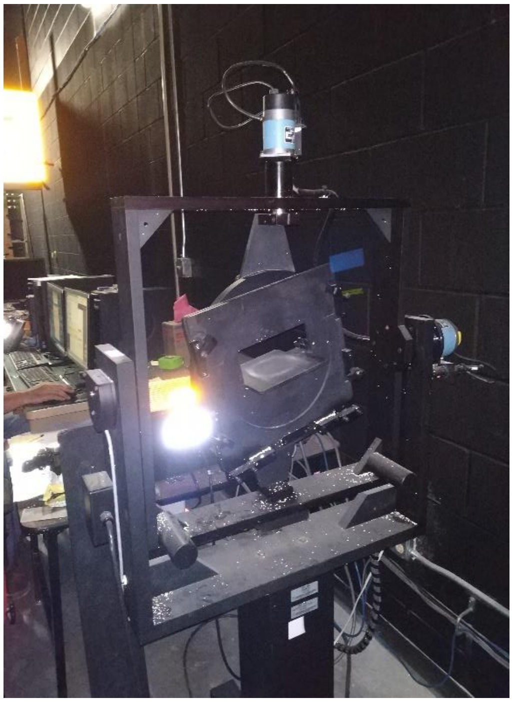


Figure 4-2 Laboratory setup - goniometer

Figure 4-3 Laboratory setup - source and receiver

4.3. Approach

When an RPM is installed in the groove, the entire face of the RPM might not be utilized for retroreflection since the edge of the groove can block the light emitted by the vehicle headlight introducing an ineffective area at the bottom of the lens (see Figures 4-4, 4-5). Hence to ensure that the RPMs installed in the groove meet the minimum retroreflectivity requirements, an estimate of critical depth for an RPM is required. The idea is that at this critical depth RPMs will have satisfactory retroreflectivity performance in the field. This means RPMs depending on their critical depths, would protrude at a certain height above the road surface maintaining adequate retroreflective surface exposed to vehicle headlight. Therefore, these measurements greatly help in mitigating the number of depths at which a model will be installed for field testing.

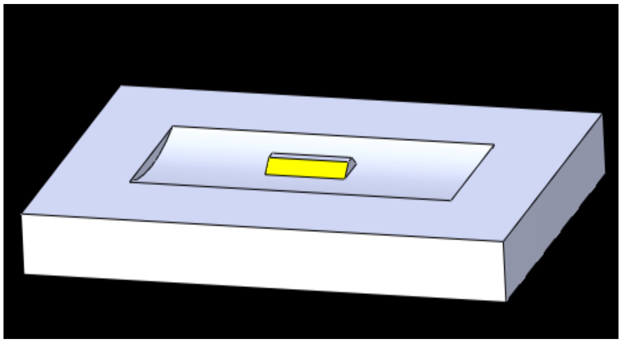


Figure 4-4 Visual presentation of RPM installed in the groove of the rumble strip

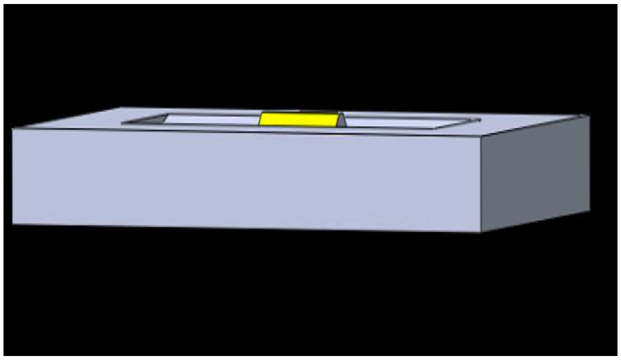


Figure 4-5 Visual presentation of lens surface blocked by the edge of the groove

At the time of this writing, there are no standards that recommend a minimum quantitative value of the RPM’s retroreflectivity in the field, and the damage assessment of the markers is being performed on subjective evaluation of the marker. This makes it challenging to define the critical depth of the RPM in terms of its retroreflectivity when installing in the groove. The authors decided to rely on the ASTM standards ASTM D4280 *(38)* and ASTM D4383 *(39)* to define the critical depth. These standards suggest the minimum retroreflectivity requirements (see Table 4-1) for the raised markers measured in terms of *coefficient of luminous* *intensity, R_I* for non-plowable raised retroreflective markers and plowable raised retroreflective markers respectively which is being used as approval criteria for the pavement markers to evaluate a satisfactory retroreflectivity performance.

Since there are several depths to be evaluated, testing the markers on the test section at several depths can be a cumbersome task. This tactic deals with shortlisting the markers' depths based on the measured *coefficient of luminous intensity, R_I* at different simulated depths. Markers embedded deeper in the groove would have reduced effective retroreflective area exposed to vehicle headlight. The goal of this laboratory testing was to eliminate certain depths of the markers to be tested in the field based on retroreflectivity criteria. To estimate the critical depth of the RPMs, markers were tested at ASTM standard angle sets ($\alpha = 0.2°$; $\beta_1 = 0°$; $\beta_2 = 0°$, $\pm 20°$; and $\varepsilon = 0°$) while varying the depth. At each depth retroreflectivity of the RPMs has been recorded. The retroreflectivity values of the RPMs for the depths at which the retroreflectivity values fall below the minimum specified in the ASTM standard is considered to be insufficient and the depth at which the retroreflectivity value catches up with the minimum specified value in the ASTM standard is defined as the critical depth for a particular RPM.

Table 4-1 Minimum required coefficient of luminous intensity Ri (38,39)

Note: Entrance angle component β1 and rotation angle ε are taken 0° (Std. Angle Sets)						
Entrance angle component β_2	Observation Angle α	Minimum Ri value, mcd/lx				
		White	**Yellow**	Red	Green	Blue
0°	0.2°	279	**167**	70	93	26
+20°/−20°	0.2°	112	**67**	28	37	10
Entrance angle component β_2	Observation Angle α	Minimum Ri value, cd/fc				
		White	**Yellow**	Red	Green	Blue
0°	0.2°	3	**1.8**	0.75	1	0.28
+20°/−20°	0.2°	1.2	**0.72**	0.3	0.4	0.11

Two-way retroreflective low-profile markers from two different manufacturers—3M and Ennis Flint—were selected from the TxDOT-approved list for this laboratory testing. All the measurements were performed on the same lens of one marker randomly selected from each manufacturer. The details of the marker are given in Table 4-2.

Table 4-2 Dimensions of the markers selected for the laboratory testing

Marker			Dimensions			
Name	Type	Model	Length	Width	Height	Slope of lens
LP1	Low Profile	Stimsonite C-40	3.96 in (10.1 cm)	1.91 in (4.9 cm)	0.48 in (1.2 cm)	35° to base
LP2		3M-190	3.9 in (99mm)	1.89 in (48 mm)	0.39 in (10 mm)	30° to base

The simulation of different depths was performed with two different approaches: first, selecting the area of interest in 100% lit RPM during the postprocessing in the software (see Figure 4-6), second, physically blocking the light making the lens partially exposed to the source. While the second approach was more time-consuming, it replicated a more realistic in-field condition.

In the second approach, the light was blocked by inserting the RPM in a 3D printed groove. The groove can accommodate the entire RPM (see Figure 4-7) and the marker can be raised by adding the plies at the bottom of the marker. The length of the groove along the direction of incident light was the same as standard groove geometry, i.e., 7 inches, and the light was blocked at the edge of the groove. Keeping in mind the groove-RPM system would be fit into the goniometer, the width of the groove was kept at 6 inches. Further, the entrance angle was calibrated such that the peak of the groove represents the road surface.

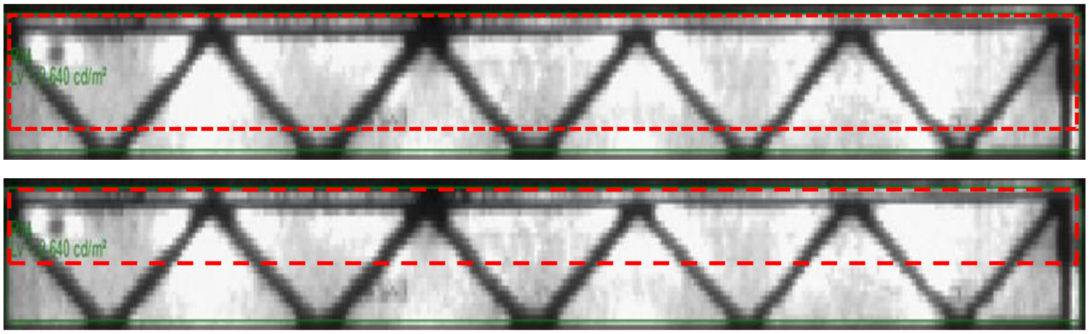


Figure 4-6 Area selection in the captured picture of the RPM

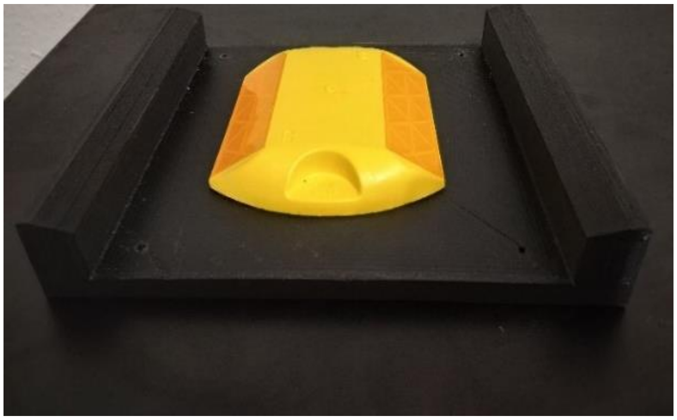


Figure 4-7 RPM in the 3D printed groove

4.4. Vehicle Position Simulation

This study represents the behavior of the RPMs as the vehicle approaches the RPM. When the vehicle moves toward the RPM embedded in a groove, the illuminated area of the RPM increases (see Figure 4-8). Because of these physical characteristics, one can look at providing a larger number of the RPMs at smaller separation so that an adequate number of RPMs with enough retroreflective surface area will be visible from any location on the roadway. But it is only possible when a significant drop in the retroreflectivity is not reported at a smaller distance of the vehicle from the RPM. This drop in the retroreflectivity could be because of the change in the angle set. When the driver approaches the RPM, the RPM would be seen more from the side than front, therefore the effective area viewed by the driver at very small vehicle-RPM distance would be close to zero. Hence, to assess the feasibility of this approach, measurement of the retroreflectivity of the RPM simulating the vehicle running towards the RPM is required.

This type of measurement creates a realistic in-field condition by considering the geometric angle sets present on the roadway which defines the RPM's actual location with respect to the approaching vehicle. Since the RPMs have a prismatic retroreflective surface, a sudden change in the R_A values is expected. Retroreflectivity of the markers is governed by parameters entrance angle, observation angle, rotation angle, and the effective area of the retroreflective surface exposed to vehicle headlight, these parameters are the function of the detection distance, vehicle type, retroreflective surface, type of headlight, etc.

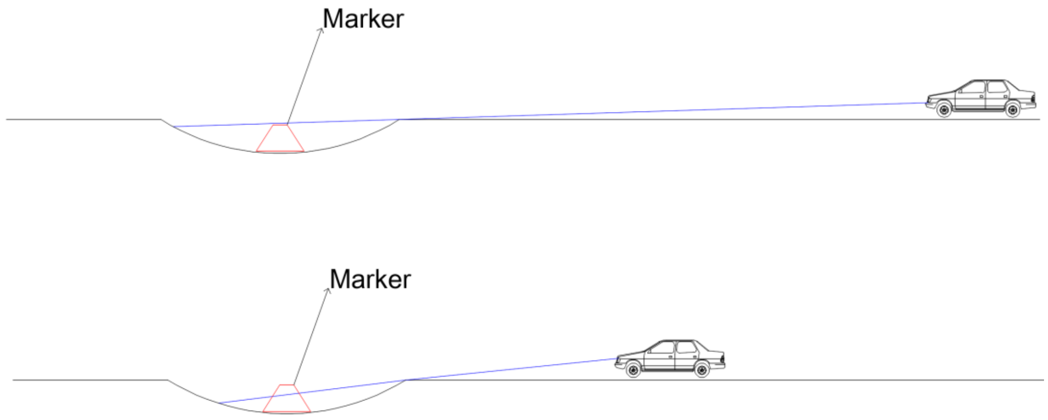


Figure 4-8 Increasing illuminated area of the RPM with decreasing RPM-vehicle distance

To define the geometric angle sets, the geometric parameters of the vehicle (source and receiver), roadway, and marker's position (retroreflector) need to be defined. These are defined as follows:

- Vehicle: A standard CEN car is chosen for this study. The relevant dimensions are the positions of the vehicle headlights and the driver's eyes.
    - The separation between headlights is 39.38 inches
    - The height of the headlights above the road surface is 25.56 inches

- Headlights are positioned 78.72 inches ahead of the Drivers eyes
    - The height of the driver's eyes is 47.28 inches above the road surface
    - Eyes are positioned 11.76 inches left to the car centerline
- Roadway: The lane width of the roadway is 12 ft.
- Marker: Since the research deals with centerline delineation of the roadway, RPM has located at half the lane width, i.e., 6 ft to the left from the car centerline. This also means that the car is approaching the marker running at the center of the lane.

The calculations have been made in the Cartesian coordinate. The origin is defined at the road surface, lying on the centerline of the car and right to the driver (see Figures 4-9, 4-10, and 4-11). The axes are defined as follows:

- Y-axis: Along the direction of traffic in the plane of the road surface
- X-axis: Perpendicular to the direction of the traffic in the plane of the road surface away from the RPM
- Z-axis: Perpendicular to the road surface in the upward direction

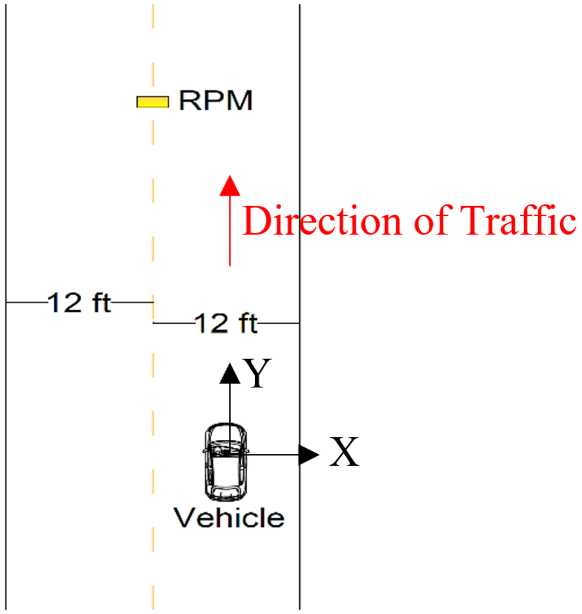


Figure 4-9 Roadway geometry for the calculation of geometric angles

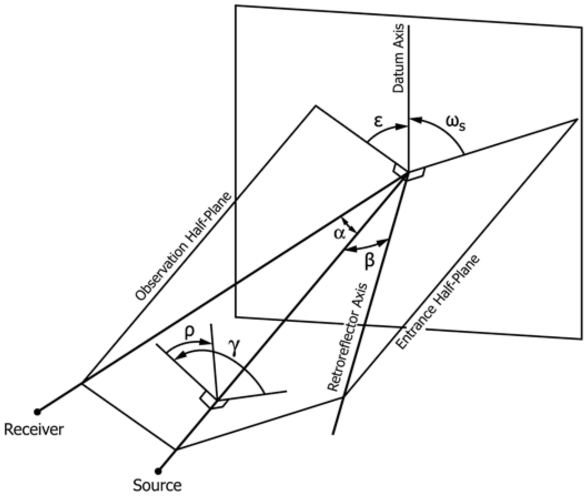


Figure 4-10: Theoretical definition of the angles in the CIE system (37)

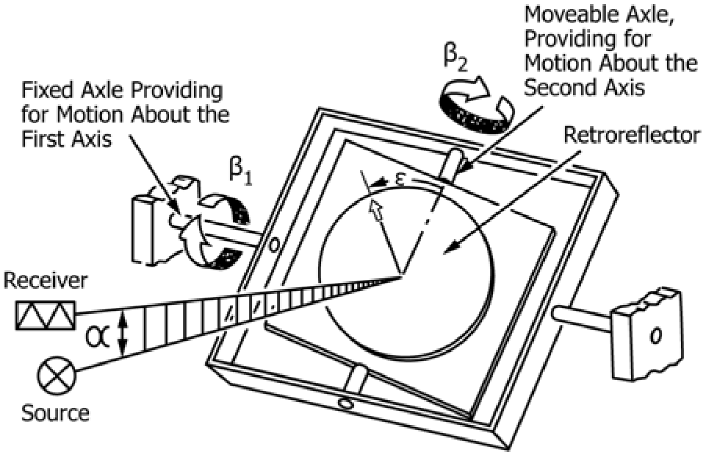
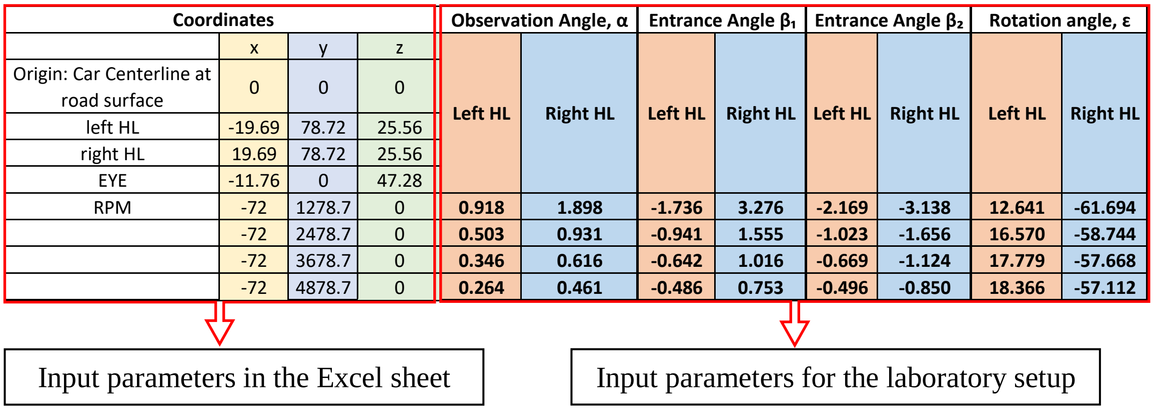


Figure 4-11: Angles controlled in the CIE goniometer (37)

These geometric parameters were computed in an Excel sheet to ease the computation efforts and automate the process of doing cumbersome calculations for each geometry set. The sheet involves the input parameters such and road geometry, vehicle dimensions, and placement of the marker. The angles were defined as specified in the ASTM standard E808–01 *(37)* and discussed earlier in the ‘Key Definitions’ section. An example is given in the screenshot taken from the excel sheet (see Figure 4-12, 4-13).

The illumination axis was defined separately for the left and right headlight of the vehicle (see Table 4-3). Whereas the equivalent retroreflection was represented as the sum of the retroreflection associated with the left and right headlights.

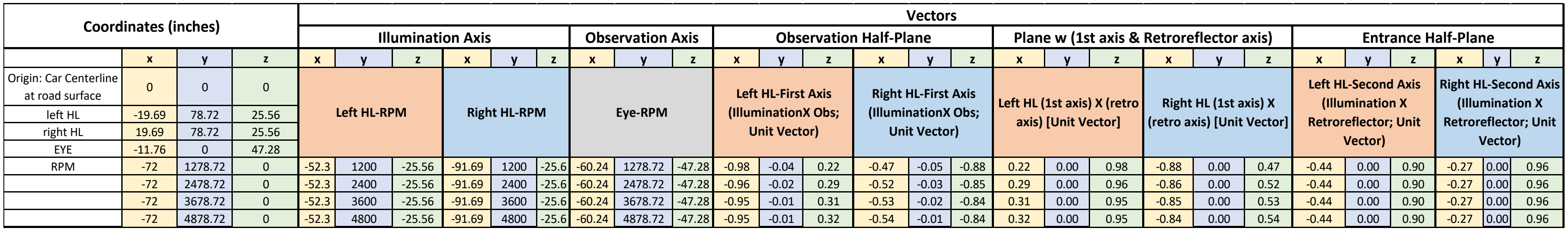


Coordinates				Observation Angle, α		Entrance Angle β_1		Entrance Angle β_2		Rotation angle, ε	
	x	y	z	Left HL	Right HL	Left HL	Right HL	Left HL	Right HL	Left HL	Right HL
Origin: Car Centerline at road surface	0	0	0								
left HL	-19.69	78.72	25.56								
right HL	19.69	78.72	25.56								
EYE	-11.76	0	47.28								
RPM	-72	1278.7	0	**0.918**	**1.898**	**-1.736**	**3.276**	**-2.169**	**-3.138**	**12.641**	**-61.694**
	-72	2478.7	0	**0.503**	**0.931**	**-0.941**	**1.555**	**-1.023**	**-1.656**	**16.570**	**-58.744**
	-72	3678.7	0	**0.346**	**0.616**	**-0.642**	**1.016**	**-0.669**	**-1.124**	**17.779**	**-57.668**
	-72	4878.7	0	**0.264**	**0.461**	**-0.486**	**0.753**	**-0.496**	**-0.850**	**18.366**	**-57.112**

Input parameters in the Excel sheet

Input parameters for the laboratory setup

Figure 4-12 Screenshot of the excel sheet for the calculation of geometric angles



Coordinates (inches)				Vectors																										
				Illumination Axis						Observation Axis			Observation Half-Plane						Plane w (1st axis & Retroreflector axis)						Entrance Half-Plane					
	x	y	z	x	y	z	x	y	z	x	y	z	x	y	z	x	y	z	x	y	z	x	y	z	x	y	z	x	y	z
Origin: Car Centerline at road surface	0	0	0	Left HL-RPM			Right HL-RPM			Eye-RPM			Left HL-First Axis (IlluminationX Obs; Unit Vector)			Right HL-First Axis (IlluminationX Obs; Unit Vector)			Left HL (1st axis) X (retro axis) [Unit Vector]			Right HL (1st axis) X (retro axis) [Unit Vector]			Left HL-Second Axis (Illumination X Retroreflector; Unit Vector)			Right HL-Second Axis (Illumination X Retroreflector; Unit Vector)		
left HL	-19.69	78.72	25.56																											
right HL	19.69	78.72	25.56																											
EYE	-11.76	0	47.28																											
RPM	-72	1278.72	0	-52.3	1200	-25.56	-91.69	1200	-25.6	-60.24	1278.72	-47.28	-0.98	-0.04	0.22	-0.47	-0.05	-0.88	0.22	0.00	0.98	-0.88	0.00	0.47	-0.44	0.00	0.90	-0.27	0.00	0.96
	-72	2478.72	0	-52.3	2400	-25.56	-91.69	2400	-25.6	-60.24	2478.72	-47.28	-0.96	-0.02	0.29	-0.52	-0.03	-0.85	0.29	0.00	0.96	-0.86	0.00	0.52	-0.44	0.00	0.90	-0.27	0.00	0.96
	-72	3678.72	0	-52.3	3600	-25.56	-91.69	3600	-25.6	-60.24	3678.72	-47.28	-0.95	-0.01	0.31	-0.53	-0.02	-0.84	0.31	0.00	0.95	-0.85	0.00	0.53	-0.44	0.00	0.90	-0.27	0.00	0.96
	-72	4878.72	0	-52.3	4800	-25.56	-91.69	4800	-25.6	-60.24	4878.72	-47.28	-0.95	-0.01	0.32	-0.54	-0.01	-0.84	0.32	0.00	0.95	-0.84	0.00	0.54	-0.44	0.00	0.90	-0.27	0.00	0.96

Figure 4-13 Intermediate calculations for the geometric angles

Table 4-3 Input parameters (geometric angles) for retroreflectivity measurements in the laboratory

Vehicle distance from RPM (ft)	**Observation Angle, α in degrees**		**Entrance Angle β_1 in degrees**		**Entrance Angle β_2 in degrees**		**Rotation angle, ε in degrees**	
	Left Headlight	Right Headlight	Left Headlight	Right Headlight	Left Headlight	Right Headlight	Left Headlight	Right Headlight
100	0.92	1.90	-1.74	3.28	-2.17	-3.14	12.64	-61.69
200	0.50	0.93	-0.94	1.55	-1.02	-1.66	16.57	-58.74
300	0.35	0.62	-0.64	1.02	-0.67	-1.12	17.78	-57.67
400	0.26	0.46	-0.49	0.75	-0.50	-0.85	18.37	-57.11

4.5. Results

The retroreflectivity values are reported in the term of the *coefficient of luminous intensity*, R_I. All the tests were performed on a new two-way yellow color marker with the same lens face. The results are bifurcated into three sections:

- Area Selection in Software: where the simulation of the depths was performed by selecting different areas in a captured picture of the fully illuminated lens at standard angle sets.
- Physically Blocked Markers: where the retroreflectivity measurements were taken at standard angle sets by inserting the markers into a 3D printed groove. In this case, only the light above the edge of the groove can reach the marker and the remaining light was blocked by the edge of the groove. So, in this case, the lens was partially illuminated.
- Vehicle Position Simulation: where the performance of the marker was observed simulating a vehicle approaching the marker. This was done by taking the retroreflectivity measurements at the angle sets of the different vehicle to RPM distances.

4.5.1. Area Selection in Software

The retroreflectivity of both markers follows a linear relationship with the area of the lens (see Figures 4-14 and 4-15; Table 4-4). The R_I values were greatest for the entrance angle $\beta 2 = 0^0$ for both markers. To compare the R_I for different markers it must be compared against the same area and same angles. However, analyzing them in the same areas was challenging due to the experimental setup. From Figures 4-14 and 4-15, it can be seen that the slope of the curves in the figures are greater for the LP1 (C40) marker than the LP2 (3M-190) marker, then overall the LP1 marker gave larger retroreflectivity than LP2 marker.

R_A is the ratio of the coefficient of luminous intensity, R_I, and the selected area, *A*. Therefore:

$$R_A = \frac{R_I}{A}$$

Also, from the results (see Figure 4-14, 4-15) it can be said that R_I is proportional to the selected area, *A*, where the coefficient of proportionality is different for each marker at each angle set. In mathematical terms:

$$R_I \propto A \quad \Rightarrow R_A \cdot A \propto A$$

$$\Rightarrow \mathrm{R_A} = constant\ for\ a\ particular\ marker\ at\ a\ certain\ angle\ set$$

This establishes that the coefficient of retroreflection R_A is uniform across the lens surface illuminated by the light source.

Table 4-4 Measured retroreflectivity values of RPMs by the area selection method

α	β_1	ε	β_2	LP2 (3M 190)		LP1 (C40)	
				Area (mm^2)	R_I (mcd/lx)	Area (mm^2)	R_I (mcd/lx)
0.2°	0°	0°	0°	605	250	540	320
				475	216	344	217
				412	183	242	142
				285	125	186	113
			20°	618	243	490	186
				412	162	344	126
				332	126	249	82
				206	63	172	53
			-20°	620	190	435	177
				467	150	252	108
				333	103	157	62
				279	83	104	45

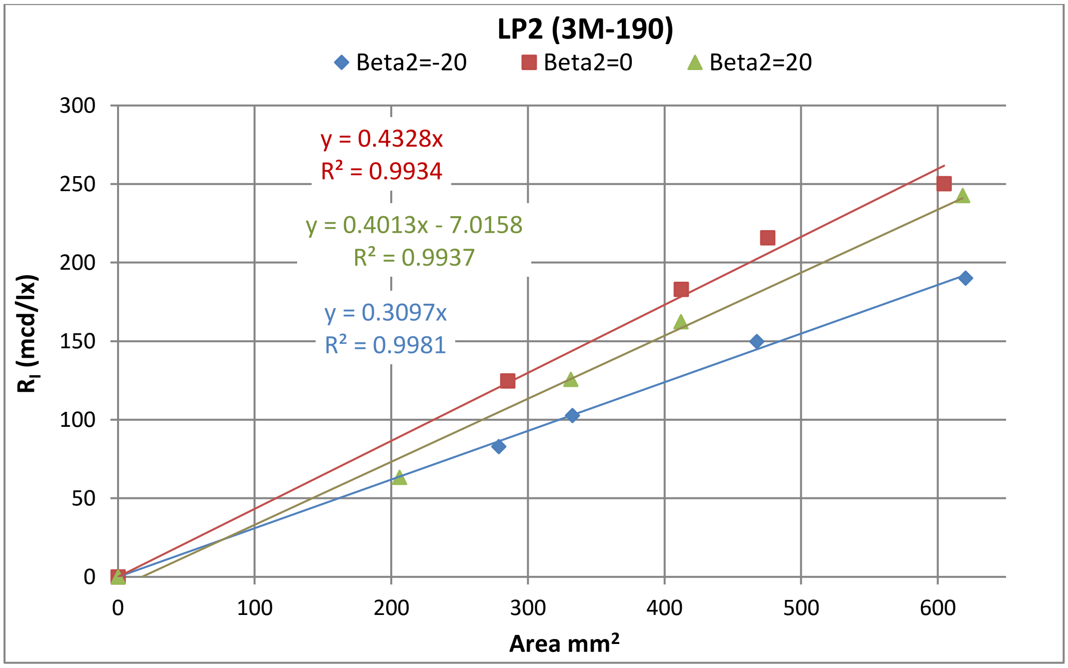


Figure 4-14 R_I vs selected area for LP2 marker by area selection method

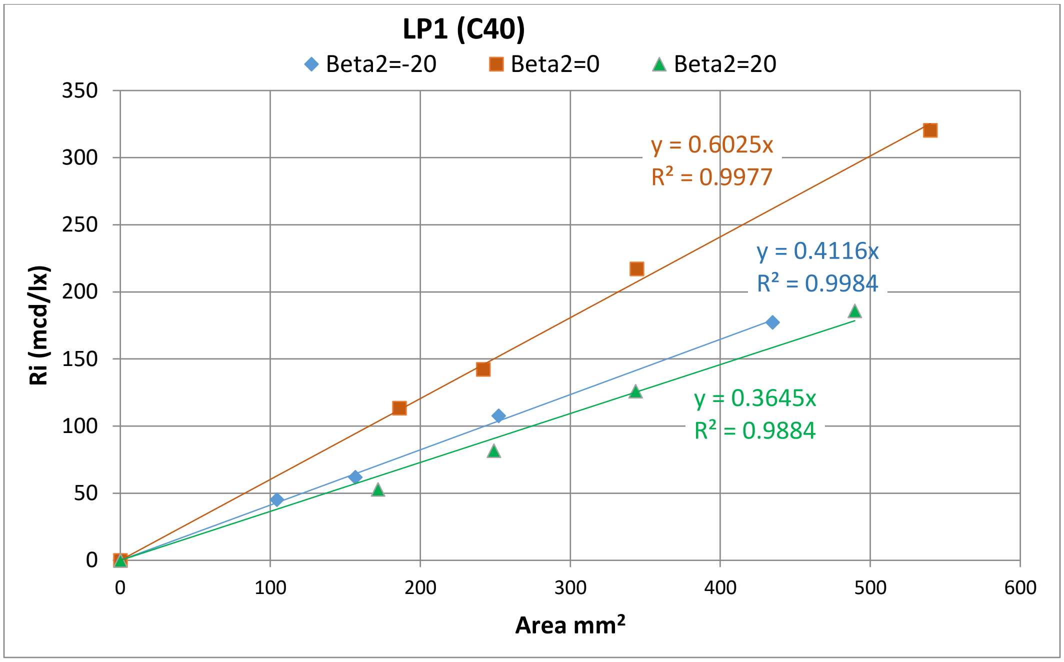


Figure 4-15 R_I vs selected area for LP1 by area selection method

4.5.2. Physically Blocked Marker

Since in the field the RPMs will be installed in the groove, a more realistic of the in-field condition was imitated in the laboratory setup by inserting the marker in the 3D printed groove (see Figure 4-7) simulating a rumble stripe. The retroreflectivity measurements were taken for each marker at five different heights and standard angle sets. The height of the marker was defined as the difference in elevation between the top surface of the marker and the road surface. Thus, smaller numbers mean that the surface of the marker was protruding higher over the surface and larger numbers mean the surface of the marker was sitting deeper in the groove. A schematic of the laboratory setup is shown in Figure 4-16. It should be noted that in this setup the relative position of the source and the marker cannot be altered. The research team wanted to make sure that the angles at which the markers were tested are in accordance with the ASTM standard angle sets as was the case in the area selection method. This was done to compare the two methods. If the results were similar in both methods, the area selection method would have been adopted for further analysis and to populate more data points because the area selection method is less time-consuming.

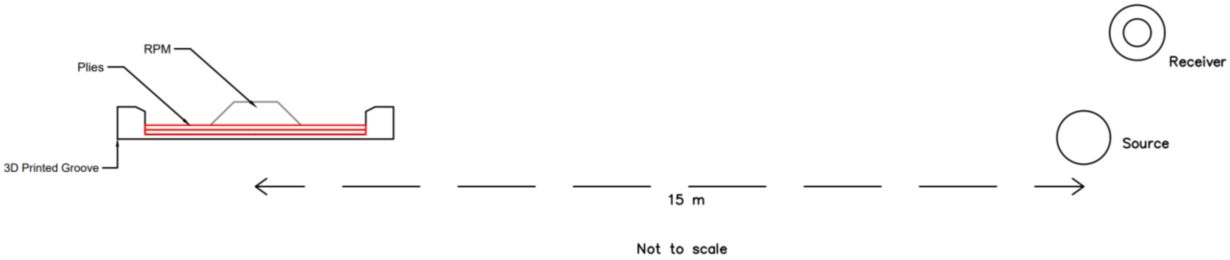


Figure 4-16 Laboratory schematic of physically blocked marker

The results with the marker in 3D printed groove show that the retroreflectivity values for both markers were less than the value obtained by the area selection method (see Table 4-5). In addition, the relationship between R_I and the illuminated area is no longer linear, rather it follows a quadratic curve (see Figure 4-17, 4-19). Therefore, this method was chosen for further measurements as it creates a more realistic scenario than the area selection method.

Again, LP1 (C40) marker gave better results than LP2 (3M-190) marker. It is easier to distinguish the separation between the curves for $\beta_2 = 0^o$ and $\beta_2 = 20^o/-20^o$ in LP1 (C40) marker as compared with LP2 (3M-190) marker. The critical heights were computed for both markers at which markers achieve the minimum R_I values at each angle set. The minimum R_I for entrance angle $\beta_2 = 0^o$ is 167 mcd/lx and for $\beta_2 = 20^o/-20^o$ it is 67 mcd/lx (see Table 4-5). Both the markers crossed the lower threshold of $R_I = 67$ mcd/lx well before the upper threshold of 167 mcd/lx (see Figure 4-18, 4-20), hence the entrance angle $\beta_2 = 0^o$ was the governing angle in the computation of the critical height of the markers. The critical height for the markers was as follows (see Figure 4-18, 4-20):

- LP1 (C40): 4.7 mm
- LP2 (3M-190): 6.4mm

From the data presented in Table 4-5, it can be observed that the retroreflectivity value of RPMs bottom mounted in the grooves of a rumble strip is reduced by approximately 43% - 67% compared to RPMs conventionally mounted on the surface of the pavement.

Table 4-5 Measured laboratory retroreflectivity values of RPMs inserted in 3D printed groove

α	β_1	ε	β_2	LP2 (3M 190)			LP1 (C40)		
				Area (mm^2)	R_I (mcd/lx)	Height above the road surface (mm)	Area (mm^2)	R_I (mcd/lx)	Height above the road surface (mm)
0.2°	0°	0°	0°	605	251	7.9	540	312	6.8
				412	159	5.8	344	177	4.7
				330	103	5.0	207	76	3.3
				247	33	4.1	94	38	2.1
				-	0	1.5	-	0	1.0
			20°	618	243	7.9	490	198	6.8
				383	138	5.8	400	98	4.7
				206	67	5.0	262	62	3.3
				177	17	4.1	76	21	2.1
				-	0	1.5	-	0	1.0
			-20°	620	191	7.9	441	119	6.8
				441	125	5.8	435	175	4.7
				333	76	5.0	236	71	3.3
				203	36	4.1	76	18	2.1
				-	0	1.5	-	0	1.0

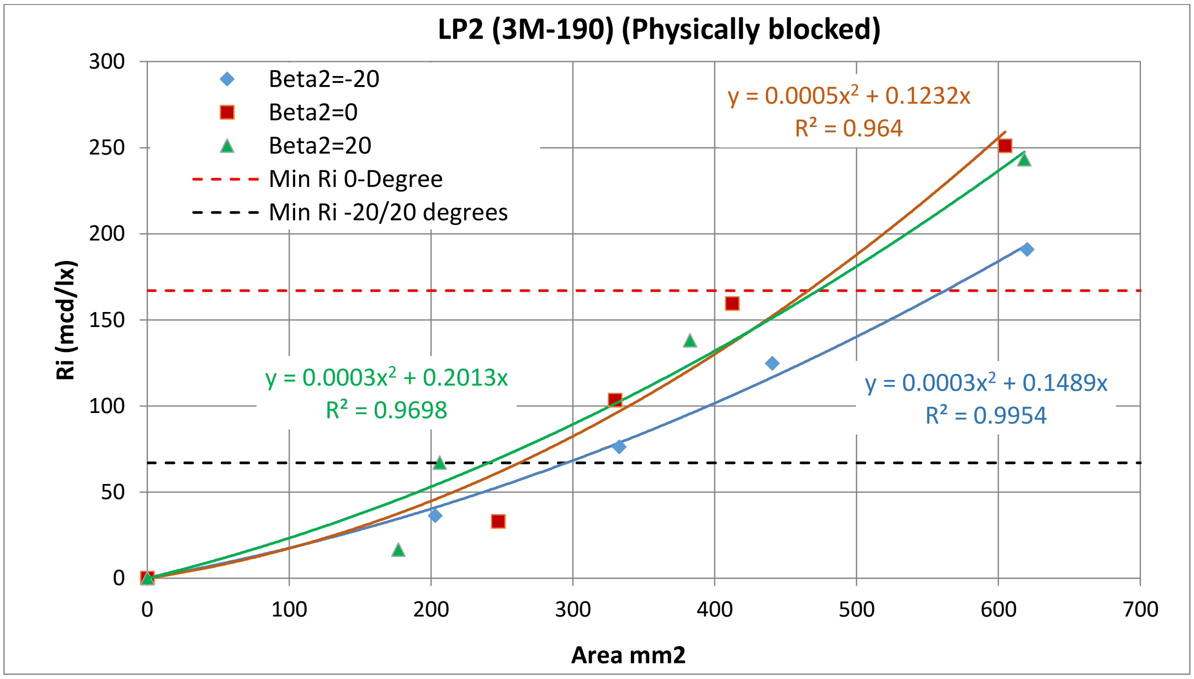


Figure 4-17 R_I vs illuminated area for LP2 Marker by physically blocking the light

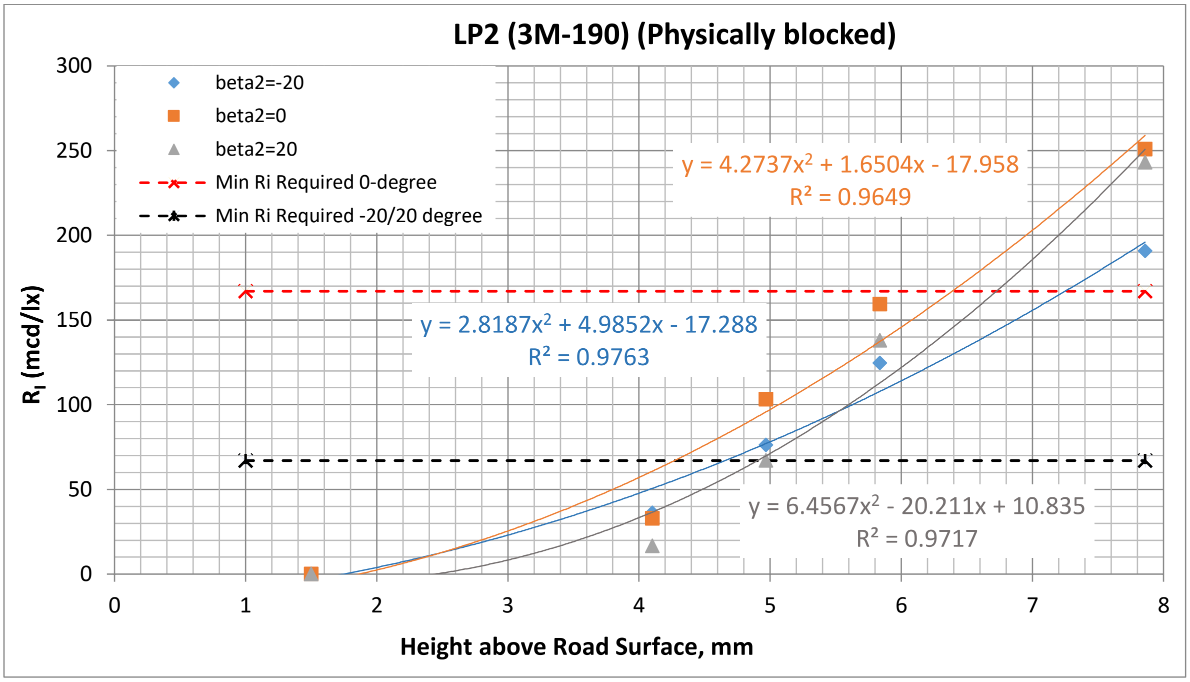


Figure 4-18 Variation in R_l with height of the LP2 marker insert by physically blocking the light

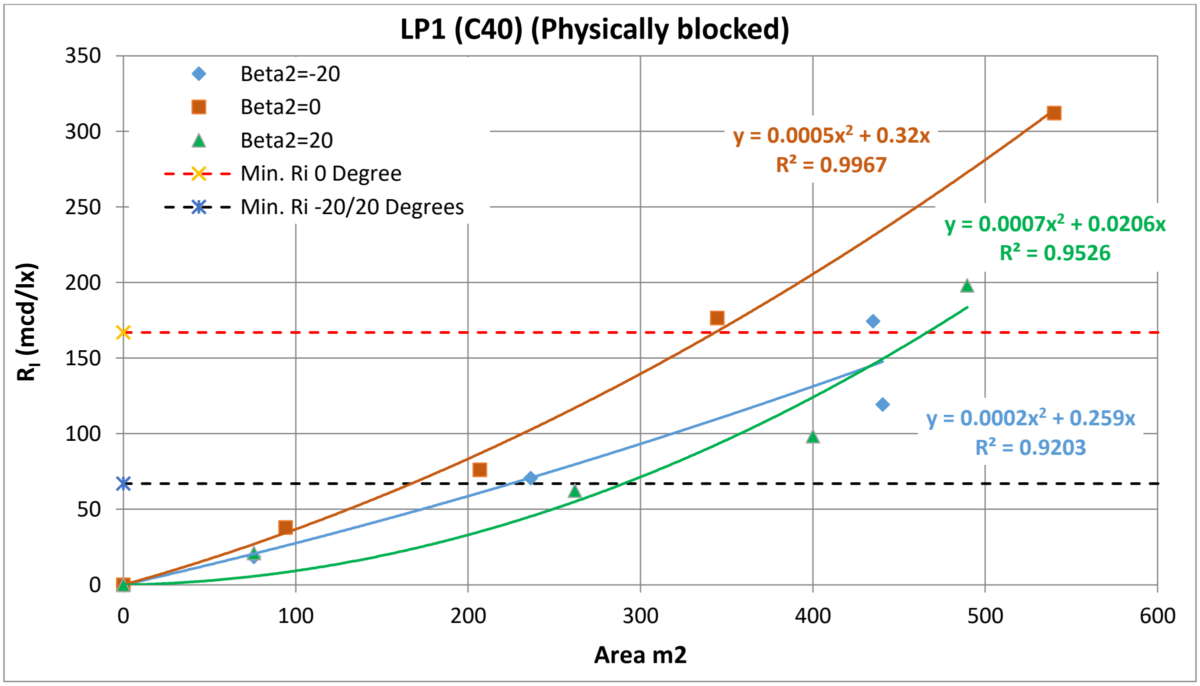


Figure 4-19 R_l vs illuminated area for LP1 marker by physically blocking the light

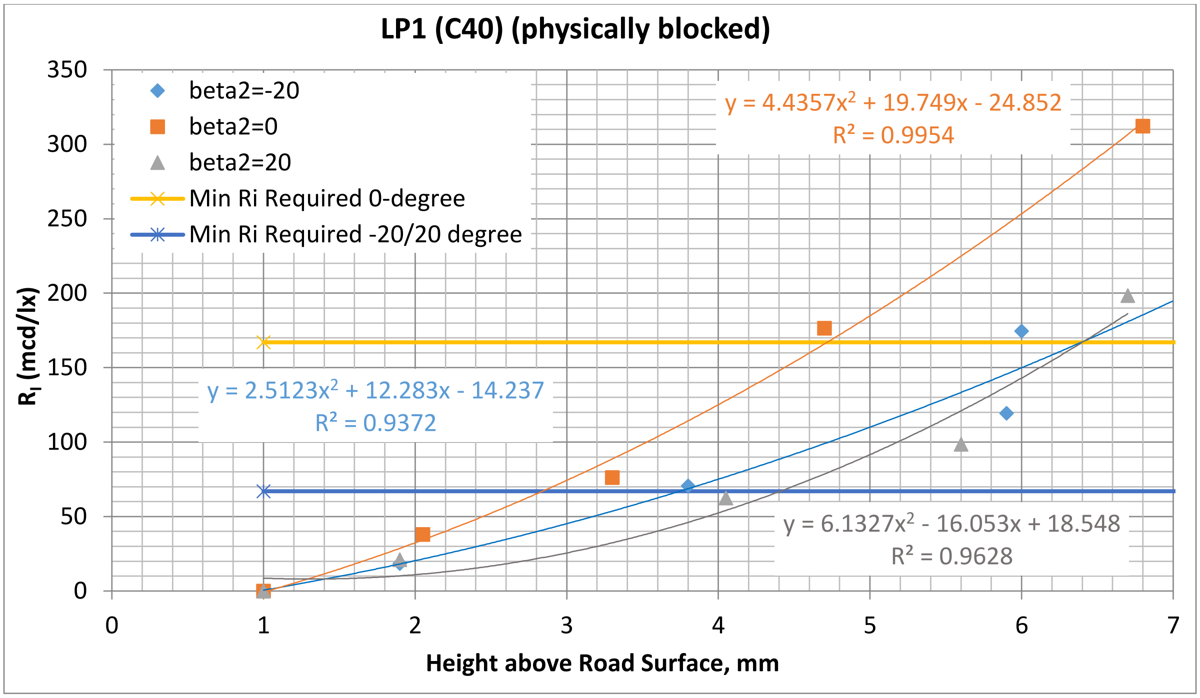


Figure 4-20 Variation in R_I with height of the insert LP1 marker by physically blocking the light

The critical heights mentioned previously are the heights at which the markers had enough illuminated area to meet the minimum retroreflectivity (see Table 4-1) at the ASTM standard angle sets of $\alpha = 0.2°$; $\beta_1 = 0°$; $\beta_2 = 0°, \pm 20°$; and $\varepsilon = 0°$. While in the field, these angles will be different and will depend on several factors. The entrance angle component β_1 is the parameter that dictates the exposed area of the RPM to the vehicle headlight. As the vehicle moves towards the RPM, β_1 increases and so does the illuminated RPM area. $\beta_1 = 0^o$ is the case in which the vehicle is infinitely away from the RPM. As discussed earlier, when the vehicle approaches the marker, the marker is seen from the side and the projected area of the RPM to the observer would also decrease. Hence to better understand what happens to the R_I values as the vehicle approaches the marker, the vehicle position with respect to the RPM was simulated. The results of this simulation study are presented in the next section, "Vehicle Position Simulation."

4.5.3. Vehicle Position Simulation

Tables 4-6 and 4-7 reflect the performance and behavior of the RPM as the vehicle moves towards the RPM on the roadway. Retroreflectivity measurements for the markers were also taken where the markers were recessed in the 3D printed groove. The Stimsonite C40 marker was at the critical height of 4.7 mm above the peak edge of the groove while 3M-190 was protruding 5.8 mm above the top edge which is also close to its critical height.

The results show a decline in the retroreflectivity as the distance between vehicle and RPM decreases; this is true for both fully lit and the recessed markers (see Figure 4-21, 4-22). A fully lit 3M-190 marker showed a steeper drop following a quadratic curve (see Figure 4-21) than a fully lit Stimsonite C40 marker where the retroreflectivity decreased linearly. Further, a sudden drop in the retroreflectivity values was observed for the recessed 3M-190 marker along with a poor relationship between the vehicle distance and the retroreflectivity. In contrast, the recessed LP1 (C40) marker displayed a much smaller drop compared to the recessed LP1 (3M-190) marker and also presented a strong relationship between the vehicle distance and retroreflectivity. Table 4-6 and Table 4-7 outline those changes.

Table 4-6 Change in R_I for LP2 (3M 190) marker with the RPM - vehicle distance

Vehicle Distance from RPM (ft)	R_I (mcd/lx) w/o blocking light			R_I (mcd/lx) for the marker at height 5.8 mm above the edge of the groove		
	Left Headlight	Right Headlight	Total	Left Headlight	Right Headlight	Total
0	0	0	0	0	0	0
100	38	-	-	-	-	-
200	101	94	195	86	1	87
300	168	104	272	25	11	36
400	192	294	486	99	38	137
Note: The observation angle for the right headlight at 100 ft was so large that it cannot be accommodated in the test setup.						

Table 4-7 Change in R_I for LP1 (C40) marker with the RPM - vehicle distance

Vehicle Distance from RPM (ft)	R_I (mcd/lx) w/o blocking light			R_I (mcd/lx) for the marker at height 4.7 mm above the edge of the groove		
	Left Headlight	Right Headlight	Total	Left Headlight	Right Headlight	Total
0	0	0	0	0	0	0
100	-	-	-	-	-	-
200	190	14	204	141	3	144
300	319	40	359	222	88	311
400	379	86	465	371	16	387

Note: The observation angle for the right headlight at 100 ft was so large that it cannot be accommodated in the test setup.

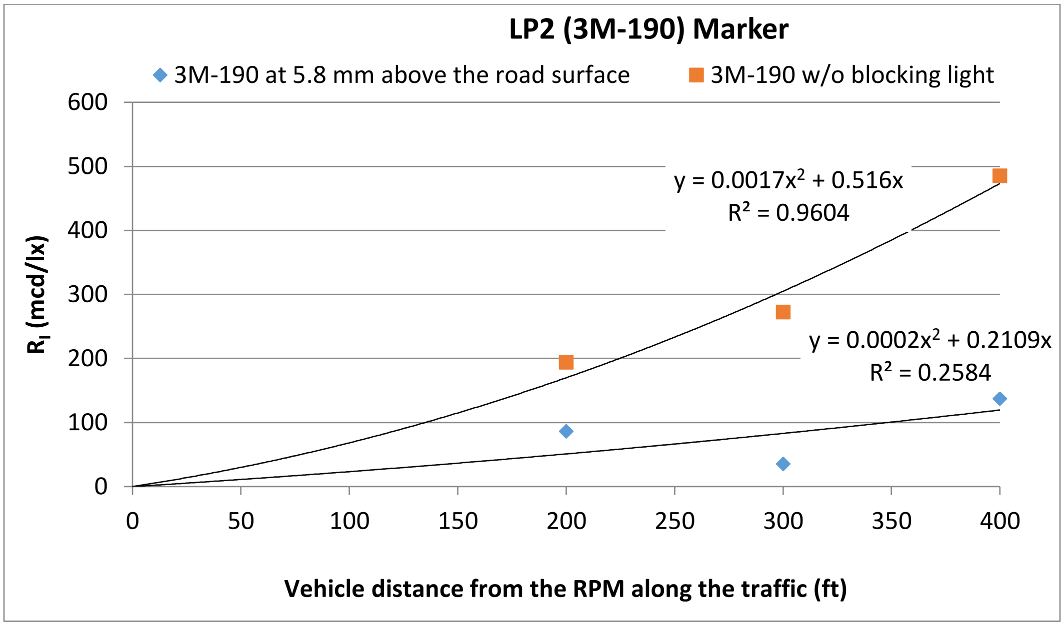


Figure 4-21 Variation of R_I for LP2 marker with the RPM - vehicle distance

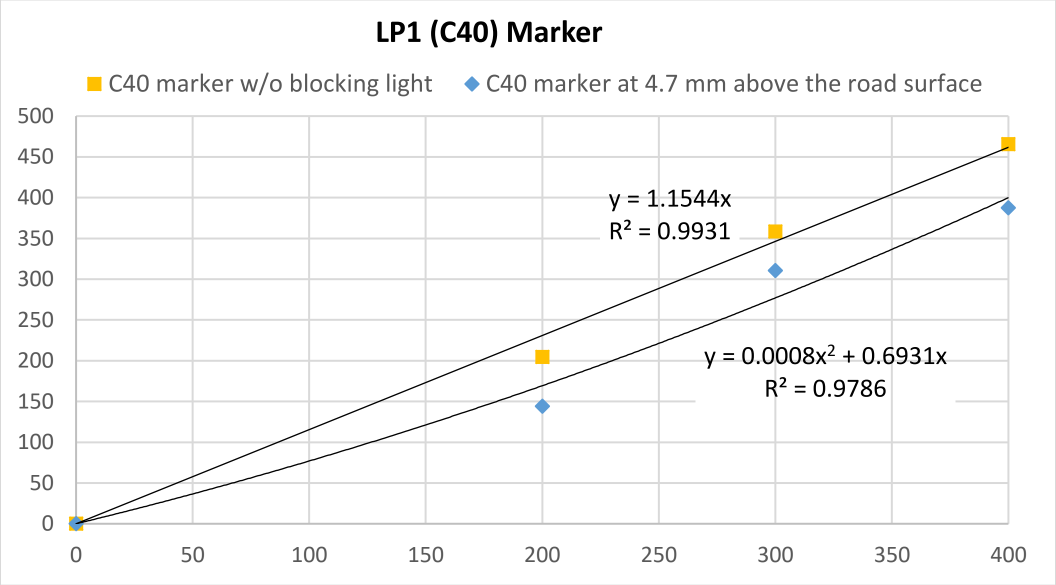


Figure 4-22 Variation of R_I for LP1 marker with the RPM - vehicle distance

RPMs are essential for long-range delineation of roadways. For the long-range delineating, at least 3 seconds of the preview time is for the location ahead of the driver. This means the minimum detection distance of the RPM is a function of the vehicle speed. For the vehicle speed of 25 miles/hr the minimum detection distance 110 ft, and at 55 miles/hr driver should be able to detect the marker at least 250 ft ahead of its current position *(19)*.

Though the retroreflectivity is smaller for the RPM in groove compared to the fully lit RPMs, the difference is not that much for the LP1 (C40) when compared to LP2 (3M-190). This study establishes that although there is a larger area of the marker illuminated to the headlight at smaller distances, the retroreflectivity values also fall because of the change in the viewing angle. Hence, a concrete judgment cannot be made just based on the R_I values to assess the benefits of decreasing the separation of RPMs. However, based on the R_I values for recessed Stimsonite C40 marker, it shows the potential of providing enough retroreflectivity and a subjective evaluation for the retroreflectivity could further establish its feasibility.

4.6. Key Findings of the Laboratory Retroreflectivity Tests

The following comments can be made based on the laboratory tests of RPM's retroreflectivity:

- As the illuminated area of the marker increases, the R_I also increases following a quadratic relationship.

- The R_I values of the RPMs are greater for the entrance angle component $\beta_2 = 0^o$ than $\beta_2 = 20^o/-20^o$ which means the driver would perceive RPMs installed on the centerline of the road, brighter when driving on the lane closer to the centerline.

- The critical height of the LP1 (C40) marker is 4.7 mm while for the LP2 (3M-190) marker it is 6.4 mm. Also, LP1 marker had better retroreflectivity performance at the standard angle sets ($\alpha = 0.2°$; $\beta_1 = 0°$; $\beta_2 = 0°, \pm 20°$; and $\varepsilon = 0°$).

- The R_I value of RPMs bottom mounted in the grooves of a rumble strip is predicted to be reduced by approximately 43% - 67% compared to RPMs conventionally mounted on the surface of the pavement.

- The R_I value decreases for both fully lit and recessed markers as the driver approaches the RPM, even though the illuminated area of the RPM increases. This is attributed to the combined effect of the geometric angles set of (α, β_1, β_2, and ε) on RPM’s retroreflectivity.

- Recessed LP1 (C40) performed better than the recessed LP2 (3M-190) marker. The drop in the retroreflectivity caused by recessing the marker was also smaller in LP1 marker than LP2 marker.

Chapter 5. Field Screening Studies

The objective of the field screening study was to evaluate the performance of the RPMs installed in the grooves of the rumble strip under the full-weight snowplow loads. The screening studies were conducted on a test pavement section. The markers were installed in two series of depths which are discussed later. The markers went under five snowplow runs and the damage to the markers and their bonding with the pavement was visually inspected and documented before and after each snowplow run.

5.1. Test Section

The test section pavement is located at The University of Texas at Austin research facility campus. Specifically, it is located on Innovation Boulevard on the Pickle Research Campus (PRC) (see Figure 5-1). The section lies between intersections on both ends; one is a dead-end and the other is a T-intersection. The distance between the intersections is 1250 ft, however the rumble strips were milled at the middle of the section to address the safety of the road users at turns. Thus, the milled section was only 800 ft long, versus 1200 ft long.

Figure 5-1 Location of test roadway section for field screening studies (Innovation Boulevard is highlighted in red)

5.1.1. Rumble Strip Geometry

An approximately 800-ft-long milled centerline rumble strip was installed as per the TxDOT standards described below:

- Width along the direction of traffic: 7” ± ½”
- Length perpendicular to the direction of traffic: 16” ± ½”
- The separation between grooves (start edge to end edge): 24” ± ½”
- Maximum depth of the groove: ½” ± ⅛”

The grooves were milled with a rotating cutting head. The geometry of the rumble strip was verified with the survey of the geometry of rumble strips conducted by the research team.

5.1.2. Retroreflective Pavement Markers

The pavement markers for this study were selected from the TxDOT-approved list. Four marker types from two different manufacturers have been chosen for the field tests (Figures 5-2 through 5-5), two of which are the low-profile markers. The dimensions of the marker body are given in Table 5-1.

Table 5-1 Dimensions of the RPMs evaluated in the field test

Name	**Model**	**Type**	**Dimensions**			**Slope of lens**
			Length	**Width**	**Height**	
LP2	3M Series 190	Low Profile	3.9 in (1 cm)	1.89 in (48 mm)	0.39 in (10 mm)	30º to base
LP1	Stimsonite Model C40		3.96 in (10.1 cm)	1.91 in (4.9 cm)	0.48 in (1.2 cm)	35º to base
RP1	3M Series 290	Regular	4 in (10.16 cm)	3.51 in (8.92 cm)	0.625 in (1.59 cm)	30º to base
RP2	Stimsonite Model C80		4.55 in (11.6 cm)	3.2 in (8.1 cm)	0.66 in (1.8 cm)	35º to base


Figure 5-2 LP2 (3M-190) markers


Figure 5-3 LP1 (C40) marker


Figure 5-4 RP2 (C80) marker


Figure 5-5 RP1 (3M-290) marker

The rumble strip has a curved surface and relatively shallow depth. Therefore, the dimensions of the marker body play a critical role in the installation of markers into the groove of the rumble strip. In the current practice, RPMs without any steel housing are installed either (1) on the road surface where the marker is highly susceptible to get dislodged from the impact of the snowplow blade, or (2) into a saw-cut groove that completely protects the RPM from any impact due to snowplow.

In situation1, when the marker is installed on a plane road surface, the snowplow blade hits the marker near to marker's bottom and rips it off the road surface. In the project test section, the RPMs were not installed according to current practice; rather the RPMs were installed in the groove of rumble strips. The hypothesis was that if the snowplow blade hits the RPM at a greater elevation, it would mitigate the impact experienced by the RPM as opposed to when the blade hits the RPM nearer to the RPM's bottom. As such the goal of the full scale test was to determine the dislodgement potential of RPMs installed using this unique approach.

A comparison of the two marker types—low-profile and regular—reveals that both have their advantages and drawbacks.

- Low-Profile Marker

    - Advantage: Can sit deeper in the groove without altering the groove geometry because of smaller width when compared to regular markers
    - Disadvantage: Smaller bottom surface area results in decreased bonding to pavements when compared to regular markers
- Regular Marker
    - Advantage: Offers a larger bottom surface area, leading to better bonding with the pavement as compared with low-profile markers
    - Disadvantage: Cannot be installed deeper than a certain depth without altering the groove geometry, due to a greater width as compared to low-profile markers

5.2. Work Plan

The work plan for the full-scale screening test consisted of four different types of markers, as mentioned earlier. After discarding the deficient grooves from the test section, the test section could accommodate a total of 76 markers with approximately 10 ft separation (4 grooves skipped) between the as shown in Figure 5-6. The separation between the markers was done to ensures that the snowplow blade meets the ground before it hits the next marker in line.

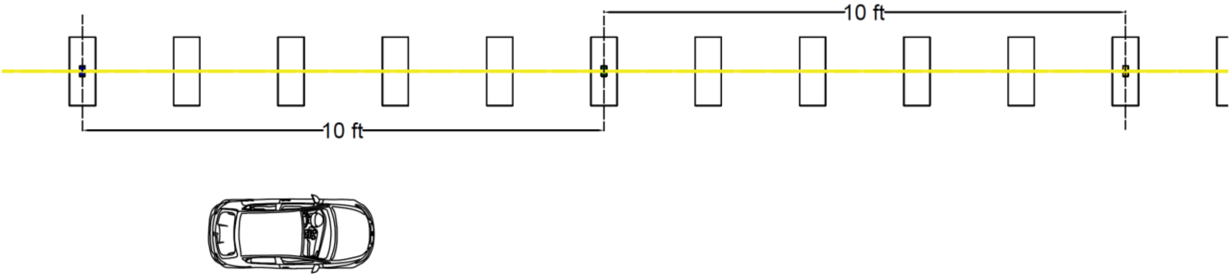


Figure 5-6 RPM installation plan

The height of the markers above the surface will be critical to both its retroreflectivity performance and snowplow resistance. The minimum critical height for the two low-profile markers was identified by the laboratory retroreflectivity tests discussed in Chapter 4. The critical height is the minimum height of the markers' top surface from measured from the road surface at which the minimum retroreflectivity has been obtained as per the ASTM specifications D4280 *(38)* and D4383 *(39)* at the standard angle sets. The critical height of the markers are as follows:

- LP1 (C40) markers: 4.7 mm

- LP2 (3M–190) markers: 6.4 mm

The ceiling rounded numbers of critical heights taken as 7 mm and 5 mm for the LP2 markers and LP1 markers respectively. Considering the same performance of lens for the regular markers from the same manufacturers and by equating the retroreflective area of the markers from the same manufacturers, the crude estimation of the critical heights for the regular markers were:

- RP1 (3M – 290) markers: 9.4 mm
- RP2 (C80) marker: 6.5 mm

Similarly, the ceiling rounded numbers of critical heights were taken as 10 mm and 7 mm for the RP1 markers and RP2 markers respectively.

The markers were installed in two different series. In Series-1, the aimed height for all the markers was 7 mm above the road surface, which is selected based on the critical heights of the marker determined from the laboratory screening tests. While in Series-2 the markers were pushed into the groove as far as possible ensuring markers had enough adhesive for bonding with pavement. Thus, the markers installed in the Series-1 had greater adhesive thickness compared with Series-2.

5.2.1. Anchorage

The markers were bonded to the pavement with a bitumen adhesive. The material properties of the adhesive meet the requirements as stated in the ASTM specification ASTM D4280. It was observed that the profile of the grooves was inconsistent, further, because the milled groove surface had ribs formed by the teeth of the roller cut, the thickness of the adhesive could not be controlled. It was ensured that the adhesive thickness does not fall below the minimum required thickness of 0.06 in (≈ 1.6 mm) specified by the ASTM standards.

5.2.2. Snowplow

Figure 5-7 shows the snowplow used for the field screening studies at the PRC test site.

Figure 5-7 Snowplow used for the field screen study

5.3. Results

In the field test, a total of five snowplow runs were made in alternate directions (see Figure 5-8). As shown in Table 5-2, the markers were installed in two series: Series-1 and Series-2. Series-1 had 40 markers while Series-2 had 36 markers in a randomized order in both series. The measurements for the height of the markers were taken at both ends in the direction perpendicular to the traffic. This process was further repeated before and after each run.

Table 5-2 Marker evaluated in the field test

	Number of markers	
	Series-1 (1 to 40)	Series-2 (41 to 76)
RP1 (3M-290)	10	8
LP1 (C-40)	10	9
RP2 (C-80)	10	10
LP2 (3M-190)	10	9
Total	40	36
Total	**76**	

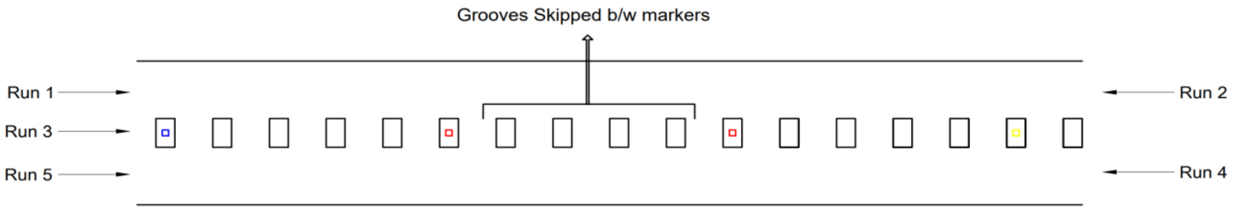


Figure 5-8 Schematic of the test section for the field test

The height of the markers reported in Figures 5-9 and 5-10 is the average height at both ends of the marker measured from the road surface to the top face of the marker. In Figures 5-9 and 5-10, the magnitude of the "Height/Depth" represents how far from the road surface the top face of the marker is. Negative values indicate that the top face of the marker was below the road surface; positive values show that the top face of the marker was above the road surface. Because of the inconsistency in the groove geometry, the height of the same type of markers varied significantly in Series-1. In Series-2, the conventional RPMs 3M-290 and Stimsonite C80 were sticking above the road surface because of their size and shape (see Figure 5-10).

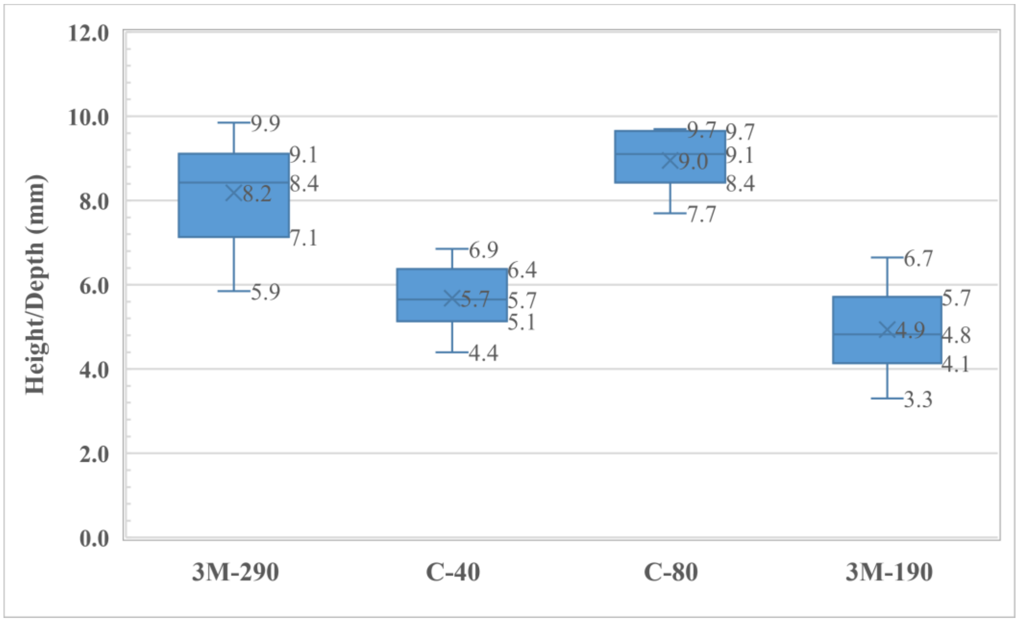


Figure 5-9 Initial heights/depths of the RPMs installed in Series-1 (top of RPMs were at 7 mm above road surface) with low profile markers (C40 and 3M-190) and regular profile markers (C80 and 3M-290)

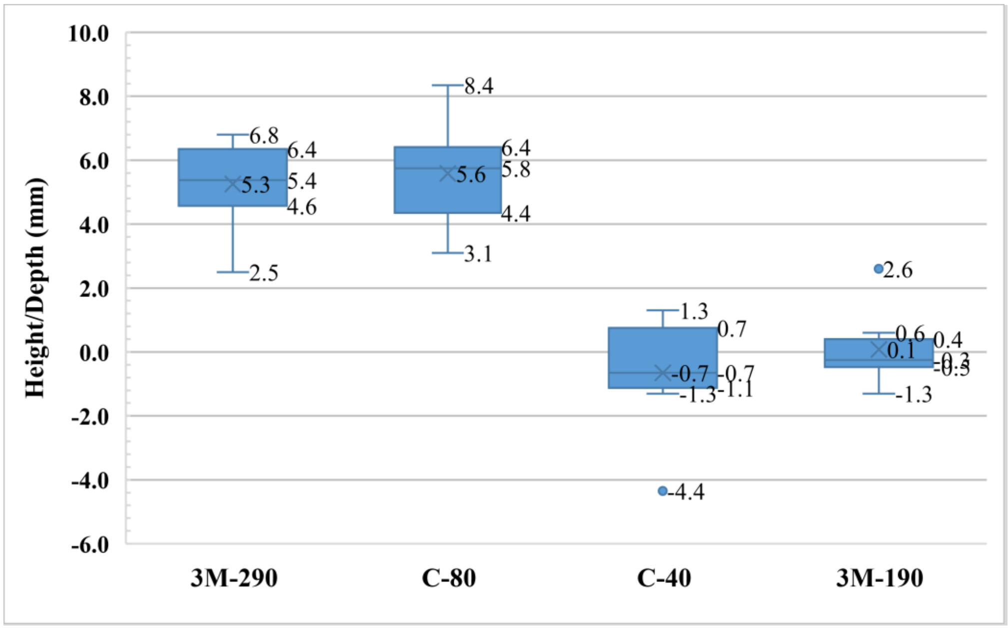


Figure 5-10 Initial heights/depths of the RPMs installed in Series-2 (RPMs were bottomed out) with low profile markers (C40 and 3M-190) and regular profile markers (C80 and 3M-290)

A rating system (see Tables 5-3 and 5-4) for the marker's condition was created separately for the lens and the bonding of the marker with the pavement. Since the temperature becomes an important parameter to assess the bonding of the RPM, the temperature for the snowplow runs was recorded along with the time and direction of the run (see Table 5-5). In addition, pictures were taken for each marker before and after each snowplow run.

Table 5-3 Rating system to assess the lens condition

Lens Condition - Visual Inspection	
Rating	**Description**
4	Excellent, Completely intact, in "Like New" condition
3	Fair, Some abrasion, none greater than 5 mm
2	Poor, Some large cuts/cracks/chips greater than 5 mm
1	Very Poor, Showing significant wear
0	Missing or damaged beyond use

Table 5-4 Rating system to assess the bonding of the RPM

Bonding Condition - Visual Inspection	
Rating	**Description**
3	Excellent, Completely intact, in "Like New" condition
2	Marker rotated but still attached to the pavement
1B	Partially delaminated (Marker - Bitumen bond)
1A	Partially delaminated (Bitumen - Pavement bond)
0	Missing or damaged beyond use
1AB	Both 1A and 1B
1A-0	Missing marker with delamination at Marker-Bitumen interface
1B-0	Missing marker with delamination at Bitumen-Pavement interface

Table 5-5 Description of the snowplow runs

	Time	Direction	Pavement Temperature
Run-1	11:00 AM	West → East	-
Run-2	12:15 PM	East → West	95.9ºF
Run-3	1:00 PM	West → East	95.6ºF
Run-4	1:42 PM	East → West	100.6ºF
Run-5	2:42 PM	West → East	100.2ºF

Table 5-6 lists the heights of the RPMs installed in Series-1 after the snowplow runs and Table 5-7 outlines the lens and bonding condition of the RPMs.

Table 5-6 Heights of the RPMs installed in Series-1 (top of RPMs were at 7mm above road surface) after the snowplow runs

Series-1																	
Serial No.	**Marker**	**Height/Depth (mm)**						**Δ Height (mm)**					**Cumulative Δ Height (mm)**				
		No Run	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**
1	**3M-290**	6.5	5.3	5.3	5.8	5.6	5.4	1.3	0.0	-0.5	0.2	0.2	1.3	1.3	0.8	1.0	1.2
2	**C-40**	4.4	1.5	2.0	1.6	1.8	1.6	2.9	-0.5	0.4	-0.2	0.2	2.9	2.4	2.8	2.6	2.8
3	**C-80**	9.7	6.7	6.8	6.6	6.5	5.4	3.0	-0.1	0.2	0.1	1.1	3.0	2.9	3.1	3.2	4.3
4	**3M-190**	5.0	4.3	3.7	4.0	4.4	4.0	0.7	0.6	-0.3	-0.4	0.4	0.7	1.3	1.0	0.6	1.0
5	**C-80**	9.7	3.4	3.4	2.6	2.5	3.5	6.3	0.0	0.8	0.1	-1.0	6.3	6.3	7.1	7.2	6.2
6	**C-40**	6.4	4.9	4.8	5.0	3.8	3.6	1.5	0.1	-0.2	1.2	0.2	1.5	1.6	1.4	2.6	2.8
7	**3M-190**	5.4	3.5	4.1	3.3	3.2	3.4	2.0	-0.6	0.8	0.1	-0.2	2.0	1.4	2.2	2.3	2.1
8	**3M-190**	3.7	3.8	2.9	1.2	1.1	0.6	-0.1	0.9	1.7	0.1	0.5	-0.1	0.8	2.5	2.6	3.1
9	**3M-290**	8.5	0.0	0.0	0.0	0.0	0.0	8.5	0.0	0.0	0.0	0.0	8.5	8.5	8.5	8.5	8.5
10	**C-80**	7.7	-0.2	0.1	-0.4	0.0	-0.2	7.9	-0.3	0.5	-0.4	0.2	7.9	7.6	8.1	7.7	7.9
11	**3M-290**	9.0	2.6	3.9	3.0	3.6	3.3	6.4	-1.3	0.9	-0.6	0.3	6.4	5.1	6.0	5.4	5.7
12	**C-80**	9.5	1.4	1.2	0.6	0.9	1.1	8.1	0.2	0.6	-0.3	-0.2	8.1	8.3	8.9	8.6	8.4
13	**C-40**	5.4	2.1	2.7	1.4	2.0	2.3	3.3	-0.6	1.3	-0.6	-0.3	3.3	2.7	4.0	3.4	3.1
14	**C-40**	6.9	0.0	0.2	-0.9	0.7	0.7	6.9	-0.2	1.1	-1.6	0.0	6.9	6.7	7.8	6.2	6.2
15	**3M-190**	6.2	0.0	0.0	0.0	0.0	0.0	6.2	0.0	0.0	0.0	0.0	6.2	6.2	6.2	6.2	6.2
16	**C-40**	5.5	4.0	4.0	3.1	3.7	2.5	1.5	0.0	0.9	-0.6	1.2	1.5	1.5	2.4	1.8	3.0
17	**C-40**	5.9	-0.5	1.1	0.7	0.1	-0.1	6.4	-1.6	0.4	0.6	0.2	6.4	4.8	5.2	5.8	6.0
18	**C-40**	6.5	5.6	3.8	4.0	3.6	2.5	0.9	1.8	-0.2	0.4	1.1	0.9	2.7	2.5	2.9	4.0
19	**C-40**	5.1	2.0	0.5	-0.2	0.7	1.2	3.1	1.5	0.7	-0.9	-0.5	3.1	4.6	5.3	4.4	3.9
20	**C-80**	7.9	0.1	0.7	0.0	0.2	0.7	7.8	-0.6	0.7	-0.2	-0.5	7.8	7.2	7.9	7.7	7.2

Series-1																	
Serial No.	**Marker**	**Height/Depth (mm)**						**Δ Height (mm)**					**Cumulative Δ Height (mm)**				
		No Run	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**
21	**C-40**	5.9	4.0	3.6	2.9	2.9	2.4	1.9	0.4	0.7	0.0	0.5	1.9	2.3	3.0	3.0	3.5
22	**C-80**	9.4	-0.1	-0.1	-0.1	-0.1	-0.1	9.4	0.0	0.0	0.0	0.0	9.4	9.4	9.4	9.4	9.4
23	**3M-190**	5.6	0.0	0.0	0.0	0.0	0.0	5.6	0.0	0.0	0.0	0.0	5.6	5.6	5.6	5.6	5.6
24	**C-80**	9.7	0.5	0.1	-0.4	0.1	0.1	9.2	0.4	0.5	-0.5	0.0	9.2	9.6	10.1	9.6	9.6
25	**3M-290**	8.3	6.6	7.1	2.0	2.1	2.0	1.8	-0.5	5.1	-0.1	0.1	1.8	1.3	6.4	6.3	6.4
26	**3M-190**	3.3	3.3	3.5	3.0	2.9	2.6	0.0	-0.2	0.5	0.1	0.3	0.0	-0.2	0.3	0.4	0.7
27	**3M-190**	4.7	4.9	4.7	4.3	4.6	3.9	-0.1	0.2	0.4	-0.3	0.7	-0.1	0.1	0.5	0.2	0.9
28	**3M-290**	8.4	0.1	0.0	-1.2	-1.2	-1.2	8.3	0.1	1.2	0.0	0.0	8.3	8.4	9.6	9.6	9.6
29	**3M-290**	7.4	3.1	3.0	2.7	2.0	3.0	4.3	0.1	0.3	0.7	-1.0	4.3	4.4	4.7	5.4	4.4
30	**3M-290**	5.9	2.1	3.2	3.2	2.9	3.3	3.8	-1.1	0.0	0.3	-0.4	3.8	2.7	2.7	3.0	2.6
31	**3M-190**	4.7	4.0	4.7	3.0	3.0	4.2	0.7	-0.7	1.7	0.0	-1.2	0.7	0.0	1.7	1.7	0.5
32	**3M-290**	8.7	0.1	0.9	0.6	0.7	1.3	8.6	-0.8	0.3	-0.1	-0.6	8.6	7.8	8.1	8.0	7.4
33	**C-80**	8.6	1.2	0.9	1.3	1.5	1.5	7.5	0.2	-0.3	-0.2	0.0	7.5	7.7	7.4	7.2	7.2
34	**C-80**	8.9	1.4	1.2	0.7	1.1	1.3	7.5	0.2	0.5	-0.4	-0.2	7.5	7.7	8.2	7.8	7.6
35	**C-80**	8.7	1.3	1.9	0.7	1.3	0.9	7.4	-0.6	1.2	-0.6	0.4	7.4	6.8	8.0	7.4	7.8
36	**C-40**	5.2	0.1	0.6	-0.2	0.4	-1.2	5.1	-0.5	0.8	-0.6	1.6	5.1	4.6	5.4	4.8	6.4
37	**3M-290**	9.5	1.4	1.8	1.3	0.7	0.6	8.1	-0.4	0.5	0.6	0.1	8.1	7.7	8.2	8.8	8.9
38	**3M-190**	4.3	4.5	4.7	3.6	4.0	3.7	-0.2	-0.2	1.1	-0.4	0.3	-0.2	-0.4	0.7	0.3	0.6
39	**3M-290**	9.9	4.0	4.7	3.8	2.8	4.3	5.9	-0.7	0.9	1.0	-1.5	5.9	5.2	6.1	7.1	5.6
40	**3M-190**	6.7	0.4	1.4	0.8	0.8	0.8	6.3	-1.0	0.6	0.0	0.0	6.3	5.3	5.9	5.9	5.9

Table 5-7 Lens and bonding condition of the RPMs installed in Series-1 (top of RPMs were at 7 mm above road surface)

Series-1													
Serial No.	**Marker**	**Lens Condition**						**Bonding Condition**					
		No Run	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**No Run**	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**
1	**3M-290**	4	3	3	3	3	3	3	3	3	3	3	3
2	**C-40**	4	1	1	1	1	1	3	3	3	3	3	3
3	**C-80**	4	3	3	3	3	3	3	3	3	3	3	3
4	**3M-190**	4	4	3	3	3	3	3	3	3	3	3	3
5	**C-80**	4	0	0	0	0	0	3	1AB	1AB	1AB	1AB	1AB
6	**C-40**	4	2	2	2	0	0	3	3	3	3	3	3
7	**3M-190**	4	2	2	2	1	1	3	1B	1B	1B	1B	1B
8	**3M-190**	4	4	3	0	0	0	3	3	3	1B	1B	1B
9	**3M-290**	4	0	0	0	0	0	3	1AB	1AB	1AB	1AB	1AB
10	**C-80**	4	0	0	0	0	0	3	1AB	1AB	1AB	1AB	1AB
11	**3M-290**	4	3	1	1	1	1	3	3	3	3	3	3
12	**C-80**	4	0	0	0	0	0	3	1AB	1AB	1AB	1AB	1AB
13	**C-40**	4	0	0	0	0	0	3	3	1B	1B	1B	1B
14	**C-40**	4	0	0	0	0	0	3	1B	1B	1B	1B	1B
15	**3M-190**	4	0	0	0	0	0	3	1B	1B-0	1B-0	1B-0	1B-0
16	**C-40**	4	1	1	1	1	1	3	3	3	3	3	3
17	**C-40**	4	1	0	0	0	0	3	3	1B	1B	1B	1AB
18	**C-40**	4	1	0	0	0	0	3	3	3	3	3	3
19	**C-40**	4	1	1	0	0	0	3	3	1B	1B	1B	1B
20	**C-80**	4	1	0	0	0	0	3	1B	1B	1B	1B	1B

Series-1													
Serial No.	**Marker**	**Lens Condition**						**Bonding Condition**					
		No Run	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**No Run**	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**
21	**C-40**	4	1	1	1	1	1	3	3	3	3	3	3
22	**C-80**	4	1	0	0	0	0	3	1AB	1AB	1AB	1AB	1AB
23	**3M-190**	4	0	0	0	0	0	3	1B	1B-0	1B-0	1B-0	1B-0
24	**C-80**	4	1	0	0	0	0	3	1AB	1AB	1AB	1AB	1AB
25	**3M-290**	4	3	3	1	1	1	3	3	3	3	3	3
26	**3M-190**	4	4	3	3	3	3	3	3	3	3	3	3
27	**3M-190**	4	4	3	3	3	3	3	3	3	3	3	3
28	**3M-290**	4	1	0	0	0	0	3	1AB	1AB	1AB	1AB	1AB
29	**3M-290**	4	2	1	1	1	1	3	3	3	3	3	3
30	**3M-290**	4	2	1	1	1	1	3	3	3	3	3	3
31	**3M-190**	4	4	3	3	3	2	3	3	3	3	3	1B
32	**3M-290**	4	2	1	1	1	1	3	3	3	3	3	3
33	**C-80**	4	1	0	0	0	0	3	1AB	1AB	1AB	1AB	1AB
34	**C-80**	4	1	0	0	0	0	3	1B	1AB	1AB	1AB	1AB
35	**C-80**	4	1	0	0	0	0	3	1AB	1AB	1AB	1AB	1AB
36	**C-40**	4	1	0	0	0	0	3	3	1B	1B	1B	1B
37	**3M-290**	4	1	0	0	0	0	3	1AB	1AB	1AB	1AB	1AB
38	**3M-190**	4	4	3	3	3	2	3	3	3	3	3	3
39	**3M-290**	4	2	1	1	1	1	3	3	3	3	3	3
40	**3M-190**	4	1	0	0	0	0	3	3	1B	1B	1AB	1AB

As can be observed in the height reductions of the markers (see Figures 5-11 through 5-20), most of the markers installed in Series-1 were damaged after the first snowplow run. The height reduction of the markers is attributed to the damage caused by the snowplow. The damage took three forms: top surface chipped off, broken marker body with plastic deformation, and missing marker. Performance of the lens degraded significantly after the first snowplow runs for RP2 (C80) and RP1 (3M-290) markers installed in Series-1 (see Figure 5-13) where the RP2 (C80) markers showed the largest drop in height (see Figure 5-11). The change in the height was greatest for first snowplow run followed by the third run for all the markers. Overall, for the markers installed in Series-1, LP2 (3M-190) marker had the best performance followed by RP1 (3M-290) marker.

The conventional RPMs RP1 (3M-290) and RP2 (C80) installed in Series-2 were sticking above the road surface because of their size and shape. Hence those markers experienced a larger impact than the low-profile markers for the initial runs (see Figure 5-16, 5-18). For all the markers except LP2 (3M-190) marker, height reduction was greatest for the first snowplow run while LP2 markers were fairly intact. The height reduction was least for the 3M-190 markers. Also, as can be seen in Figure 5-13, the low-profile markers showed better lens performance than the conventional RPMs.

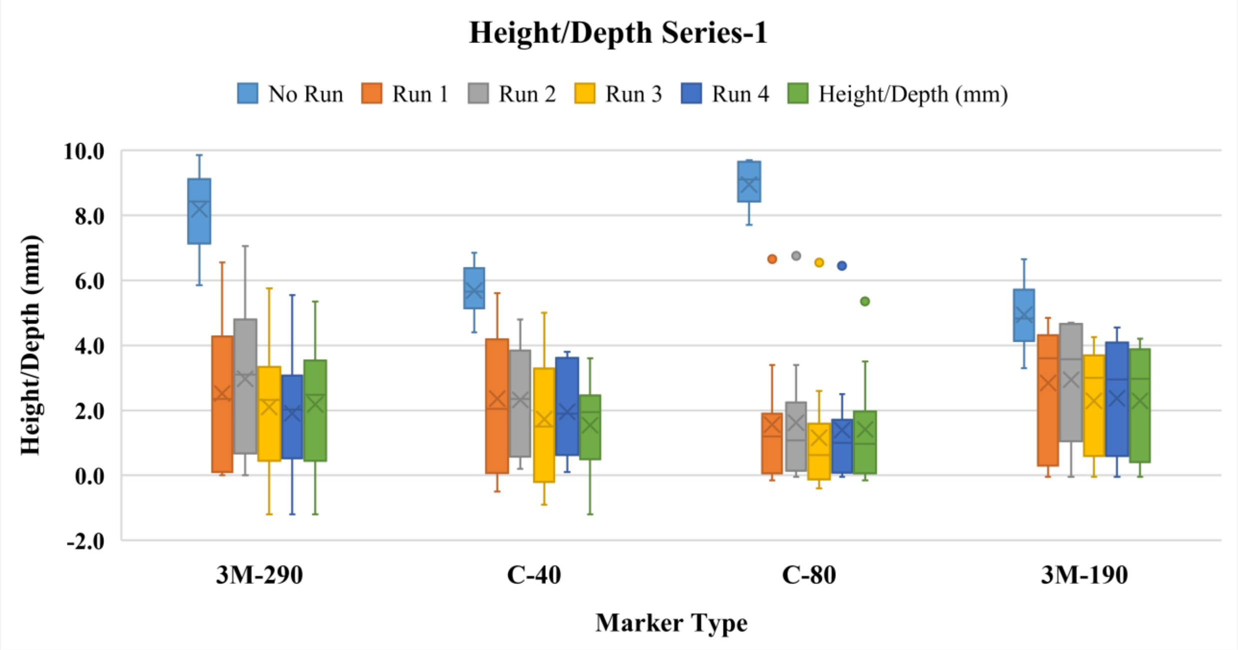


Figure 5-11 Heights/depths of the RPMs installed in Series-1 (top of RPMs were at 7 mm above road surface) with low profile markers (C40 and 3M-190) and regular profile markers (C80 and 3M-290)

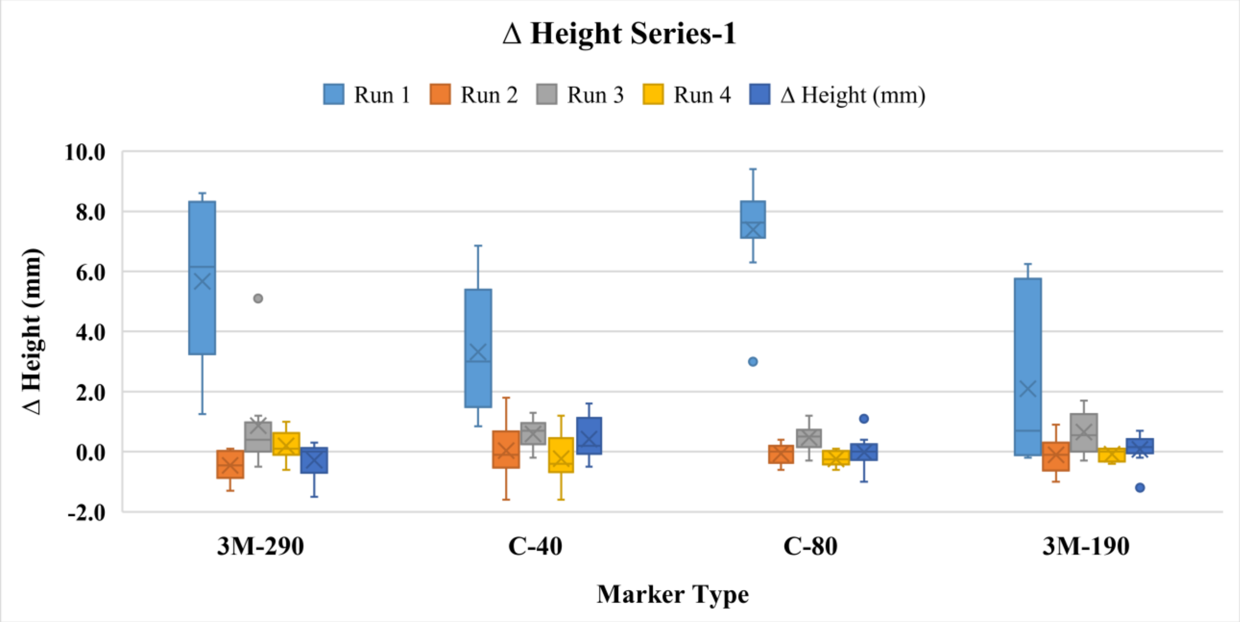


Figure 5-12 Height reductions of the RPMs installed in Series-1 (top of RPMs were at 7 mm above road surface) with low profile markers (C40 and 3M-190) and regular profile markers (C80 and 3M-290)

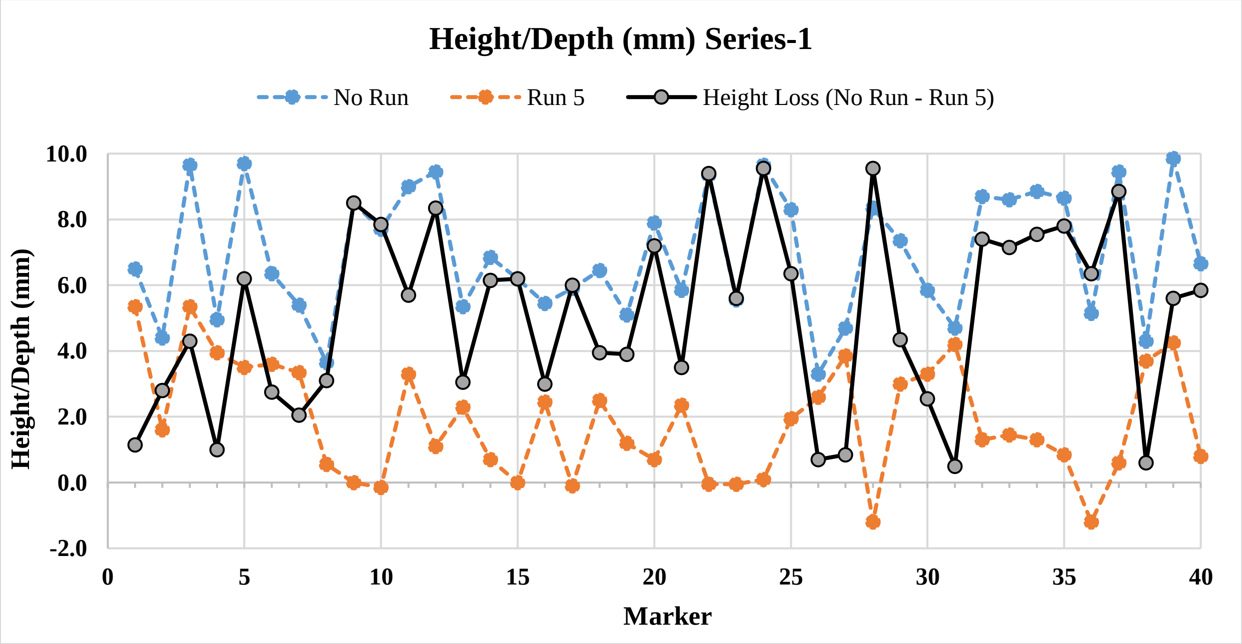


Figure 5-13 Height/depth of the RPMs installed in Series-1 (top of RPMs were at 7 mm above road surface) with low profile markers (C40 and 3M-190) and regular profile markers (C80 and 3M-290)

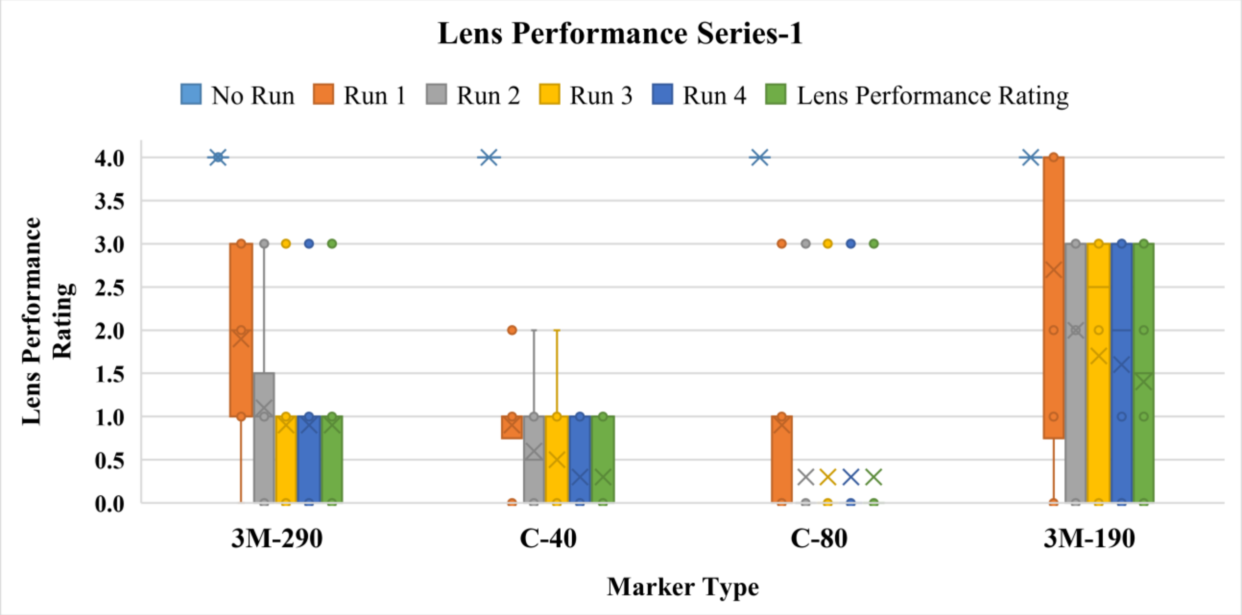


Figure 5-14 Lens condition of the RPMs installed in Series-1 (top of RPMs were at 7 mm above road surface) with low profile markers (C40 and 3M-190) and regular profile markers (C80 and 3M-290)

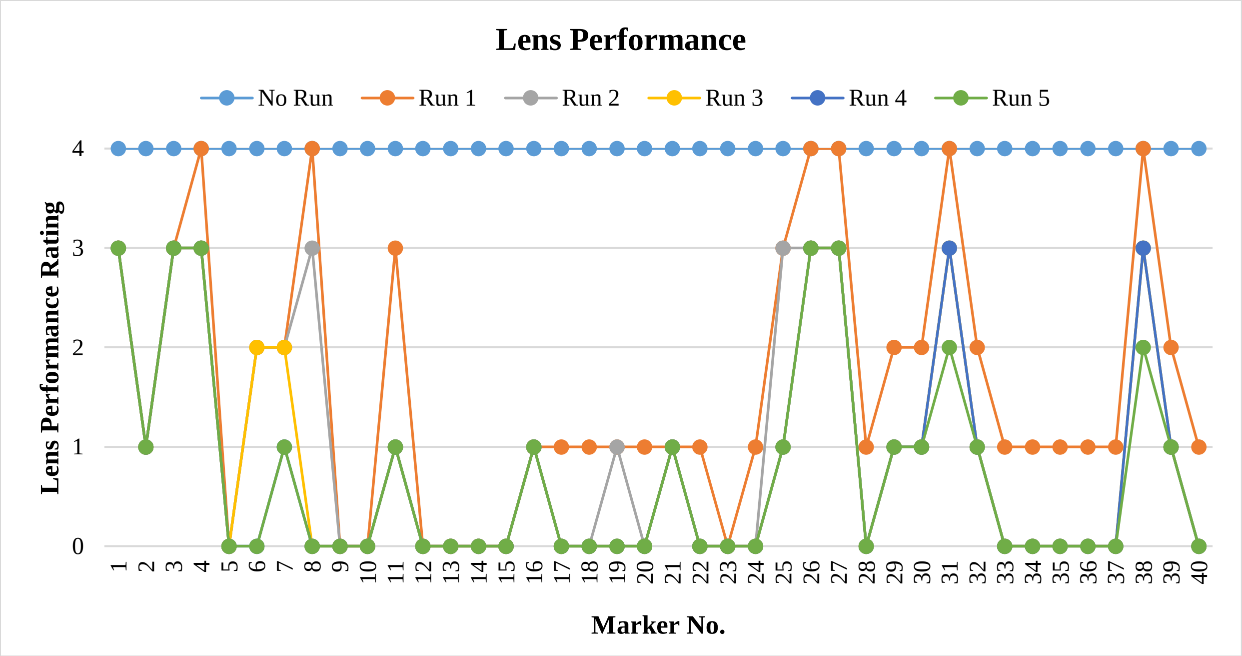


Figure 5-15 Lens condition of the RPMs installed in Series-1 (top of RPMs were at 7 mm above road surface) (individual)

Table 5-8 lists the heights of the RPMs installed in Series-2 after the snowplow runs and Table 5-9 outlines the lens and bonding condition of the RPMs.

Table 5-8 Heights of the RPMs installed in Series-2 (RPMs were bottomed out) after the snowplow runs

Series-2																	
Serial No.	**Marker**	**Height/Depth (mm)**						**Δ Height (mm)**					**Cumulative Δ Height (mm)**				
		No Run	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**
41	**3M-290**	2.5	2.4	2.5	2.3	1.9	2.2	0.2	-0.1	0.2	0.4	-0.3	0.2	0.1	0.3	0.7	0.4
42	**C-80**	4.7	4.3	0.0	0.0	0.0	0.0	0.4	4.3	0.0	0.0	0.0	0.4	4.8	4.8	4.8	4.8
43	**C-80**	6.2	4.2	4.3	2.1	1.9	1.7	2.0	-0.1	2.2	0.2	0.2	2.0	1.9	4.1	4.3	4.5
44	**C-80**	3.1	3.4	3.4	3.1	3.3	3.0	-0.3	0.0	0.3	-0.2	0.3	-0.3	-0.3	0.1	-0.2	0.2
45	**C-80**	5.5	4.2	4.2	4.3	4.4	1.2	1.4	0.0	-0.1	-0.1	3.2	1.4	1.4	1.3	1.2	4.4
46	**C-40**	0.8	-0.8	-0.5	-0.5	-2.6	-2.6	1.6	-0.3	0.0	2.1	0.0	1.6	1.3	1.3	3.4	3.4
47	**3M-190**	-0.3	-0.1	0.1	-0.3	-0.4	-0.7	-0.2	-0.2	0.4	0.1	0.3	-0.2	-0.4	0.0	0.1	0.4
48	**3M-290**	5.7	2.8	0.6	3.2	3.4	3.1	2.9	2.2	-2.6	-0.2	0.3	2.9	5.1	2.5	2.3	2.6
49	**C-40**	-0.9	-0.3	-0.9	-1.1	-1.2	-2.2	-0.6	0.6	0.2	0.1	1.0	-0.6	0.0	0.2	0.3	1.3
50	**C-80**	6.2	6.1	5.8	5.8	5.7	5.5	0.1	0.3	0.0	0.1	0.2	0.1	0.4	0.4	0.5	0.7
51	**3M-190**	-1.3	-1.2	-1.2	-1.2	-1.8	-1.0	-0.1	0.0	0.0	0.6	-0.8	-0.1	-0.1	-0.1	0.5	-0.3
52	**3M-290**	6.2	6.0	5.2	5.6	5.2	5.6	0.3	0.8	-0.4	0.4	-0.4	0.3	1.1	0.7	1.1	0.7
53	**C-40**	-1.3	-0.7	-1.0	-1.3	0.9	-0.6	-0.6	0.3	0.3	-2.2	1.5	-0.6	-0.3	0.0	-2.2	-0.7
54	**3M-290**	6.8	0.0	0.0	0.0	0.0	0.0	6.8	0.0	0.0	0.0	0.0	6.8	6.8	6.8	6.8	6.8
55	**C-40**	1.3	-0.1	0.1	0.4	0.0	0.4	1.4	-0.2	-0.3	0.4	-0.4	1.4	1.2	0.9	1.3	0.9
56	**3M-190**	2.6	2.2	1.2	2.5	2.1	2.1	0.4	1.0	-1.3	0.4	0.0	0.4	1.4	0.1	0.5	0.5
57	**3M-290**	5.1	0.8	0.2	1.1	0.8	0.6	4.2	0.6	-0.8	0.2	0.2	4.2	4.8	4.0	4.2	4.4
58	**3M-290**	5.0	4.1	4.1	4.1	4.0	5.2	0.9	0.0	0.0	0.1	-1.2	0.9	0.9	0.9	1.0	-0.2
59	**C-40**	-0.9	-0.8	-1.4	-1.0	-1.2	-1.2	-0.2	0.6	-0.4	0.2	0.0	-0.2	0.4	0.0	0.2	0.2
60	**3M-190**	-0.3	-0.7	-0.4	-1.4	-0.1	-0.5	0.4	-0.3	1.0	-1.3	0.4	0.4	0.1	1.1	-0.2	0.2
61	**3M-190**	0.2	0.0	0.0	0.1	-0.6	0.2	0.2	0.0	-0.1	0.7	-0.8	0.2	0.2	0.1	0.8	0.0

Series-2																
Serial No.	**Marker**	**Height/Depth (mm)**						**Δ Height (mm)**					**Cumulative Δ Height (mm)**			
		No Run	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**	**Run 1**	**Run 2**	**Run 3**	**Run 4**	**Run 5**
62	**3M-190**	0.6	0.7	0.6	0.6	0.7	-0.9	-0.1	0.1	0.0	-0.1	1.6	-0.1	0.0	0.0	-0.1	1.5
63	**3M-290**	6.4	2.9	3.3	2.3	2.0	2.4	3.5	-0.4	1.0	0.3	-0.4	3.5	3.1	4.1	4.4	4.0
64	**3M-190**	-0.4	-0.2	-0.3	-0.3	-0.5	-0.1	-0.2	0.1	0.0	0.2	-0.4	-0.2	-0.1	-0.1	0.1	-0.3
65	**3M-190**	0.1	-0.1	-0.2	0.6	-0.3	-0.1	0.2	0.1	-0.8	0.9	-0.2	0.2	0.3	-0.5	0.4	0.2
66	**C-40**	-4.4	-4.7	-3.4	-5.5	-5.3	-5.3	0.3	-1.3	2.1	-0.2	0.0	0.3	-1.0	1.2	0.9	0.9
67	**3M-190**	-0.6	-0.5	-0.7	-0.6	-0.3	-0.9	-0.2	0.2	-0.1	-0.3	0.6	-0.2	0.0	-0.1	-0.4	0.3
68	**C-40**	-0.5	-0.8	-0.7	-0.5	-0.6	-0.8	0.3	-0.1	-0.2	0.1	0.2	0.3	0.2	-0.1	0.1	0.3
69	**C-40**	-0.7	-3.7	-2.7	-2.4	-3.4	-2.8	3.0	-1.0	-0.3	1.0	-0.6	3.0	2.0	1.7	2.7	2.1
70	**3M-290**	4.5	4.2	3.8	-0.1	-1.2	-1.2	0.3	0.4	3.9	1.1	0.0	0.3	0.7	4.6	5.7	5.7
71	**C-80**	3.3	3.1	3.0	2.7	2.3	2.5	0.2	0.1	0.3	0.4	-0.2	0.2	0.3	0.6	1.1	0.8
72	**C-80**	7.1	3.4	3.3	3.5	3.2	3.1	3.7	0.1	-0.2	0.3	0.1	3.7	3.8	3.6	3.9	4.0
73	**C-80**	8.4	1.6	1.8	1.8	1.6	1.6	6.8	-0.2	0.0	0.2	0.0	6.8	6.6	6.6	6.8	6.8
74	**C-80**	6.0	5.8	5.6	5.7	5.4	5.5	0.1	0.2	-0.1	0.3	-0.1	0.1	0.3	0.2	0.5	0.4
75	**C-40**	0.7	-1.0	-0.8	-0.7	-1.7	-2.0	1.7	-0.2	-0.1	1.0	0.3	1.7	1.5	1.4	2.4	2.7
76	**C-80**	5.6	3.5	3.7	3.7	3.4	3.2	2.1	-0.2	0.0	0.3	0.2	2.1	1.9	1.9	2.2	2.4

Table 5-9 Lens and bonding condition of the RPMs installed in Series-2 (RPMs were bottomed out)

Series-2													
Serial No.	Marker	Lens Condition						Bonding Condition					
		No Run	Run 1	Run 2	Run 3	Run 4	Run 5	No Run	Run 1	Run 2	Run 3	Run 4	Run 5
41	**3M-290**	4	4	3	3	3	3	3	3	3	3	3	3
42	**C-80**	4	1	0	0	0	0	3	0	0	0	0	0
43	**C-80**	4	2	2	0	0	0	3	3	3	3	3	3
44	**C-80**	4	4	3	3	3	3	3	3	3	3	3	3
45	**C-80**	4	4	3	3	3	3	3	3	3	3	3	3
46	**C-40**	4	2	1	1	0	0	3	3	3	3	3	3
47	**3M-190**	4	4	4	3	3	3	3	3	3	3	3	3
48	**3M-290**	4	3	1	1	1	1	3	3	3	3	3	3
49	**C-40**	4	4	4	4	4	4	3	3	3	3	3	3
50	**C-80**	4	4	3	3	3	3	3	3	3	3	3	3
51	**3M-190**	4	4	4	3	3	3	3	3	3	3	3	3
52	**3M-290**	4	4	3	3	3	3	3	3	3	3	3	3
53	**C-40**	4	4	3	3	3	3	3	3	3	3	3	3
54	**3M-290**	4	1	1	1	1	1	3	3	3	3	3	3
55	**C-40**	4	2	2	2	2	2	3	3	3	3	3	3
56	**3M-190**	4	4	4	3	3	3	3	3	3	3	3	3
57	**3M-290**	4	1	1	1	1	1	3	3	3	3	3	3
58	**3M-290**	4	3	3	3	3	3	3	3	3	3	3	3
59	**C-40**	4	4	4	4	4	4	3	3	3	3	3	3
60	**3M-190**	4	4	4	3	3	3	3	3	3	3	3	3
61	**3M-190**	4	4	4	3	3	3	3	3	3	3	3	3

Series-2													
Serial No.	Marker	Lens Condition						Bonding Condition					
		No Run	Run 1	Run 2	Run 3	Run 4	Run 5	No Run	Run 1	Run 2	Run 3	Run 4	Run 5
62	**3M-190**	4	4	4	3	3	3	3	3	3	3	3	3
63	**3M-290**	4	1	1	1	1	1	3	3	3	3	3	3
64	**3M-190**	4	4	4	3	3	3	3	3	3	3	3	3
65	**3M-190**	4	4	4	4	3	3	3	3	3	3	3	3
66	**C-40**	4	4	4	4	4	4	3	3	3	3	3	3
67	**3M-190**	4	4	4	3	3	3	3	3	3	3	3	3
68	**C-40**	4	4	4	3	3	3	3	3	3	3	3	3
69	**C-40**	4	2	1	1	1	1	3	3	3	3	3	3
70	**3M-290**	4	3	3	1	1	1	3	3	3	1B	1B	1B
71	**C-80**	4	3	3	3	3	3	3	3	3	3	3	3
72	**C-80**	4	1	0	0	0	0	3	3	3	3	3	3
73	**C-80**	4	1	0	0	0	0	3	1A	1AB	1AB	1AB	1AB
74	**C-80**	4	3	3	3	3	3	3	3	3	3	3	3
75	**C-40**	4	4	4	4	4	4	3	3	3	3	3	3
76	**C-80**	4	2	2	1	1	1	3	3	3	3	3	3

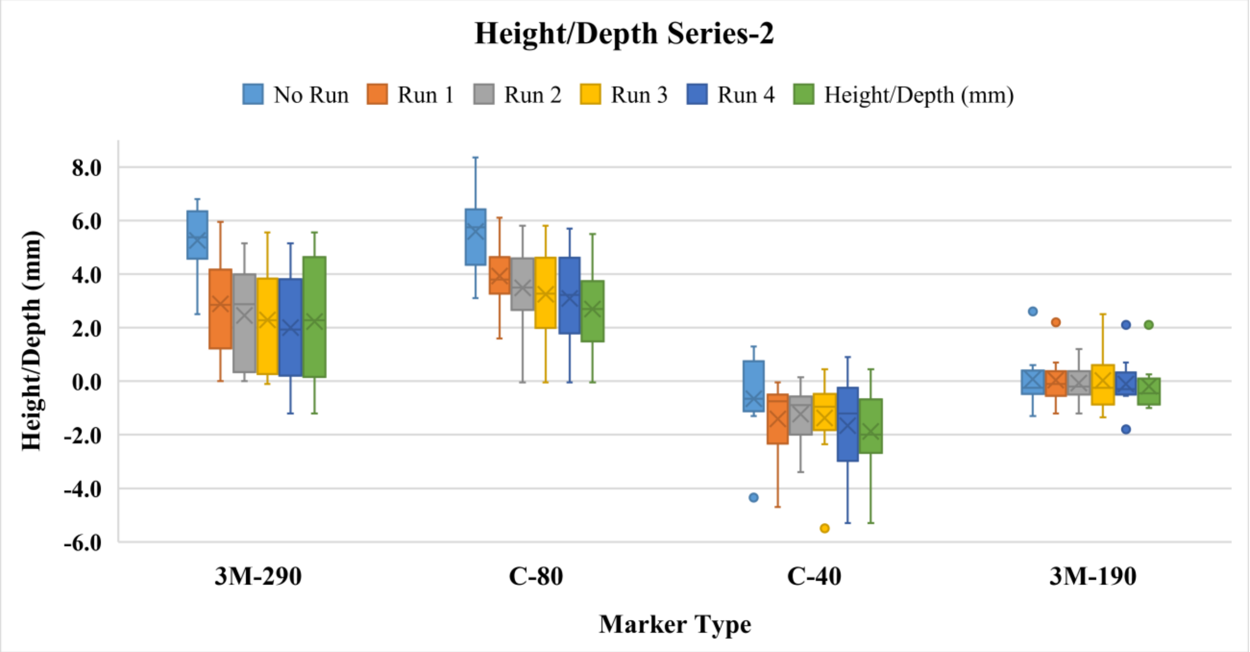


Figure 5-16 Heights/depths of the RPMs installed in Series-2 (RPMs were bottomed out) with low profile markers (C40 and 3M-190) and regular profile markers (C80 and 3M-290)

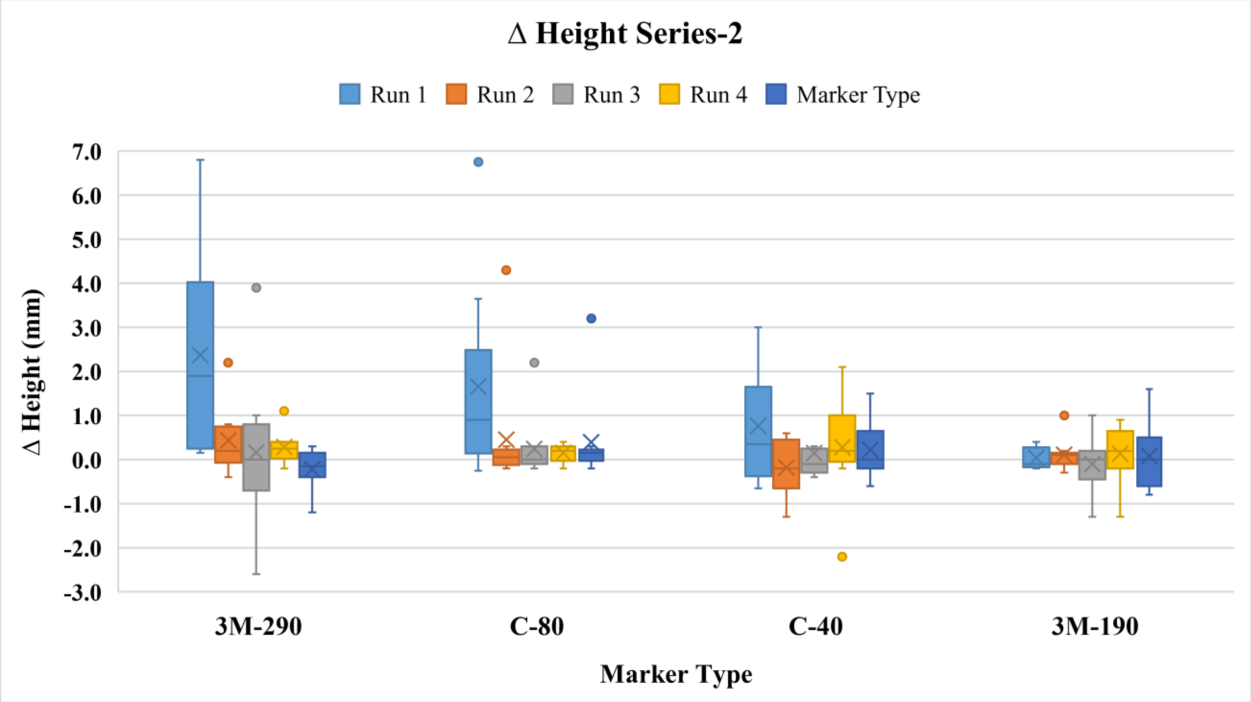


Figure 5-17 Height reductions of the RPMs installed in Series-2 (RPMs were bottomed out) with low profile markers (C40 and 3M-190) and regular profile markers (C80 and 3M-290)

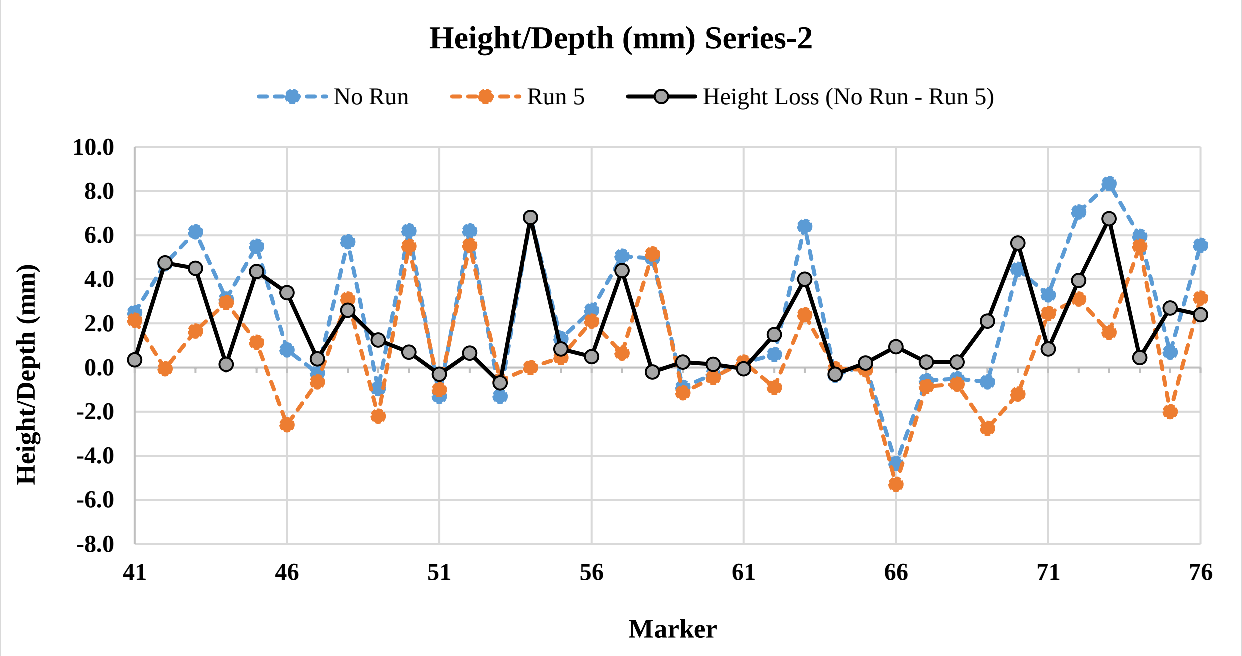


Figure 5-18 Height/depth of the RPMs installed in Series-2 (RPMs were bottomed out) with low profile markers (C40 and 3M-190) and regular profile markers (C80 and 3M-290)

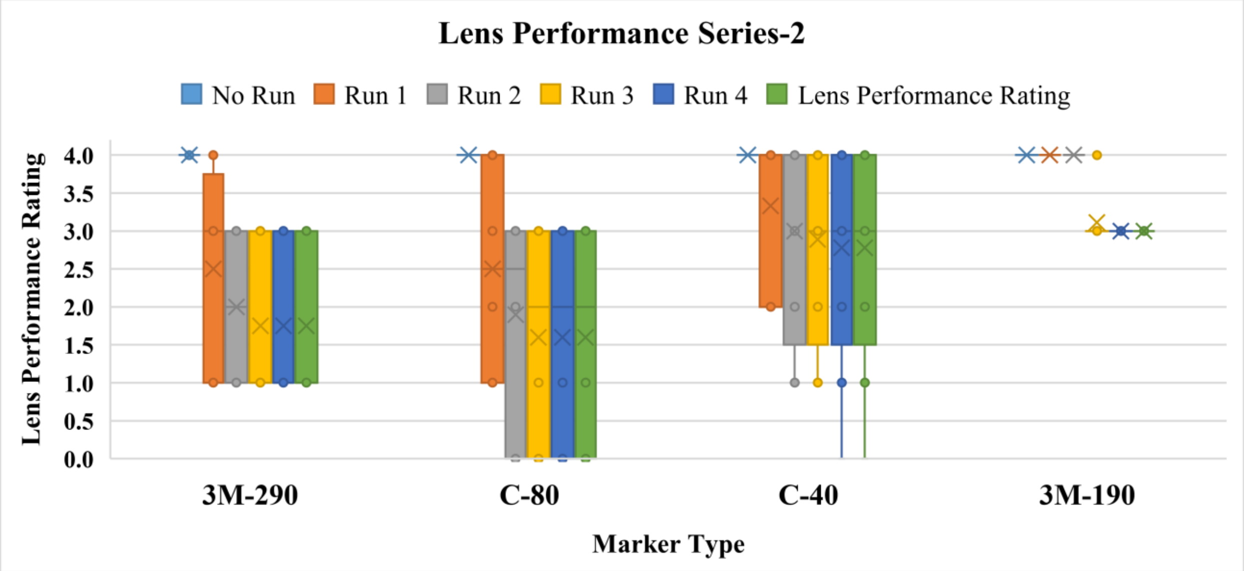


Figure 5-19 Lens condition of the RPMs installed in Series-2 (RPMs were bottomed out) with low profile markers (C40 and 3M-190) and regular profile markers (C80 and 3M-290)

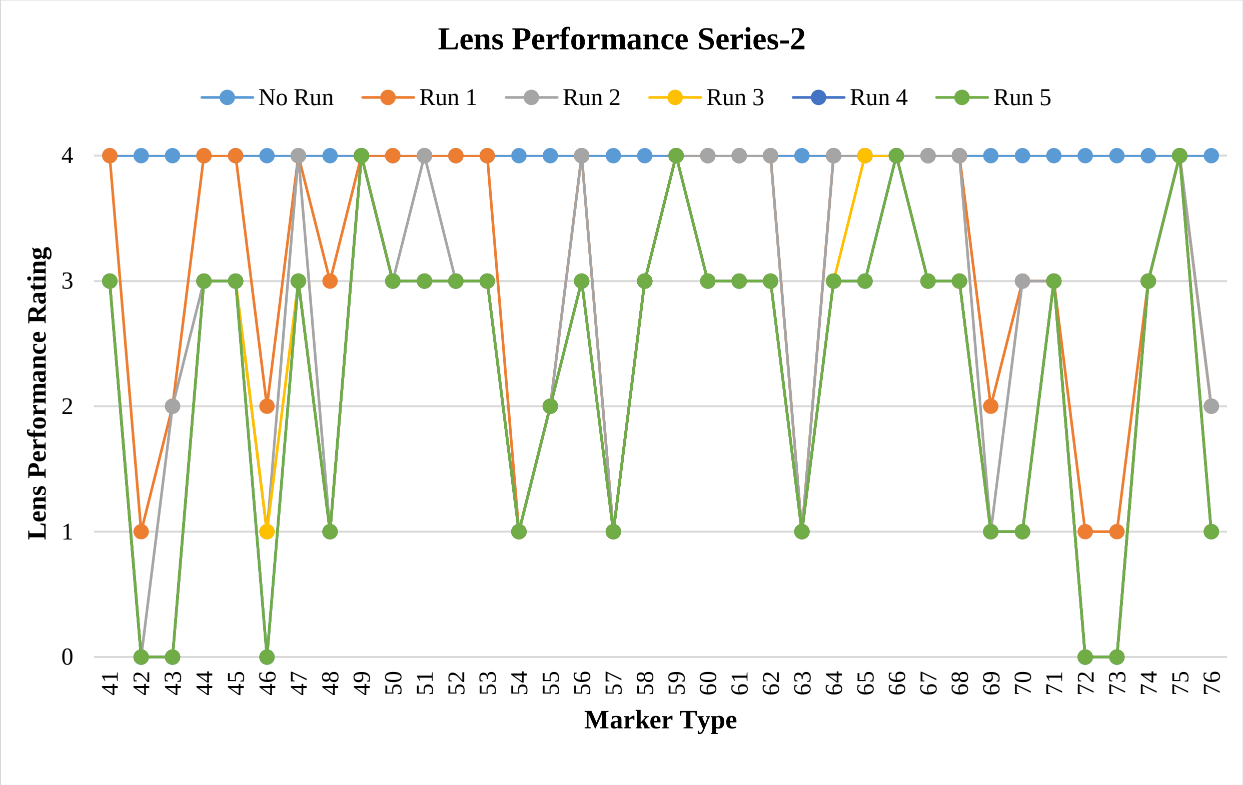


Figure 5-20 Lens condition of the RPMs installed in Series-2 (RPMs were bottomed out) (Individual)

Chapter 6. Field Studies on In-Service Roadways

The objective of this field study was to apply the findings presented in the previous chapter to selected in-service roadways maintained by TxDOT. The scope of the field studies on in-service roadways included:

- Installation of selected RPM in existing rumble strips on two-lane two-way rural highway sections.
- Evaluation of the performance of these installed RPMs after real-life snowplowing events.

For this purpose, the project selected two highway segments in two different TxDOT districts based on the traffic conditions and possibilities of snowfall. The RPMs were installed in the existing rumble strips through coordination with the district's officials. The performance of these RPMs were evaluated after they were subjected to snowplowing events due to winter weather. The following sections present the field study process, protocols, and markers performance after real snowplowing operations.

6.1. Work Plan

The work plan (see Figure 6-1) for performance evaluations of the use of RPMs in rumble strips on in-service highways after real-event snowplow operations included:

- Selection of RPMs to be used on in-service highways based on screening studies presented in the previous chapter
- Selection of field test site location based on historical winter weather conditions and discussion with the TxDOT officials.
- Procurement of selected RPMs and shipment to the pertinent field site office.
- Coordination with the pertinent TxDOT Office for installation of the RPMs in existing centerline rumble strips on selected highway stretches.
- Planning and organizing field visits to the test location for performance analysis after major snowplowing events. The performance evaluations incorporated visual inspections of the markers and assessments of damages

due to snowplow impact, as well as quantitative and qualitative visibility assessment of markers at night.

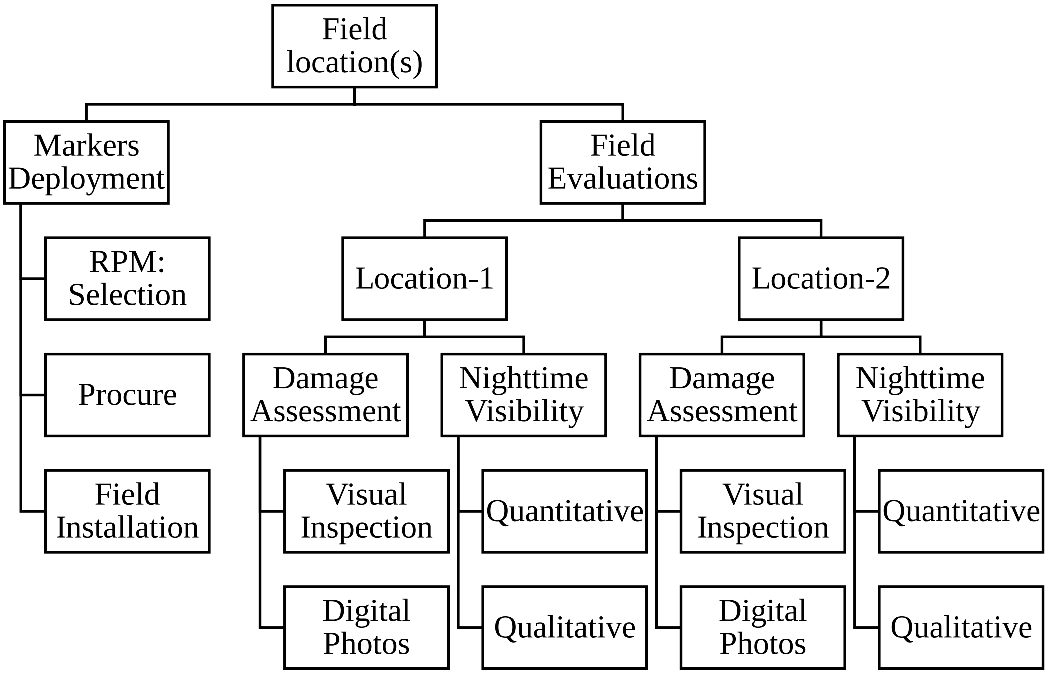


Figure 6-1 Field study work plan

6.2. Marker Deployment at the Field Sites

The first phase of the field study was the deployment of RPMs at each field site's location. The deployment process included the selection of markers to be installed in the existing rumble strips on selected highway locations, the selection of highway segments for field evaluations, and the procurement and installation of the markers at the field sites.

6.2.1. Retroreflective Pavement Markers

The pavement markers for the field study were selected based on the screening study conducted on the test site at PRC of UT Austin (see Chapter 5). Four types of markers were tested during the screening study and three out of four types were selected based on their performance for this phase of the project. Among the selected RPMs, one was a regular-profile marker and two were low-profile snowplowable markers. The RPMs selected for the field installations in centerline rumble strips and performance evaluation on in-service roadways are given in Table 6-1.

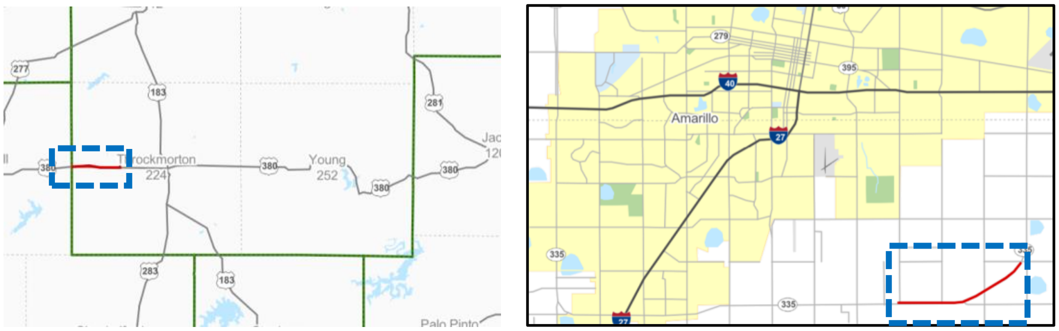
Table 6-1 Markers for field installations

Designation	Manufacturer	Model
LP1	Ennis Flint	Stimsonite C40
LP2	3M	3M Series 190
RP1	3M	3M Series 290

6.2.2. Field Site Locations

To achieve a snowplowable and cost-effective configuration of selected RPMs as rumble inserts, a field performance study on two-lane two-way highway segments in two different locations of the northern region of Texas was conducted. The test site locations were selected based on the historical winter weather patterns (Appendix 1), availability of existing centerline rumble strips, and expert opinion from TxDOT personnel.

The first test location was in Wichita Falls districts and the second location was in Amarillo Districts of TxDOT. The first test section was located on US Highway 380 in Throckmorton County and the second field site located on State Loop 335 in Randall County. Figure 6-2 illustrates the location of the highway segments that were used for the installation of RPMs and their performance evaluation after real-life snowplowing operations.



Location -1 (US 380)

Location – 2 (SL 335)

Figure 6-2 Field site locations

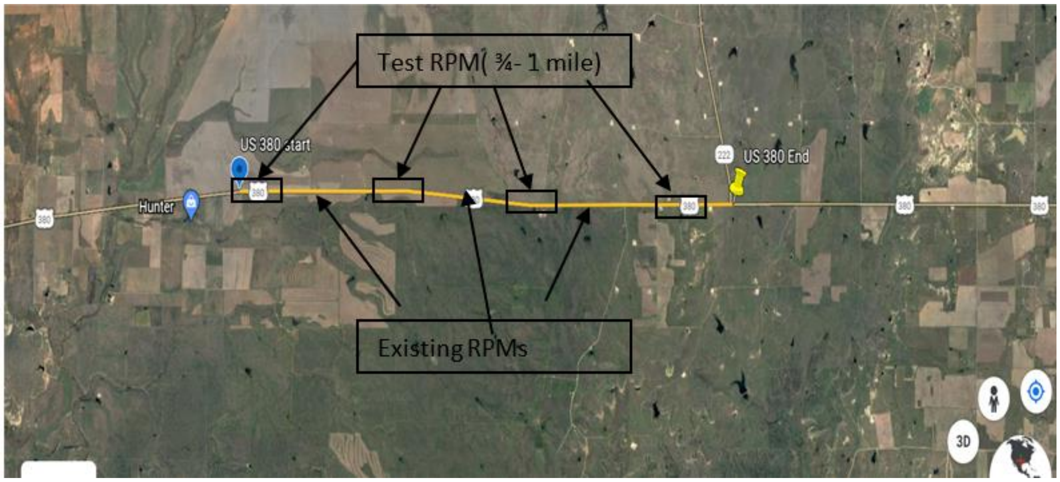
Table 6-2 shows the field site location details and traffic conditions:

Table 6-2 Field site locations

	County	Highway	From	To	Annual Average Daily Traffic	Truck Traffic (%)	Speed Limit (mph)
Location-1	Throckmorton	US 380	Haskell County Line	SH 222	1078	16.9	75
Location-2	Randall	SL 335	I-40 South	Osage	8000–26,000	6.0	50–75

6.2.3. RPM Installations

The project team worked with retroreflective pavement marker manufacturers to procure the selected RPMs and ship the RPMs to pertinent TxDOT district personnel. The researchers coordinated with the respective TxDOT officials for the installations of markers in the existing rumble strips of the highway segments selected for the field performance evaluations. The Wichita Falls District Office installed the three types of markers in the rumble strips available on US-380 segments using bitumen adhesive in late January 2021, while the Amarillo District Office installed the LP1 (C40) markers using epoxy. The Amarillo District Office used epoxy because epoxy is recommended by the manufacturer of the RPMs for installation of these RPMs (note, that is for snowplowable configurations). However, there was not sufficient epoxy to complete the installation and thus rest of the RPMs were installed using bitumen adhesive in the existing rumble strips on SL 335 (see Figure 6-3).



(a) Location-1 US 380, Throckmorton County, Wichita Falls District

(b) Location-2 SL 335, Randall County, Amarillo District

Figure 6-3 Installation configurations of test RPMs at Field site locations

RP1 markers (3M-290) were installed in rumble strips of the first segment of the US-380 test site following existing markers on the pavement surface. The low-profile markers were installed similarly (see Figure 6-4). The Amarillo District Office installed the RPM in rumble strips of SL 335 in early February 2021. LP1 (C40) marker was installed first in the existing rumble strips of SL 335 following LP2 (3M-190) marker and RP1 (3M-290) marker. One of the major differences between the two field site locations is the rumble strip geometry. The rumble strips on the US-380 field site are deeper than standard groove depth (½” ± ⅛”) while rumble strips on the SL-335 test location were shallower (~0.2”) than standard groove depth. Another difference observed was that the SL-335 pavement was resurfaced, and new grooves were cut before installation of the test markers, while test markers have been installed in the existing groove on US 380. Table 6-3 lists the marker installation sites.

Table 6-3 Markers installed in field study sites

Location	Markers	Model	Number Installed	Bonding
Location 1 (US 380)	LP1	Stimsonite C40	200	Bitumen
	LP2	3M Series 190	100	Bitumen
	RP1	3M Series 290	100	Bitumen
Location 2 (SL 335)	LP1	Stimsonite C40	97	Epoxy
	LP2	3M Series 190	100	Bitumen
	RP1	3M Series 290	60	Bitumen

Location -1 US 380 Location-2 SL 335

Figure 6-4 Example of RPMs installed in rumble strips in two field locations

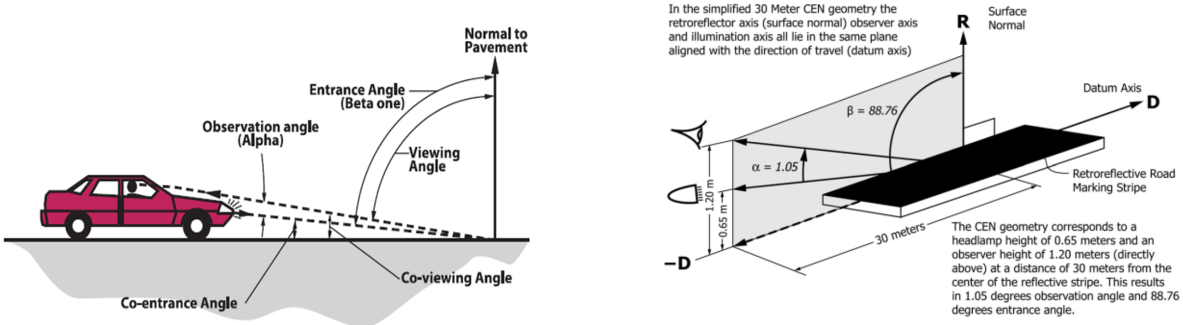
6.3. Field Evaluations

The project team conducted two field visits to the field sites for qualitative and quantitative assessments of the performance of markers after they experienced multiple snowplowing cycles due to winter weather events. Each field visit included assessment of damages to markers due to snowplow operations and assessment of nighttime visibility of markers. The damage assessments comprised of a visual inspection of each marker installed in the rumble strip on the test highway segments, capturing digital photos of each marker and adjacent pavement surface for further evaluations. The nighttime visibility was measured both qualitatively and quantitatively. The project team developed field visibility measurement equipment for appraising nighttime visibility of markers installed in rumble strips.

6.3.1. Visibility Measurement Equipment

The project team designed and fabricated RPM visibility data collection equipment *(48)*. The equipment comprises an industrial-grade hand truck that houses a charged coupled device (CCD) photometric camera, a standard headlight, an inverter, a 12v battery for power supply, and a panel for a laptop computer (see Figure 6-5). The project team investigated the possible methods to use a field device to measure the nighttime visibility data of RPMs in rumble strips and decided to follow ASTM E1710 *(49)* specifications for the data collection geometry. The Radiant Vision Prometric I-29 CCD photometer with a Nikon telephoto lens was borrowed from TxDOT for use in the field visibility data collection unit. The camera is configured and operated through Prometric software system using a laptop. The field visibility measurement equipment was fabricated in a way that the equipment can achieve an observation angle of 1.05 degrees and an entrance angle of 88.67 degrees from 30 meters from a target marker (see Figure 6-6) as per the specification of ASTM E 1710 *(49)*.

Figure 6-5 Photometric data collection equipment for field study



In the simplified 30 Meter CEN geometry the retroreflector axis (surface normal) observer axis and illumination axis all lie in the same plane aligned with the direction of travel (datum axis)

The CEN geometry corresponds to a headlamp height of 0.65 meters and an observer height of 1.20 meters (directly above) at a distance of 30 meters from the center of the reflective stripe. This results in 1.05 degrees observation angle and 88.76 degrees entrance angle.

Figure 6-6 Illustration of 30-m geometry ASTM E1710 (49)

6.3.2. Field Visits

The project team conducted field surveys to evaluate the performance of RPMs installed in the rumble strips of two field locations. The field visits were planned to be conducted after winter snowfall events so that the project team could evaluate the performance of the markers after they experience multiple cycles of snowplowing operations. Texas experienced a historic and unprecedented winter storm during mid-February in 2021. The field study locations were also impacted by the winter storm and experience significant amount of snowfall. The snow events led to multiple cycles of snowplows running over the markers installed on test highway sections. The project team conducted two field visits after major snow events—location-1 (US 380) was visited during mid-March 2021 and location-2 (SL 335) during early May 2021. Each field visit comprised of daytime visual inspections of each marker installed in rumble strips and nighttime quantitative and qualitative visibility assessment of randomly selected markers in rumble strips.

6.3.2.1. Visual Assessment of Markers

This phase of the field study included a visual inspection of each test marker installed in rumble strips on the test highway segments after they experienced multiple cycles of snowplow runs after the major snowstorm. The project team closely inspected each marker on the test highway segments and captured digital photos of each marker along the rumble strip for further analysis and damage assessment due to snowplow impacts. After analysis of data collected during the daytime visual assessment, the conditions of the markers were classified into 3 broad categories (see Figure 6-7):

- Good: These are markers that were fully functional. No visible defects were identified on the marker body and lens
- Damaged: These markers include markers that had major defects after the snowplow operations. Damaged markers can be further classified as damaged lens, damaged markers body, and damaged bonding.
- Missing: This category refers to locations in which the marker was absent due to being de-bonded from the surface. It was found that some markers were missing due to debonding of marker-adhesive interface while others were de-bonded due to failing at the pavement adhesive interface. Some markers were found shattered with little residue left in the rumble strips.

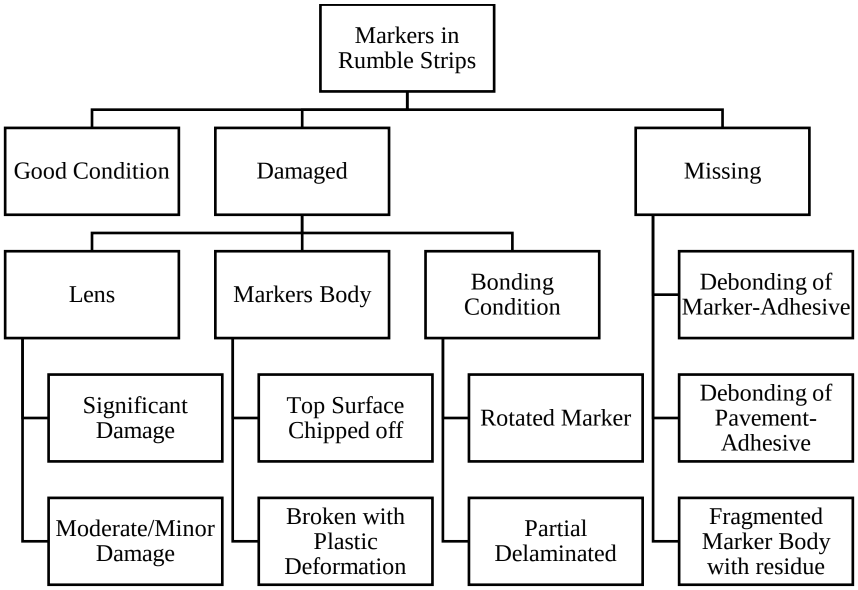


Figure 6-7 Classification system for the physical condition of the markers

6.3.2.1.1. Visual Assessment Results – Location-1 (US 380 Throckmorton County, Wichita Falls District)

Visual assessments of markers installed in rumbles strips of US-380 test segments in Throckmorton County were conducted during the field visit to determine the conditions of the markers after multiple cycles of snowplowing events. The Wichita

Falls District Office mentioned that the RPMs experienced four to five cycles of snowplowing before the visual inspections were conducted. The project team inspected each marker for any kind of damages and took photos of markers along with rumble strips. Most of the markers survived the snowplowing events and were in fully functional shape (see Figure 6-8). As mentioned previously, the centerline rumble strips on US 380 were deeper than the standard half-inch depth which implies that markers were sitting below the pavement top surface. Thus, LP1(C40) and LP2 (3M-190) markers were sitting well below the pavement surface and experienced the least impact of snowplow blades. However, regular-profile markers (3M-290) were sitting higher than low-profile markers and hence experienced greater impact than that of low-profile markers. Visual inspection data showed that all low-profile markers were in good shape (that is, they are fully functional without any damage) (see Figure 6-8). As stated earlier, regular-profile markers experienced greater impact of snowplow blades since they are sitting higher in the rumble strips compared to low-profile markers. Figure 6-8 shows that only 5% of the regular-profile markers were damaged by the snowplow blades and 95% of the regular-profile markers remained in fully functional shape. Among the damaged markers, four markers were found with significant lens damage which impaired their ability of centerline delineation. All the damaged markers had their top surface chipped off due to abrasion of snowplow blades. The visual observations and analysis revealed that 100% of low-profile markers survived snowplowing without any damages and 96% of regular-profile markers remained functional after snowplowing operations. Visual assessment of markers also revealed that there was no boding failure at marker-adhesive and adhesive pavement interface. The reason behind good bonding performance of the RPMs at this field location compared to the field screening tests might be due to the thickness of bitumen at the field location-1 being greater than what used during field screening study. It is worth mentioning that the project team observed that most of the existing surface-mounted RPMs were dislodged on previous snowplowing events. Appendix 2 shows some example pictures of markers on the US-380 location.

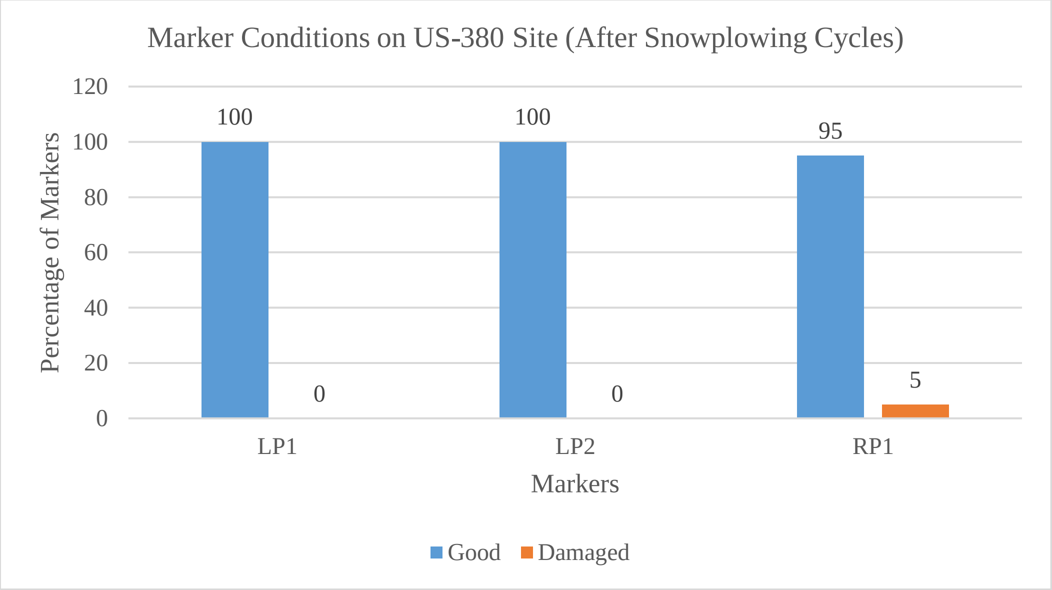


Figure 6-8 Condition of markers after snowplowing cycles in Location-1 (US 380, Wichita Falls District)

6.3.2.1.2. Visual Assessment Results – Location-2 (SL 335 Randall County, Amarillo District)

Visual assessment of markers in location-2 was conducted during early May with the support of the Amarillo District’s field maintenance office. Each marker was identified and inspected during the visual assessment of marker conditions after several cycle of snowplowing operations. Digital photos of each marker were also captured. The Amarillo District’s test location experienced more snowplowing cycles compared to Location-1 due to frequent snowfall events since the installation of test markers in early February 2021. The depth of rumble strips on SL-335 test segment (~0.2”) was significantly shallower than standard depth of rumble strips (0.5”). The geometric configuration of rumble strips increases the propensity of markers to be impacted by the snowplow blades. The visual assessments of markers revealed that percentage of damaged and missing markers in location-2 was higher than that of in location-1. Test markers on SL 335 were sitting significantly higher compared to the markers on US 380. Although the top surface of the markers in location-2 sitting almost on the pavement surface, survival of markers under multiple cycles of snowplow runs was significantly higher than the conventional markers (markers installed on pavement surface rather than in rumble strips). The Low-profile markers performed quite well compared to the performance of regular-profile markers. Figures 6-9, 6-10, and 6-11 summarize the condition of the RPMs after multiple cycles of real-event snowplow operations. These figures are based on the visual assessment. Appendix 3 shows some example pictures of markers at the SL-335 location.

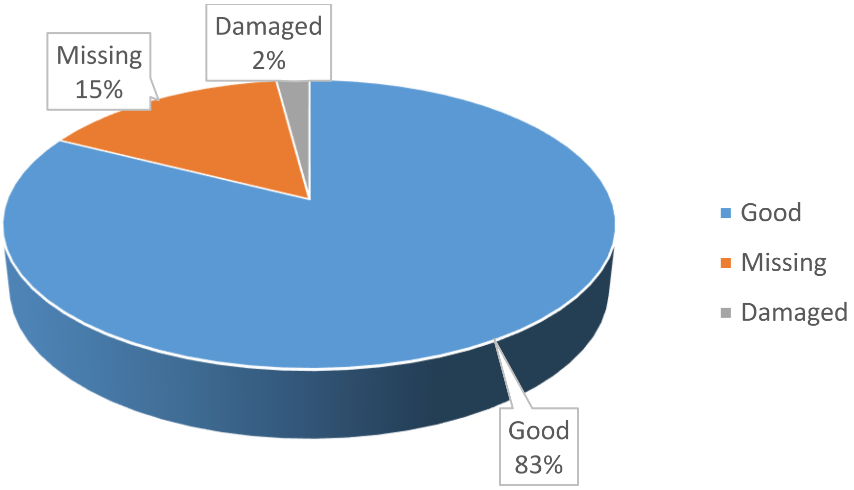


Figure 6-9 Condition of LP1 (C40) markers after multiple snowplowing events in Location-2 (SL 335, Amarillo District)

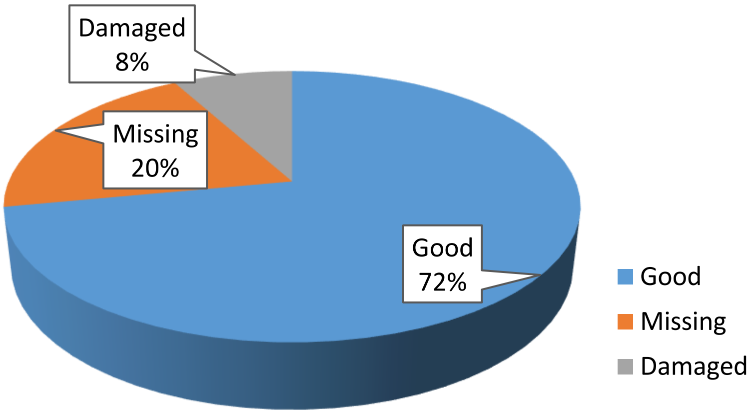


Figure 6-10 Condition of LP2 (3M-190) markers after multiple snowplowing events Location-2 (SL 335, Amarillo District)

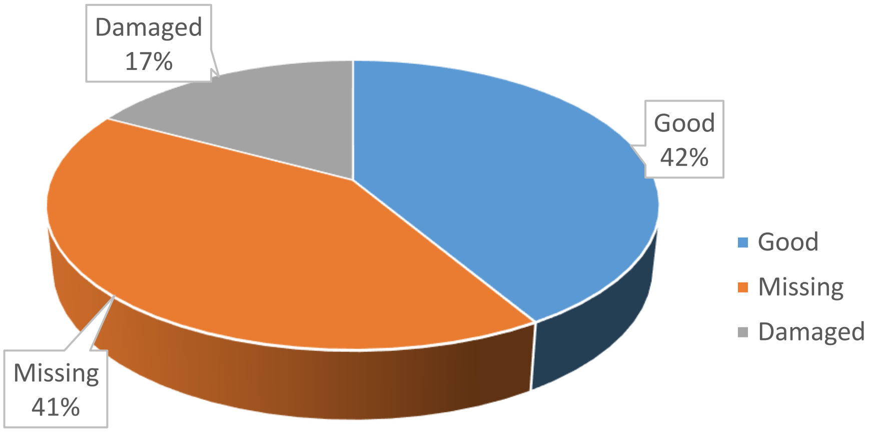


Figure 6-11 Condition of regular-profile marker (3M-290) after multiple snowplowing events Location-2 (SL 335, Amarillo District)

As shown in Figure 6-9, 83% of the low-profile marker LP1 (C40) were in good shape (that is, they have full functionality) while 17% of the low-profile marker LP1 were either damaged or missing. In terms of resistance to snowplow impact, LP1 performed well since only two markers were found with minor damage but still functional. Only 15% of low-profile marker, LP1 are missing due to debonding of marker-adhesive interface and debonding of pavement-adhesive interface.

Epoxy was used to attach low-profile marker-1 to the rumble strips. It can be stated that epoxy adhesive may a be viable option as an adhesive for the rumble inserts. From Figure 6-10, it is seen that 72% of low-profile marker LP2 (Series 190) survived multiple cycles of snowplow runs with full functionality and little or no damages. However, the percentage of damaged or missing low-profile marker LP2 was 28% which is relatively higher than that of LP1 (C40). Only 8% of LP2 were damaged due to the snowplowing operations with six markers broken significantly and two markers had top surface scraped off with functional lens. Most of the missing LP2 markers were dislodged due to bonding failure at the marker-bitumen interfaces. Regular-profile markers RP1 (3M-290) were sitting higher relative to the low-profile markers due to shallow rumble strips; as such, they were more prone to the impact of snowplow blades. Visual assessments of regular-profile markers reveal that 41% of RP1 markers were missing and damaged while 29% of regular profile, RP1 markers were in good condition. Among the damaged regular-profile markers, 11 markers were found broken or with their top scraped off, creating significant lens impairment; one marker was found fairly damaged with some functionality. All the missing regular-profile markers were delaminated at the marker-bitumen interfaces. As mentioned earlier, the rumble strips in location-2 were significantly shallow, situating the top of the test markers well above the pavement surface. Despite this fact, the test markers performed relatively well if compared to the conventional markers on the pavement surface It can be stated that with rumble strips of standard specifications, it is possible to limit the loss of markers.

6.3.2.2. Nighttime Visibility Assessment of RPMs in Rumble Strips

The second phase of the field study was to determine the nighttime visibility of randomly selected markers in terms of retroreflectivity. To assess the visibility of markers at night, the project team collected luminance and illuminance data on randomly selected markers in each study location with the help of data collection of equipment as mentioned in Section 6.3.1. The luminance data were collected under live traffic conditions in each location. For safety, the project team coordinated with the pertinent TxDOT Office for traffic control and other logistics support. The data were collected from 8:00 p.m. to 4:00 a.m. The luminance data of a selected RPM were collected by positioning the field data collection equipment at a 30-m distance on the centerline of the roadway. Once the position of the equipment and marker was determined, the standard headlight in low beam was used to illuminate the marker. Then, the CCD camera was focused on the illuminated marker and software system was used to capture images of the marker. This focusing and capturing took 10 to 20 minutes for each marker. The time was dependent on the position of the marker in the rumble strips, background pavement markings, thickness of the adhesive around the marker, and condition of the lens on each individual marker. Also, ambient conditions such as wind speed and/or wind gust, lights from incoming vehicles, and surrounding ambient lighting affected the measurement timing and quality significantly. In addition to capturing image of marker with the CCD camera, illuminance measurement for each selected marker was collected. The mathematical approach used for the determination of the retroreflectivity of markers is described in Chapter 4.

It must be noted that one of the deficiencies of the camera used in this project was that camera was configured for the laboratory setup and calibrated for the 15-m distance. However, the field condition is different from the laboratory setup which affects the quality of the luminance data. In addition, ASTM E1710 *(49)* specification was used for field measurement which is different from measurement angles prescribed in ASTM E808-01 *(37)* that typically used to measure pavement markers luminance in the lab.

6.3.2.2.1. Nighttime Visibility Results – Location-1 (US 380 Throckmorton County, Wichita Falls District)

The project team conducted nighttime visibility of selected test RPMs in rumble strips on US 380 on March 11, 2021, from 8:00 p.m. to 3:00 a.m. The average temperature was around 68^0F and wind speed was 10–15 mph gusting up to 20 mph. The maintenance office of Wichita Falls District Office provided traffic control support. The project team selected six markers of each type totaling 18 measurements for nighttime quantitative visibility assessment from 30m (~100ft). As mentioned earlier, the depth of rumble strips in Location-1 (US 380) are greater than that of the standard depth of 0.5 inches and the bitumen around each marker was much thicker. These two factors contributed to the diminished illumination of markers, which affected the retroreflectivity values of markers. Stray lights from surrounding infrastructures and traffic control vehicles also affected the retroreflectivity of markers. Finally, the strong wind gust caused the data collection equipment to move and hence affected the measurement time and measured values.

Figure 6-12 shows the mean retroreflectivity of six selected RPMs of each type along with standard deviations. The high variability of retroreflectivity is attributed to the factors mentioned above and individual marker configurations. From Figure 6-12, it is seen that regular-profile markers (3M-290) were more retroreflective than low-profile markers. This is because regular-profile markers receive more light as they are sitting higher than the low-profile markers in the deep rumble strips. Low-profile marker LP1 and low-profile marker LP2 showed a similar retroreflectivity level.

Overall, from the results of the nighttime visibility measurements it can be concluded that regular profile markers in rumble strips can delineate the centerline of the test segments. The low value of the low-profile markers makes it hard to determine from the quantitative measurements, as such a qualitative assessment was conducted (see Section 6.3.2.3). It is worth mentioning that a single headlamp was used in low beams to illuminate markers while measurements have been made. As such, with a two-headlamp configuration (which is the case of vehicles) the RPMs in rumble strips should be more visible and provide ample delineation during nighttime. Also, appropriate geometric configurations of the rumble insert should provide adequate retroreflectivity.

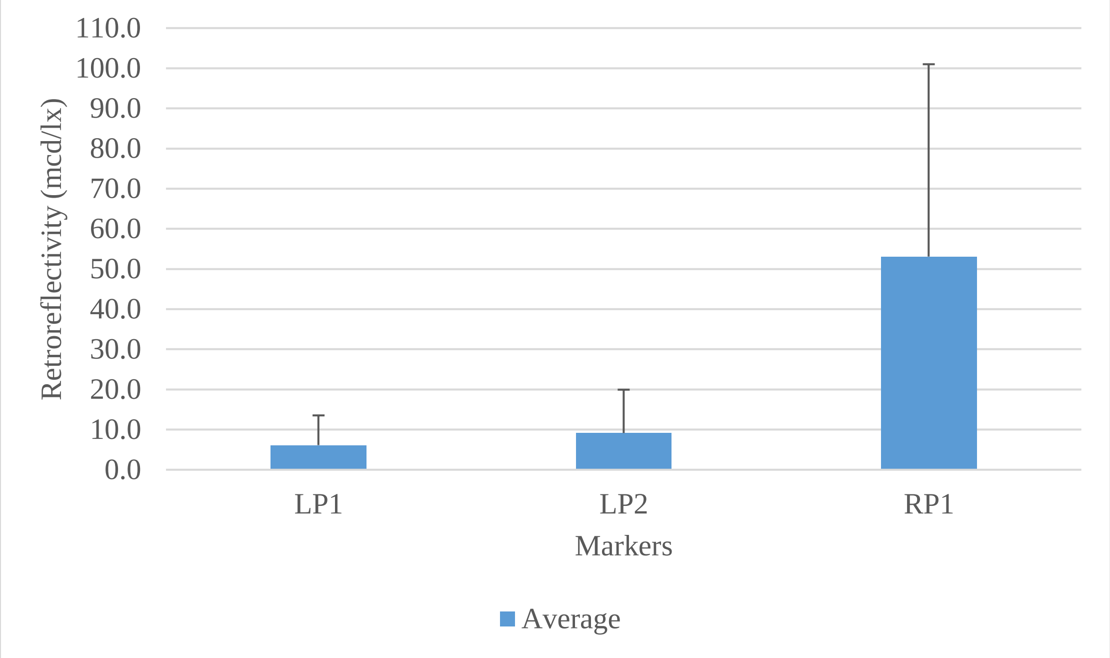


Figure 6-12 Retroreflectivity of RPMs at 100ft in Location-1 (US 380 Throckmorton County, Wichita Falls District)

6.3.2.2.2. Nighttime Visibility Results – Location-2 (SL 335 Randall County, Amarillo District)

Nighttime visibility measurements for RPMs installed in rumble strips on SL 335 were performed on May 06, 2021, from 9:00 p.m. to 4:00 a.m. The temperature during the measurements was around 50^0F and wind speed around 15–20 mph gusting up to 28 mph. The Amarillo District Office provided traffic management and control during the measurement of nighttime luminance and illuminance. In addition to the wind gust, there was significant number of incoming traffic passing through the test sections which contributed significant amount of stray light. These factors significantly affected the luminance and illuminance measurement and hence decrease the retroreflectivity values of markers. The project team used the field data collection equipment to measure randomly selected six markers of each type from 30 m that the observation angle was 1.05^0 and entrance angle 88.76^0.

Figure 6-13 represents the average retroreflectivity values of each type of marker along with their variabilities. It can be seen that the regular-profile markers RP1 (3M-290) showed higher retroreflectivity than low-profile markers. Low-profile marker, LP1 (C40) showed slightly better visibility than low-profile marker, LP2 (3M-190).

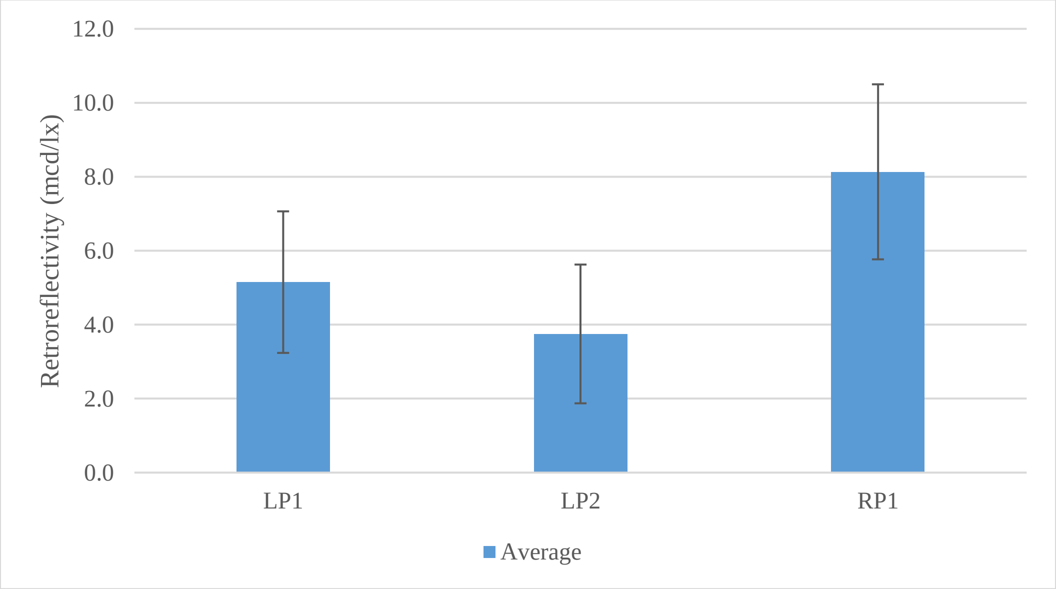


Figure 6-13 Retroreflectivity of RPMs at 100ft in Location-2 (SL 335 Randall County, Amarillo District)

6.3.2.3. Nighttime Qualitative Visibility of Markers

In addition to the quantitative visibility assessment, a qualitative assessment of the nighttime visibility of test markers from the driver's perspective was conducted. To qualitatively assess the marker's visibility, the team members drove a vehicle with LED headlights and observed how many markers were illuminated. Additionally, videos were taken. It was observed that RPMs were well illuminated at the Location-1 (US 380) (see Figure 6-14), with the regular-profile markers were being more visible than low-profile markers. At Location-2 (SL 335), qualitative assessment showed that markers were illuminated very well regardless of their type (see Figure 6-15). This is in agreement with the results from the quantitative nighttime visibility tests. In Figure 6-12 (Location 1), the regular profile markers retroreflectivity values were approximately 5 times greater than the low profile markers; whereas as in Figure 6-13, the retroreflectivity values were all similar. Thus, the results show that the retroreflectivity measurements can be used to establish trends (i.e., which one is more retroreflectivity), but the values should not be used to determine whether a marker is visible or not at a specific location. At both locations, from about 500 ft, four to six markers were visible on average (see Figure 6-14 and 6-15). This corresponds to markers being illuminated at 740 ft to 900 ft from the driver.

Figure 6-14 Qualitative visibility of RPMs in Location 1 (US 380, Wichita Falls District), illuminated markers circled

Figure 6-15 Qualitative visibility of RPMs in Location 2 (SL 335, Amarillo District), illuminated markers circled

From the qualitative assessment, it can be seen that the nighttime visibility level of the centerline rumble insert markers was sufficient to delineate the centerline of the test segments.

6.4. Visibility of Rumble Inserts in Wet Condition

To assess the nighttime visibility of RPM in rumble strips, a water screening assessment conducted on the test roadway section at PRC at the University. The goal of the water screening tests was to evaluate the quantitative and qualitative visibility of RPMs in rumble strips in wet conditions at night to determine whether the RPMs would be able to be seen under a rainfall event.

6.4.1. Rain Simulator

A rain simulator was built to facilitate the water screening test of RPMs in rumble strips at the PRC test roadway. The rain simulator consisted of a submersible pump, a water tank, piping systems, and sprinklers (see Figure 6-16). The system was connected to a diesel generator, which powers the submersible pump. The whole system was placed on a platform that was moved using a forklift (see Figure 6-17). The forklift moved the rain simulator and placed the system adjacent to a rumble insert so that the sprinkler can spray water on the rumble strip. The rain simulator was able to submerge the RPM in rumble strip in a minute (see Figure 6-18).

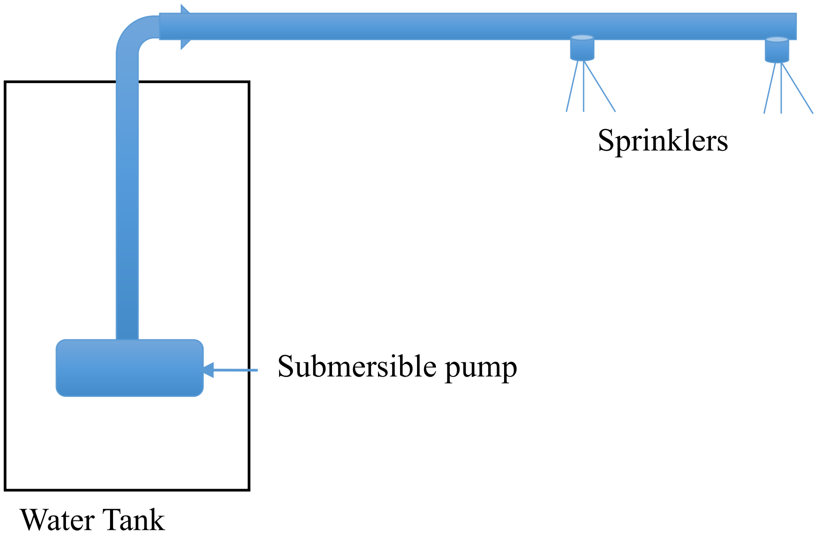


Figure 6-16 Rain simulator components

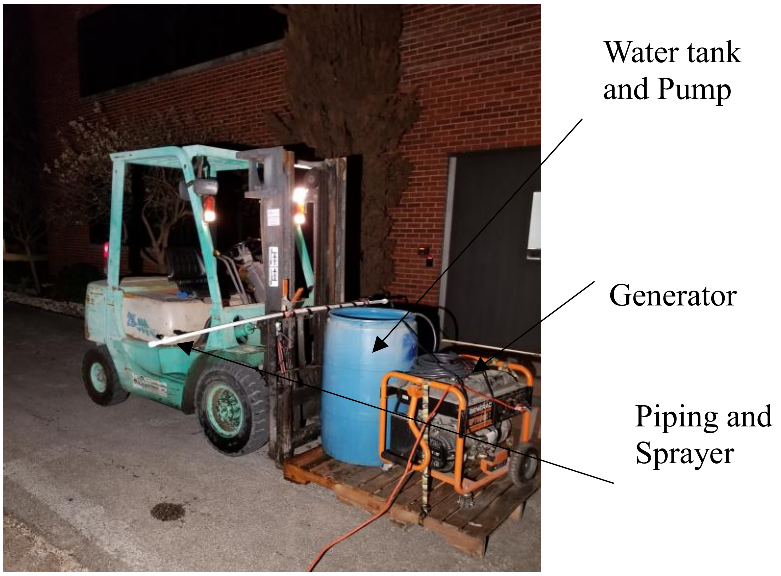


Figure 6-17 Rain simulator on Forklift

Figure 6-18 Water spraying on an RPM installed in rumble strip using the rain simulator

6.4.2. Qualitative Visibility in Wet Condition

Nighttime visibility of RPMs in rumble strips at the PRC test location was assessed qualitatively in wet conditions. The wet condition was simulated by spraying water on the rumble strips and submerging the RPM. Figure 6-19 shows the digital photos of visibility of the RPMs from 100 ft and approximately 300 ft. It can be observed that the RPMs are visible after they submerged by rainwater from different distances. The results show that the even under wet conditions, the method of using RPMs in rumble strips can be used to delineated the center of the roadways during nighttime conditions.

Visibility of water-filled rumble inserts (100 ft)

Visibility of water-filled rumble inserts (approximately 300 ft)

Figure 6-19 Qualitative nighttime visibility of RPM in rumble strips in wet condition on PRC test roadway

6.4.3. Quantitative Visibility in Wet Condition

, The research team conducted the photometric measurements of the RPMs installed in rumble strips in dry condition using the field-testing equipment (see Figure 6-5). Then rain simulator was used to spray water on the RPM in rumble strip for 90 seconds, and the photometric measurement of the RPM was taken after 90 seconds of spraying water. Three of each type of marker were used to evaluate the changes in visibility of RPMs in rumble strips due to wet weather conditions. Figures 6-20 and 6-21 present the changes in nighttime retroreflectivity levels due to wet weather conditions from 100 ft and 50 ft respectively. It should be noted that the expected retroreflectivity might be different from the results presented in Figures 6-20 and 6-21. This is because of the limitation of the configuration and calibration of the imaging device which is configured for laboratory settings for 15 m (50 ft) measurement distances. The quantitative measurement revealed that the visibility is reduced when RPMs in rumble strips are submerged by the rainwater. However, it can be stated that RPMs were still visible at night in wet conditions, which is also supported by the qualitative visibility observations. The regular-profile marker's visibility in wet weather conditions was better than that of the low-profile markers since regular-profile markers were sitting higher in the rumble strips.

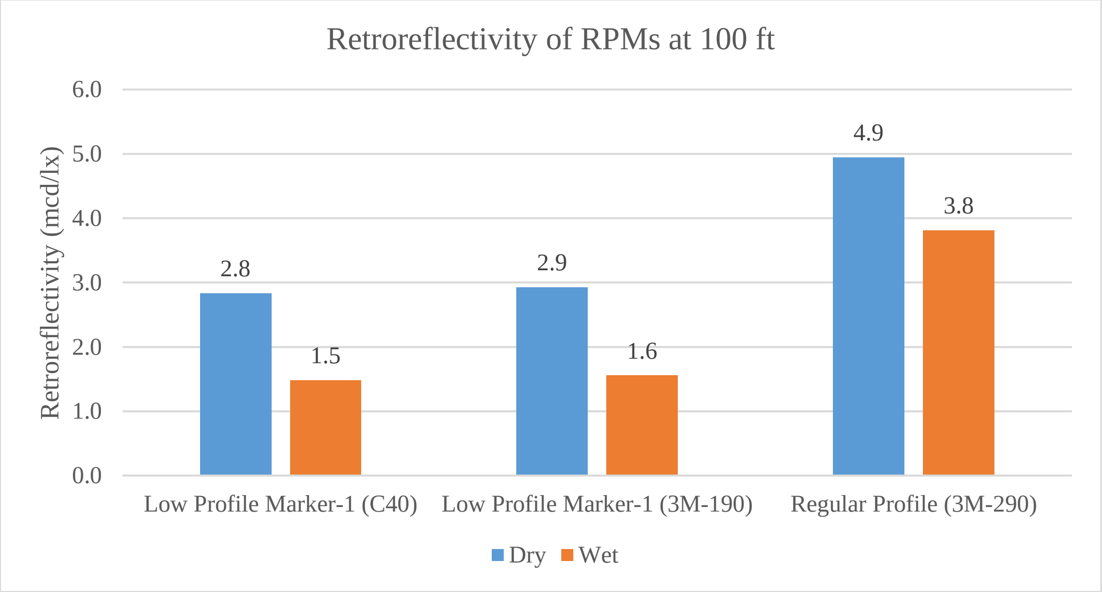


Figure 6-20 Changes in nighttime retroreflectivity level due to wet weather condition from 100 ft distance on PRC test roadway

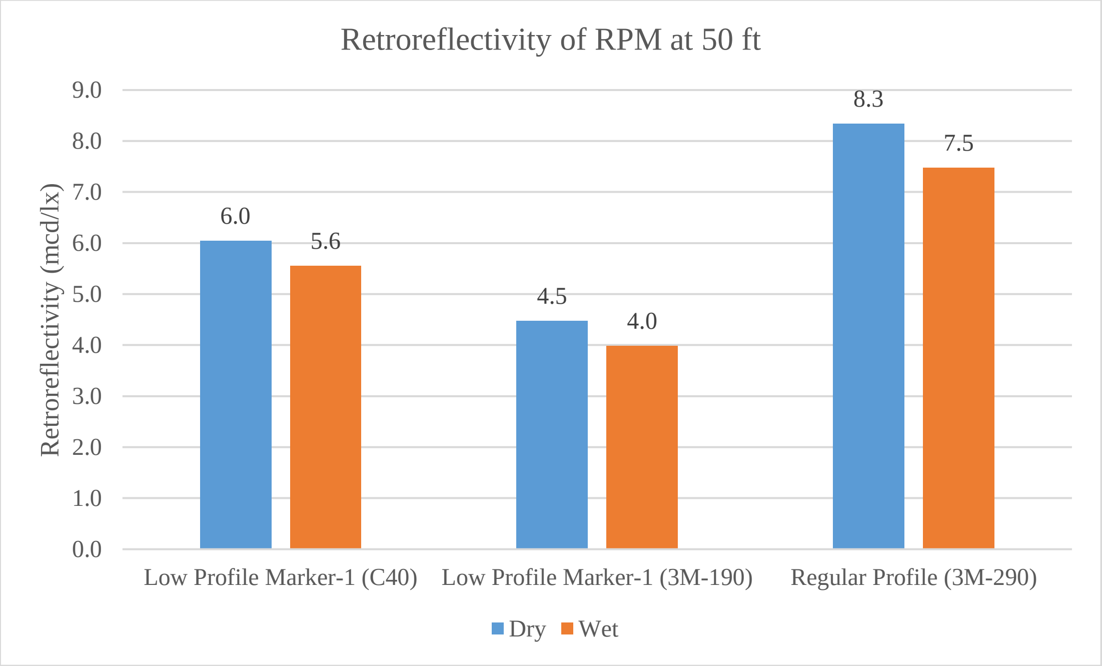


Figure 6-21 Changes in nighttime retroreflectivity level due to wet weather condition from 100 ft distance on PRC test roadway

6.5. Summary

The following summaries can be made based on the field study of test markers on in-service roadways:

- Test markers in location-1 (US 380, Wichita Falls District) performed extremely well even after being subjected to multiple cycles of snowplow runs. Only 5% of regular-profile markers were impacted, and no markers were delaminated from the rumble strips. Although the rumble strip's depth and adhesive thickness were greater than the standard practices, RPMs would likely perform similarly with standard geometry and adhesive thickness.

- Location-2 (SL 335, Amarillo District) had very shallow depth rumble strips. Owing to this fact, low-profile markers performed quite well with a more than 75% RPMs remained in place. Although only 41% of regular-profile markers remained in good condition after snowplow operations. This number can be increased with appropriate rumble strip depth.

- Test segments in Location-2 experimented with two types of adhesives-epoxy and bitumen. It can be stated that both adhesives performed almost similarly in terms of holding the marker in place, with the epoxy slightly outperforming the bitumen adhesives. However, due to cost and common practices, bitumen is recommended for use for RPMs installed in rumble strips in asphalt pavements.

- Nighttime visibility assessment revealed that the rumble inserts method can be used to delineate the centerline of two-lane highways under nighttime conditions.

- The RPMs nighttime visibility was reduced in wet weather conditions (when they submerged in rainwater). However, qualitative and quantitative analysis showed that the RPMs in rumble strips were visible in wet weather conditions.

Chapter 7. Flexible Memory Markers

In this phase of the project, we explore an innovative approach that includes not only installing markers in RPMs, but also designing a new marker system. This new marker should be flexible enough to bend under snowplow to prevent it from being dislodged and have enough elasticity that it returns to its original position after the snowplow load is removed, aka “flexible memory markers”. This chapter discusses the design and fabrication of these new flexible memory markers and their observed performance under an impact load as a proof of concept.

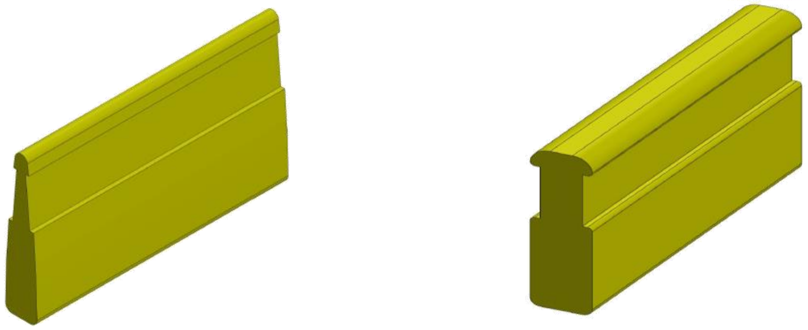
7.1. Innovative Flexible Memory Marker Components

The inception of the design of innovative flexible memory markers stemmed from the idea that the flexible marker would have a resilient body that can withstand the dynamic loading from snowplow blades and the flexible memory markers would have a flexible support system that can anchor the marker to the pavement but also provide flexibility so that it can bend when impacted by a moving load. In addition to the marker body and flexible support system, the marker would also incorporate provisions for attaching reflective materials for delineation purposes. Therefore, the flexible memory marker has three key components:

- Marker Body:
    - Must be designed to fits the geometric configurations of rumble strips and is made with resilient UV-resistant materials.
- Support System:
    - Must be flexible and elastic so that it allows the marker body to bend and return back to its original configuration.
- Reflective Material:
    - Must be positioned high enough on the marker body to allow it to be visible to traffic and not torn off from the marker body under snowplow loads.

7.1.1. Molds for Fabrication of Initial Flexible Markers

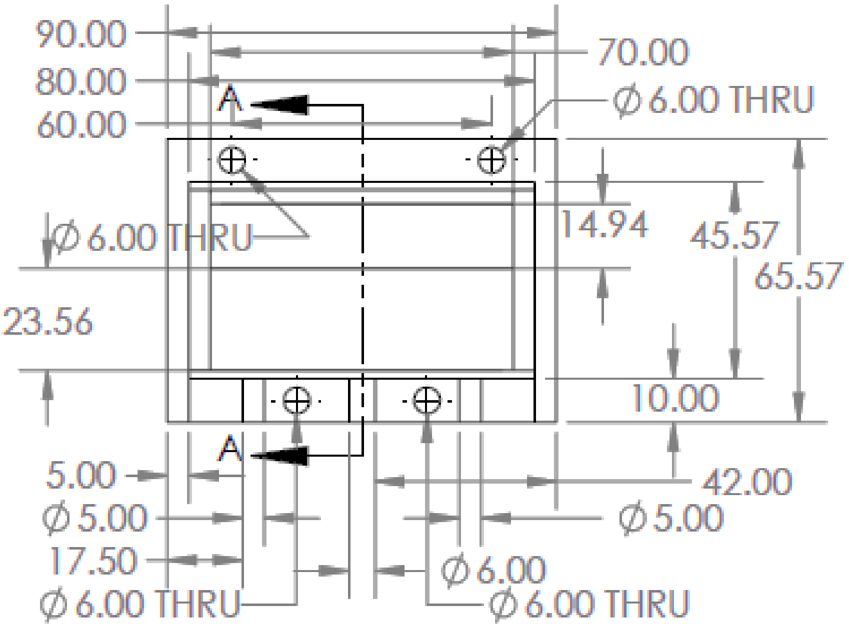
The project team explored different options for the fabrication of marker body prior to finalizing on a geometry for the marker body. The dimensions of marker body were selected considering the geometry of rumble strips as well as focusing on the visibility of the markers. The research team designed and fabricated two different mold shapes (See Figure 7-1): one is tapered design to match the curvature of the rumble strip groove (Type-1) and the other is a rectangular shape with more thickness at the top than the other marker (Type-2).



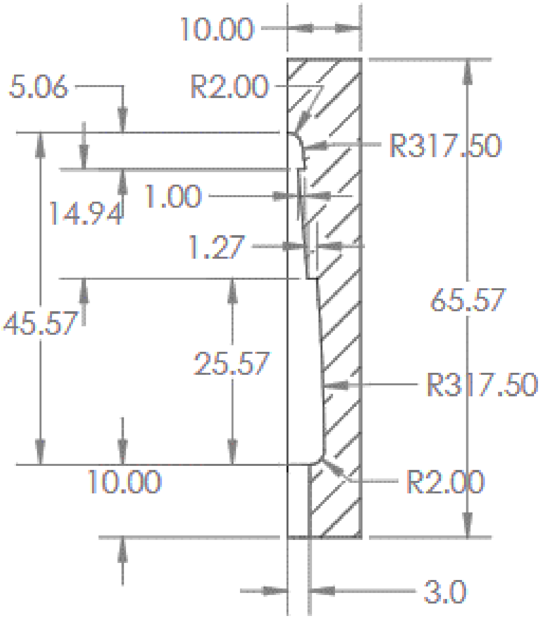
Type-1 (Tapered) Type-2 (Non-tapered)

Figure 7-1 Innovative flexible memory markers body shapes when fabricated using molds

The height and length of both of the molds were the same, 45.57 mm and 80.00 mm, respectively. Figures 7-2 and Figures 7-3 shows the computer aided designs for the molds for Marker Type-1 and Marker Type-2, respectively. Mold of Type-1 marker had 10 mm thickness at the bottom and 4 mm thickness at the top, while mold-2 has 12.5 mm thickness throughout its height. Figures 7-1 and 7-2 show the dimensions of Type-1 and Type-2 molds respectively.

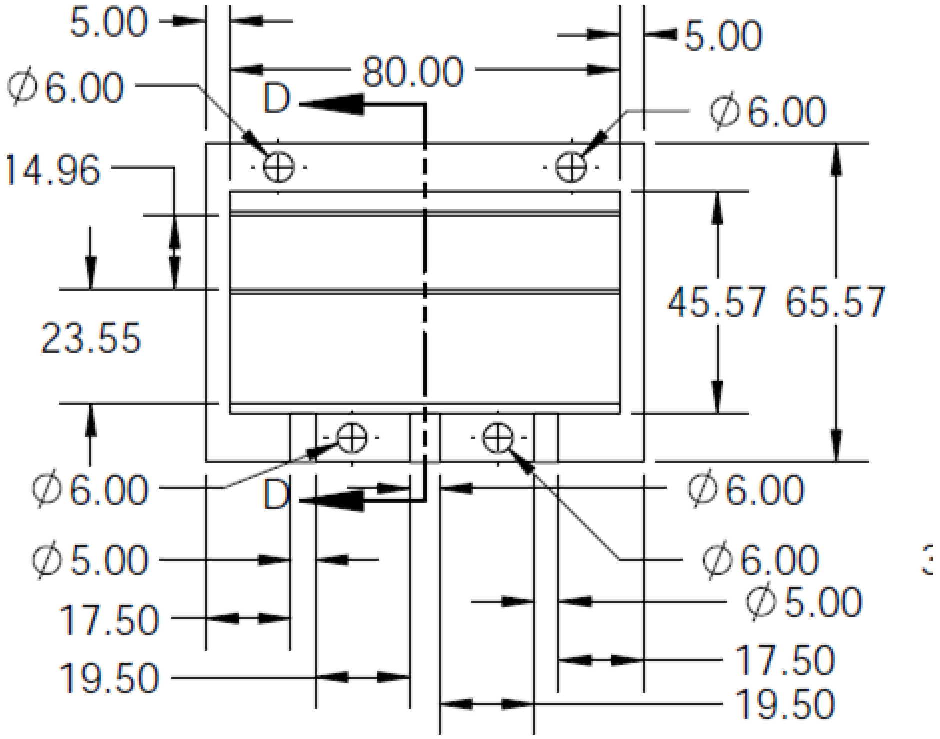


(a) Mold-1: Front View for Type-1 (Tapered Marker)

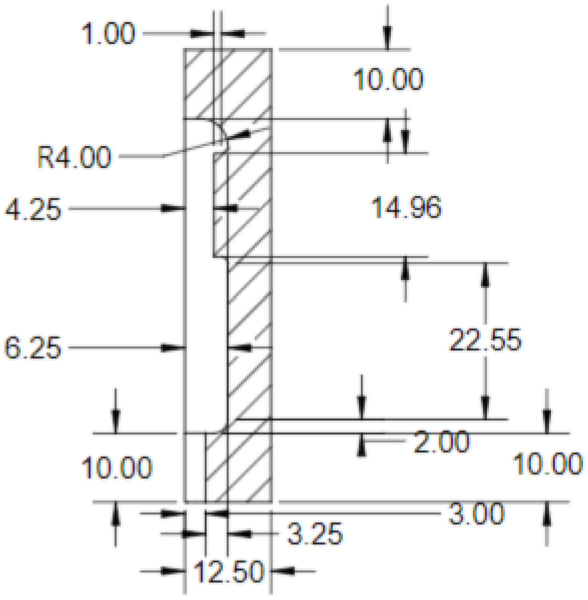


(b) Mold-1: Cross Section Type-1 (Tapered Marker)

Figure 7-2 Flexible memory marker mold with dimensions (Type-1: Tapered Marker)



(a) Mold -2: Front View of Type-2 (Non-tapered Marker)



(b) Mold-2: Cross Section of Type-2 (Non-tapered Marker)

Figure 7-3 Flexible memory marker mold with dimensions (Type-2 Non-tapered Marker)

7.1.2. Materials for Marker Body

Since the flexible memory markers may need to endure a significant impact from the snowplow blades and other heavy traffic loadings, the project team decided to use rigid and resilient material for the fabrication of the marker body. After careful investigation, the project team selected Alumilite Performance 80D *(50)*, a rigid urethane elastomer for the initial prototype of innovative flexible memory markers.

7.1.3. Flexible Support/Anchorage System

The project team explored the different ideas for the flexible support system for flexible memory markers and decided to use torsion springs since this helical spring can provide extra torque which will help to bend under dynamic loads and allow the body to regain its original position. The different torsion spring configurations were considered in this work are listed below:

- 90^0 deflection of spring
- 180^0 deflection of spring
- Outer Diameter of spring
- Wind direction of spring coil
- Wire diameter of coil
- Torque capacity of spring

A total of 18 spring configurations was produced considering the above-mentioned variables. Table 7-1 shows the specific spring parameters selected for study in this project.

Table 7-1 Torsion spring parameters for the flexible memory markers

Name	Outer Diameter (in.)	Rod Size (in.)	Wire Diameter (in.)	Coils	Leg Length (in.)	Deflection Angle (deg.)	Direction of Wind
499-059L	0.499	0.312	0.059	4.25	2	90	LEFT
499-059R	0.499	0.312	0.059	4.25	2	90	RIGHT
619-048L	0.619	0.406	0.047	5	2	180	LEFT
619-048R	0.619	0.406	0.047	5	2	180	RIGHT
625-070L	0.625	0.406	0.07	8	2	180	LEFT
625-070R	0.625	0.406	0.07	8	2	180	RIGHT
637-075L	0.637	0.39	0.075	4.25	2	90	LEFT
637-075R	0.637	0.39	0.075	4.25	2	90	RIGHT
672-075L	0.672	0.418	0.075	8	2	180	LEFT
672-075R	0.672	0.418	0.075	8	2	180	RIGHT
678-078L	0.678	0.406	0.078	4.25	2	90	LEFT
678-078R	0.678	0.406	0.078	4.25	2	90	RIGHT

7.1.4. Fabrication of Flexible Memory Markers

The project team fabricated the molds from using the Mechanical Engineering Shop at the University of Texas at Austin. Figure 7-4 shows examples of fabricated flexible memory markers.

Type-1 Type-2

Figure 7-4 Examples of fabricated tapered and non-tapered markers with 90^0 deflection springs

7.2. Observational Study

As proof of concept, a scaled-impact test that mimic the blow of snowplow blade was conducted to evaluate how the markers performed under dynamic loadings and to examine failure mechanisms. This impact test was conducted using a pendulum set-up.

7.2.1. The Pendulum Setup

The pendulum system that was designed by the research team consists of a pendulum arm support, a pendulum arm, and flexible marker mounting system (see Figure 7-5). The pendulum arm was connected to the support through a circular rod and circular bearings. A marker mounting platform for the pendulum set-up was built from a concrete column, the concrete column had a drill press vise to attach the marker for impact loading. The pendulum could impact the marker using a total of 140 lbs. weight from a height of 5.5 feet, that is the pendulum could hit the markers with around 1000 J energy. Figure 7-6 shows pictures of the pendulum setup.

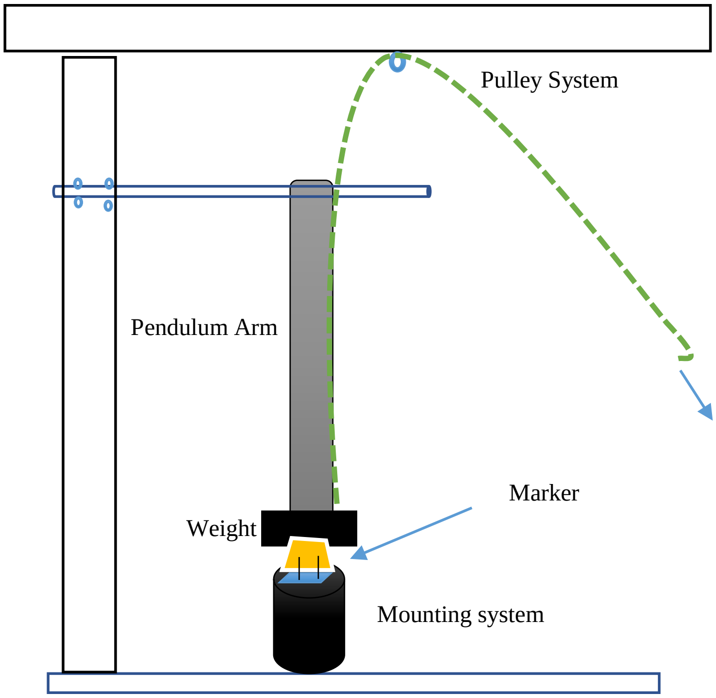


Figure 7-5 Schematic for pendulum setup for flexible memory markers

Figure 7-6 Laboratory pendulum impact testing setup for flexible memory markers

7.2.2. Impact Testing of Flexible Memory Markers

The fabricated flexible memory markers were tested under the impact load imparted by the pendulum set up to observe the behavior of markers body and springs support. The goals of the testing were twofold:

- Observe the behavior of markers body, i.e., whether they absorbed the impact force, and whether they get damaged due to impact load.
- Observe the performance of spring supports when the marker received impact of the pendulum, i.e., whether springs help the marker to bend under impact load and regain its original position, whether if there any damages to the springs.

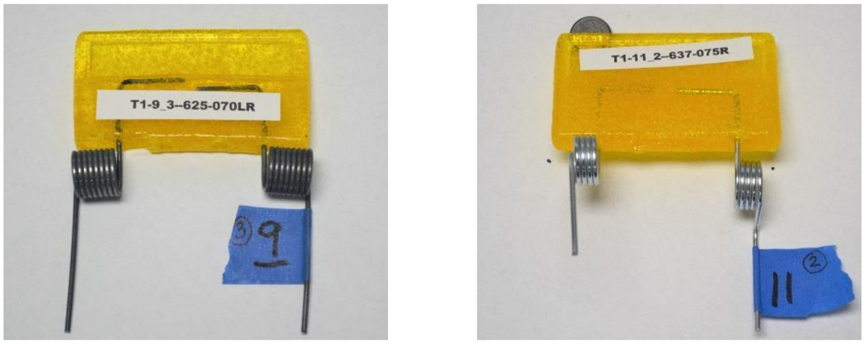
A total of 72 markers were tested using the pendulum setup, that is 36 markers of each type of marker body were tested. Spring configurations of flexible markers were varied by spring outer diameter, spring wire diameter, deflection angle, and combining spring winding directions. Three markers of each spring configuration were tested using the pendulum (see Table 7-2). Figure 7-7 shows some examples of markers spring configurations. During the observational study with impact loading, each marker received 10 impacts of the pendulum.

Table 7-2 Flexible memory marker test matrix

Marker Type-1					**Marker Type -2**				
Outer Dia. (in.)	**Wire Dia. (in.)**	**Wind Direction**	**Deal. Angle**	**No.**	**Outer Dia. (in.)**	**Wire Dia. (in.)**	**Wind Direction**	**Defl. Angle**	**No.**
0.619	0.048	Right-Right	180^0	3	0.619	0.048	Right-Right	180^0	3
		Left-Right		3			Left-Right		3
0.625	0.07	Right-Right		3	0.625	0.07	Right-Right		3
		Left-Right		3			Left-Right		3
0.672	0.075	Right-Right		3	0.672	0.075	Right-Right		3
		Left-Right		3			Left-Right		3
Total				**18**	**Total**				**18**
0.499	0.059	Right-Right	90^0	3	0.499	0.059	Right-Right	90^0	3
		Left-Right		3			Left-Right		3
0.637	0.075	Right-Right		3	0.637	0.075	Right-Right		3
		Left-Right		3			Left-Right		3
0.678	0.078	Right-Right		3	0.678	0.078	Right-Right		3
		Left-Right		3			Left-Right		3
Total				**18**	**Total**				**18**

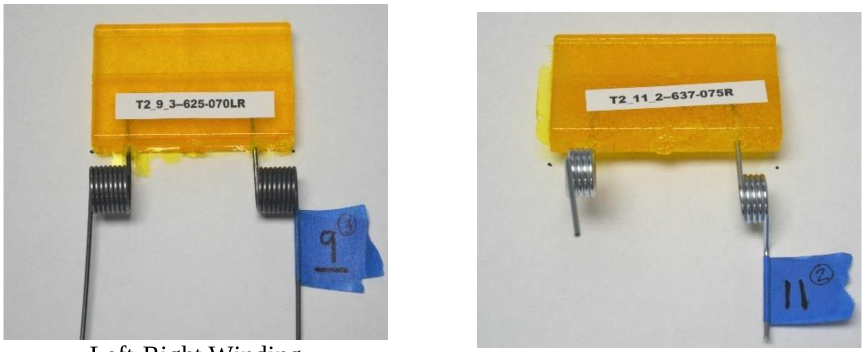
Def. Angle 180^0 Def. Angle 90^0

Type-1



Left-Right Winding Right – Right Winding

Type-2



Left-Right Winding Right – Right Winding

Figure 7-7 Examples of flexible memory marker's spring configurations

7.2.3. Observations from Impact Tests of Flexible Markers

Each marker received 10 impacts of the pendulum and marker was visually inspected after each impact. In addition, digital photographs of each tested marker were taken to reference the changes under the impact of the pendulum.

The main observation of impact tests of markers is that flexible memory markers deflected under the impact load and was able revert to initial state upon removal of impact load. That is the markers supported the initial concept of the research hypothesis. However, the following types of damages under the impact of pendulum were observed:

- Springs were bent, bent, and rotated, which made marker tilted. Springs were permanently set or no longer fully regained original position. (See Figure 7-8 and Figure 7-9.)
- Springs started uncoiling that is the spring wire started elongated and the spring's coils twisted. (See Figure 7-10.)

- Spring’s leg of 90^0 springs were straightened which made markers tilted. (See Figure 7-11.)

- Fractured marker body. (See Figure 7-12.)

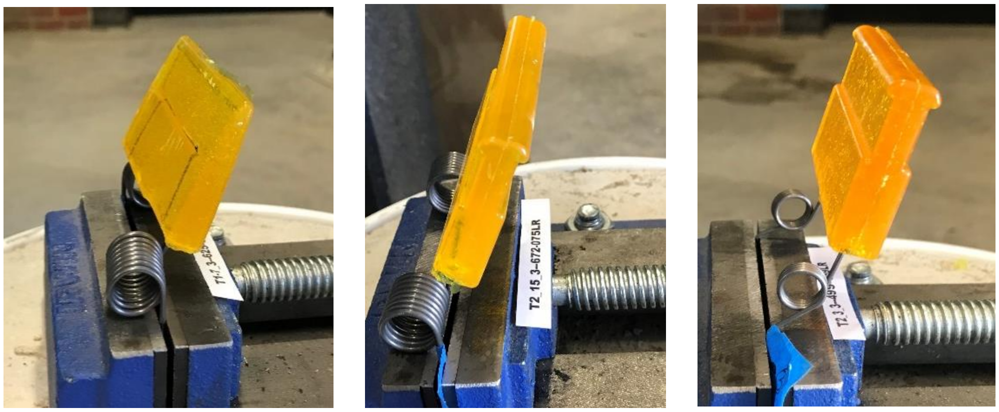


Figure 7-8 Examples of markers with spring bent due to impact loading

Figure 7-9 Examples of markers with spring bent and rotated due to impact loading

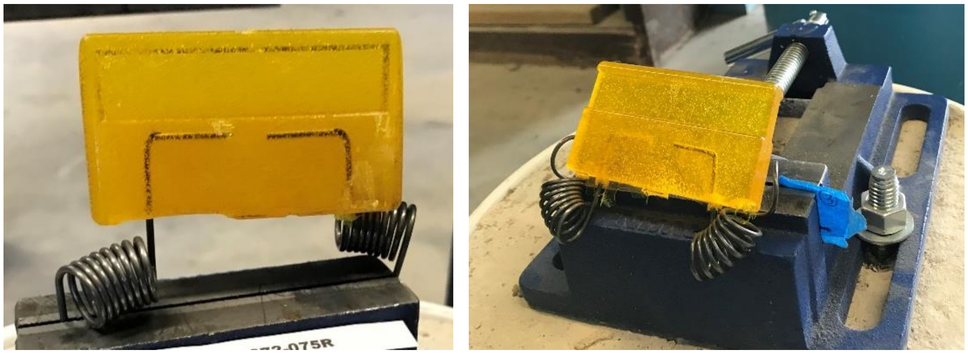


Figure 7-10 Examples of markers with spring bent, rotated, and uncoiled due to impact loading

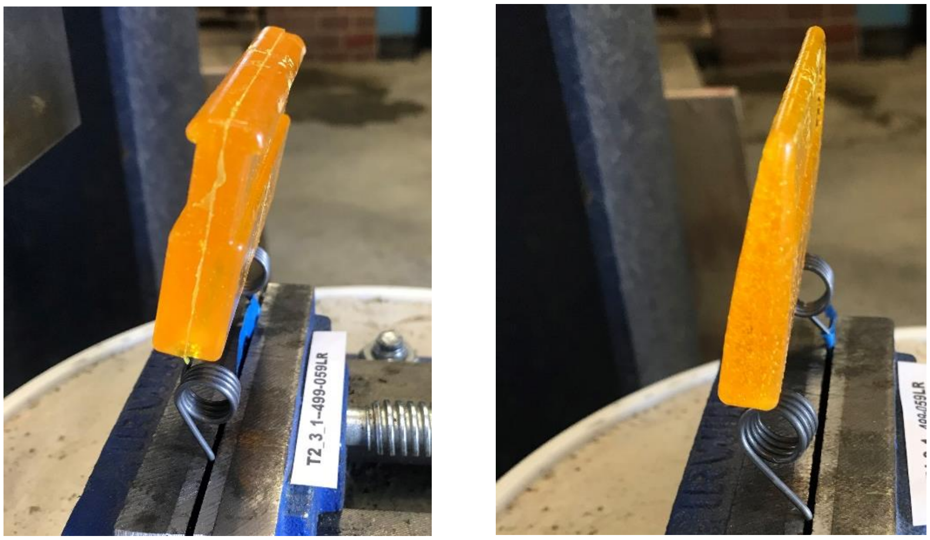


Figure 7-11 Examples of markers with spring leg of 90^0 spring's start straighten due to impact loading

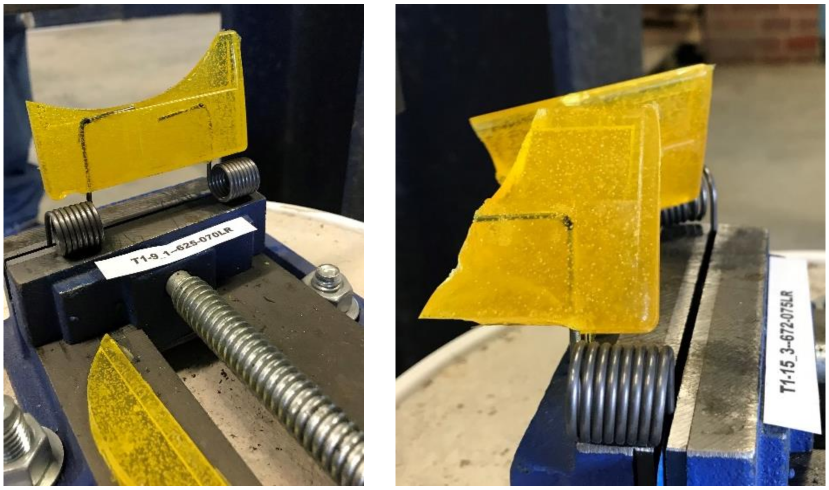


Figure 7-12 Examples of fractured markers due to impact loading

Figure 7-13 shows the different types of damages to the springs noticed due to impact loadings in Type-1 flexible markers with 180^0 spring configurations. A total of 18 Type-1 flexible markers with 180^0 springs were tested and damages to springs were noticed in 15 flexible markers. It was observed that Type-1 flexible markers with 90^0 deflection angle springs showed comparatively better performance in terms of damages to springs (see Figure 7-14). Almost half of the 18 Type-1 flexible markers with 90^0 springs had springs in good conditions.

Figure 7-15 shows number of flexible markers with different types of spring damages in Type-2 flexible markers with 180^0 deflection angle springs. About one-third of the Type-2 flexible markers with 180^0-spring configurations showed no visible damages to springs while the rest of the springs were experienced different degrees of permanent set, that is springs were not able to regain original position fully after removal of impact loads. Type-2 flexible markers with 90^0 deflection angle spring configurations showed the similar performance. That is, no visible damages to spring were observed in one-third of Type-2 flexible markers with 90^0 spring configurations (see Figure 7-16).

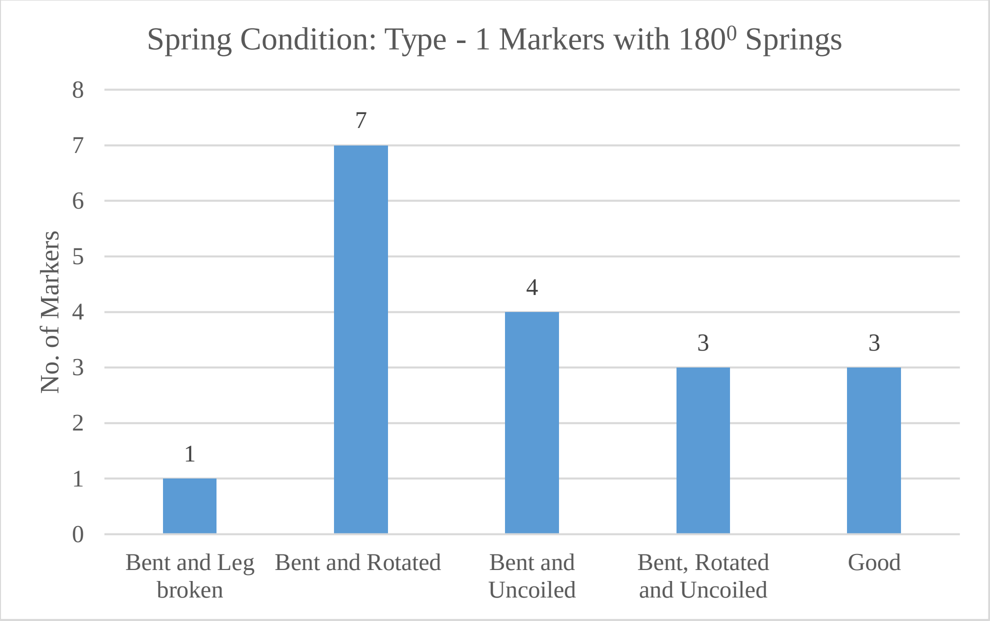


Figure 7-13 Types of spring damages (by number of springs) observed in Type-1 flexible markers (tapered marker) with 180^0 deflection springs

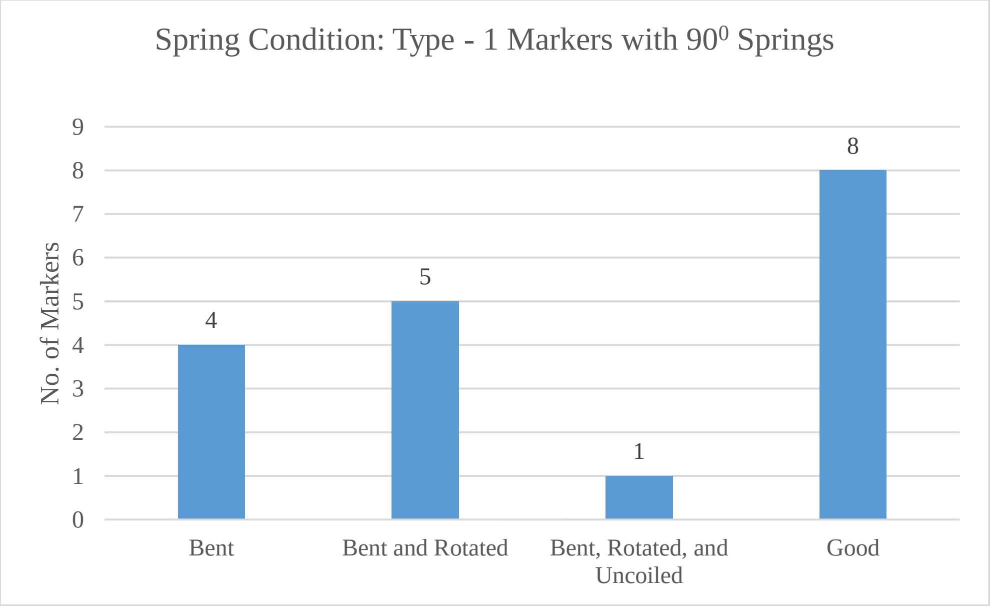


Figure 7-14 Types of spring damages (by number of springs) observed in Type-1 flexible markers (tapered marker) with 90^0 deflection springs

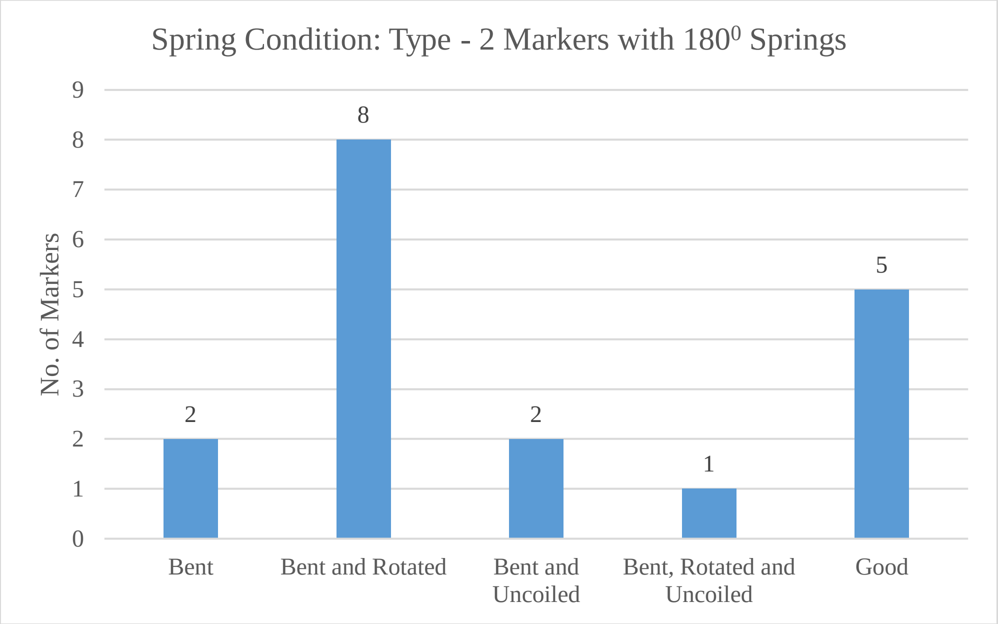


Figure 7-15 Types of spring damages (by number of springs) observed in Type-2 flexible markers (non-tapered marker)with 180^0 deflection springs

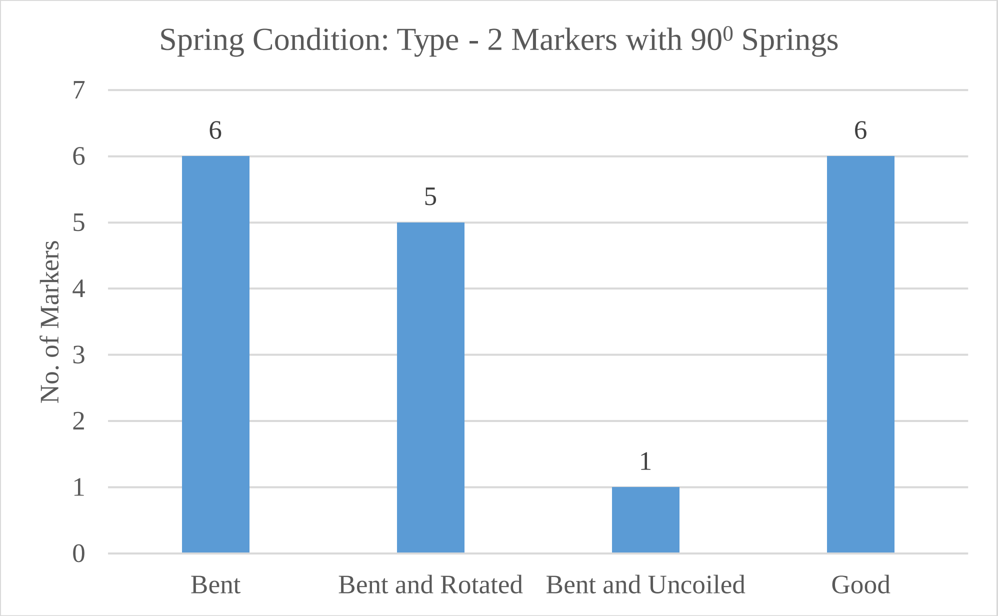


Figure 7-16 Types of spring damages (by number of springs) observed in Type-2 flexible markers (non-tapered marker) with 90^0 deflection springs

The conditions of flexible marker's body were also inspected after each impact of the pendulum and recorded if there were any fractures. Further investigation of the data revealed that Type-1 flexible markers (tapered markers) experienced more fractures compared to Type-2 flexible markers (thicker markers) (see Figure 7-17).

Most of the fractures in Type-1 markers occurred around the tapered top where reflective materials would be attached. Only one marker among 36 Type-2 markers was fractured at the top. As such, a non-tapered design is recommended since it is more resilient than that of flexible markers with a tapered top edge.

Figure 7-18 shows the number of markers after impact testing that exhibited nonfunctional, partially functional, and fully functional behavior. The functionality is defined as whether flexible markers were able to regain their original position (remain vertical with respect to horizontal surface) after the removal of impact loads. If a flexible marker was returned to its original position fully without any permanent torsion or twisting after the testing, it is regarded as fully functional. If a flexible marker was slightly inclined after returning to its original position, it is considered partially functional. Flexible markers which bent to a position that they would not be able to reflect light to road users were classified as non-functional. Type-2 markers showed better functionality than the Type-1 markers (see Figure 7-18). However, only 14% of 72 flexible markers had fractured bodies.

The observations of flexible marker after impact of pendulum also revealed that spring winding combination right-right performed well as compared with flexible markers with left-right winding spring combination. It was also found that markers with larger wire diameter springs showed relatively better performance under impact loads than flexible markers with thin wire diameters.

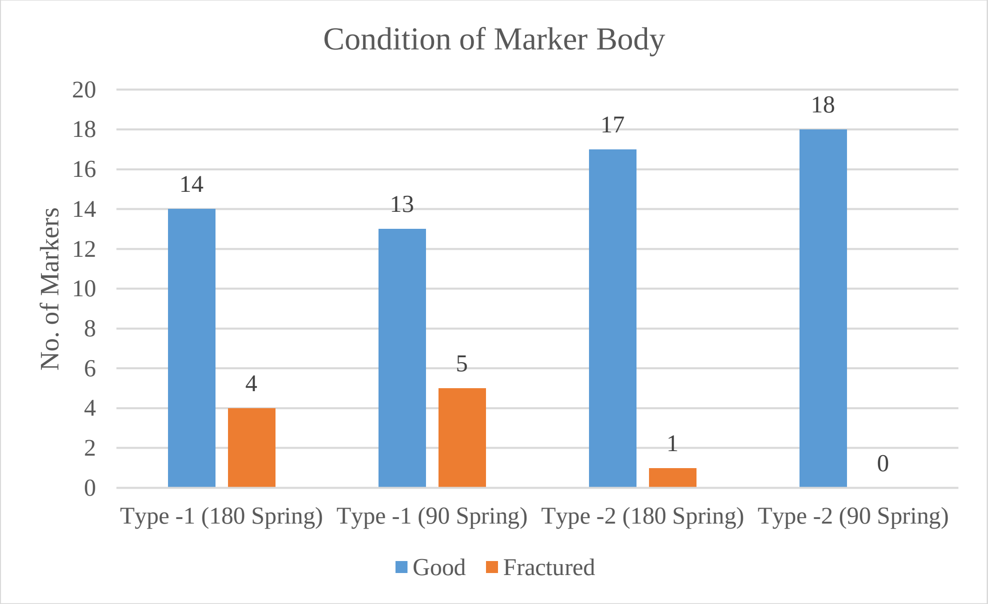


Figure 7-17 Flexible markers body condition (whether it fractured or not) in different types of markers

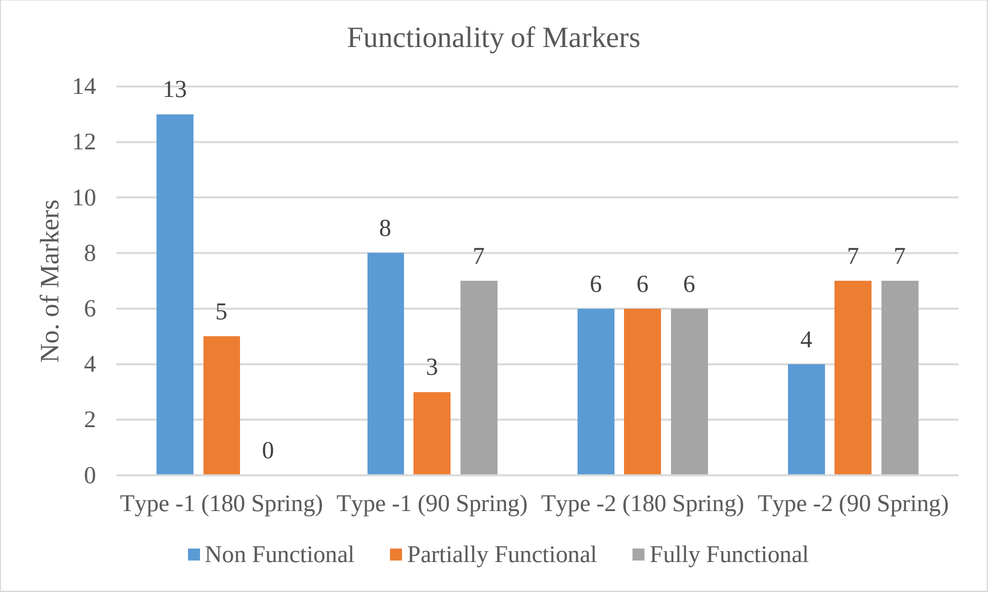


Figure 7-18 Functionality of flexible markers

7.3. Summary

A prototype of an innovative marker system using a flexible memory approach was designed and tested. The fabricated markers were tested under impact loading to observe if the initial design needs further improvement before they could be tested on test roadway. It is observed that flexible markers aligned with the initial concept and that a flexible memory marker approach is a promising technology for tackling the problem of loss of RPMs due to snow plow operations. When failure occurred, the dominant failure mechanism was at the spring. Thus, further investigation is needed to identify durable, resilient spring configurations. It is also observed that Type-2 flexible markers (non-tapered markers) showed promising performance over Type-1 flexible markers (tapered markers). Therefore, it is recommended that the future investigations use the non-tapered design. Once the spring system is redesigned, follow-up impact tests and testing at the PRC test site should be conducted.

Chapter 8. Summary and Conclusions

Retroreflective pavement markers (RPMs) are used extensively for highway delineation, especially on highway centerlines, to warn road users to avoid head-on collisions at night and during poor weather conditions. RPMs are installed on the surface of the pavement using adhesive material and are at risk of being inadvertently removed by snowplows during winter weather operations, particularly in northern Texas. Most of the northern districts of the Texas Department of Transportation (TxDOT) reported damage to more than 70% of the RPMs each year owing to winter weather operations, with some districts reporting 90% of all markers loss due to snowplow operations. This loss of RPMs increases the maintenance costs of these districts and also creates unsafe driving conditions during inclement weather. Pavement sections in many regions across the state often use centerline rumble strips to provide audible and vibration alerts to drivers that vehicle have drifted from their lanes. This project employed a novel approach in which RPMs are embedded in the trough region of existing rumble strips to mitigate the loss of RPMs due to snowplowing. This research project also assessed whether RPMs embedded within rumble strips (herein called rumble inserts) can be used for nighttime centerline delineation.

The project explored two innovative approaches to arrive at a cost-effective and snowplow-resistant configuration for roadways containing rumble insert markers: (1) use of existing commercially available RPMs inset within the trough regions of existing rumble strips and (2) use of innovative, newly developed flexible memory markers as rumble insert markers.

For Approach 1, the physical condition and nighttime visibility of the RPMs were evaluated using laboratory tests, test section pilot tests, and field studies. In the field study, select RPMs were installed in existing rumble strips in two in-service TxDOT highway sections; the performance of the installed rumble inserts after multiple cycles of real-event snowplowing operations was evaluated. In addition, the project investigated the performance of RPMs installed using Approach 1 in wet weather conditions.

With respect to Approach 2, this project designed a new marker system consisting of flexible memory markers using resilient materials and spring support systems. To test the flexible memory markers, the research team designed and built an impact testing setup that mimics the snowplow blade's impact on the markers.

The main findings and recommendations from this project are as follows:

- Embedding commercial RPMs into rumble strips is an effective method to reduce losses of and damages to RPMs during snowplow operations. The majority of the markers remained in service after snowplow operations; in some cases, 100% of the markers remained present.

- Both epoxy and bitumen are suitable adhesives for embedding commercially available RPMs into rumble strips. However, bitumen adhesive is recommended due to the ease of installation and setup time.

- Quality control of the depth of the rumble strip groove will be important as the depth of the rumble groove has a significant effect on the visibility and snowplow resistance of the RPMs. The standard 0.5-inch depth is recommended for the centerline rumble inserts. Otherwise, a classification system is needed to determine the cut-off depth for when regular profile markers can be used in the rumble strip grooves.

- Low-profile markers showed a better ability to withstand snowplows as compared to regular-profile markers. However, the regular-profile RPMs showed better nighttime visibility than low-profile markers.

- Based on laboratory analysis, the retroreflectivity value of RPMs bottom mounted in the grooves of a rumble strip is reduced by approximately 43-67% compared to RPMs conventionally mounted on the surface of the pavement. However, from the quantitative and qualitative visibility field assessment study it was proven that there was still significant retroreflectivity for nighttime centerline delineation in field conditions. Also, the majority of RPMs surface mounted are not present on the surface after snowplow operations, whereas the majority of the RPMs installed in the grooves do remain after snowplow operations. In other words, even if the surface mounted RPMs have a higher retroreflectivity value they are not available for nighttime delineation since they are removed during snow plow operations, whereas most of RPMs in rumble strips were available to help delineate the centerline.

- Nighttime visibility analysis showed that retroreflectivity of RPMs installed in the grooves is sufficient to provide nighttime delineation, with over 900 feet of the RPMs being visible by the naked eye of a driver.

- The retroreflectivity of rumble inserts may be reduced when the inserts are submerged under rainwater. However, the RPMs in rumble strips can delineate the centerline in wet conditions.

- The innovative flexible memory markers could be a promising technology for highway centerline delineation for regions with high levels of winter weather operations. The initial design showed elastic behavior when subjected to impact loads.

This project demonstrates that existing centerline rumble strips can be converted into multifunctional rumble strips that provide not an only auditory and vibratory warning to drivers, but also increase roadway safety by enhancing the ability of drivers to detect lanes during nighttime conditions prior to and after snowplow operations. This research provides insight into the opportunities and challenges of embedding RPMs in existing rumble strips as an approach to provide centerline delineation in regions with winter weather operations. Embedding RPMs in existing highway rumble strips is an engineering design improvement that reduces the dislodgment of RPMs due to winter weather operations significantly, which in turn decreases the costs of replacing RPMs, improves nighttime lane delineation detection by drivers on roadways, and enhances roadway safety conditions.

The project recommends the implementation of this approach on multiple highways in regions of Texas that experience snowfall events to evaluate life cycle performance of the approach and validate the RPM detection distance. A standard drawing (see Appendix 5) and specification (see Appendix 6) has been completed as part of this project for installation of commercially available RPMs in rumble strip grooves. The innovative flexible memory markers designed and developed in this project are a new product that is promising for roadway delineation, especially in regions with high levels of winter weather operations and maintenance. Based on this study's findings, the research team recommends that the innovative flexible memory marker is further investigated to explore its features as well as the possibility of creating commercially viable prototypes.

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Appendix 1. 30-Year Minimum Average Temperature

Figures A1-1 through A1-4 show the 30-year (1981–2010) average minimum monthly temperature across the United States for winter months November to February.

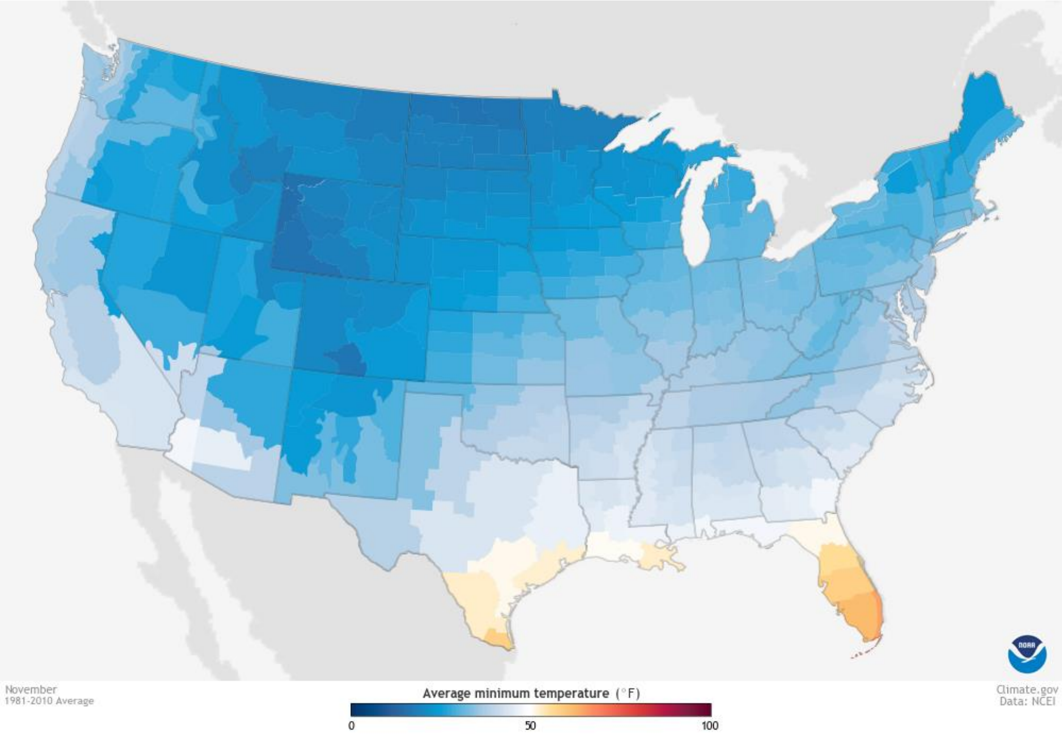


Figure A1-1 November average minimum temperature

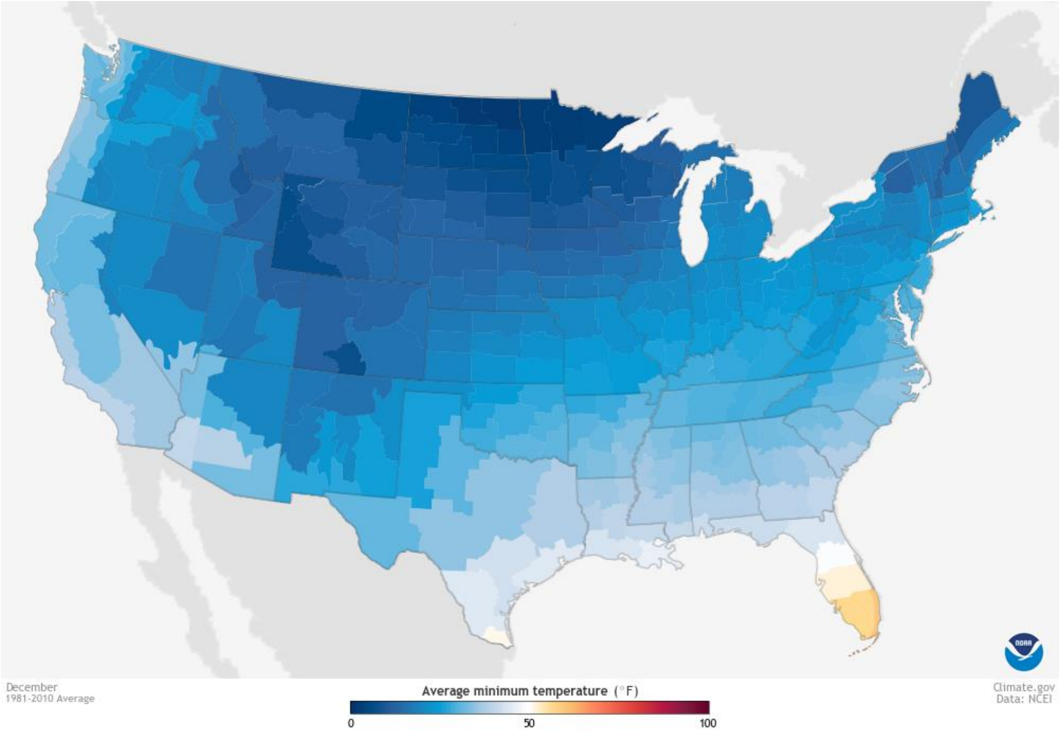


Figure A1-2 December average minimum temperature

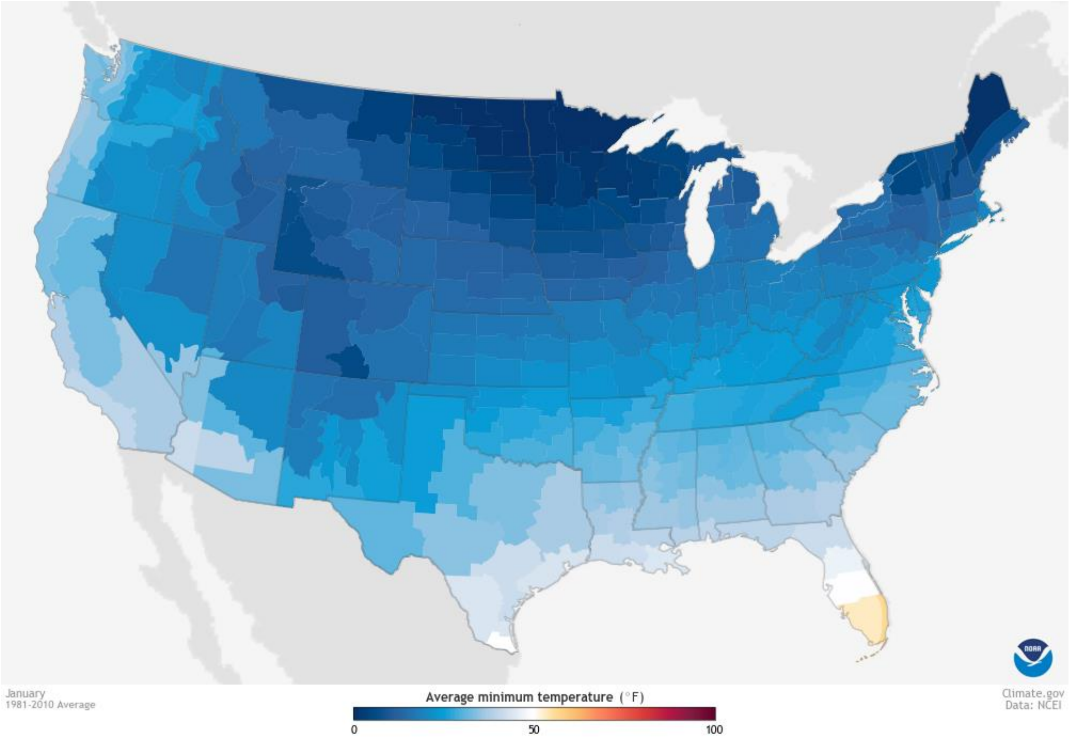


Figure A1-3 January average minimum temperature

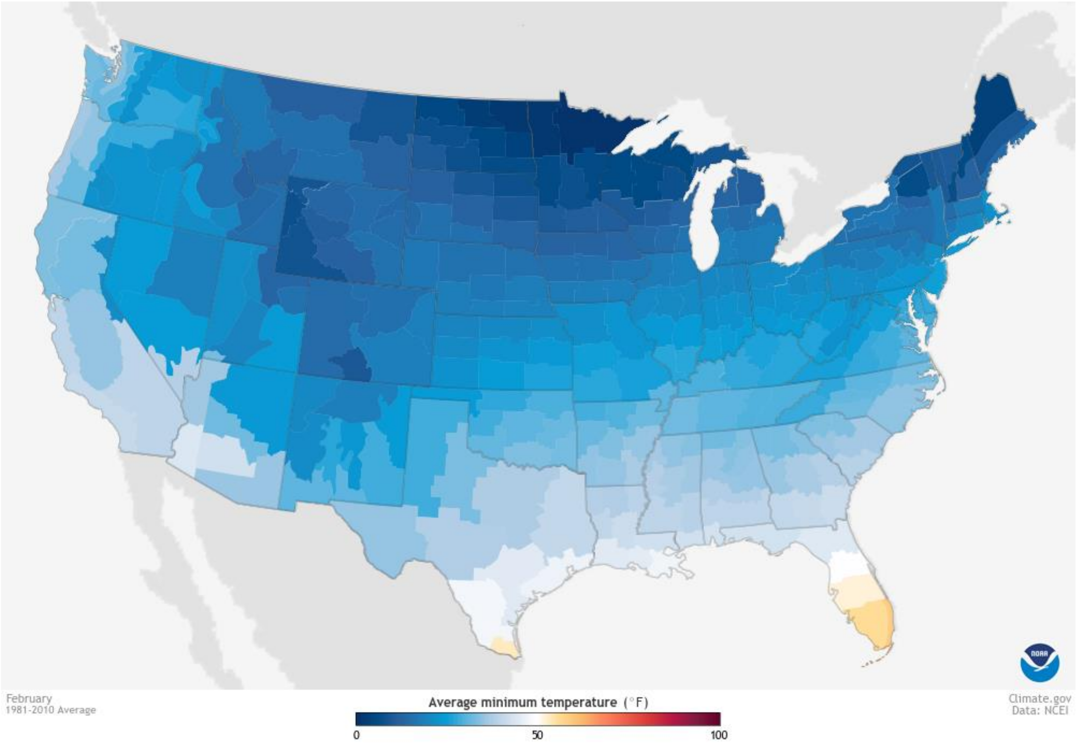


Figure A1-4 February average minimum temperature

Appendix 2. Markers in Location 1 (US 380, Throckmorton County)

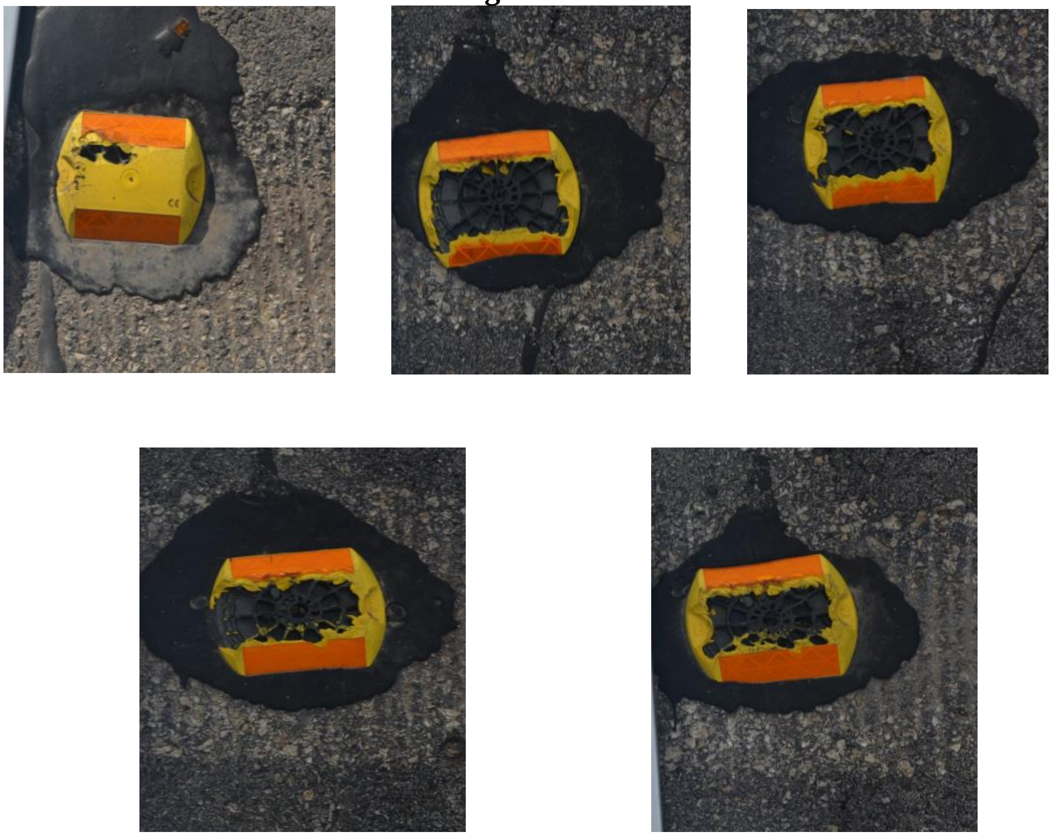
Markers in Good Shape

Low-profile Marker -2 (Series 190)

Low-profile Marker -1 (C40)

Regular-profile Marker (Series 290)

Damaged Markers



Appendix 3. Markers in Location 2 (SL 335, Randall County)

Markers in Good Shape

Low-profile Marker -1 (C40)

Low-profile Marker -2 (Series 190)

Regular-profile Marker (Series 290)

Damaged Markers

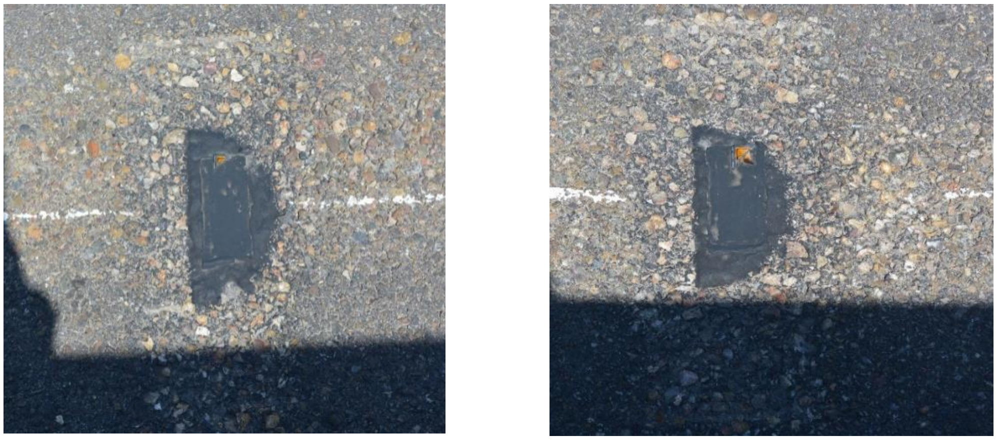
Low-profile Marker -1 (C40)

Low-profile Marker -2 (Series 190)

Regular-profile Marker (Series 290)

Missing Markers

Low-profile Marker -1 (C40)



Low-profile Marker -2 (Series 190)

Regular-profile Marker (Series 290)

Appendix 4. Value of Research (VoR)

Introduction

The scope of the TxDOT project 0-6995 includes that the research team at the University of Texas at Austin has prepared an estimated value of research corresponding to the research outcome of the project. For the establishment of VoR, eleven functional categories of both qualitative and economic areas have been identified. The functional areas are presented in Table A4-1.

Table A4-1. Functional Areas of Project 0-6995

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

The project identified four functional areas that contributed to the qualitative benefits:

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

The qualitative benefits related to the performance of this project are summarized as follows:

Level of Knowledge:

Project 0-6995 results in a significant increase in the "Level of Knowledge" which advances the understanding and insights of TxDOT infrastructure. The key outcomes derived from the performance of this research will comprise innovative, snowplowable, and cost-effective configurations of commercially available RPMs as well as inventive flexible memory markers to be installed in existing rumble strips. These configurations can be translated into a knowledge base regarding rumble inserts as alternative highway delineation practices. The knowledge on 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 decision-making in the areas pertaining to highway delineation practices and also reduce the uncertainty involved in maintenance and operation resource management and allocations. The level of knowledge in the area of rumble inserts 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 insights on better highway delineation practices which will be translated into better infrastructure and better maintenance strategies. These factors will enhance the perception of the traveling public of uniform and safe driving conditions, which in turn increase TxDOT customer satisfaction ratings.

Engineering Design Improvement:

The product that stems from this research is snowplowable and cost-effective configuration of highway delineation. The configuration incorporates the design and installations of RPM and flexible markers in rumble strips and their performance, which enhances the engineering know-how in the area of rumble inserts as an alternative highway delineation practice.

Safety:

The research outcomes from this project will limit the loss of RPMs due to winter weather operations and heavy traffic loads, reduce the frequency of maintenance and replacement, and enhance the service life of RPMs. These results will enhance the delineation of the centerline by RPM at night and will reduce head-on collisions at night. The safety benefits of the project will increase with the volume of traffic (1). The project outcomes will improve the visibility in wet weather at night that would reduce run-off-road crashes and head-on crashes on gentle curves (1). The project's RPM configurations may improve daytime visibility under wet weather conditions (1) which might result in a reduction in daytime wet weather accidents.

In summary, the project will contribute to enhancing the safety of the traveling public.

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 RPM in rumble strips would withstand winter weather operations, 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 the reliable performance of overall highway performance. The reliable system will increase the economic efficiency of highway management and operations.

Increased Service Life – The innovative snowplowable RPM configurations will minimize the loss of RPM due to winter weather operations and will increase the retention of RPM under regular traffic. Therefore, the RPMs will provide longer service than the RPMs with current practice. This increase in service will reduce the cost related to maintenance and replacement results in better economic returns.

Improve productivity and Work Efficiency – As mentioned previously the project outcomes will results in the long service life of RPMs and reduce the frequency of replacement and maintenance of RPM. These benefits will improve better resource allocations and results in better performance from maintenance teams.

Traffic and Congestion Reduction – The project will reduce the frequency and amount of RPM maintenance and replacement which will reduce the traffic slowdown due to work zone. 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 reduction in RPM loss and increased service life of RPM in rumble strips.

Infrastructure Conditions – the RPM 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 – As mentioned earlier, one of the major benefits from the performance of project is reduction in nighttime head-on crashes and nighttime wet weather crashes. Reduction in number of crashes will results in greater savings in property damages and fatality, which renders decrease in cost due to accidents.

Quantitative Analysis of Economic Benefits

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

The quantitative analysis of Project 0-6995's value as related to the functional area of reduced maintenance and replacement costs and the increased service life is shown in Figure A4-1. However, other functional areas are also simplicity involved with these two functional areas. The estimated total savings of conducting this project is approximately **$6.5 million,** which equates to a net present value of approximately **$4.7 million**. The payback period is **0.24 years** and the cost-benefit ratio is **14.**

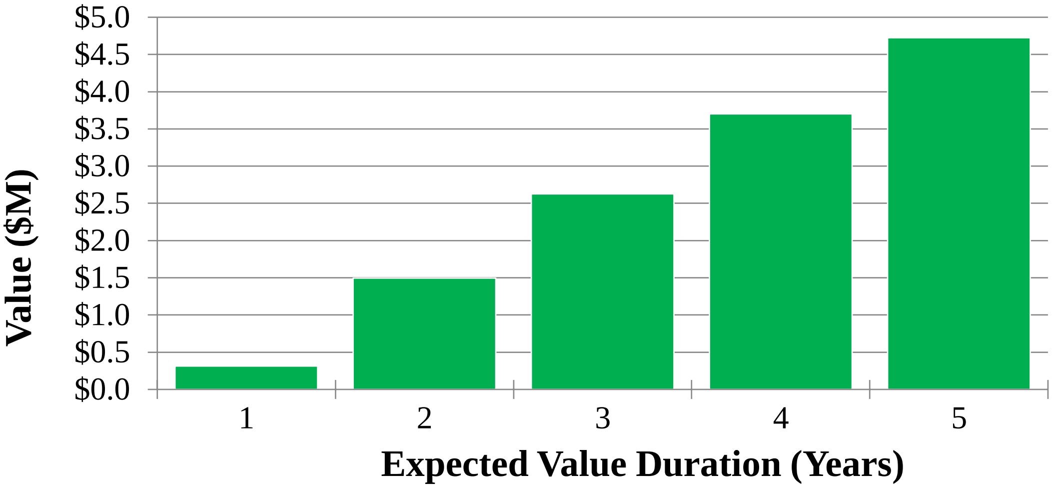
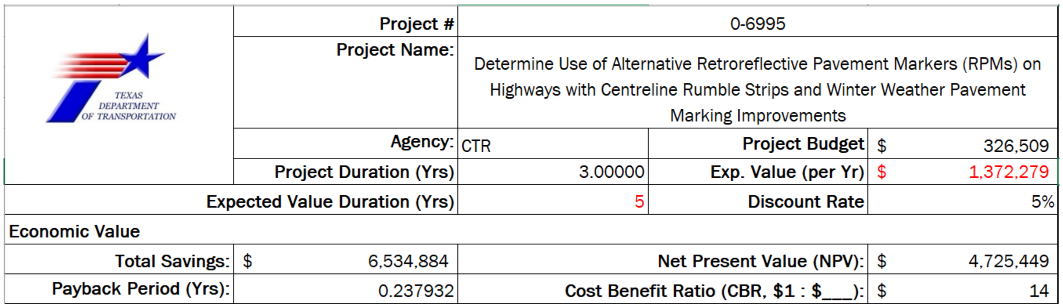


Figure A4-1 Preliminary Estimates of Net Present Value of the Project 0-6995

Explanation of VoR

Figure A4-2 represents the input and output of the project's value analysis that aid in plotting Figure A4-1. 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), that the research team had full freedom to vary. Therefore, the inputs for these two terms governed the outputs of the economic analysis.



TEXAS DEPARTMENT OF TRANSPORTATION	Project #	0-6995		
	Project Name:	Determine Use of Alternative Retroreflective Pavement Markers (RPMs) on Highways with Centreline Rumble Strips and Winter Weather Pavement Marking Improvements		
	Agency:	CTR	Project Budget	$ 326,509
	Project Duration (Yrs)	3.00000	Exp. Value (per Yr)	$ 1,372,279
Expected Value Duration (Yrs)		5	Discount Rate	5%
Economic Value				
Total Savings:	$ 6,534,884		Net Present Value (NPV):	$ 4,725,449
Payback Period (Yrs):	0.237932		Cost Benefit Ratio (CBR, $1 : $___):	$ 14

Figure A4-2 Input and Output of Value of the Project 0-6995

Each input term is presented in detail as follows :

Project Budget: $326,509 is the total budget of the project. This value is determined from the project's contract.

Project Duration (Yrs): The project is initiated on September 1, 2018, and The project will be terminated on August 31, 2021. Therefore, the project duration is 3.0 years was inputted as the project duration.

Exp. Value (per Year): A value of $2,145,500 was used as the expected value per year. This value is based on data collected from the survey conducted (presented in Chapter 3), discussion with TxDOT personnel, and information extracted from the available literature. For the preliminary estimates of the value of research for Project 0-6995, the research team used the following information and assumed following scenarios.

The project mainly deals with the two-lane two-way highways where rumble strips can be used for the installation of RPMs. 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 literature 14 districts – Abilene, Atlanta, Amarillo, Brownwood, Bryan, Childress, Dallas, El Paso, Fort Worth, Lubbock, Paris, San Angelo, Waco, and Wichita Falls (2). Based on the identified districts, TxDOT Roadway Inventory data (3) have been used to estimate the two-lane two-way highway miles. The estimated miles of two-lane two-way highways in the above-mentioned districts was 29703 miles. The researchers assumed that 40% of these highways may have rumble strips, which entailed 11,881 miles of road segments. Following the survey results, these districts lose about 50–90% of the RPM every year due to winter weather operations and regular traffic operations. For the estimation of VoR, it is assumed that on average 60% of RPM lost per year. It is found from the survey that the materials and installation cost of replacing each RPM is $2.50 to $3.97. A value of $3.50 has been assumed for VoR estimation. Also, the average service life of RPM with typical winter conditions in the above-mentioned districts ranges from 5 months to 1 year. However, if RPMs are not impacted by winter weather operations, the typical service life of RPMs is 3 to 5 years (4).

It is assumed the typical spacing between RPM is 80 feet that translate into 66 RPM per mile. Therefore, in conventional practices, the total number of RPM for 11,881 miles is 784,160. If 60% of these RPM needs maintenance and replacement that would require 470,496 RPM per year. The total cost of RPM replacement for conventional practices is $1,646,734.32.

Based on the analysis done in this project it is found the in case of low-profile markers on average 10% of the marker needs maintenance and replacements. Therefore, to replace the 10% marker on 11,881 miles of roadway we need 78,416 RPMs per year. The cost of replacement and maintenance of RPMs under project configuration would require $274,455.72. So, the estimated cost differential is $1,372,278.60.

Expected Value Duration (Yrs): An expected duration of 5 years was assumed. As mentioned previously the typical service life of raised pavement markers ranges from 3 to 5 years (4).

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

Output values
The following terms were determined automatically in the spreadsheet (Figure A4-2): 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 (5).

References for VoR

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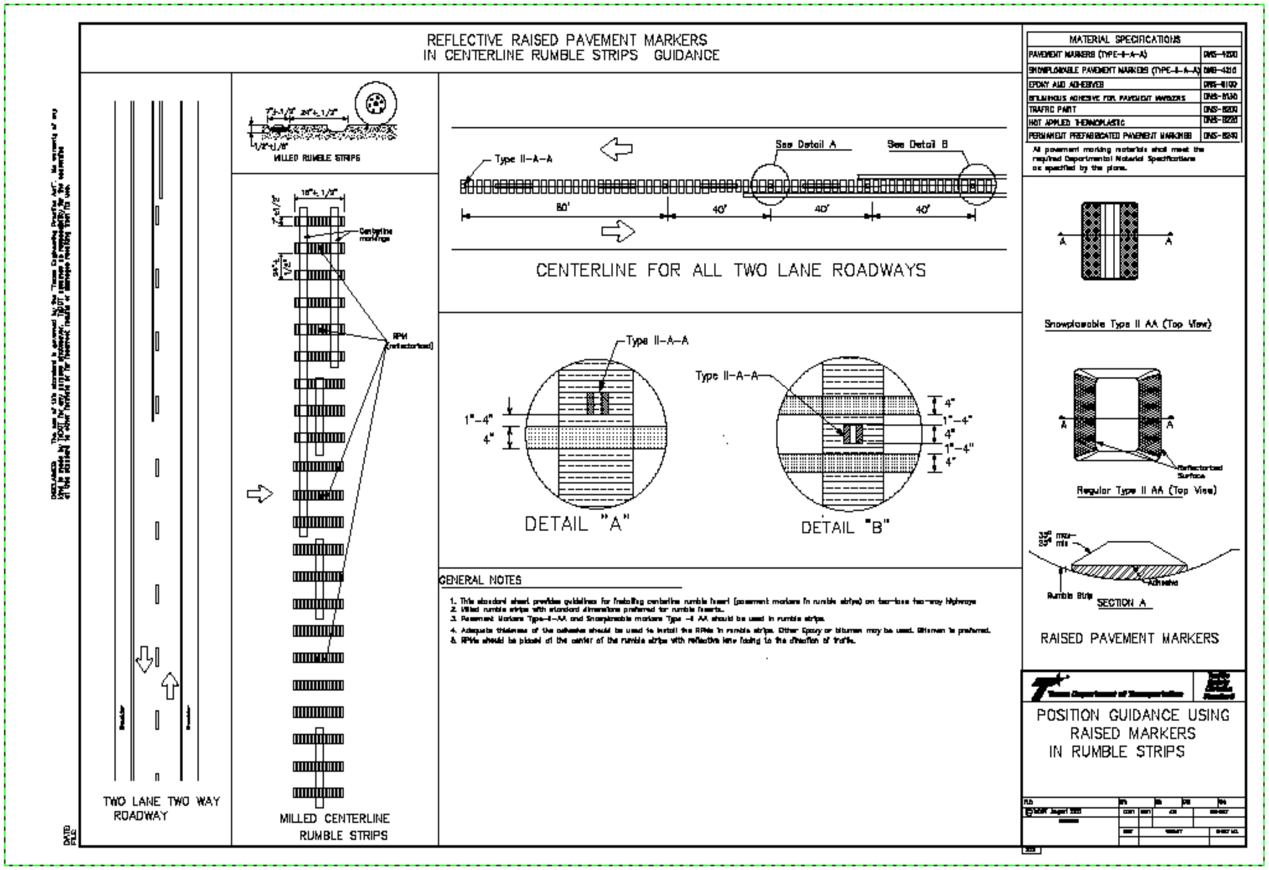
Appendix 5. Installation Plan for RPMs in Rumble Strips



MATERIAL SPECIFICATIONS	
PAVEMENT MARKERS (TYPE-II-A-A)	DMS-4200
SNOWPLOWABLE PAVEMENT MARKERS (TYPE-II-A-A)	DMS-4210
EPOXY AND ADHESIVES	DMS-6100
BITUMINOUS ADHESIVE FOR PAVEMENT MARKERS	DMS-6130
TRAFFIC PAINT	DMS-8200
HOT APPLIED THERMOPLASTIC	DMS-8220
PERMANENT PREFABRICATED PAVEMENT MARKINGS	DMS-8240

All pavement marking materials shall meet the required Departmental Material Specifications as specified by the plans.

GENERAL NOTES

1. This standard sheet provides guidelines for installing centerline rumble insert (pavement markers in rumble strips) on two-lane two-way highways
2. Milled rumble strips with standard dimensions preferred for rumble inserts.
3. Pavement Markers Type-II-AA and Snowplowable markers Type -II AA should be used in rumble strips.
4. Adequate thickness of the adhesive should be used to install the RPMs in rumble strips. Either Epoxy or bitumen may be used. Bitumen is preferred.
5. RPMs should be placed at the center of the rumble strips with reflective lens facing to the direction of traffic.

Appendix 6. Installation Specification for RPMs in Rumble Strips

The following specification is an update to TxDOT Item 672 for installation of RPMs in centerline rumble strips:

Item 672 (Update)
Raised Pavement Markers

1. DESCRIPTION

Furnish and install raised pavement markers (RPMs) and RPMs inset into centerline rumble strip

2. MATERIALS

1.1. **Markers**. Furnish RPMs in accordance with the following Department Material Specifications:

- **Reflectorized Pavement Markers**. DMS-4200, "Pavement Markers (Reflectorized)," types I-A, and, II-A-A.
- **Plowable Reflectorized Pavement Markers**. DMS-4210, "Snowplowable Pavement Markers," types I-A, and II-A-A.

The following are descriptions for each type of RPM:

- **Type I-A**. The approach face must retro-reflect amber light. The body, other than the retro-reflective face, must be yellow.
- **Type II-A-A**. The 2 retro-reflective faces (approach and trailing) must retro-reflect amber light. The body, other than the retro-reflective faces, must be yellow.

1.2. **Adhesives**. Furnish adhesives that conform to the following requirements:

- DMS-6100, "Epoxies and Adhesives," Type II—Traffic Marker Adhesives.
- DMS-6130, "Bituminous Adhesive for Pavement Markers."
- The Contractor may propose alternate adhesive materials for consideration and approval.

Sampling. The Engineer will sample in accordance with Tex-729-I.

3. CONSTRUCTION

Furnish Centerline line Rumble Strips in accordance with Item 533, "Milled Rumble Strips" with dimensions shown on the plan.

Remove existing RPMs in accordance with Item 677, “Eliminating Existing Pavement Markings and Markers,” except for measurement and payment.

Remove any remaining adhesives from and around the Rumble strips and Furnish RPMs for each class from the same manufacturer.

Prepare all surfaces in accordance with Item 678, “Pavement Surface Preparation for Markings,” when shown on the plans.

Ensure the bond surfaces are free of dirt, curing compound, grease, oil, moisture, loose or unsound pavement markings, and any other material that would adversely affect the adhesive bond.

Establish pavement marking guides to mark the lateral location of RPMs as shown on the plans and as directed. Do not make permanent marks on the roadway for the guides.

Place RPMs in the center of the Rumble Strip. Place RPMs in proper alignment with the guides. Acceptable placement deviations are shown on the plans.

Remove RPMs placed out of alignment or sequence, as shown on the plans or stated in this specification, at Contractor’s expense, in accordance with Item 677, “Eliminating Existing Pavement Markings and Markers” (except for measurement and payment).

Use the following adhesive materials for placement of reflectorized pavement markers, and traffic buttons unless otherwise shown on the plans:

Standard or flexible bituminous adhesive for applications on bituminous pavements, and

Epoxy adhesive or flexible bituminous adhesive for applications on hydraulic cement concrete pavements.

Use epoxy adhesive for plowable reflectorized pavement markers. Apply enough adhesives to:

ensure that 100% of the bonding area of RPMs is in contact with the adhesive, and

ensure that RPMs, except for plowable markers, are seated on a continuous layer of adhesive and not in contact with the pavement surface.

Apply adhesives in accordance with manufacturer’s recommendations unless otherwise required by this Article. Apply bituminous adhesive only when pavement temperature and RPM temperature are 40°F or higher. Do not heat bituminous adhesive above 400°F. Machine agitate bituminous adhesive continuously before application to ensure even heat distribution.

Machine-mix epoxy adhesive. Apply epoxy adhesive only when pavement temperature is 50°F or higher.

Furnish RPMs free of rust, scale, dirt, oil, grease, moisture, and contaminants that might adversely affect the adhesive bond.

Place RPMs immediately after the adhesive is applied and ensure proper bonding. Do not use adhesives or any other material that impairs the functional retro-reflectivity of the RPMs.

Provide a 30-day performance period that begins the day following written acceptance for each separate location. The date of written acceptance will be the last calendar day of each month for the RPMs installed that month for the completed separate project locations. This written acceptance does not constitute final acceptance.

Replace all missing, broken or non-reflective RPMs. Visual evaluations will be used for these determinations. Upon request, the Engineer will allow a Contractor representative to accompany the Engineer on these evaluations.

The Engineer may exclude RPMs from the replacement provisions of the performance, provided the Engineer determines the failure is a result of causes other than defective material or inadequate installation procedures. Examples of outside causes are extreme wear at intersections, damage by snow or ice removal, and pavement failure.

Replace all missing or non-reflective RPMs identified during the performance period within 30 days after notification. The end of the performance period does not relieve the Contractor from the performance deficiencies requiring corrective action identified during the performance period.

4. MEASUREMENT

This Item will be measured by each RPM.

This is a plans quantity measurement Item. The quantity to be paid is the quantity shown in the proposal, unless modified by Article 9.2., “Plans Quantity Measurement.” Additional measurements or calculations will be made if adjustments are required.

5. PAYMENT

The work performed and materials furnished in accordance with this Item and measured as provided under “Measurement” will be paid for at the unit price bid for “Reflectorized Pavement Marker,” “Traffic Button,” or “Plowable Reflectorized Pavement Marker” of the types specified. This price is full compensation for removing existing markers; furnishing and installing RPMs; and materials, equipment, labor, tools, and incidentals.

No additional payment will be made for replacement of RPMs failing to meet the performance requirements.

Center for Transportation Research
The University of Texas at Austin
3925 W. Braker Lane, 4th Floor
Austin TX 78759
512.232.3100
https://ctr.utexas.edu