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Synthesis of Best Application and Verification Practices for Long-Life Pavement Markings: Final Report

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16. Abstract
Proper application of pavement markings plays an important role in enhancing the safety of roadway users. The purpose of this study is to carefully synthesize information on the usage of various types of pavement marking materials (including but not limited to the types of marking materials and quality control approaches, types of specifications, and application rate verification) to identify marking equipment ability and markings payment bases and develop recommendations with regard to different U.S. states and several foreign countries, and to compare them with the Texas Department of Transportation's (TxDOT) pavement marking practices.

To achieve these objectives, a comprehensive online survey was designed in which a wide range of practical information was collected with respect to marking material types and quality control approaches, types of specifications and application rate verification, and equipment and payment bases from field engineers in other states and countries. In addition, manuals and research papers or reports related to pavement marking materials for other state-level departments of transportation (DOTs) and foreign countries were thoroughly reviewed and synthesized. The TxDOT (2004) Pavement Marking Handbook does not incorporate more recently available marking technologies or quality control procedures for the new marking materials. The researchers therefore recommend adoption of best practices from other states and countries to improve the existing handbook. The implementation of the recommendations would help to enhance the efficiency of TxDOT pavement marking practices, including those for marking durability and retro-reflectivity.

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Synthesis of Best Application and Verification Practices for Long-Life Pavement Markings: Final Report

Research Report (0-7135-R1)

Submitted: August 31, 2022

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Disclaimer

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Federal Highway Administration (FHWA) or the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation.

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Chapter 1: Introduction

Proper application of pavement markings plays an important role in enhancing the safety of roadway users. The importance of this study is to carefully synthesize various information on the usage of various types of pavement marking materials (including but not limited to the types of marking materials and quality control approaches, types of specifications and application rate verification), to identify equipment ability and markings payment bases and develop recommendations with regard to different U.S. states and several foreign countries, and to compare them with pavement marking practices by the Texas Department of Transportation (TxDOT). To achieve these objectives, a comprehensive online survey was designed in which a wide range of practical information was collected with respect to marking material types and quality control approaches, types of specifications and application rate verification, and equipment and payment bases from field engineers of the various states and other countries.

In addition to conducting an online survey, manuals and research papers that are related to pavement marking materials for other state-level departments of transportation (DOTs) and foreign countries have been thoroughly reviewed and synthesized.

The TxDOT (2004) Pavement Marking Handbook does not incorporate the recently available marking technologies and quality control procedures for the new marking materials. It is therefore recommended to adopt the best practices in other states and countries to improve the existing manual. The implementation of the recommendations would help to enhance the efficiency of TxDOT pavement marking practices, including those for marking durability and retro-reflectivity.

Chapter 2: Information Synthesis from Literature and Survey

2.1 Overview

This chapter synthesizes information necessary for the identification of best-case examples of quality control of liquid and thermoplastic pavement marking material applications. To achieve this objective, the research team:

- Reviewed practices across the U.S. and other countries collected from various sources, such as government manuals, reports, guidebooks, research papers, and other publications.
- Conducted a survey via SurveyMonkey.com in the U.S. and other countries and analyzed and synthesized the collected information.

The NCHRP synthesis report and reviewed guidelines did not make any recommendations on current limitations or problems, nor did they attempt to differentiate or rank order pavement marking materials or practices in an efficient and applicable way. The remaining pavement service life should also have drawn more attention since it affects the long-term performance of pavement markings.

Additionally, it is necessary to review effective and practical applications for long-life pavement markings under various conditions due to the number of variables influencing the performance of long-term pavement markings. Most transportation agencies cannot guarantee whether the applications of pavement markings are adequate and rely on common regional practice in the decision-making process.

The amount and selection of marking materials can directly determine pavement marking's longevity and life-cycle costs, and it is vital for transportation agencies to control these key parameters in both liquid and thermoplastic marking practices.

2.2 Information Synthesis and Literature Review

2.2.1 Significance of Pavement Marking

Markings on highways and private roads open to public travel have essential functions in providing guidance and information for the road user, which are specified in the Manual on Uniform Traffic Control Devices for Streets and Highways (MUTCD, 2009, with Revisions 1 and 2 in 2012) and in the TMUTCD (2011, with Revision 2 in 2014). Major marking types include (1) pavement and curb markings, (2) delineators, (3) colored pavements, (4) channelizing devices, and (5) islands. In some cases, markings are used to supplement other traffic control devices such as signs, signals, and other markings. In other occurrences, markings are used alone to effectively convey regulations, guidance, or warnings in locations where it is impossible to convey this essential information to road users using other devices (MUTCD, 2012).

Pavement markings have the potential to reduce traffic crashes in both daylight and darkness. With the advancement in pavement marking material technologies, such as durable markings, brighter markings, and markings that continue to retro-reflect even during rainy conditions, the visibility and durability of pavement markings have been enhanced and proven to be effective in transportation safety (Carlson et al., 2009). Smadi et al. (2010) verified that pavement markings have positive impacts on transportation safety. Especially with the improvement of retro-reflectivity, pavement markings can significantly reduce nighttime crashes, and it has also been shown that retro-reflectivity testing has a confidence level over 90% for all line types (Smadi et al., 2010).

Early pavement marking studies have demonstrated the significance of pavement markings on crash frequency. A Federal Highway Administration (FHWA, 1981) report concluded that improving pavement markings would decrease fatal and injury crashes at night. The report showed a 16% reduction in crashes for added edge lines and 12% for center lines and edge lines.

Using credible studies, Miller (1991) found that an average crash reduction of 21% could be attributed to pavement markings. Similarly, Bali et al. (1987) examined delineation treatments on rural two-lane highways in a 10-state study including more than 500 sites and found that adding edge lines and centerlines reduced crashes by 36%. The B/C ratio for adding edge lines to rural two-lane highways is a function of average daily traffic (ADT), as shown in **Figure 1**.

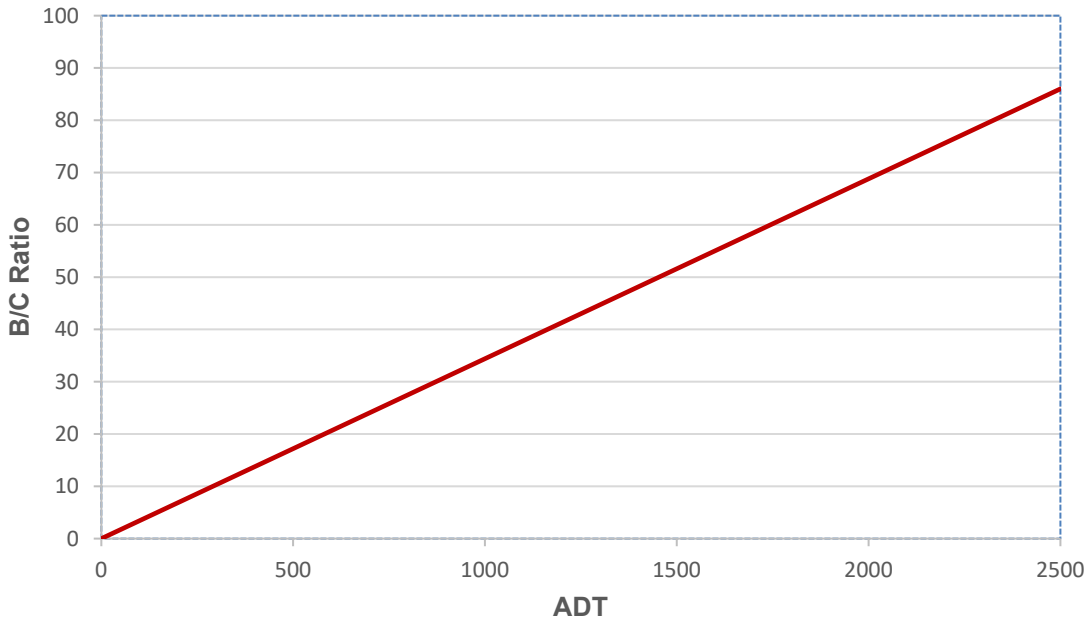


Figure 1 The B/C Ratio for Adding Edge Lines on Rural Two-Lane Highways

Recently, Chang et al. (2019) observed a statistically significant difference in driver lane deviation at night with respect to changes in the marking width, i.e., 6-inch marking width versus 4-inch. Smadi and Veneziano (2018) developed a prioritization approach and spreadsheet tool to assist local agencies using available budgets in developing valuable pavement markings. This study prioritized pavement markings

between different sites and estimated the cost of each alternative in the decision-making process. Pike and Bommanayakanahalli (2018) also presented a calculator tool for the estimation of markings' life cycle costs to compare the overall costs between durable markings and nondurable markings. The factors that influence the life cycle cost, including crash costs, traffic delay, and administrative costs, are also compared with this calculator tool. Park et al. (2019) evaluated the safety effectiveness of wet-weather pavement markings based on wet-night crash data; the evaluation results indicate positive safety effects of wet-weather pavement markings.

2.2.2 Limitations and Problems of Pavement Markings

The MUTCD (2012) summarized the limitations of pavement markings: (1) visibility of the markings could be limited by snow, debris, and water on or adjacent to the markings; and (2) marking durability is affected by material characteristics, traffic volumes, weather, and location. However, under most highway conditions, markings provide essential information, allowing minimal diversion of attention from the roadway.

The NCHRP Synthesis 306 report, while highlighting practices of transportation agencies for providing long-term markings for their highway systems in 2002, identified pavement markings problems as follows (Migletz and Graham, 2002):

- The top four problems for transportation agencies that influence the performance of long-life pavement markings are (1) finding the funding for pavement marking programs, (2) nighttime visibility in rain and fog, (3) quality control when markings are installed, and (4) a shortage of quality labor, for which transportation agencies can only directly focus on the quality of pavement markings installation.
- The most common factors determining pavement marking materials include (1) type of line, (2) pavement surface, (3) traffic volume, and (4)

type of street and highway. The criteria for the materials selection need to be addressed for better performance of pavement markings.

- The consideration of specifications and practices is needed since many transportation agencies cannot guarantee the application of the markings is adequate, although they are satisfied with the specifications.
- As a quality control process, surface preparation becomes more complicated when using durable materials and on Portland Cement Concrete (PCC) pavements (or rigid pavements).
- Durable markings help increase the service life of pavement markings and are important for long-life markings. Currently, it is becoming a trend to apply durable markings. Meanwhile, however, the application of this type of marking has demanding requirements, including specialized equipment and skilled workers.

According to a study conducted by Choubane et al. (2018), the measurement of visibility and retro-reflectivity of pavement markings requires improvement for subjective visual surveys and the tedious and potentially hazardous hand-held measurements. Pike and Bommanayakanahalli (2018) suggested that the material cost of durable markings is higher than that for nondurable markings, although durable markings have significant advantages. Fares et al. (2012) noticed that the major factors for fatal motor vehicle crashes are pavement markings that have insufficient or poorly completed maintenance.

2.2.3 Types of Marking Materials Applied and Factors Affecting Selection

The materials for pavement markings are commonly categorized into four major types: (1) paint (solvent-borne and waterborne), (2) thermosets (polyester and epoxy), (3) thermoplastics, and (4) tapes. Their performance is measured by (1) appearance, (2) durability, and (3) retro-reflectivity (Lee et al., 1999). The service life of pavement marking materials can be modeled as a function of time. The

manufacturing regions, quality control, and specifications can also contribute to its service life (Migletz et al., 2001).

The NCHRP Synthesis 306 report showed the result of a survey in which eight different state agencies considered the parameters for marking materials selection criteria. It concluded that the material selection process always leads to choosing between durable markings and paint markings. The most common factors in the selection are the type of line, pavement surface, traffic volume, and type of street and highway, while the service life of the remaining pavement is given less consideration (Migletz and Graham, 2002). The factors included in the different state agencies' materials selecting criteria are specified in **Table 1**.

Table 1 Factors Used in Selecting Pavement Marking Materials

State Transportation Agency	Type of Line	Pavement Surface	Traffic Volume (ADT)	Type of Street and Highway	Pavement Condition	Remaining Pavement Service Life	Area	Snow Removal Area	Brightness Benefit Factor	Speed	Length of Project
Arkansas	X	X	X	X							
Kansas	X		X			X			X		
Maryland	X	X	X	X			X			X	
Ohio	X	X	X		X						
North Dakota	X	X	X		X						
Tennessee	X	X	X	X							
Washington	X			X	X	X	X	X			
Wisconsin	X	X		X		X	X				X
Total	8	6	6	5	3	3	3	1	1	1	1

Source: Table 18, Chapter 5, Material Selection Criteria, NCHRP SYNTHESIS 306, Long-Term Pavement Marking Practices

The TxDOT Pavement Marking Handbook (2004) categorizes the factors that influence pavement marking performance into three major groups: (1) roadway surface, (2) traffic, and (3) environment. The handbook provides tables for guidance on pavement marking material selection for hot-mix asphalt (HMA) surfaces, hydraulic cement concrete surfaces, and surface treatments.

In a 2003 report, TxDOT identified effective pavement marking materials, which are especially effective on Texas Portland Cement Concrete roadways. The report recommended proper surface preparation and material application

procedures, and it introduced a common material failure, a de-bonding issue in pavement markings (Gates et al., 2003).

The Virginia Department of Transportation (VDOT) conducted a report in 2001 focusing on evaluating the effectiveness of pavement marking materials used by VDOT for guidance development (Cottrell and Hanson, 2001). Another report conducted by the Louisiana Department of Transportation and Development (LaDOTD) in 2010 discussed the selection of marking materials under specific conditions. The benefits of increasing the retro-reflectivity specifications of pavement markings were also evaluated (Fu and Wilmot, 2010).

2.2.4 Quality Control Methods and Approaches

In Texas, quality control is the objective of installation and field inspection, according to the TxDOT Pavement Marking Handbook (2004). This inspection procedure includes measuring pavement marking thickness, width, color, bead dispersion and depth, and nighttime appearance. Additionally, a final acceptance is required as a quality assurance measure to ensure continued inspection of the markings for a certain period after installation of all the markings.

A method used by VDOT to test pavement markings quality control includes five procedures (2004):

- Checking for moisture in the pavement
- Determination of the wet film thickness of liquid markings
- Determination of film thickness for thermoplastic markings
- Determination of application rate of glass beads applied by pressurized spray or drop-on methods
- Visual inspection

In 2010, the Oregon Department of Transportation (ODOT) conducted a report to enhance pavement marking quality control procedures. The quality control

information on the pavement marking evaluation at test sites was presented. The study addressed the importance of surface preparation prior to the marking installation, and it stated that the selection of inspection sites should also be considered in the quality control procedures (van Schalkwyk, 2010). A study in 2021 by Xu et al. introduced current approaches to assessing the quality and performance of long-term pavement markings. It suggests that the retro-reflectivity and skid resistance characteristics regulated by the European Technical Standard IS EN 1436 are necessary for the evaluation of marking quality.

The application rates are also verified in the quality control procedures according to state agencies. This is checked by calculating the material amount within a certain marking mileage and comparing the result with the amount used by the marking contractor (Migletz and Graham, 2002).

2.2.5 Pavement Marking Specifications Implementation

FHWA MUTCD (2009 edition with Revisions 1 and 2, May 2012) provides standard specifications for each state to standardize the suitable pavement marking criteria. The color specifications mentioned in MUTCD and TMUTCD are used to determine the color of pavement marking materials for the designers.

Currently, TxDOT has implemented two specifications in the pavement marking manual: pavement marking material specifications and pavement marking construction specifications. The material specifications are categorized as different types of pavement markings: (1) traffic paint, (2) hot-applied thermoplastic, (3) permanent prefabricated pavement markings, (4) removable prefabricated pavement markings, (5) temporary flexible-reflective roadway marker tabs, (6) multipolymers pavement markings, and (7) glass traffic beads (TxDOT, 2004). The construction specifications include standard and special specifications; the surface preparation specification is included in the standard portion.

Thomas-Meyers et al. (2003) proposed a recommendation for current color specification by MUTCD: specifying a range of marking colors chromaticity acceptable

for pavement so that the visibility of markings in the daytime and nighttime and on various pavement types can be acceptable. Shuler (1976) developed a practical specification for the marking material selection criteria in early practice and suggested that the evaluation of possible increasing benefits should also be adopted in the proposed specifications.

NCHRP Synthesis 408 introduces pavement marking warranty specifications in the U.S. and Canada (Markow, 2010). The report compares the materials or performance covered by the warranty specification, the warranty period, and the examples of types of markings covered between several state agencies. According to the report, the types of warranty specifications are mainly categorized into two types: (1) methods-based specifications (materials and workmanship), and (2) performance-based specifications (pure performance regardless of marking materials). The warranty specification period is mainly decided based on the marking materials. Durable markings tend to have longer warranty durations, while the warranty periods of nondurable markings are relatively short.

2.2.6 Current Practice in Texas: TxDOT Handbook (2004)

2.2.6.1 Roadway Surface Characteristics Affecting Pavement Marking Materials

The roadway surface upon which a given material is placed is one of the most important factors influencing pavement marking performance. In Texas, pavement markings are placed upon three general types of roadway surfaces: (1) hot-mix asphalt concrete (HMAC), (2) hydraulic cement concrete (HCC, the most common type being Portland cement concrete), and (3) open-graded bituminous pavements (referred to as surface treatments in this handbook, but also known as seal coats). Engineers can expect a given pavement marking material to perform differently on each of the different surface types. There are three major pavement surface characteristics that affect marking performance: (1) surface roughness, (2) heat sensitivity, and (3) surface porosity. Some of the typical consequences are shown in **Figures 2-4**.

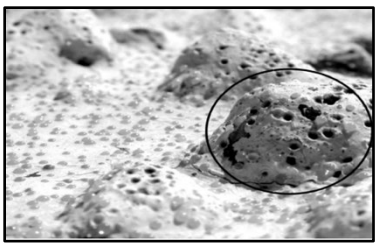


Figure 2 Typical Consequences of Pavement Markings Impacted by Roadway Surface Characteristics (*Poor Material Durability on Top of Aggregates*)

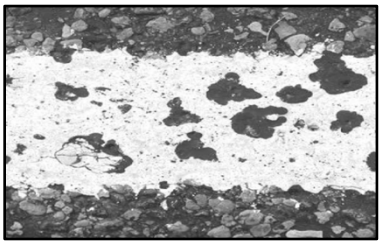


Figure 3 Typical Consequences of Pavement Markings Impacted by Roadway Surface Characteristics (*Asphalt Boiling Through Hot Thermoplastic*)

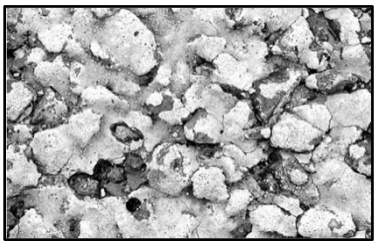


Figure 4 Typical Consequences of Pavement Markings Impacted by Roadway Surface Characteristics (*Poor Material Coverage on Backside of Aggregate*)

The surface roughness can play a major role in the way a marking performs over time. Pavement markings on rough pavement surfaces, such as those with surface treatments, commonly have lower retro-reflectivity and shortened service lives compared to identical markings on smooth pavement surfaces.

The heat sensitivity of a pavement surface determines the bonding characteristics between the surface and most hot-applied marking materials. At temperatures greater than 160 °F, asphalt behaves as a viscous liquid, which allows for thermal bonding with many hot-applied pavement marking materials.

The surface porosity of a pavement surface determines the mechanical bonding characteristics for pavement markings with the surface. Mechanical bonding

occurs when the pavement marking material seeps into the pores of the pavement surface and creates a tight mechanical bond upon drying. Thermoplastics and other hot-applied pavement markings adhere to concrete through mechanical bonding.

2.2.6.2 Material Selection Process

Most of the pavement markings placed on roadways by the TxDOT over the past five years fall into one of three categories: (1) thermoplastic, (2) water-based paint, and (3) preformed tape. However, other marking materials exist that have shown positive performance either in Texas or elsewhere, which warrants their discussion in the TxDOT handbook. The category of marking materials is decided based on the type of binder material used. **Table 2** shows the pavement materials and their usage according to the TxDOT pavement marking handbook.

Table 2 Pavement Material and Their Usage in Texas

Material	**Brief Usage Note**	**Special Approval Required***
Thermoplastic	See DMS-8220	
Water-based paint	See DMS-8220	
Preformed tapes	See DMS-8240	
Epoxy	Experimental use in Texas	Yes
Polyuria	Experimental use in Texas	Yes
Modified urethane	Experimental use in Texas	Yes
Methyl methacrylate (MMA)	Extensive use in other states	Yes
Profiled thermoplastic	Experimental use in Texas	
Contrast marking	Experimental use in Texas	
Heated-in-place thermoplastic	Transverse line, words, and symbols only	
Ceramic buttons	Previously used extensively in Texas	

*Material designated here as experimental require special approval from TRF or CST-MAT for use.

Source: Table 2-4, Section 4, Pavement Marking Material Descriptions, Pavement Marking Handbook, TxDOT.

The use of experimental materials may also be considered for problematic areas where listed common materials may not have provided the desired performance. The material specifications are categorized under different types of

pavement markings: (1) traffic paint, (2) hot-applied thermoplastic, (3) permanent prefabricated pavement markings, (4) removable prefabricated pavement markings, (5) temporary flexible-reflective roadway marker tabs, and (6) glass traffic beads.

The handbook provides tables for guidance on pavement marking material selection on HMA surfaces, hydraulic cement concrete surfaces, and surface treatments. Under each surface condition, the selection of materials is decided based on traffic characteristics (e.g., annual average daily traffic (AADT)) and pavement remaining service life. The highest recommended pavement marking materials and alternate materials are given under each suitable situation. Although the performance of pavement materials varies based on different factors, they may be used as either a transverse (short-line) or longitudinal (long-line) application. The comparison of marking materials characteristics is shown in **Table 3**.

Table 3 Pavement Marking Materials Characteristics Comparison

Material	**Use Based on Pavement Surface**			**Lane Closure Required**	**TxDOT Specifications**	**See Table#**
	Conc.	**Asp.**	**Seal**			
Thermoplastic	L	Y	Y	No	Yes	2-6, 2-7, 2-8
Water-based paint	Y*	Y*	Y*	No	Yes	2-9, 2-10
Preformed tape	Y	Y	N	Yes	Yes	2-11
Epoxy	Y	Y	L	Yes	Yes**	2-12, 2-13
Polyurea	Y	Y	L	Yes	Yes**	2-14
Modified Urethane	L	L	L	Yes	Yes**	2-15
Methyl methacrylate	L	L	L	Yes	No	2-17
Profiled thermoplastic	Y	Y	N	No	Yes	
Contrast markings	Y	Y	L	No	No	
Heated-in-place thermoplastic (not for use in longline)	Y	Y	Y	Yes	Yes	
Ceramic buttons	L	N	N	Yes	No	2-15

Y = Suitable for use

N = Not recommended
L = Limited use
* = Refer to Table 2-10 for traffic volume condition
** = Refer to multipolymer specification SS 1513
Source: Table 2-5, Section 4, Pavement Marking Material Descriptions, Pavement Marking Handbook, TxDOT

TxDOT Item 666 "Retroreflectorized Pavement Markings" describes how to furnish and place retroreflectorized, non-retroreflectorized (shadow) and profile pavement markings. Guidance is given on (1) materials, (2) the general equipment requirements and material placement requirements for equipment, (3) construction before opening to traffic, unless short-term or work zone markings are allowed, (4) measurement (by the foot; by each word, symbol, or shape; or by any other unit), and (5) payment.

2.2.6.3 Installation and Inspection for Quality Control and Measurement

Proper inspection is required for a high-quality pavement marking installation. Before the application inspection, a pre-installation inspection is needed to inspect the roadway and weather conditions, striping equipment, and marking layout. Several parameters are tested in the pre-installation inspection: (1) surface moisture, (2) dirt and debris, (3) air and pavement temperature, (4) material temperature, (5) lateral placement guides for new pavement surfaces, (6) striping equipment, and (7) traffic control.

The inspection procedure includes the measurement of pavement marking thickness, width, color, bead dispersion and depth, and nighttime appearance. Additionally, material disposal is required; the inspector will dispose of marking materials when performing test sprays or flushes. After the inspection during the application, as quality assurance measure, the inspector conducts additional inspections of the markings for a certain period after all the markings are placed, which practice is needed as part of final acceptance. It consists of two inspection tasks: (1) measurement of quantities for contract payment items, and (2) measurement of marking retro-reflectivity. According to the current TxDOT

pavement marking contract, the markings are required to reach minimum levels of retro-reflectivity within a specified number of days after placement of the markings.

2.2.7 Practices in Other States

2.2.7.1 Virginia Department of Transportation

The pavement marking standards and specifications of VDOT are constantly updated to prudently reduce costs and ensure safety benefits. The specifications include statistical quality calculations to calculate temporary marking quantities separately for each phase. The marking materials are categorized into four major types (Type A, Type B, Type D, and Type E), with several classes under Type B and Type D. With no official policy on marking materials, the pavement marking selection is mainly decided in accordance with Memorandum TE-261.1. When choosing among different marking material alternatives, the life cycle cost and compatibility between different marking materials for restriping are considered (VDOT, 2019). The pavement marking selection process is shown in **Figure 5**.

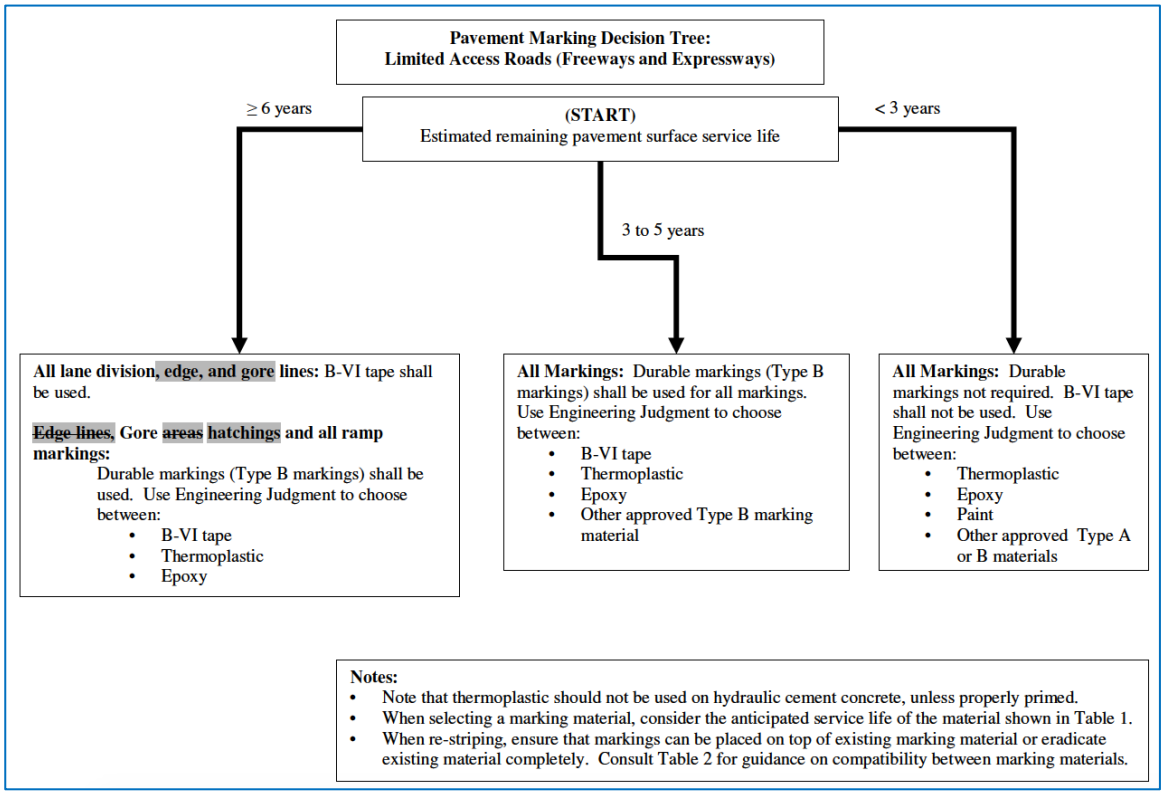


Figure 5 Pavement Marking Selection Process by VDOT

2.2.7.2 Minnesota DOT

Two essential requirements for Minnesota DOT (MnDOT) pavement markings are (1) specified colors must be identifiable during day and night, and (2) minimum visibility standards must be maintained throughout the material's lifetime. Durability, workability, drying and non-track time, accommodation of heavy traffic volumes, replacement of material, safety, and environmental concerns are considered in selecting marking materials (MnDOT, 2008).

Table 4 shows the statewide policy regarding selecting marking materials on multilane divided or undivided roadways. For the remaining pavement surface life, the anticipated life of the existing pavement is based on planned projects, and the anticipated life of the surface is based on preventive maintenance plans. The special markings mentioned in Table 4 include transverse markings (i.e., stop bars and crosswalks), gore markings, and word and symbol markings.

Table 4 Multilane Divided or Undivided Roadway Marking Materials Selection

Remaining Pavement Surface Life (years)	Edge line	Centerline, Lane Line, and Special Markings
0-2	Paint	Paint
2-6	Epoxy	Epoxy
6+	Epoxy	Tape

Source: 7-4.01, Materials, Chapter 7, Pavement Marking, Traffic Engineering Manual.

MnDOT highlights the significant impact of traffic volumes and resulting snow and ice operations on the performance of pavement markings. **Table 5** outlines the life expectancy of various materials based on traffic volumes.

Table 5 Life Expectancy of Pavement Materials vs Average Daily Traffic by MnDOT

Material	Average Daily Traffic	
	<1,500	>1,500
Latex Paint	>1 year	1 year
Epoxy (plural Component Liquid)	> 5 years	3-5 years

Preformed Polymer Tape	> 5 years	> 5 years

Source: 7-4.01, Materials, Chapter 7, Pavement Marking, Traffic Engineering Manual, MnDOT.

In Minnesota, all marking materials must be on the MnDOT's Qualified Products List and must be installed according to the manufacturer's specifications. This may include the removal of existing pavement markings and other surface treatments as recommended by the manufacturer.

2.2.7.3 North Dakota Department of Transportation

The North Dakota Department of Transportation (NDDOT) considers pavement condition and remaining pavement service life in providing an appropriate pavement marking. According to the NDDOT Design Manual, the pavement marking should meet the principles and standards set forth in the MUTCD. The pavement markings should also provide delineation after bare pavement is attained in snow and ice conditions. The priority requirements in selecting marking materials are compatibility with the anticipated life of the surfacing section or consistency with the expected life of the existing pavement marking materials on adjacent roadway sections.

The expected life of pavement marking by materials and ADT is shown in **Table 6**. The selected pavement marking material should have an anticipated life expectancy that is the same or less than the anticipated life expectancy before the application of subsequent surface treatment (NDDOT, 2000).

Table 6 Pavement Marking Life Expectancy vs Average Daily Traffic by NDDOT

Materials	**ADT**		
	<1,500	1,500-4,000	>4,000
Paint	1 yr.	1 yr.	<1 yr.
Epoxy	> 5 yrs.	4 to 5 yrs.	3 to 4 yrs.

Grooved Epoxy	> 5 yrs.	> 5 yrs.	> 5 yrs.
Tape	> 5 yrs.	> 5 yrs.	> 5 yrs.
Grooved Tape	> 8 yrs.	> 8 yrs.	> 8 yrs.

Source: Appendix III-10A, Pavement Marking Material Selection, Chapter III, Roadway Design, NDDOT Design Manual, NDDOT

The NDDOT pavement material selection guidelines include several parameters: (1) road type, (2) pavement condition, (3) ADT, and (4) line type. The anticipated surface life is based on the design life of the new pavement or the anticipated time before the next surface treatment. The road type is only considered for the surface life expected to exceed 4 years and is grouped into asphalt and concrete types. The selection of marking materials is also varied depending upon traffic volume and line types. The ADT range is below 1,500 to over 4,000, and the line types are categorized into edge line and centerline in the pavement marking materials selecting matrix according to the NDDOT Roadway Design Manual. **Table 7** emphasizes the marking materials selecting matrix on different highways in rural areas.

Table 7 Rural Pavement Marking Materials Selecting Matrix from The NDDOT Roadway Design Manual

Anticipated Surface life (years)		**ADT**					
		<1,500		1,500-4,000		>4,000	
		Edge-line	Centerline	Edge-line	Centerline	Edge-line	Centerline
(a) Two-Lane Two-Way Highways							
0 to 2		Paint	Paint	Paint	Paint	Paint	Paint
2 to 4		Paint	Paint	Paint	Epoxy	Epoxy	Epoxy
4 to 6	Asphalt	Paint	Paint	Epoxy	Epoxy	Epoxy	Epoxy
	Concrete	Paint	Paint	Epoxy	Epoxy	Epoxy	Epoxy
6+	Asphalt	Paint	Paint	Epoxy	Epoxy	Grooved Epoxy (A)	Epoxy
	Concrete	Paint	Paint	Epoxy	Epoxy	Grooved Epoxy (A)	Epoxy
(b) Multilane Divided and Undivided Highways							
0 to 2		Paint	Paint	Paint	Paint	Paint	Paint

2 to 4		Paint	Paint	Paint	Epoxy	Epoxy	Epoxy
4 to 6	Asphalt	Epoxy	Epoxy	Epoxy	Grooved Epoxy (A)	Epoxy	Grooved Epoxy (A)
	Concrete	Epoxy	Epoxy	Epoxy	Grooved Epoxy (A)	Epoxy	Grooved Epoxy (A)
6+	Asphalt	Epoxy	Epoxy	Epoxy	Grooved Epoxy (A)	Grooved Epoxy (A)	Grooved Epoxy (A)
	Concrete	Epoxy	Epoxy	Epoxy	Grooved Epoxy (A)	Grooved Epoxy (A)	Grooved Epoxy (A)

2.3 Survey

2.3.1 Survey Design

Comprehensive questionnaires/surveys were designed and distributed through the SurveyMonkey website to field pavement marking material practitioners to gain an understanding of their viewpoints related to different aspects of the various pavement marking materials. Initially, the TSU research team prepared a first draft of the survey on a Microsoft Word document and submitted it to the TxDOT Project Director (PD) on September 06, 2021, for the feedback and approval of the Project Management Committee (PMC). After a virtual meeting on September 13, 2021 (between the TSU research team and TxDOT PMC) and communications via emails, the survey design was approved and uploaded on the SurveyMonkey website on September 30, 2021.

The survey was subdivided into three parts. The first part of the survey included questions related to the participants' contact information and other general information, such as the overall performance of pavement markings and the names of marking materials used in the participants' area. To thoroughly understand all aspects of every pavement marking material from field engineers' perspectives, the second part of the survey, which included a Pavement Marking Evaluation, was designed to gather specific information regarding pavement marking specifications, quality control approaches, maintenance methodologies, challenges, and recommendations on the languages being used and methods of application verification of pavement markings. Specifically, in part two of the survey, 13

questions were prepared relating to thermoplastic pavement markings, 12 questions related to the water-based paint pavement markings and prefabricated pavement markings, 16 questions were regarding polymer pavement marking materials, and 17 questions were related to profiled thermoplastic. Finally, the third part of the survey focused on new technology and material, and participant recommendations on improving the TxDOT pavement marking material handbook. For further information regarding the survey, please refer to Appendix A of this research report.

2.3.2 Survey Distribution

2.3.2.1 Survey Distribution Procedure

As per the instruction of the PMC, the TSU research team created two separate surveys on the SurveyMonkey website: one for participants inside Texas and another for participants from other states and foreign countries. Except for the participant contact information and a few additional questions regarding pavement marking in the external survey, the two surveys contain highly identical information.

Subsequently, following the approval of the final survey version by the TxDOT team, the TSU research team distributed the external survey on October 13, 2021, targeting participants from foreign countries, such as Canada, China, the United Arab Emirates, Saudi Arabia, the U.K., and several other countries. The list of the participants from foreign countries was prepared based on a Google search, where the team found many agencies/individuals who are practically involved in the design and implementation of pavement markings. In addition, the list of participants was also shared with the PD and PMC for their review and information. Via dissemination message, the research team specified a deadline to respond to the external survey of October 25, 2021, which was extended to November 04, 2021 for those who did not timely respond to the survey, and gave notice in the reminder message sent on October 25, 2021. Two participants from the Middle East have responded to the external survey.

Except for the MnDOT, where one of TSU researchers directly sent the external survey to an official in this organization, the PMC helped to distribute the internal

survey to participants in Texas and in all other states' DOTs within the U.S. on October 13, 2021, through platforms such as AASHTO. The PMC set the deadline to respond to the internal survey as November 12, 2021. Upon reaching the survey response deadline, a total of 39 responses were received from participants of various states, with 4 responses deleted as they skipped all the questions.

2.3.2.2 Survey Respondents Distribution

A total of 35 qualified pavement marking practitioners, both at national and international levels, participated in the survey. Of these, 3 were from foreign countries: Canada, Saudi Arabia, and Lebanon, 14 were from Texas, and the remaining 18 were from other states within the U.S. **Figure 6** shows the geolocation of the respondents who participated in the survey from various states.

Figure 6 Respondents Geolocation Distribution in the U.S. Marked in Green Ovals

Figure 7 shows the geolocation distribution of the survey's respondents who participated from different TxDOT districts.

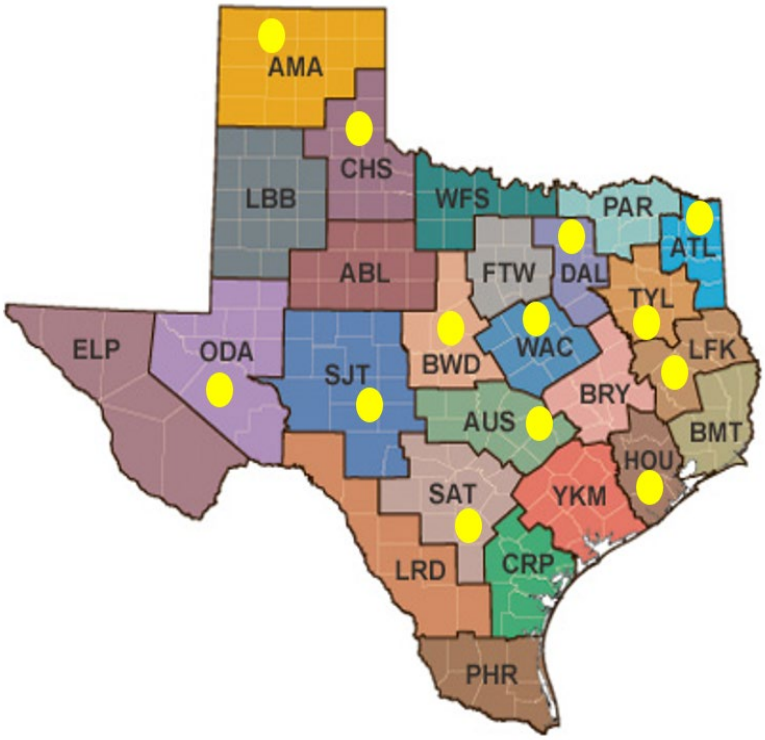


Figure 7 Respondents Geolocation Distribution in Twelve TxDOT Districts Marked in Yellow Ovals

2.3.3 Survey Analysis and Results

As mentioned earlier, 3 survey participants responded to the external survey: 1 from the MnDOT and 2 from foreign countries. To make the survey analysis consistent and concise, the TSU researchers decided to combine the results of the external survey with those of the internal one.

2.3.3.1 Part one - Basic Information

This section of the survey contained two questions. The first question was about the overall performance of the pavement marking materials in the participants' area. Out of the 35 respondents, 32 answered this question; 16 participants rated average, 12 people rated above average, 3 people rated below average, and only 1 individual rated the pavement marking outstanding. **Figure 8** shows the distribution of the responses.

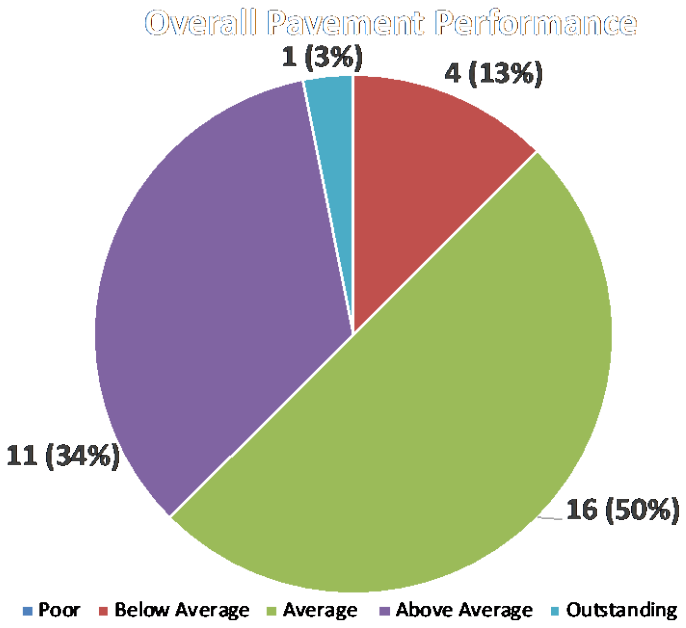


Figure 8 Overall Performance of Pavement Marking Material in the Respondents Area

The second question of this survey section asked the respondents to answer which pavement marking material types that have mostly been used in their area. There were 33 respondents who participated in answering this question, among which, the thermoplastic and water-based paint markings had the highest responses, and no one chose methyl methacrylate (MMA). New pavement marking types were used by 3 respondents in their area, in addition to the marking types specified in the survey. These markings include all-weather thermoplastic, preformed thermoplastic, and alkyd paint marking. **Figure 9** shows detailed information related to this question.

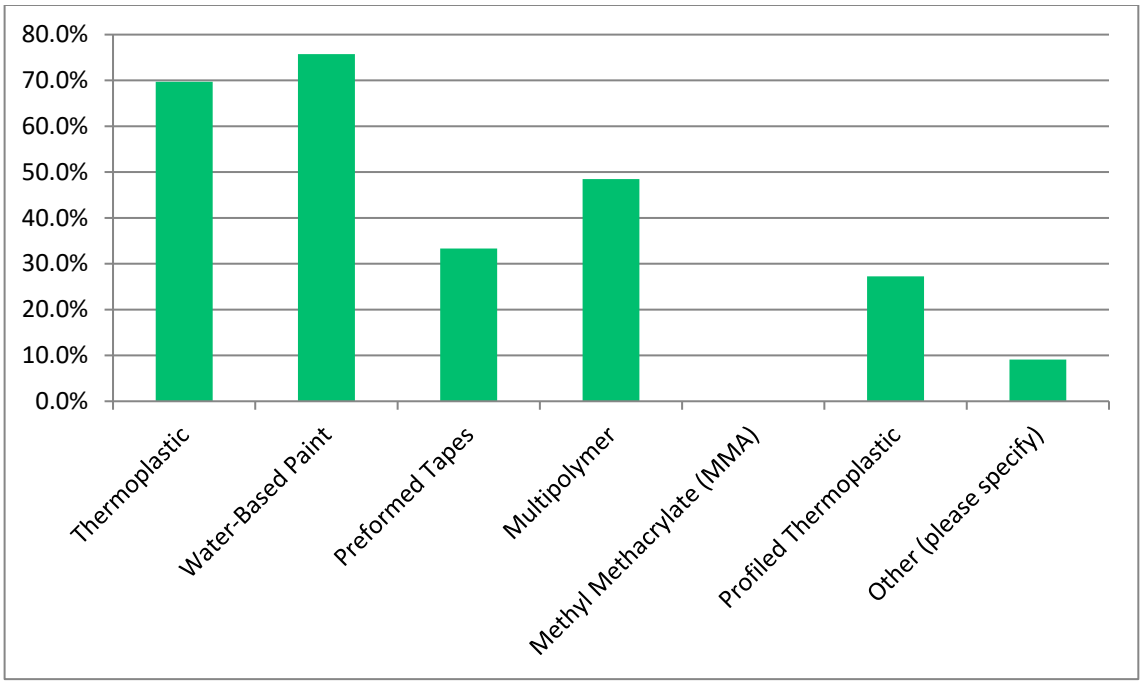


Figure 9 Pavement Markings Material Types That are Mostly Used in the Respondents Area.

2.3.3.2 Part Two - Pavement Markings Evaluation

As stated in the Survey Design section of this report, the second part of the survey was designed to collect information from participants regarding each marking material, such as thermoplastic, water-based paint, preformed tapes (prefabricated pavement marking), and profiled thermoplastic. In this section, the results were combined and presented together for each similar question related to the different pavement markings.

2.3.3.2.1 On the Practice/Usage of the Pavement Marking

For thermoplastic pavement marking, 24 respondents confirmed that this marking material is used in their area, 3 people indicated that thermoplastic is not used in their locations, and 8 people skipped this question. Those whose responses were "no" for thermoplastic usage in their area provided reasons, such as (1) being nondurable during winter road maintenance, (2) limited availability of equipment or

vendors, and (3) availability of other types of thermoplastics like all-weather thermoplastic and preformed thermoplastic.

For water-based paint, 27 respondents said “yes,” confirming that this marking was used in their area, 2 people said “no,” and 6 individuals skipped this question. The 2 who said “no” reasoned that they only use high-build water-based paint.

For preformed tapes (prefabricated pavement marking), 21 participants said “yes,” confirming that they practice this type of pavement marking, 7 people said “no,” and 7 people skipped to answer this question. Those who said “no” provided reasons, such as (1) high cost, and (2) lack of adequate performance during the winter season. Particularly, one of the respondents wrote, “Preformed tapes are rarely used because of constructability issues with placement procedures that require inlaying the tapes on the flexible pavement before the surface falls below 160 degrees F. It was difficult to place the products properly, and the product didn't last long for the higher price. Temporary tape is sometimes but rarely used in large projects with numerous work zone changes in the Las Vegas area. Infrequently, the permanent tape is used for crosswalks in the Las Vegas area.”

For multipolymer pavement marking, 20 people reported “yes,” 8 participants said that this pavement marking is not used in their area, and 7 people skipped this question. Although multipolymer markings were used in the past, as per participants' points of view, currently, this type of marking is not extensively used throughout the U.S. The reasons for its limited usage in the participants’ areas include (1) requiring excessively high cost, (2) not requiring very high durable marking in their states, and (3) difficulties in finding a contractor to implement this type of marking.

For profiled thermoplastic, 11 people confirmed the usage of this marking in their areas, 13 said “no,” and 11 participants skipped this question. The participants noted that reasons for the non-usage of this marking in their states are (1) not obtaining satisfactory results during the testing process, (2) challenges in heating thermoplastic material, and (3) not being durable in states experiencing snowfall.

Figure 10 shows the response distribution of participants on different pavement marking material types used in their areas.

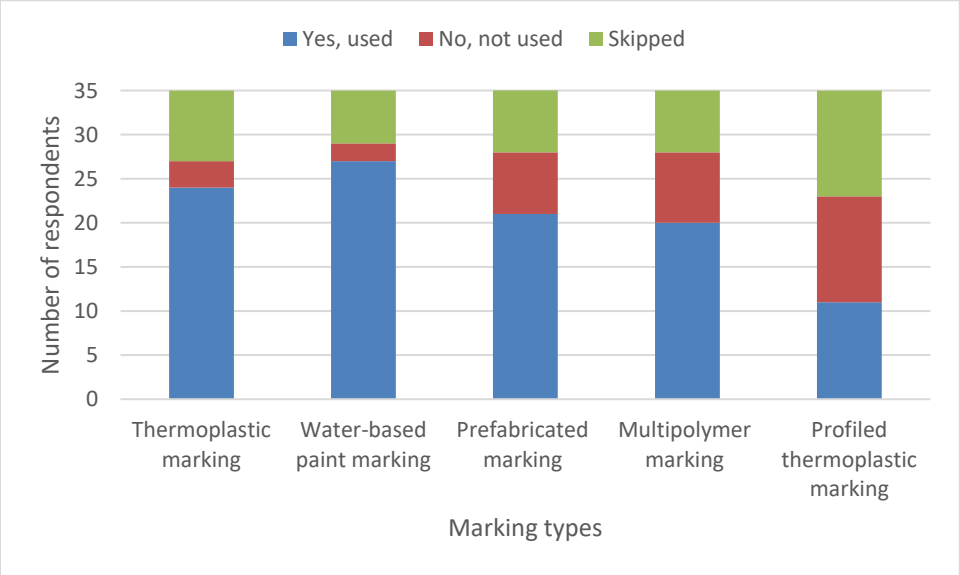


Figure 10 Pavement Marking Material Types of Usage in Respondents Area

2.3.3.2.2 Survey Participants' Views on Marking Usage on Different Pavement Types

The question was basically designed to understand the participants' viewpoints regarding the application of pavement marking types on various pavement types. Specifically, the question was phrased "what pavement type(s) do you use for this particular marking in your area?"

Table 8 shows a detailed summary of respondents' input regarding this subject.

Table 8 Participants Response Distribution on Marking Material Application on Pavement Types

Pavement Types	Thermoplastic marking	Water-based paint marking	Prefabricated marking	Multipolymer marking	Profiled thermoplastic marking
Flexible Pavement	22	24	18	15	11
Perpetual Pavement	6	8	7	7	2
Rigid Pavement	16	17	16	14	6

Concrete Older than Three years	14	17	15	16	5
Concrete Less than Three Years	13	16	15	16	4
Composite Pavement	4	8	5	8	1
Other Types	3	6	2	2	2
Other Types from Respondents' view	Long Line thermo on Asphalt. Preformed thermo on asphalt and concrete	We only use high build water base paint	All	All	N/A
	All asphalt, very little concrete		Generally, on conc surfaces and continental crosswalks	None	Used on projects with seal coat surfaces or other that do not have the thickness to used milled in
	PFC		PFC	None	
Answered	**24**	**27**	**20**	**22**	**12**
Skipped	**11**	**8**	**15**	**13**	**23**

2.3.3.2.3 Respondents' Viewpoints on the Field Life Expectancy of Various Marking Types

This question was designed to understand the views of participants regarding the performance and durability of pavement marking implemented practically in field projects. Specifically, the question was phrased as "Per your practice, what is the life expectancy of this marking in your district?"

For thermoplastic, out of the 35 participants, 24 people provided the practical life expectancy for this question, while the other 11 individuals skipped answering this question. **Table 9** reveals further details related to the response of every participant for each specific pavement marking type. The survey respondents provided a variety of responses regarding the life expectancy of pavement markings. Some of them backed their responses with their field experience, which will be a good asset for this research.

Table 9 Survey Respondents View on Pavement Marking Life Expectancy

Res.	**Thermoplastic marking**	**Water-based paint marking**	**Prefabricated marking**	**Multipolymer marking**	**Profiled thermoplastic marking**
	Responses _Marking Life Expectancy				
1	3 to 4 years	1 to 2 years	3 to 4 years	3 to 4 years	3 to 5 years

Res.	Thermoplastic marking	Water-based paint marking	Prefabricated marking	Multipolymer marking	Profiled thermoplastic marking
	Responses _Marking Life Expectancy				
2	2 to 3 years	1 year	2 to 3 years	2 to 3 years	3 to 4 years
3	Expect 4-5 years. We are hesitant to use on concrete are trying multipolymer to see if that lasts longer	1 year	less than 5 years	In areas without snowplow use, these products generally last 1.5 to 2.5 years in urban environments with higher traffic volumes and 3 to 3+ years in rural environments with lower traffic volumes. In areas where snowplow use is prevalent the service life is reduced as compared to where there is no snowplow use.	N/A
4	3 to 4 years	Areas without snowplow damage approx. 1 to 1.5 years in urban or high trafficked areas; 2 to 2.5 years in more rural areas and lower trafficked areas. In areas where snowplows are used the service life is substantially reduced to as little as 6 months to 1 year service life.	3 to 4 years	Expect 7-8 years, but just placed first big project this year. Have had in one other location for at least 8 years and it looks ok	5 years
5	5 Years	Less than one year. Water-Based paint is used annually to re-mark all marking on the road network. This measure ensures the presence of lines until the following spring and restores the marking's night visibility (retro reflectivity).	2 to 3 years	3 to 4 years	4 to 5 years
6	5 to 7 years	If surface applied, less than a year typically. If a recessed high build is used, around 3 -4 years.	3 years	In Quebec, we use only Epoxy as Multipolymer. Epoxy is used on all new surface courses to give the marking a durable base coat. Our performance requirements (durability) are defined over two years for medium service life materials and over four years for long service life materials.	6 years
7	4 to 5 years	2 to 3 years	5 years	We mainly use slow dry epoxy, except in cold weather where we use faster curing multipolymers. The expected life surface applied is around 3-5 years and recessed around 5-7 years. Our MnDOT Provisions for Pavement Marking Operations lays out all of our expected life info: https://edocs-public.dot.state.mn.us/edocs_public/DMResultSet/download?docId=4899502	3 to 7 years
8	3 years	12-18 months	6 years or so	3 years	4 to 6 years
9	5 years	1 to 2 years	3+ years	3 years	Depends on the ADT and type of vehicles
10	3 to 5 years or so	less than 1 year	3 to 5 years	3 to 5 years	5 to 7 years
11	3+ years	6 to 12 months	5-7 years, longer on lower ADT roads	Epoxy and Modified Urethane - 4+ years. MMA - 6+ years	

Res.	Thermoplastic marking	Water-based paint marking	Prefabricated marking	Multipolymer marking	Profiled thermoplastic marking
	Responses _Marking Life Expectancy				
12	IH systems 1.5 yrs. Other systems 5 yrs.	We restripe major routes (5,500 miles of divided and undivided) every year typically regardless of retro reflectivity reading in the spring to assure these routes have the best line possible (although in tough times like this year with paint shortages we will skip route if they meet or exceed our new line requirements for maintenance operations of 300 millicandelas for white and 225 for yellow). We stripe our two lanes minor road with AADT greater than 400 every other year (50% of the routes stipend per year, we maintain a total of 15,500 miles in this category all of which get a centerline and edge line) and minor two-lane routes 400 AADT and less once every 3 years (33% of these routes stripe per year, we maintain 12,500 miles of these low volume routes in our state system all of which get a centerline)	3 to 4 years	3+year	
13	5 to 7 years, longer on low ADT roads	1 Year	5 years -surface applied (rare) or 8 years -grooved	5 to 7 years, longer on lower ADT roads	
14	6 years	2 years	3 to 5 years	2 to 3 years	
15	2 to 3 years	1 year	Varies widely based on flushed pavement surfaces	3 to 5 years	
16	3 to 7 years	12 to 18 months	8+ yrs.	3 to 7 years	
17	3 to 5 years	<1 year	5 to 7 years	5 years	
18	Depends on Riding Surface; generally, between 3 and 6 years.	6 months- year	Type B will last up to 10 years. Type C will last about 1to 2 years due to plows.	3 to 7 years	
19	Varies depending on the road ADT and vehicle types.	1 year		Not Used	
20	3 years	1 to 2 years		1 to 3 years	
21	Three years on most high-volume roads and 5 years on low volume	1-2 yrs.		5 years	
22	3 years	One to two years			
23	1 to 2 years	Less than 1 year			
24		1 to 2 years on high volume roads and 3 to 5 years on low volume roads			
25		1 to 3 years			
26		Higher volume roads typically have a life expectancy of 6-8 months.			
27	60 mil - low ADT > 2-year 100 mil - Low ADT-> 3 years	Depends on ADT - 3 - 9 months	Less than "push in" thermos markings		2 to 4 years

2.3.3.2.4 Performance Influencing Factors of Pavement Markings

This question was primarily designed to understand the most significant factors involved in the performance of pavement marking. The questions were phrased as "What is (are) the most significant performance influencing factor(s) of this marking? (Multiple Choices)."

As illustrated in **Table 10**, from traffic volume to designed speed limit, the respondents selected various broad factors affecting the pavement marking performance. However, according to **Figure 11,** the traffic volume followed by pavement surface, snow removal area, pavement condition, and type of highways were selected by most respondents as the main factors that could affect the performance and durability of pavement markings.

Table 10 Performance Influence Factor of Pavement Markings – Respondents' Input

	Pavement Marking Type	Thermoplastic	Water-based Paint	Prefabricated	Multipolymer	Profiled thermoplastic
		Responses				
Performance Influence Factors	Pavement surface	17	11	16	12	10
	Traffic Volume	21	23	18	16	8
	Type of street and highway	9	6	9	10	4
	Pavement condition	11	11	11	9	4
	Snow removal area	15	15	9	11	4
	Brightness benefit factor	5	3	6	5	3
	Designed speed limit	1	0	0	0	1
	Length of the project	1	1	1	1	0
	MIL thickness	15	4	3	2	5
	Environment	5	3	10	7	1
	Type of lines	1	10	7	6	3
	Age of the pavement	5	6	3	2	0
	Others	2				3
	Others - Specified by the respondents	Amount of turning movements over the pavement message - Condition of existing stripe				use on edge line when not enough shoulder for a rumble bar. Width of the roadway
	Answered	25	27	21	22	23
	Skipped	10	8	14	13	23

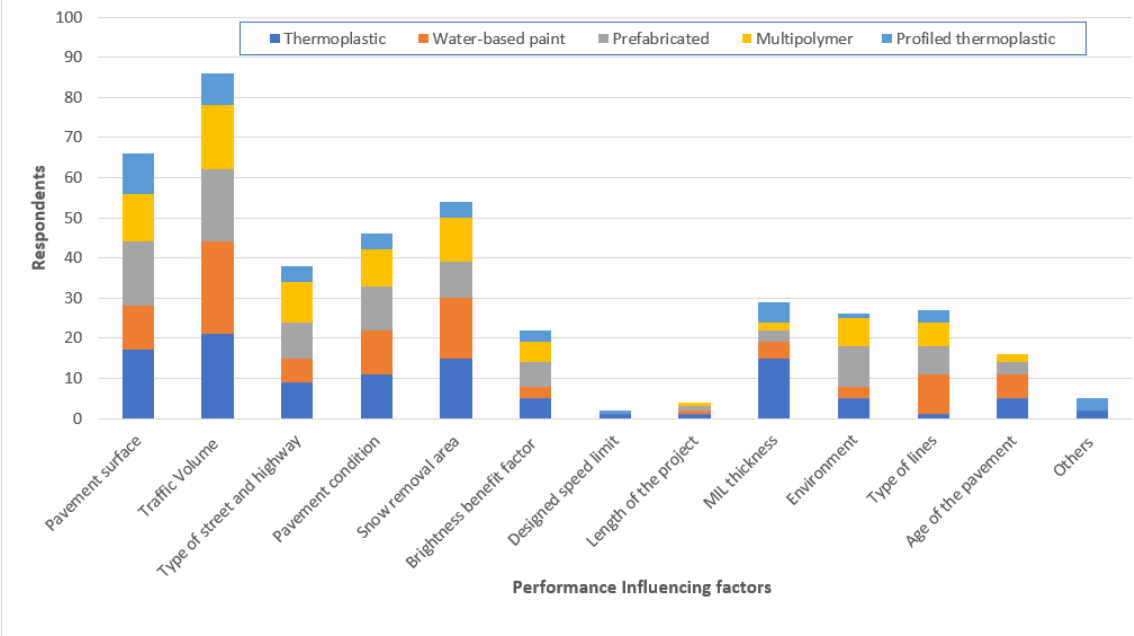
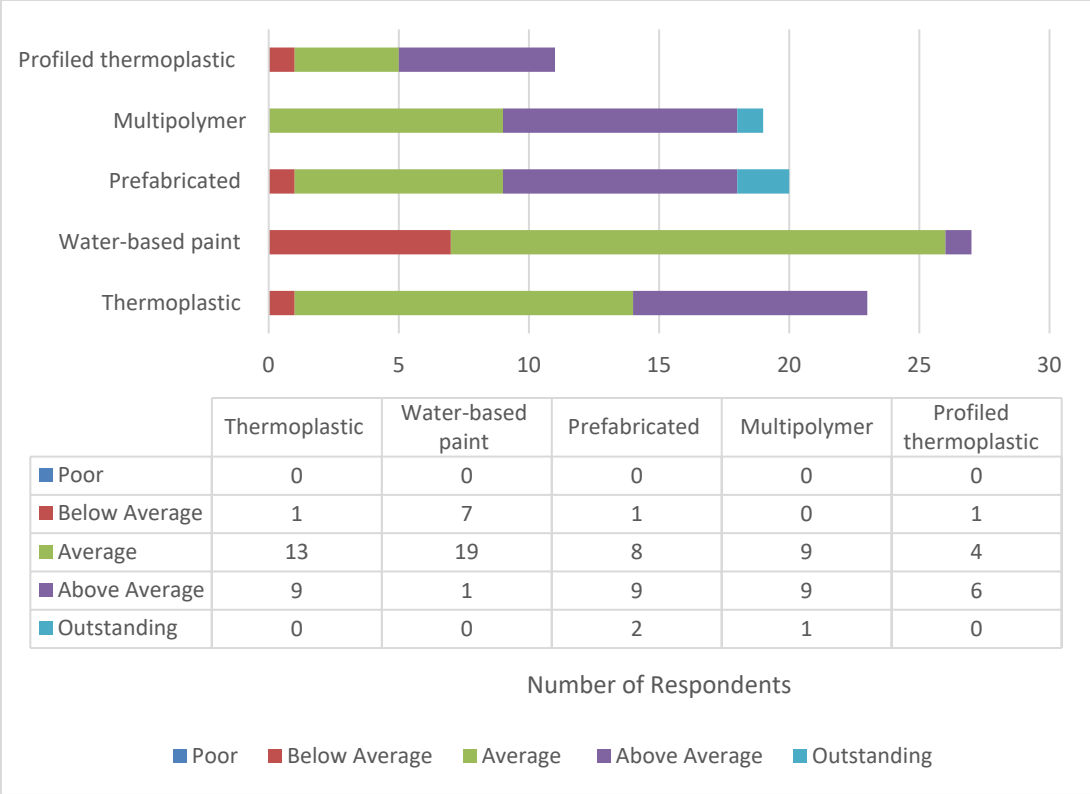


Figure 11 Performance Influence Factors of Different Pavement Markings Based on the Respondents Viewpoint.

2.3.3.2.5 Respondents' Views on the Performance Rating of Marking Material

This question was primarily designed to understand the performance of various marking material types from respondents' perspectives. The question was phrased as "What is the performance rating of this marking in your district/division?" As indicated in **Figure 12**, for thermoplastic, out of the 23 participants, 13 rated the performance of this marking as "average," and 9 people rated it "above average." For water-based paint marking, out of the 27 respondents, 19 people rated it "average," 7 rated it "below average," and only 1 selected it as "above average." For prefabricated multipolymer and profiled thermoplastic, fewer than half of the respondents chose "average," 1 chose "below average," and the remaining respondents rated these markings above average.



	Thermoplastic	Water-based paint	Prefabricated	Multipolymer	Profiled thermoplastic
Poor	0	0	0	0	0
Below Average	1	7	1	0	1
Average	13	19	8	9	4
Above Average	9	1	9	9	6
Outstanding	0	0	2	1	0

Figure 12 Performance Rating of Each Specific Pavement Marking Based Respondents Viewpoint

2.3.3.2.6 Respondents' Views on Marking Material Selection Factors

This question was basically designed to understand the most crucial material selection factors when the relevant authorities decide to install markings on a particular road project. The question was phrased as "What are the considered selection factors of this pavement marking? (Multiple Choices)." As identical questions were asked for all marking types, the survey results for this question were combined in one single figure and table.

As illustrated in **Figure 13** and **Table 11,** from the ADT and type of road to speed limit and pavement condition, the respondents selected broad factors playing a role in the selection of marking material. However, according to **Figure 13**, the ADT, followed by pavement surface, snow removal area, type of highways/roads, and remaining pavement service life, were selected by many respondents as the main factors that could affect the decision of road authorities in the selection of pavement

markings. In addition, some of the participants noted selection factors other than those specified in this question. These factors include (1) surface type, (2) cost, and (3) road safety.

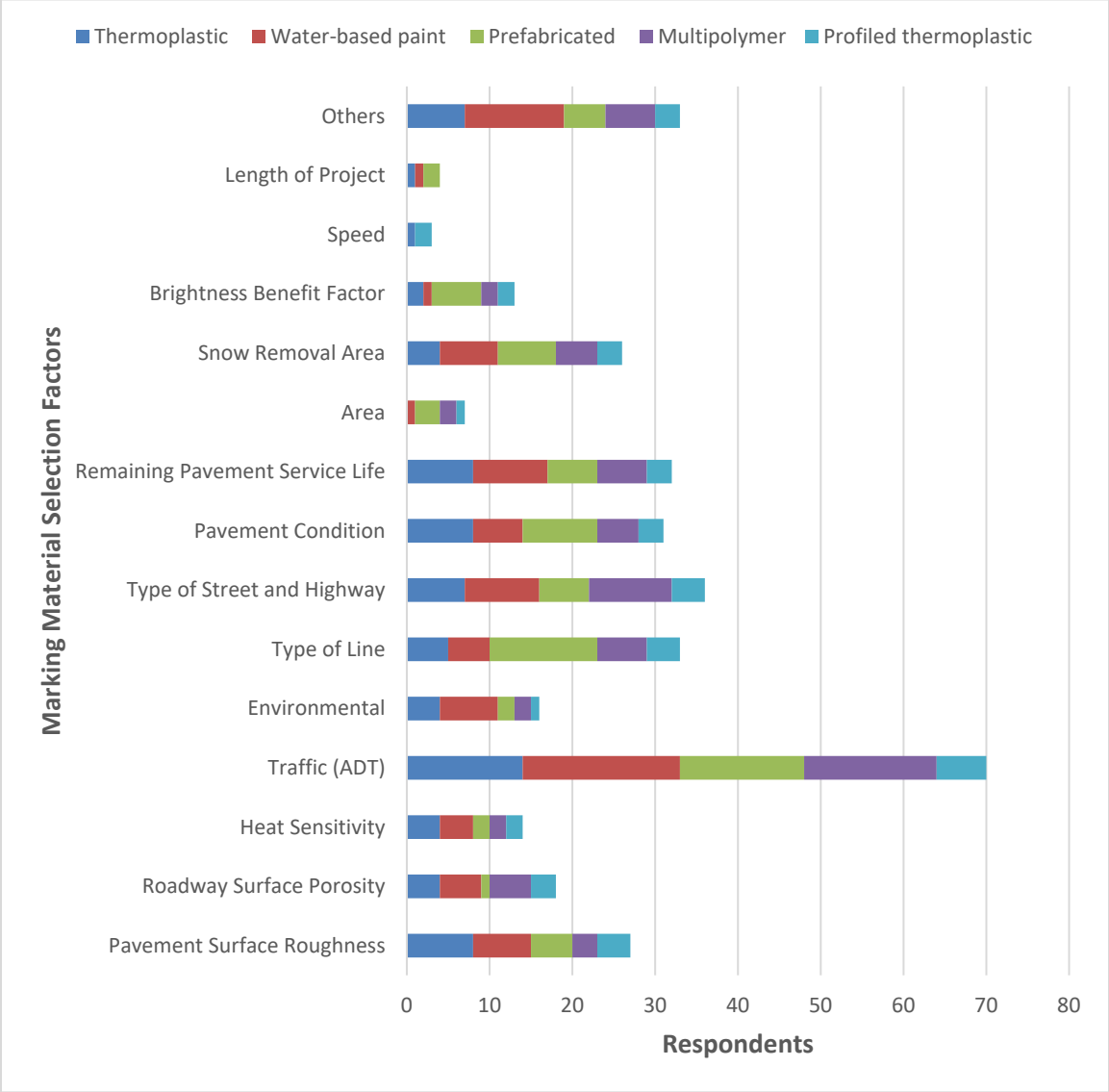


Figure 13 Pavement Marking Material Selection Factors Based on the Respondents viewpoint.

Table 11 Pavement Marking Material Selection Factors

Pavement Marking Type	Thermoplastic	Water-based Paint	Prefabricated	Multipolymer	Profiled thermoplastic
	Responses				
Pavement Surface Roughness	8	7	5	3	4
Roadway Surface Porosity	4	5	1	5	3
Heat Sensitivity	4	4	2	2	2
Traffic (ADT)	14	19	15	16	6
Environmental	4	7	2	2	1
Type of Line	5	5	13	6	4
Type of Street and Highway	7	9	6	10	4
Pavement Condition	8	6	9	5	3
Remaining Pavement Service Life	8	9	6	6	3
Area	0	1	3	2	1
Snow Removal Area	4	7	7	5	3
Brightness Benefit Factor	2	1	6	2	2
Speed	1	0	0	0	2
Length of Project	1	1	2	0	0
Others	7	12	5	6	3
Others - Specified by the respondents	Pavement age, pavement type, historically wet area so we use all weather thermoplastic. Cost	Used temporary. Used in rural areas. Used annually. Cost. Surface type.	Applied in places where durability matters	Used mostly in urban areas such as Las Vegas, Reno, Elko, as well as interstates and higher volume trafficked routes.	dark, rural with high ROR/head on crashes w/ higher than 45 MPH posted speed. Safety
	TDOT is over 90% Thermoplastic on all types of pavements	Used for short term.	Type of surface	surface type, Final stripe applications	
	Permanent Stripe vs. Temporary	Temporary stripe	Do not use except temp. application		Accident reports and condition of existing stripe, and shoulder widen and pavement surface thickness
Answered	24	27	21	21	11
Skipped	10	8	14	14	24

2.3.3.2.7 Respondents' Views on Road Marking Material Thickness

This question was designed to understand the normal thickness of thermoplastic and profiled thermoplastic used in practice from field engineers' points of view. As similar questions were asked for all marking types, the survey results for these questions were combined in **Table 12**. As indicated in **Table 12**, the survey participants noted different thicknesses for these markings. For thermoplastic, the thickness of road marking ranges from 60 to 125 mils, and for profiled thermoplastic, it ranges from 60 to 350 mils, based on the respondents' views.

Table 12 Responses to Marking Material Thickness

	Thermoplastic	Profiled thermoplastic
1	90 and 125 mils	350
2	90 - 100 mil	60 to 90 mils
3	100 mil	n/a
4	2	100 mils
5	90 or 125 mils	90-125 mils
6	100 mil	90 Mil for centerline and 60 Mil for edge line
7	90	125 to 145 mils
8	120 mil	100
9	90 mil-125 mil	Bumps and long line combined barely meeting the spec min.
10	90 mil at the edge and not more than 125 mil in the center for long line markings	90 mil cap and 300 mil bumps. All of our profile has been done in a two-step process.
11	60 mils for retrace 100 mils else.	
12	90	
13	90 mil	
14	100 mils	
15	100mil for new applications; 60 mil for restripes (generally 3 cycles before removing and resetting cycle)	
16	100 MIL on Seals and 90 MIL on ACP/Concrete	
17	90	
18	90 mil new and 60mil restripe	
19	Depends on if it is retraced 90 MIL or a new surface 100MIL	
20	100 mils - Varies	100 mill & 500 mil Bump
Answered	20	11
Skipped	15	24

2.3.3.2.8 Respondents' Views on Pavement Marking Maintenance Approaches

This question was primarily designed to understand the practical pavement marking maintenance approaches from participants' points of view. Particularly, the question was phrased as "What is (are) the typical maintenance method(s) for this Pavement Marking? (Multiple Choices)." As identical questions were asked for all marking types, the survey results for these similar questions were combined and presented in one chart and table.

As illustrated in **Figure 14** and **Table 13**, from the visual nighttime inspection method to the comparison panel technique, the respondents selected various approaches for quality control of pavement markings. However, according to **Figure 14**, the nighttime inspection method, followed by the measured retro-reflectivity method and expected service life method, are selected as primary techniques for quality control of pavement marking material by many respondents.

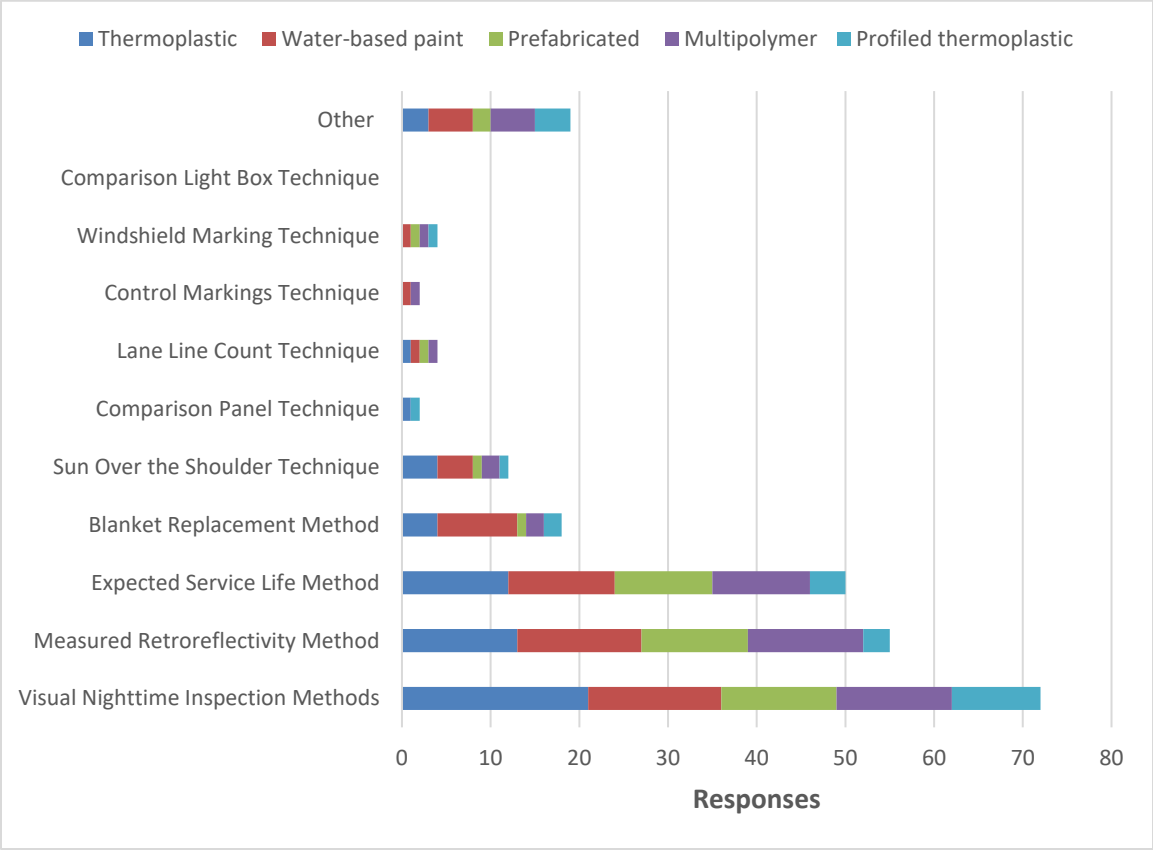


Figure 14 Pavement Marking Maintenance Approach Respondents Input

Table 13 Pavement Marking Maintenance Approaches- Respondents Input

Res	Maintenance Method	Thermoplastic	Water-based Paint	Prefabricated	Multipolymer	Profiled thermoplastic
		Responses				
1	Visual Nighttime Inspection Methods	21	15	13	13	10
2	Measured Retro reflectivity Method	13	14	12	13	3
3	Expected Service Life Method	12	12	11	11	4
4	Blanket Replacement Method	4	9	1	2	2
5	Sun Over the Shoulder Technique	4	4	1	2	1
6	Comparison Panel Technique	1	0	0	0	1
7	Lane Line Count Technique	1	1	1	1	0
8	Control Markings Technique	0	1	0	1	0
9	Windshield Marking Technique	0	1	1	1	1
10	Comparison Light Box Technique	0	0	0	0	0
11	Other	3	5	2	5	4
	Others - Specified by the respondents	Test line durability	After pavement repair. Replaced on a timed interval. Test line durability	Test line durability	Test line durability	On-site inspection to see if still audible.
		Once service life has been reached, waterborne paint is over the top. Only measure reflectivity at install. Used to contract retro reflectivity readings yearly through RMC project have discontinued the practice.	In Quebec, the Water-Based Paint is used annually to re-mark all marking on the road network. We have application rate and thickness requirements. We also have requirements for initial retro reflectivity.	For long line marking if we used this type of material, it would likely be a combination of handheld and mobile retro data collection and visual nighttime inspection from the driver's seat.	Replaced on a schedule or when the stripe is gone.	Audible Check, Drive on
	Answered	17	28	21	21	11
	Skipped	18	7	14	14	24

2.3.3.2.9 Respondents' Views on Challenges of TxDOT Pavement Marking Material Quality Control Procedures

This question was primarily designed to understand any challenges in the TxDOT quality control procedures for pavement marking from participants' points of view. More importantly, this question aimed to collect field practitioners' suggestions/recommendations for improving the TxDOT quality control manual. Particularly, the question was phrased as "Do you face any specific challenges in satisfying the inspection/quality control criteria on Thermoplastic Pavement Marking specified in the TxDOT manual? Please also specify if you have any specific recommendations for improvement in the TxDOT quality control procedures." As similar questions were asked for all marking types, the survey results for these questions were combined in one table. As is shown in **Table 14**, we have received some valuable recommendations.

Table 14 Challenges on TxDOT Pavement Marking Quality Control Procedures-Respondents View

Res.	Thermoplastic	Water-based Paint	Prefabricated	Multipolymer	Profiled thermoplastic
1	Retro readings taken from 3 to 10 days may not be as beneficial if they were taken 20 to 30 days. May be more accurate to wait longer	We have a higher min air/pavement temp required (50F) instead of 40F	Preparation, especially of concrete, is vital to the performance of tape	Nevada DOT respondent does not follow the TxDOT manual requirements.	No
2	None	Must inspect	None	No	None
3	The installation using a torch can vary wildly depending on the installer. We should prefer them getting torched a little too much versus not enough, the bond created is more important than perfect retros. The installer can always add elements afterward as well.	Nevada DOT respondent does not use TxDOT manual.	No	Sometimes, we observe phenomenon darkening of the marking lines with Epoxy (result of poor mixing of components or too much of either of the two components. This has a direct impact on the marking's durability.	N/A
4	None	It's difficult to establish with accuracy the application rate (thickness).	None	No	No
5	N/A	N/A	N/A	N/A	rough or uneven surface
6	We don't use TxDOT manual	N/A	N/A	N/A	Not anymore
7	N/A Link does not work in the pdf.	N/A	N/A. Link doesn't work in PDF form	N/A. Link will not work in PDF	Yes. Contractor place bumps and then wait months to return to perform

Res.	Thermoplastic	Water-based Paint	Prefabricated	Multipolymer	Profiled thermoplastic
					the long line over them.
8	N/A	We don't use TxDOT manual	N/A	No	No
9	WE don't use TxDOT manual	N/A Links in PDF don't work	no, biggest challenge is cost.	Dry times 20+ minutes	
10	NO	For Missouri for Paint applied by contractors we utilize mobile retro services to validate applications and performance criteria before accepting long line markings. We use this service to perform Quality Assurance reviews on random segments of our maintained applied striping to get a feel for the statewide performance of our markings applied by our crews.	No problems	Not used	
11	Mobile Reflectometer	No.	No	No	
12	No Qc/Qa challenges. Would like to see minimum retro requirements raised for standard spec 666.	We don't use TxDOT manual.			
13	N/A	Temperature and snowplows			
14	Measurement of retro reflectivity on a Grade 3 seal coat is difficult.	no			
15					TCP Concerns Keep traffic off Bumps until set And brightness Of stripe

2.3.3.2.10 Respondents' Views on Special Specifications Used for Marking Materials

This question was primarily designed to understand any special specifications used for each specific pavement marking type from the participants' points of view. More importantly, this question aimed to identify manuals and handbooks for pavement marking from other states/countries, which could be used for future tasks of this research project. Particularly, the question was phrased as "Do you use any other special specification for Thermoplastic Pavement Marking (Y/N)?" As a similar question was asked for all pavement marking types, the survey results for these

similar questions were combined in **Figure 15**. Subsequently, the research team received valuable feedback and manuals, as shown in **Table 15**.

Figure 15 Special Specification for Thermoplastic Pavement Marking Respondents View

Table 15 Special Specifications for Thermoplastic Pavement Marking-Respondents Input

Res.	Thermoplastic	Water-based Paint	Prefabricated	Multipolymer
1	Pavement age requirement: For pavements one year of older, spray thermoplastic shall be applied when the pavement surface and the ambient air temperature are 70F For pavements less than six months old, spray thermoplastic shall be applied when the pavement surface and the ambient air temperature are 50F and rising Spray thermoplastic applied at 45 mils.	Traffic paint Type 1 shall be applied when the pavement and air temperature are 50F and above. Traffic paint Type 1A shall be applied when the pavement and air temperature are between 35F and 50F. ii. Glass beads Type A shall be applied at the rate of 15 pounds per 100 square feet of Type 1 traffic paint applied. iii. Glass beads Type A shall be applied at the rate of 8 pounds per 100 square feet of Type 1A traffic paint applied. iv. Type 1 traffic paint shall be applied at the rate of 22 gallons per mile of 4-inch solid line and/or at 1.25 gallons per 100 square feet. v. Type 1A traffic paint shall be applied at the rate of 16 gallons per mile of 4-inch solid line and/or at 0.94 gallon per 100 square feet. vi. Coning of the line is required because the pavement marking is not track free in 2 minutes or less.	TEM 301-20.3 Preformed Thermoplastic thickness specs for bicycle facility markings (90 vs 125 mil)	Nevada DOT 2014 Standard Specifications for Road and Bridge Construction Sections 632, 729, and 730 as well as additional pull sheet changes since the original manual publication. Pull sheet changes available upon request. https://www.dot.nv.gov/doing-business/about-ndot/ndot-divisions/engineering/design/standard-specifications-and-plans
2	AWT 6149	Don't have the # but we use a high build paint to cap thermoplastic to extend the life of the thermo	No	for grooved in markings.

Res.	Thermoplastic	Water-based Paint	Prefabricated	Multipolymer
3	Specification in PennDOT Publication 408, Section 960	Nevada DOT Standard Specifications for Road and Bridge Construction Sections 632, 729, and 730 along with the associated pull sheet changes since original publication of the manual.	PennDOT Pub 408, Section 965 for Preformed Thermoplastic, and special provisions for preformed striping tape.	Item 6020, Item 6038
4	CDOT Standard specification	https://edocspublic.dot.state.mn.us/edocs_public/DMResultSet/download?docId=13891275 - See 2582	CDOT Spec and Standard	No
5	UDOT specification # 2768	PennDOT Publication 408, Section 962	Spec. # 07268	
6	KDOT Specification 806 - Durable Pavement Marking	CDOT standard specification	KDOT Specification 806 - Durable Pavement Markings	KDOT Specification 2200
7	CDOT Specification	UDOT spec # 07265	Grooved (wet reflective)	Manufacturer recommendations
8	Grooved	KDOT Specification 807 - Painted Pavement Marking	Iowa DOT standards and specifications.	Must be evaluated by NTPEP
9	AASHTO M249	CDOT Spec	https://www.tn.gov/tdot/tdot-construction-division/transportation-construction-division-resources.html	
10	SS6040	High build		
11		Iowa DOT standards and specifications.		
12		Performance-based restripe not a large amount used across the state		
13		Must be NTPEP evaluated.		
14	Elimination - Water blasting grind stripe material only, not road surface and black thermo			

For multipolymers and profiled thermoplastics, questions about material and construction specifications were asked in the survey. The research team received some references and feedback for the specifications of these two types of markings, which will be used in future tasks of this project.

2.3.3.2.11 Respondents' Views on Challenges of the Specifications for Marking Practice

This question was primarily designed to gather information related to challenges in implementing pavement marking specifications and manuals from participants' points of view. More importantly, this question aimed to collect any suggestions/recommendations for improving the specifications that are used in practice. Particularly, the question was phrased as "Do you face any challenges with implementing the specifications you are using for this marking (Y/N)?" As similar questions were asked for all marking types, the survey results for these similar

questions were combined in one table and chart. As is shown in **Figure 16** and **Table 16**, we have received some valuable recommendations.

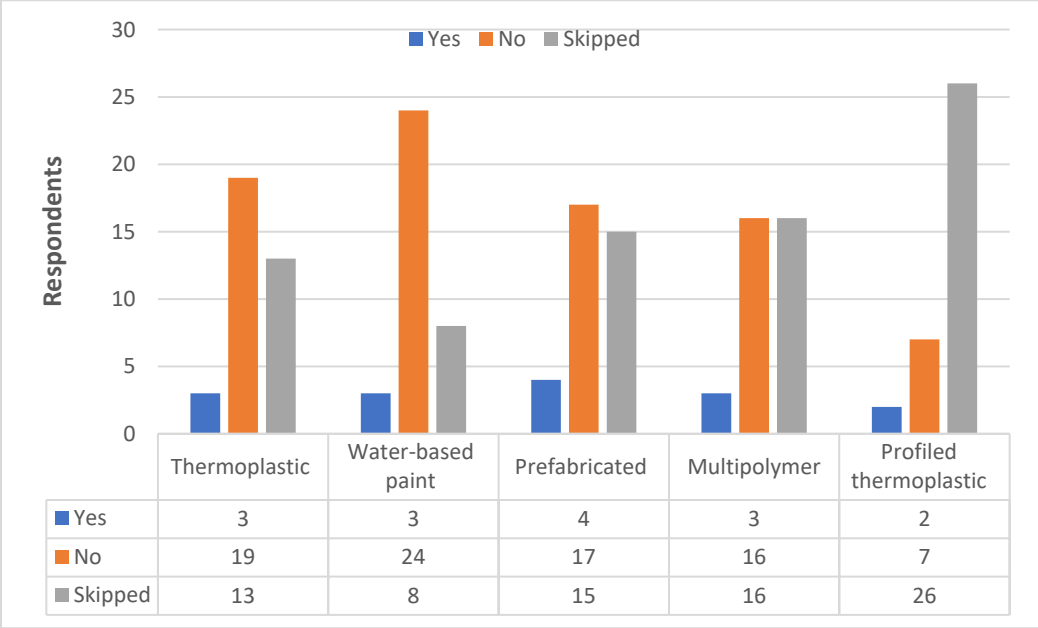


Figure 16 Respondents View on the Challenges of Specifications That Were Used in Practice

Table 16 Response of the Survey Participants on The Challenges of the Specifications That Were Used in Practice

	Challenges on Marking Specifications				
Res.	**Thermoplastic**	**Water-based Paint**	**Prefabricated**	**Multipolymer**	**Profiled thermoplastic**
1	Late season installations of thermo in Kansas tend to fail over winter months.	Surface type and AADT play a factor in the longevity of waterborne traffic paint	Most regions refuse to use Preformed anymore due to perceived poor performance.	Until recently we were only using/allowing slow cure epoxy which made installation times long and required MOT. We have just introduced an updated spec to allow fast dry epoxy which we anticipate will help with this issue.	embedding beads for surface top.

2	Currently having issues with meeting reflectivity due to bead types available.	Striping in the spring really cannot begin until our roads are washed clean of winter chemicals with a few good rains and then temperature is the other defining parameter. Our specs specify 50 degrees and climbing for air and surface temperature before striping and we recommend 60 degrees and climbing for our major roads to get a quicker no track time with the heavier traffic volumes.	Weather application window	Products are not used highly inside of the State. Causing cost and availability to be challenges.	The time frame for the long line as well as ensuring bump thickness.
3		Recently has been a shortage and we have used a 30 MIL thermo in its place.	Improper application of prefabricated pavement markings	verifying consistent thickness and doming of the marking due to incorrect application temperature and equipment.	
4	Humidity/Wetness test without sun				

2.3.3.2.12 Respondents' Views on Application Verification of Pavement Marking

This question was designed to gather information related to application verification of pavement marking during quality control measures from participants' perspectives. Particularly, the question was phrased as "How would you verify the application rate of this marking in the field, i.e., thickness, volume, or rate, during your quality control procedure?" As similar questions were asked for all marking types, the survey results for these questions were combined in one table. As shown in **Table 17**, we have received a variety of information and feedback regarding how to validate the application of pavement marking, which will greatly help in future tasks.

Table 17 Participants Response on Application Verification of Pavement Marking

Res no.	Thermoplastic	Water-based Paint	Prefabricated	Multipolymer	Profiled thermoplastic
	Responses				
1	Reading from on Board Computers.	TEM 350-8.4 - Data Logging System	Data Logging System attached to striping installation equipment	TEM 350-8.4 Data Logging System	n/a
2	Visual inspection, use tape and micrometer	Yield determination.	visual inspection	Inspection	Micrometer
3	By taking measurements	thickness using tape and micrometer	Inspect contractor while markings are being installed.	Tape and micrometer	Thickness gauge

Res no.	Thermoplastic	Water-based Paint	Prefabricated	Multipolymer	Profiled thermoplastic
4	N/A - I'm guessing this is directed toward long liquid lines	Thickness verified by Nevada Test Methods T509B or T510A. Volume determined by quantity delivered to job site.	thickness	For Epoxy applied on our contracts, the verification of the application rate is not mandatory since the contractor is normally subject to performance requirements. However, for verification purposes, the supervisor can check the application rate using the wet film measurement method. The validation method based on the quantities in the tanks is more complex, since there are two tanks on the stripping truck, one for each of the components.	Visual
5	Take sample mil checks.	We have two main methods for verifying the applications rates of Water-Based Paint Marking, the validation of quantities forms the tanks of stripping truck and the measurement of the wet film thickness with a paint thickness gauge.	We use prefab on stop bars, school zones, crosswalks, arrows, and words. Not really a rate on these types of applications.	Draw down or Data Logging System files	Volume
6	thickness	Draw down and/or Data Logging System File	Adhesion test. Chisel test.	thickness	Test sections prior to beginning.
7	We only use preform	Verify with the contractor.	Check thickness before placement.	Mil plate and on-board computers	Thickness.
8	Preformed Thermoplastic only for messages	thickness	On-site inspections, mobile retro reflectivity/width inspections	Physical mil checks for the first mile, then KDOT uses data logging system to verify mils and application rates.	
9	Mil checks are required. Mils are verified with calipers by inspector	Mil plates and on-board computer	Reflectivity and Adhesion	micrometer	
10	micrometer	By number of feet painted and the gallons they use and convert them to mill thickness and to make sure it satisfies the spec.	Beginning and Ending location.	Footage & usage counters quality control strips	
11	On-site inspection, and mobile retro reflectivity/width reviews	Data logger. Either Epic Solution or Skip line data logging equipment	quantities	DLS, field inspection	
12	TEM 350-8.4 - Data Logging System According to C&MS Items 640, striping equipment for traffic paint, polyester, thermoplastic, epoxy, spray thermoplastic and work zone marking shall be equipped with a computerized Data Logging System (DLS). The data recording requirements depends on the material type and shall include the following information for long line markings only: 1. Measure and record application vehicle speed to the nearest 0.1 miles per	For maintenance operations, the TMA driver immediately behind the striper typically conducts the quality control at the beginning of a run, getting out of the truck, if possible, to make sure the line width is good and that the bead application rate and embedment is sufficient. We call for 60% bead embedment, mil thickness calibrations are the starting point, but bead embedment is used to adjust thickness for any given pavement surface. For contractor applied lines they the specs call us for a minimum mil thickness, but also requires the contractor to increase	I may be misinterpreting what you mean by "prefabricated pavement markings" as this is not a term we use, but again assuming preformed thermoplastic or cold applied tapes since these are prefabricated in specific shapes and thicknesses the quality control is typically done through out materials lab certify the product meets specification upon award of a materials contract and quality	Thickness by using Nevada Test Method T509B or T510A. Volume by amount of quantity delivered to job site.	

Res no.	Thermoplastic	Water-based Paint	Prefabricated	Multipolymer	Profiled thermoplastic
	hour. 2. Measure and record the weight and/or volume amount of material used by color. 3. Measure and record the weight or volume amount of material used by line type. 4. Measure and record the weight of glass beads. 5. Measure and record the weight of wet reflective optics 6. Measure and record the pavement surface temperature. 7. Measure and record the air temperature. 8. Measure and record the dew point (thermoplastic and spray thermoplastic not included) 9. Measure and record the humidity (thermoplastic and spray thermoplastic not included). 10. Calculate and record average materials application rates and film thickness over the section painted. 11. Measure and record temperature in the kettle and at the point of application (thermoplastic and spray thermoplastic only)	mil thickness to achieve 60% bead embedment. Our inspectors typically do not inspect the embedment (although I know of one case where they have) so we rely on mobile retro readings to validate the quality of the line, but those readings are taken 30-45 days after the application to allow a poor application to become more evident by allowing more time for possible bead loss.	assurance testing if there are any questions after the award.		
13	Mil thickness gauged	On-site inspection	The thickness is set by the manufacturer. The volume is measured by how many sheets are used.	Spray a sign blank and test the mil thickness with a standard mill gauge card.	
14	inspection	On board computers		quantities	
15	We are using quantities	wet film gauge		Not used	
16	Spot check thicknesses with tape and caliper.	Data Logging System submittal, field inspection personnel		Mil gauge	
17	We make the contractor perform a test section prior to beginning the work.	inspection			
18	I am unsure if we are doing this. Will check into it.	Yield based on volume and rate.			
19	Thickness, rate.	Mobile Reflectometer			

Res no.	Thermoplastic	Water-based Paint	Prefabricated	Multipolymer	Profiled thermoplastic
20	A micrometer is used to check thickness. The rate is figured by calculating how many tons are used per linear foot.	Rate. We check the gallons per mile on occasion if we see an issue with the look of the stripe. The speed of the paint truck is a factor as well.			
21		Mil gauge			
22		The volume is calculated by making sure they are using 20 gallons per mile.			
23	Duct Tape or AL Plate Placed prior to striping - verify striper speed, pull tape/plate and measure with caliper	Speed of striping rig, pavement absorption, bleed thru stripe and gallons per feet.	Review Material Packaging		Measure in the field

2.3.3.2.13 Respondents' Comments on Improvement of Pavement Marking

This question was originally designed to gather the general comments of the participants on the improvement of pavement marking. Particularly, the question was phrased as "Do you have any comments and improvement suggestions on this marking?" As similar questions were asked for all marking types, the survey results for these similar questions were combined in one table. As is shown in **Table 18**, we have received some valuable recommendations.

Table 18 Survey Participants Comments and Suggestions on Marking Improvement

Res, No.	Thermoplastic	Water-based paint	Prefabricated	Multipolymer
	Responses			
1	It has better performance on Asphalt surfaces than concrete surfaces.	In the south of the state where numerous days of beating sunlight hit the pavements, sometimes the water-based paints are durable and retroreflective, but the yellow color fades to a point whereas the line needs re-striping despite the durability and higher reflectivity measurements.	We answer this as tape	Have material supplier warranty material before it is placed on PQL. Have material supplier certify contractor to use material. Hold contractor to observation period to ensure markings are applied correctly.
2	We do not used Thermoplastics for long lines	It's important to follow the installation conditions. Weather and road condition will directly influence the marking's durability.	Make sure there is enough heat applied, or pressure applied to ensure longevity of marking.	Glass beads are included in unit price
3	Apply within Manufacturer's Temp time. Applying them to cold shortens life cycle.	Grooved waterborne paint last longer than 1 year	Use Wet Reflective Tapes and put in Groove	

4	On profile thermo stipe I wish we would make the installation a single pass or give a time frame the long line must be placed over the bumps.	Using the right sized glass bead for the final dry film thickness	It seems like the market needs more competitors with comparable products.	
5	Calibration is the first step, making sure you start the process on the right foot, but QC during operations to make sure the application rates match the road surface is very important as one calibration doesn't work for all surfaces. Speed is also a very critical aspect of striper operations, especially as you are applying larger glass beads. For our crews 10 mph is the recommended speed for our smaller P beads (12 mph max) and with the larger Type L bead that has more inertia 8 mph is the maximum application speed with many crews traveling at 7 mph. Speed affects application rates as well as bead embedment and consistent speed is also very critical as variations in speed result in variations in application rates as calibration is fixed for one speed. Most of our stripers are set up with a type of slow speed cruise control using programming features of the Cummins engine and Allison transmission. A truck will have a setting for each bead type using the engine RPM hold feature and locking the transmission into a specific gear to maintain a very consistent travel speed. Currently the operator must modulate braking downhill (RPM hold works great on flat and uphill on its own) to keep from picking up speed, but we have been working with Cummins to update engine programing to incorporate the engine brake automatically on downhill runs. We also conduct annual trainings for our crews through our paint vendor to keep the up to speed on the best practices of pavement markings...also to help address the large turnover rates with employees we are experiencing		With respect to intersection markings, while they are more costly up front, the long-term benefits of more reliable presence and the decrease in resource demands compared to having to repeatedly refresh painted markings makes them more cost effective in the long run...especially as staffing becomes more challenging.	Link to NDDOT design manual for current PMM selection guide, located in Ch III: Roadway Design: https://www.dot.nd.gov/manuals/design/designmanual/designmanual.htm
6				Two-step process - pay each step individually, bumps vs. stripe, better tracking of footage

2.3.3.3 Part Three – New Technology and Material

As stated earlier in this report, part three of the survey was designed to collect information with regard to new technology and material used for pavement marking. The first question was phrased as "Do you know some of the new technologies and materials used as pavement markings? (Y/N)" Out of the 35 individuals, 12 responded "yes," confirming that some new technologies are available, 15 said "no," and 8 skipped this question. **Figure 17** and **Table 19** show the respondents' distribution for new technology.

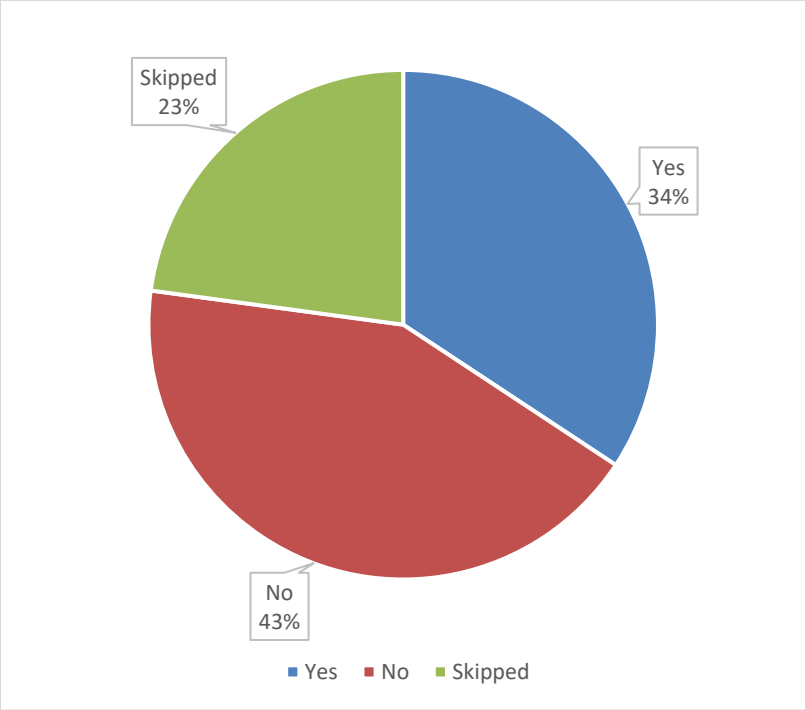


Figure 17 Respondents Distribution on New Technology

Table 19 Respondents Suggestions on New Marking Material and Technology

Responses	Suggestions
1	Recessed wet reflective pavement markings
2	Nevada DOT uses quite a bit of preformed thermoplastic pavement markings for crosswalks, stop bars, yield bars, arrows, legends, and symbols. NDOT also uses raised reflective and non-reflective pavement markings for inside lane lines in Las Vegas area. NDOT is currently in the process of writing a newer test method for the use of mobile retro-reflectivity equipment.
3	We are using structured pavement markings as an all-weather marking without ceramic elements
4	Low VOC Alkyld Paint, Temporary Removable Pavement Marking Tape, Antiskid products.
5	MnDOT has adopted policy to use the special provision for initial wet continuous numbers of 200 mcd/m2/lux for long lines on projects with bid letting dates for 2022 and into the future based on research conducted by TTI on our behalf: https://researchprojects.dot.state.mn.us/projectpages/pages/projectDetails.jsf?id=18068&type=CONTRACT&jftfdi=&jffi=projectDetails%3Fid%3D18068%26type%3DCONTRACT The special provision can be found under 2582 in the following: https://edocspublic.dot.state.mn.us/edocs_public/DMResultSet/download?docId=13891275
6	what new technologies are you referring?
7	Wet weather tape and wet weather wet reflective beads are used.
8	Use of data loggers on striping trucks. Mobile Retro Units. New equipment / processes.

9	MMA, polymer thermoplastic
10	I have heard of ribbon placement. We haven't used it though.
11	SS6439 SS6373 SS6149
12	Element Retroreflective

The follow-up question that was asked in this survey directed participants to define the conditions in which new materials and technology have been used. **Table 20** shows some valuable points that the respondents mentioned regarding this subject.

Table 20 New Pavement Marking Material and Technology- Participants Response

Respondents	**Responses**
1	All resurfacing and reconstruction projects on ODOT-maintained interstate and multilane highways should receive R-WR markings as their eventual final permanent long line pavement markings as defined in the C&MS 641.08 (e.g., edge line, lane line, centerline, and channelizing lines over 200 feet). This includes the corresponding entrance and exit ramps. Cities and other jurisdictions are not required to implement R-WR markings. For information on wet reflective work zone pavement, markings, see 605-11.11.1.
2	On various projects
3	In the medium to long term, if we obtain good results on our Test deck with the Low VOC alkyd paints, we could replace high VOC alkyd paints with low VOC ones. As we observe on our test deck, the low COV alkyd paints have lower durability the water-based paint, we will use the low VOC alkyd paints only between October 15 and May 1st as we use high VOC alkyd paints now.
4	They will be used on new construction, reconstruction, and overlay projects with a centerline length of 1 mile or more.
5	N/A
6	We are using them on high-volume roads.
7	Data loggers - verify material (binder) mils and glass bead drop rates. Mobile Retro Units - verify retro values on lines. Either purchased or used by DOT or contractor.
8	Case by case
9	May try for a concrete pavement job.
10	SS approval by TRF & DES
11	Add w/TY II & III Beads

In addition to the above recommendations, some participants provided useful references on new technology and marking materials, significantly assisting the research in future chapters.

The last question of this survey aimed to gather information regarding participants' overall suggestions and comments on the improvement of TxDOT pavement marking materials. Out of the 35 respondents, only 4 people provided their recommendation, as is shown in **Table 21**.

Table 21 Respondents' Comments on the Improvement of TxDOT Manual

Respondents	Suggestions on TxDOT Manual
1	Possible use of data loggers.
2	The TxDOT manual is dated 2004. Perhaps it is time to review/update the manual based on everything learned since 2004 as well as current practices and slap a new 2022 date on it :) Best of luck, and feel free to email with any questions.
3	Extend the time to take retros past 10 days, too easy to use excessive cheap beads, but long term does not have as good retro
4	If not in place, already consider having pavement marking installers and inspectors' QA/QC certified through an in-house certification. See: Mid-Atlantic Region Technician Certification Program (MARTCP) https://www.roads.maryland.gov/mdotsha/pages/Index.aspx?PageId=53

Chapter 3: Investigation of Types of Marking Materials and Quality Control Approaches

3.1 Overview

Chapter 3 aims to identify the best-case examples and review practices for various marking materials used across the U.S. and other countries and to investigate the reasons for using a particular marking material on different pavement types. In addition, this chapter also explores the quality control approaches and methods, including verifying selected thickness or quantity of markings among other practices, in Texas and other states, and in other countries. The research team investigated the following two aspects:

(1) **Types of marking materials used and reasons**

- Pavement marking material selection process
- Application process of marking materials
- Reasons certain pavement materials are not used or not extensively used anymore
- Types of new materials that are in the experimental stage but with promising applications, and
- Recommendations on incorporating advanced/new marking materials, and TxDOT marking materials selection process

(2) **Quality Control Approaches and Methods**

- Surface preparation practices and specifications prior to marking installations, selections of inspection site, and compilation of surface preparation when using durable materials and on Portland cement concrete (PCC) pavements (or rigid pavements), hot-mix asphalt (HMA) pavements, and roadways with a seal coat surface
- Quality control practices and specifications of pavement marking materials

- Pavement marking thickness, width, color, bead dispersion and depth, and nighttime appearance that may impact pavement marking quality
- Best quality assurance measures that continue inspection of the markings for a certain period after placing all markings
- Standards in other states and countries that can be a reference to Texas as a necessary step for evaluating marking quality
- Verification of application rates, and
- Recommendations on pavement marking quality control procedures.

3.2 Types of Marking Materials Used and Reasons

From thermoplastic and water-based paint to methyl methacrylate (MMA), many roadway marking material types have been used across the different U.S. states and in other countries. In this section, related information regarding various marking material types is synthesized.

3.2.1 Thermoplastic

3.2.1.1 Usage of Thermoplastic

Thermoplastic has been the most commonly used marking material in the U.S. in the past six decades. A mixture of four main materials, such as binder, pigment, glass beads, and filler material (usually calcium carbonate, sand, or both), could make thermoplastic. In Texas, thermoplastic pavement marking is widely used due to its sound characteristics, including high durability, readiness for immediate use, high retro-reflectivity, and relatively lower cost (TxDOT, 2004). TxDOT identified this marking as a Type I pavement marking material whose specifications fall under DMS-8220. In the survey conducted in Task 2, all 13 participants from various districts of Texas confirmed that thermoplastic marking is widely used in their areas.

Thermoplastic is also recommended for use in California, per the California Department of Transportation (Caltrans, 2019), mainly in high fog areas where there are visibility concerns, open-graded friction course (OGFC) asphalt, bituminous seals, PCC, and HMA. The Colorado Department of Transportation (CDOT, 2020), however,

only preformed thermoplastic is used for transverse lines and symbols. **Table 22** synthesizes the usage of thermoplastic across the various U.S. states and the possible reasons why this marking is not being used in some states.

Table 22 Thermoplastic Usage Across 14 U.S. States

No	State	Thermoplastic Usage	Source
1	California	Used mainly on fog areas where there are visibility concerns, open-graded friction course (OGFC) asphalt, bituminous seals, PCC, and HMA	(Caltrans, 2019)
2	Colorado	Only preformed thermoplastic is used for transverse lines and symbols	(CDOT, 2020)
3	Illinois	Widely used on HMA, but not on PCC	(IDOT, 2021 and 2015)
4	Iowa[1]	Not used nor have any specifications, but the State's manual predicted its application if specified in a contract	(Iowa DOT, 2015)
5	Kansas	Widely used on asphalt but not on PCC. Material specifications are available both for sprayed and preformed thermoplastic	(KDOT, 2015)
6	Minnesota[2]	No hot applied thermoplastic is used. only preformed thermoplastic is used for transverse lines and symbols	(MnDOT, 2015)
7	Nevada	Hot applied thermoplastic is not used for longline pavement markings. However, preformed thermoplastic is used crosswalks, stop bars, yield bars, legends, arrows, and symbols	(NDOT, 2014), and Survey respondents from Nevada
8	North Dakota[3]	Not used nor having any specifications for this marking	(NDDOT, 2020)
9	New York	Used mainly for longline and hatch	(NYSDOT, 2002)
10	Ohio	Used on asphalt, but it is not recommended for striping long line markings on routes with 2500 or less ADT since these materials must be removed before a chip seal coat can be applied to the pavement	(Ohio DOT, 2021)
11	Oregon	Used and recommended. Both sprayed, and extrusion thermoplastic types were applied in the State.	(Oregon DOT, 2021)
12	Texas	Used mainly on Asphalt and Seal coat, but limited use on concrete	(TxDOT, 2004)
13	Washington	Used across the State and classified as type A	(WSDOT, 2021)
14	Wisconsin	Not an approved material in the State's construction manual	(WisDOT, 2021)

Notes: Reasons if thermoplastic is not being used

[1] A participant of this research survey in Task 2 from Iowa State mentioned that thermoplastic marking is not used in their State because there is limited availability of equipment and vendors/contractors for installation of this marking.

[2] A participant of this research survey from Minnesota also confirmed this issue. Minnesota marking manual reasoned that preformed thermoplastic provides the convenience of both preformed tape and hot-applied thermoplastic.

[3] Require contractors with special equipment that may not be readily available in North Dakota. In addition, the cost of thermoplastic might be prohibitive.

From **Table 22**, it could be concluded that, except for Texas, where the limited use of thermoplastic on concrete is allowed, all the rest of the studied states apply this marking on asphalt, primarily on HMA. **Figure 18** plots the thermoplastic practice distribution across the 14 states covered by Table **22**.

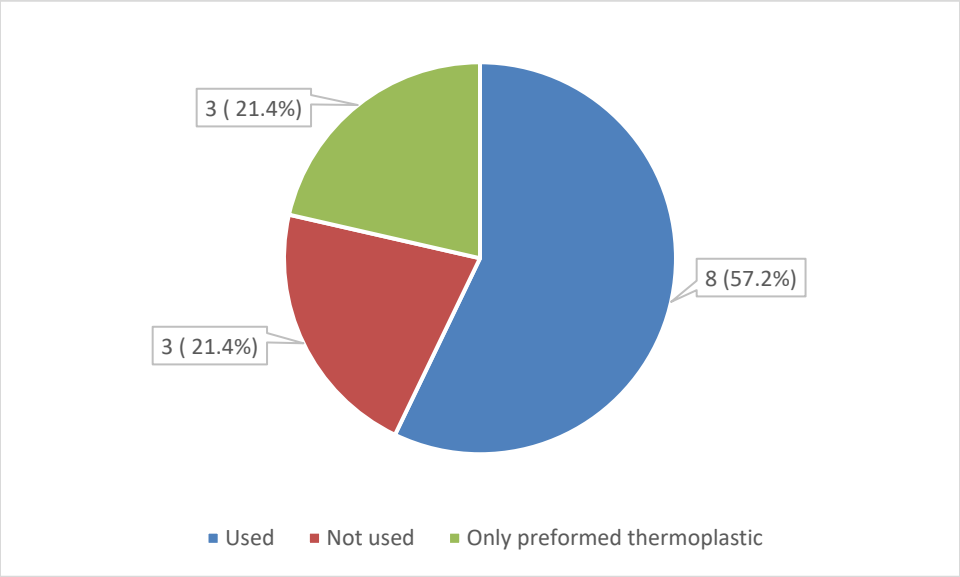


Figure 18 Thermoplastic Practice Distribution Across 14 U.S. States

Internationally, thermoplastic is also approved and widely used by transportation authorities in Australia and some European countries. The Queensland Department of Transport (TMR, 2019) in Australia divided thermoplastic marking into four types: spray, extruded, screed, and preformed thermoplastic. Due to the specialized nature of the equipment required for the application of thermoplastic, except for the screed type of thermoplastic, the other three types of thermoplastic markings are usually installed by private contractors in Queensland (TMR, 2019). According to the U.K.'s Department for Transport (DFT, 2019), hot-applied thermoplastic is usually installed on important roads, such as motorways (interstate highways) in European countries. However, in Quebec, Canada, no thermoplastic marking is used as its transportation authority does not approve this type of marking (Transports Québec, 2019). This fact is also confirmed by a survey participant from Quebec in Task 2. The survey participant mentioned that Quebec Ministère des Transports (Transports Québec) tested thermoplastic marking, but the

result reveals that the marking is not durable enough during winter road maintenance.

3.2.1.2 Thermoplastic Application Process and Methods

Having an effective application procedure and strategy for pavement marking installation is essential to implement the markings appropriately. The durability and retro-reflectivity of thermoplastic markings are highly contingent on its installation procedures since this marking material is highly sensitive to the temperature and pavement surface conditions. According to TxDOT (2004), three application methods are identified for thermoplastic: hot-sprayed, gravity extrusion, and ribbon application. Even though the hot-sprayed application method may not be effective for markings thicker than 100 mils (1 mil = 0.001 inch), it is still the most common approach practiced in Texas. The reason is that, with the hot-sprayed method, the marking can be installed at a faster rate and provides a high surface bond compared to the other two approaches (TxDOT, 2004). Similarly, TMR (2019) also recommends five methods for thermoplastic application, including screeding, spraying, extrusion, profiling, or as preformed material. According to the manual, the application of extruded thermoplastic markings is cost-effective for larger quantities of the marking. For smaller amounts, preformed thermoplastics may be more suitable.

To install thermoplastic marking effectively, TxDOT (2004) recommends that the pavement surface should be clean and dry, and the minimum ambient temperature should not be lower than 55 °F. On the other hand, TMR (2019) mandated that primer, if recommended by the manufacturer, be applied to the surface immediately in advance but concurrent with the application of thermoplastic material. TMR also requires thermoplastic to be applied at a temperature between 180 °C and 200 °C, and meanwhile, that glass beads be applied immediately to the surface of the molten thermoplastic material at a rate of no less than 120 g/m^2. The manual also noted that the minimum thermoplastic application thickness both for longitudinal lines and transverse markings should be at least 79 mils. Considering the importance of ambient temperature during the application of thermoplastics, the Illinois Department of Transportation (IDOT, 2016) restricted the application period

of this marking material between April 15 and November 1 in Illinois. During the installation, DFT (2019) allowed a tolerance of plus or minus 25 mm in the lateral positioning of lane lines.

Since the durability of thermoplastic marking is directly proportional to the application thickness of the material, many states have developed specific guidance regarding the selection of the thickness of this marking. For instance, TxDOT (2014) classified appropriate thermoplastic application thickness into three categories: 100 mils for new markings and retracing water-based markings on surface treatments involving seal coat, 60 mils for retracing on thermoplastic pavement markings, and 90 mils for all other Type I markings. On the other hand, Caltrans (2019) categorized appropriate thermoplastic application thickness based on the pavement surface condition, 100 mils for open-graded friction course and bituminous seals with wet-night or fog area visibility concerns, and 60 mils, 80 mils, or 100 mils (depending on the durability requirements of markings) for PCC and HMA. **Table 23** summarizes different states' and countries' thermoplastic application thickness requirements, while **Figure 19** plots the thermoplastic application thickness across several U.S. states and Australia.

Table 23 Thermoplastic Application Thickness and Glass Beads Rate Across the U.S. States and Australia

No	States	Thermoplastic application thickness	Glass beads rate	Sources
1	**California**	100 mils for open-graded friction course and bituminous seals with wet-night or fog area visibility concerns, and 60 mils, 80 mils, or 100 mils (depending on the durability requirements of markings) for PCC and HMA.	8 lb /100 sqft	(Caltrans, 2019), (Caltrans, 2018)
2	**Illinois**	100 - 110 mils	Not specified in the manual	(IDOT, 2021 and 2015)
3	**Kansas**	For longitudinal markings, a minimum of 90 mils at the edges and a maximum of 125 mils at the center of the stripe. For transverse markings and symbols, a minimum of 125 mils at the edges and a maximum of 160 mils at the center	Not specified in the manual	(KDOT, 2015)
4	**New York**	126 - 189 mils	5.12 lb /100 sqft	(NYSDOT, 2002)
5	**Ohio**[1]	125 mils	12 lb /100 sqft	(Ohio DOT, 2021)
6	**Oregon**	90 - 120 mils	not specified	(Oregon DOT, 2021)
7	**Texas**[2]	100 mils for new markings and retracing water-based markings on surface treatments involving seal coat, 60 mils for retracing on thermoplastic pavement markings, and 90 mils for all other Type I markings	30% - 45% of the total weight of the entire material	(TxDOT, 2014)
8	**Washington**	30 mils for the sprayed thermoplastic material. 125 mils for extruded material	Applied based on the manufacturers' recommendation	(WSDOT, 2021)
9	**Australia**	79 mils	2.46 lb /100 sqft	

Notes

[1] A participant of this research survey from Ohio State specified the normal thermoplastic thickness 90 and 125 mils.

[2] Survey participants from Texas in Task 2 also specified a range of 60 - 100 mils as normal thermoplastic thickness.

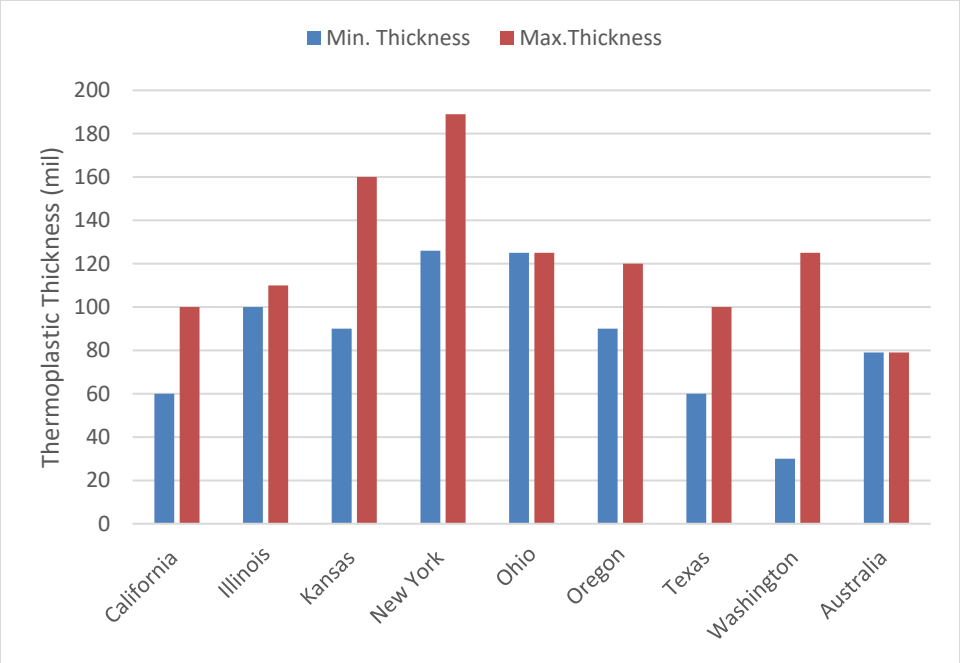


Figure 19 Thermoplastic Application Thickness Across Several U.S. States and Australia

From Table 23 and Figure 19, it can be concluded that New York and Kansas apply thermoplastic with greater thicknesses than Texas. On the other hand, Washington State recommended a much thinner thickness (30 mils) for sprayed thermoplastic, which may not be durable. As mentioned previously, the thickness of thermoplastic directly impacts the service life of the marking. Therefore, it could be cost-effective and appropriate if the thickness of thermoplastic is considered based on the type of roadway and pavement surface condition during the marking material selection process, which will be discussed in Section 3.2.8.

3.2.2 Water-Based Traffic Paint

3.2.2.1 Usage of Water-Based Traffic Paint

Water-based paint marking material is a commonly used marking material in the U.S. One of the important features of traffic paint is that it requires a low initial cost, which makes this marking a favorable option for locations that need markings with low durability. According to TxDOT (2004), traffic paint was widely used in the past in Texas, but its usage has declined due to the popularity of thermoplastic

materials. Three essential elements of traffic paint include pigment, binder, and glass beads. Due to environmental concerns and safety hazards, TxDOT does not use solvent-based paint, which contains a much higher percentage of volatile organic compounds (VOCs). Instead, TxDOT utilizes water-based paint that is highly environmentally friendly and much easier to implement in the field. In TxDOT specifications, this marking is recognized as Type II pavement marking, falling under the specification of DMS-8200.

According to the Wisconsin Department of Transportation (WSDOT, 2021), traffic paint is commonly used across the entire state on all pavement types with a thickness of 16 mils. However, the Washington State Department of Transportation (WSDOT, 2021) argues that installing high-build waterborne paint provides additional service life and more retro-reflectivity than standard waterborne paint since it allows application thickness of greater than 15 mils to accommodate the use of larger beads. WSDOT also indicates another type of traffic paint named low-temperature waterborne paint, designed for application temperature of 35 °F, which allows marking application later into the fall. VDOT (2021) mentions some main advantages of waterborne paint markings: low cost, fast application and drying time, and no solvents required for clean-up. VDOT (2021) specifies the main characteristics of waterborne paint as follows:

- Heat sensitive
- Freezes easily
- Strong ammonia odor
- Humidity may affect drying times
- Can be flushed out with water and/or ammonia
- Generally, not a hazardous waste for disposal - placarding is not required (depending on formulation)
- Reacts adversely to metals other than stainless steel, and
- Requires specially lined drums to prevent chemical reactions, and can settle in the drum.

Water-based paint is widely used in Canada. In 2016, 95% of the total roads were marked with water-based paint. According to Transports Québec (2019), annually, almost all 90,000 km of lines making up the Quebec Ministry of Transport's network have been re-marked with this short-life service material to restore night visibility to markings and ensure the presence of lines until the following spring. Before a water-based paint may be used by crews under contract or by the Ministry's crews, it must be certified. **Figure 20** plots the evolution of the marking products used by Transports Quebec.

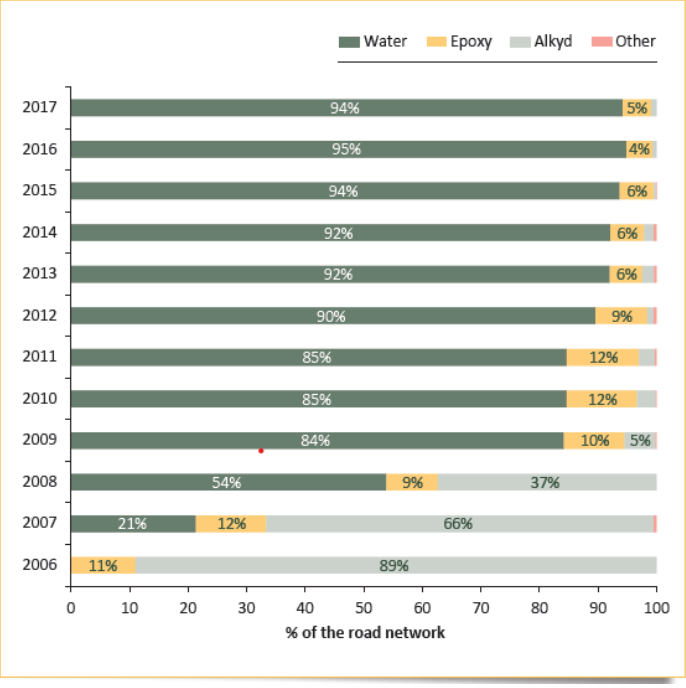


Figure 20 Evolution of the Marking Products Used at the Quebec Ministry of Transportation (*Transports Quebec, 2019*)

For further information, **Table 24** summarizes the usage of traffic paint across various states and other countries.

Table 24 Traffic Paint Usage Across U.S. States and Other Countries

No	States	Traffic Paint Usage	Sources
1	**California**	Both water-based and Acetone based paints are used in the State under State Specification PTWB-01R2 and State Specification PT-150VOC(A). In California, this marking is usually recommended for temporary delineation.	(Caltrans, 2018), (Caltrans, 2019)
2	**Colorado**	High-build waterborne paint is used for lane markings on paved pedestrian/bicycle paths under section 708.05 (material specification) CDOT. Corundum can be applied on the marking surface at a drop rate of 3 – 4 pounds per gallon of paint to enhance skid resistance	(CDOT, 2020)
3	**Illinois**	The usage of water-based paint is recommended for surface road marking (not recessed marking) on the HMA but not on PCC	(IDOT, 2015)
4	**Iowa**	Many types of traffic paints are used and recommended, including standard waterborne paint, solvent-based paint, durable paint, and high-build waterborne paint. However, Solvent-based paint is only allowed if temperature requirements for other types of paint cannot be met.	(Iowa DOT, 2015)
5	**Kansas**	Water-born traffic paint is used for an interim stripe or temporary traffic paint purposes under KDOT specification 807.	(KDOT, 2015)
6	**Minnesota**	Traffic paint is used, but it is not recommended for roadways with high AADT.	(MnDOT, 2015)
7	**Nevada**	Water-born traffic paint is widely used under NDOT specification 729 section on all pavement types.	(NDOT, 2014), and Survey respondents from Nevada
8	**North Dakota**	Water-base pavement marking is widely used for both temporary and permanent purposes under NKDOT specification 880.01	(NDDOT, 2020)
9	**New York**	Traffic paint (standard reflectorized pavement marking paints) is used for longline pavement marking only. This pavement is considered as a non-durable pavement marking used on roadways with low traffic volume (less than 5000 AADT)	(NYSDOT, 2002)
10	**Ohio**	Water-based paint marking is used in the State under the section of 642 Ohio DOT specifications	(Ohio DOT, 2021)
11	**Oregon**	Water-born traffic paint is used for non-durable marking purposes under the specification of Oregon DOT 00860.	(Oregon DOT, 2021)
12	**Texas**	Traffic paint was widely used in the past in Texas State, but its usage has been declined due to the popularity of thermoplastic material. In TxDOT specifications, this marking is recognized as Type II pavement marking, falling under the specification of DMS-8200.	(TxDOT, 2004)
13	**Washington**	Both high-build waterborne paint and standard water-born paint are used across the State	(WSDOT, 2021)
14	**Wisconsin**	Traffic paint is commonly used across the entire State on all pavement types with a thickness of 16 mils.	(WisDOT, 2021)
15	**Australia**	Water-borne Road marking paint is used for roads surfaced with a sprayed seal, hot and cold mixed asphalt, and concrete.	(TMR, 2019)
16	**Canada**	Water-based paint is widely used in Quebec, Canada. Annually, almost all the 90,000 km of lines making up the Ministry's network are re-marked with water-based paint.	(Transports Québec, 2019)

From **Table 24**, it can be conceived that traffic paint is widely used in all locations due to its cost-effectiveness and rapid application. However, the purpose of its application differs slightly from one location to another. Some U.S. states, such as Washington, Nevada, and Iowa, use several types of traffic paint, including high-build and standard water-based paint for durable and non-durable markings. In contrast, the other states like California and Kansas utilize it only for temporary markings.

3.2.2.2 Water-Based Traffic Paint Application Processes and Methods

Installing traffic paint requires a unique strategy to ensure that the marking service life extends to its maximum threshold. Most states developed their construction and material specifications for effective application of this marking. According to TxDOT (2004), traffic paint can be applied by the spraying method. During the application, the surface of the pavement should be clean and free of moisture, ensuring proper bonding between marking and pavement surface. During the application, ambient temperature should not be less than 40 °F as the material is highly sensitive to changes in temperature and moisture. The Ohio Department of Transportation (ODOT, 2021) uses two types of traffic paint: Type 1 (standard water-based paint) and Type 1A (cold weather traffic paint materials). Type 1A is applicable when the pavement and air temperatures are between 35 °F and 50 °F, whereas Type 1 can be applied when the temperature is above 50 °F.

MnDOT (2015) indicates that traffic paint markings could be applied in two ways: conventional and airless. In the conventional method, an air jet at the tip of the paint gun is used to break up or atomize the paint. The tip then defines the shape of the spray to produce a properly applied line. The quantity of atomizing air needed to sufficiently break up the paint will depend largely on the paint's rheological or flow characteristics. On the other hand, in an airless system, the paint is forced out through a tiny hole in the tip of the gun at high pressure, typically 2,500 to 3,000 psi. The hole size determines how much of the paint is applied, and the angle of the inner surfaces of the tip determines the width. Unlike with the conventional system, there is no air mixed with the paint in the gun. The pressure created by the pump mechanism

explosively forces the paint through the gun tip, breaking the paint up into very small particles. The primary method for altering the width and thickness of the applied line is to change the tip. **Table 25** summarizes some important information from various sources regarding traffic paint application.

Table 25 Traffic Paint Application Across 13 U.S. States and Canada

No	States	Traffic Paint Type	Minimum Application thickness	Minimum Application rate	Minimum Glass beads rate	Minimum Air Temperature (F)	Sources
1	**California**	Waterborne	N/A	215 sqft/gal both 1sth and 2nd coat	5 lb/gal	50	(Caltrans, 2018)
		Acetone-based	N/A	360 sqft/gal for 1sth and 150 sqft/gal for the 2nd coat	5 lb/gal	40	
2	**Colorado**	high-build Waterborne	23 -24 mils	67 - 70 sqft/gal	9-10 lb/gal	45	(CDOT, 2021)
		Low Temperature Waterborne	17-18 mils	89 - 93 sqft/gal	7-8 lb/gal	35	
3	**Illinois**	water-based	15 mils	N/A	N/A	N/A	(IDOT, 2015)
4	**Iowa**	Water-borne	14 mils	N/A	9 lb/gal	45 for standard 35 for low temperature marking	(Iowa DOT, 2015)
		Solvent-based	16 mils	N/A	9 lb/gal	no restriction	
5	**Kansas**	water-borne	18 mils	88 sqft/gal for solid line and 350 for broken line	12 lb/gal	40	(KDOT, 2015)
6	**Minnesota**	Waterborne	12 - 25 mils	133 - 80 sqft/gal	N/A	50	(MnDOT, 2015)
7	**Nevada**	Water-borne	8 mils	N/A	6lb/gal	45	(NDOT, 2014)
8	**North Dakota**	Water based	15 mils	N/A	N/A	72.5	(NDDOT, 2020)
9	**New York**	Water borne	15 mils - 30 mils	N/A	6.25 lb/gal	50	(NYSDOT, 2002)
10	**Ohio**	Type 1		80 sqft/gal	15 lb/100 sqft	50	(Ohio DOT, 2021)
		Type 1A		106 sqft/gal	8 lb/100 sqft	35	
11	**Oregon**	Traffic Paint	15 mils	103 sqft/gal	5 lb/gal		(Oregon DOT, 2021)
12	**Texas**	Water- based	15 - 25 mils	88 sqft/gal on concrete and 80 sqft/gal on surface treatment		50	(TxDOT, 2014 and 2004)
13	**Washington**[1]	water-based	first coat 10 mils and second coat 15 mils				(WSDOT, 2021)
14	**Canada**	Water-based	16 mils	48 L/km	0.6 kg/L	50	(Transports Québec, 2019)

		Alkyd paint	16 mils	48 L/km	0.6 kg/L	32	
		Low-VOC alkyd paint	16 mils	48 L/km	0.6 kg/L	32	

Note:

[1] The use of large glass or composite beads is limited to high-build waterborne paint and other materials with a thickness of at least 22 mils

3.2.3 Preformed Tapes

3.2.3.1 Usages of Preformed Tapes

Generally, the preformed tape is a urethane or pliant polymer film with glass beads embedded on the surface to improve its retro-reflectivity and its skid resistance. Preformed tapes are supplied in continuous rolls of various widths and lengths and available in sheeting form, which can be cut into different words and symbols (TMR, 2019). Preformed tapes do not require costly application equipment, experienced operators, or curing time, which could be counted as the main advantages of preformed tapes over sprayed or extruded materials (TxDOT, 2004). In addition, according to TxDOT, because of the preformed tapes' durability, applying preformed tapes may be suitable and cost-effective in challenging areas that require frequent remarking due to high AADT. The main disadvantage of this marking is its slow application procedure and its cost. In the TxDOT (2014) manual, the preformed tape is divided into two classifications: (1) "permanent prefabricated pavement markings," falling under material specifications of DMS-8240 and the construction specification Item 668, and (2) "temporary (removable) prefabricated pavement marking" falling under material specifications of DMS-8241.

Standard preformed pavement marking tape composed of rows of diamond-shaped and raised elements is shown in **Figure 21**.

Figure 21 Preformed Tape (MnDOT, 2015)

For further information, **Table 26** summarizes the usage of preformed tape marking across various states and other countries, while **Figure 22** plots the preformed tapes distribution across 14 states, Canada, and Australia.

Table 26 Preformed Tape Usage Across 14 U.S. States, Canada, and Australia

No	States	Preformed Tapes Usage	Sources
1	**California**	Not used nor have any specification for it	(Caltrans, 2018)
2	**Colorado**	Used for transverse markings on both asphalt and PCC. As per CDOT specification, this marking is classified into three types: Type I, II, and III. Type I and Type II are essentially the same, except that Type II comes with contrast coloring. Type III is not used in Colorado	(CDOT, 2020)
3	**Illinois**	Used for long and transverse lines on both asphalt and PCC.	(IDOT, 2015)
4	**Iowa**[1]	Used both for temporary (removable tape) and permanent	(Iowa DOT, 2015)
5	**Kansas**[2]	Used in the State under specification of KDOT 806 - Durable markings	(KDOT, 2015)
6	**Minnesota**[3]	Both permanent and temporary tapes are used.	(MnDOT, 2015)
7	**Nevada**	Its specification is available in the State's manual. However, a survey participant from NDOT stated that Preformed tapes are rarely used because of constructability issues with placement procedures that require inlaying the tapes on the flexible pavement before the surface falls below 160 degrees F. It was challenging to place the products properly, and the product didn't last long for the higher price. Temporary tape is sometimes but rarely used in large projects with numerous work zone changes in the Las Vegas area. Infrequently, the permanent tape is used for crosswalks in the Las Vegas area.	(NDOT, 2014), and Survey respondents from Nevada
8	**North Dakota**	Preformed patterned pavement marking film is used in the State	(NDDOT, 2020)
9	**New York**	Used primarily for special markings such as stop lines, crosswalks, arrows, words, symbols, and lane lines located at intersections	(NYSDOT, 2002)

10	**Ohio**[4]	Limited use. Preformed pavement is used in special places under C&MS Item 645.	(Ohio DOT, 2021)
11	**Oregon**	This marking is designated as Type C in the Oregon DOT specification. However, Oregon DOT discontinued this method in 2007 due to low usage and performance issues in prior years.	(Oregon DOT, 2021)
12	**Texas**[5]	Used for transverse markings, mainly stop bars, arrows, etc. In the TxDOT manual, the preformed tape is divided into two classifications: "permanent" falling under material specifications of DMS-8240 and construction specification "Item 668" and "temporary (removable)" falling under material specification of DMS-8241.	(TxDOT, 2004 and 2014)
13	**Washington**	Used and identified as Type C, cold applied preformed tape, in the state specification.	(WSDOT, 2021)
14	**Wisconsin**	Limited use. Permanent tape is used for freeways when pavement service life is more than eight years	(WisDOT, 2021)
15	**Australia**	Used in areas where long life is desired, and thermoplastic equipment is not available at the location or for quantity reasons	(TMR, 2019)
16	**Canada**[6]	Not used	(Transports Québec, 2019)

Note

[1] It seems like the market needs more competitors with comparable products

[2] A survey participant from KDOT noted that its effortless installation and its ability to be applied in multiple surfaces are the main considered selection factors for this marking

[3] A survey participant from MDOT responded that preformed marking tape is used on concrete in the State. However, MDOT manual it is indirectly mentioned that this marking can be used on HMA as well

[4] A survey participant from Ohio DOT responded that due to the high cost of preformed material, it is only considered for use where extra-long life is needed or in certain applications, such as bridge decks where thermoplastic has not adhered well.

[5] Six participants confirmed that preformed tapes are used in their locations. However, five people responded that it is not used because of time and expenses. Specifically, one participant wrote, "It is used in our state, but rarely. We prefer liquid pavement markings but will use preformed if it's cheaper than dealing with an epoxy truck. Maintenance forces use "burn downs" for words and symbols, and plan on replacing them every year."

[6] A survey participant from Canada noted that "we usually have not good results on our Test Deck with this kind of products. Prefabricated Pavement Marking is not very durable during winter road maintenance".

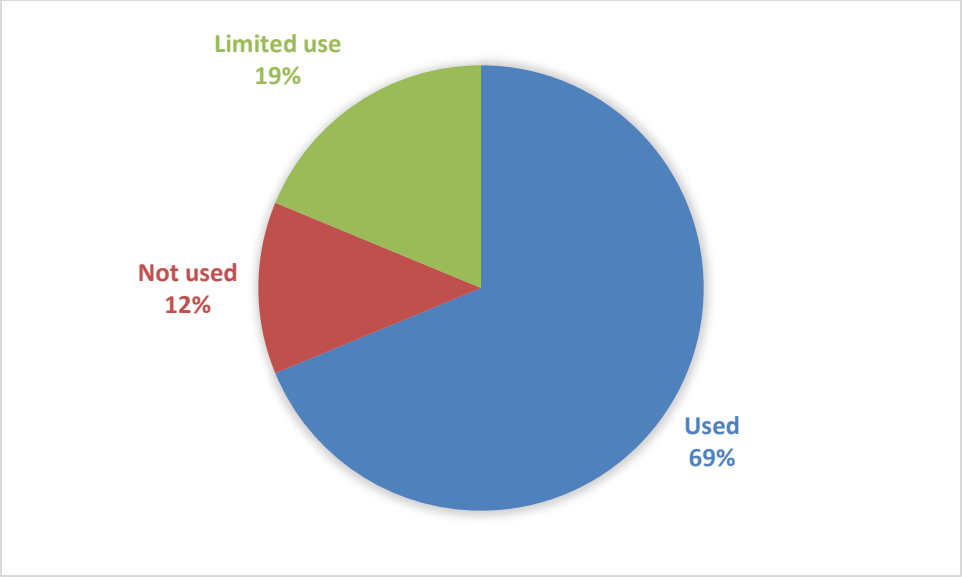


Figure 22 Preformed Tapes Distribution Across 14 U.S. States, Canada, and Australia

From **Table 26** and **Figure 22**, it could be inferred that preformed tape material is usually used for transverse markings in areas with severe traffic volumes and high service life pavement. Furthermore, since performed tapes are easy to apply and do not require highly sophisticated equipment and experienced operators, the markings could be cost-effective in locations where a limited quantity of markings is needed, even though preformed tape material costs might be high. Considering the rental cost of equipment and operators for applying extruded or sprayed materials, the application of preformed tapes still might be effective.

3.2.3.2 Preformed Tapes Application Processes and Methods

According to the MnDOT (2015), preformed tapes are generally applied using a roller applicator. Then, using a walk-behind tamper cart, the installed tape is pressed onto the road surface, and weights are stacked on this cart to provide the necessary force to press the tape to the road. This roller applicator and tamper procedure helps ensure that the tape is applied straight, especially in longline applications. Based on the TxDOT (2004), there are two approaches for installing preformed tapes: the inlay and overlay. The inlay method is suitable for newly

constructed or resurfaced asphalt pavement where the pavement should be warm, at 130 °F. When the patterned tape is inlaid, no primer is used. It is inlaid with the last pass of the paving roller; the temperature of the HMA is critical (MnDOT, 2015). On the other hand, the overlay method is effective on existing pavement and concrete pavement where the tape is applied directly on and bonded to the surface with an adhesive (TxDOT, 2004). Good bonding plays a vital part in the durability performance of the preformed tape marking. Therefore, during the application, it is highly important to ensure that the pavement surface is free of any contaminants and strictly follows the manufacturer's recommendations. **Table 27** reveals some troubleshooting guides from the MnDOT pavement marking guidelines.

Table 27 Preformed Tape Troubleshooting Guide

Problem	Cause	Effect	Remedy
Material rolls up or shifts	▪ Not bonded prior to traffic ▪ Tape crossing traffic ▪ No primer adhesive	Loss of effectiveness	Replace material with proper tamping, adhesive, and primer
Poor material adhesion	▪ Moisture in Pavement ▪ Dirty surface ▪ No primer ▪ Expired shelf life ▪ Incorrect milling heads	▪ Errant delineation ▪ Loss of material ▪ No delineation	Replace material applying properly

Source: (MnDOT, 2015)

IDOT (2016) specified that the minimum application thickness of preformed tapes should be 60 mils, and the air temperature should be less than 50 °F when the marking is applied using the overlay approach. The manual also mandated that all contractors apply this marking from April 15 to October 15 of each year. The NDDOT (2020) mentioned that the minimum initial skid resistance value of preformed tape after its application should be 45 BPN when it is tested, according to ASTM E 303. Also, the manual mandates that the minimum thickness of this marking should range from 20 mils to 65 mils at the thinnest and the thickest portions of the cross-section, respectively.

3.2.4 Multipolymers

The most common multipolymer marking materials include epoxy, polyuria, modified urethane, and MMA. According to our survey in Chapter 2, 5 individuals out of 11 participants from Texas indicated that multipolymers are used in their districts, whereas 6 respondents mentioned that these marking materials are not used in their districts. Regarding the multipolymers' non-usage in Texas, one of the participants stated, "most of our roads are seal coat and with our seal coat program we are on a 7-year cycle. We have not seen enough extended life from the Multipolymer to justify the additional cost over Thermos." On the other hand, another participant from Texas mentioned that there are a very limited number of contractors available for the implementation of this type of marking material. Considering the importance of these materials and their applications in various states, each of the multipolymer sub-classification materials will be discussed separately in the subsequent subsections.

3.2.4.1 Epoxy

Epoxy falls under the categorization of durable and sprayable markings, which generally consist of two materials: pigment and binder. Generally, glass beads are added to the pigment and binder as it is being applied to the pavement surface. The binder is made of two materials: resin and catalyst. When mixed, these components chemically react to form a hard material that bonds the color pigments and glass beads to the pavement's surface (Goldbaum, 2010). Compared to traffic paint, epoxy is very costly; in some cases, its cost slightly exceeds even thermoplastic marking materials (TxDOT, 2004). If properly installed based on the standard specifications, the main advantages of epoxy paint are its durability under different roadway conditions and low ambient temperature requirement (as low as 35 °F). In contrast, the main disadvantages of epoxy marking include longer drying (curing time), fading due to color instability under ultraviolet lighting, and not being restriped on marking materials other than epoxy (TxDOT, 2002).

Although epoxy is used as experimental material in Texas and no specific material specification has been developed for this marking, many states have

developed specifications for epoxy and its application. Indeed, epoxy is the second most widely used marking material in states like Colorado, Montana, New Jersey, Ohio, and Wisconsin (Nahrwold, 2012). According to CDOT (2021), before installing modified epoxy paints, the pavement surface should be cleaned with a high-pressure air blast or water blast, depending on the manufacturer's recommendation, to remove loose material. In addition, CDOT's manual mandates that every epoxy component be heated to a temperature range of 80 °F – 140 °F prior to mixing. Likewise, after mixing, the same temperature range should also be applied at the gun tip for the application of combined material. Furthermore, according to IDOT (2016), epoxy should be applied with a thickness of 20 mils and glass beads rate of 10 lb./gal. **Table 28** provides further information regarding the usage and application of epoxy across many U.S. states.

Table 28 Multipolymers Marking Material Usage, Application Thickness, Glass Beads Application Rate, and Minimum Air Temperature Requirement Across 14 U.S. States and Canada

No	States	Multi-polymer Type	Usage	App. thickness	Glass beads app. rate	Mini. Air Temp. (F)	Sources
1	**California**	Fast curing epoxy	Used, but requires special authorization		11.7 lb./gallon for large-gradation and 8.3 lb./gallon	36	(Caltrans, 2018)
		Fast curing polyurea	Used, but requires special authorization		11.7 lb./gallon for large-gradation and 8.3 lb./gallon	36	
		MMA	Do not have any specifications. However, the state marking manual introduce it as potential marking for snow removal area				
2	**Colorado**[1]	Modified Epoxy	Used, and have both material and construction specification available in the State's manual	18 mil	23 lb./gallon	35	(CDOT, 2021)
		MMA	Used, and have both material and construction specification available in the State's manual	60 mils	First bead applicator 10 lb./gallon and second bead applicator 6lb/gallon		
3	**Illinois** [2]	Epoxy	Used, and have both material and construction specification available in the State's manual	20 mils	10 lb./gallon	35	(IDOT, 2015 and 2016)

		Polyurea	Used, and have both material and construction specification available in the State's manual	20 mils on new HMA surface and 15 mils for all other surfaces		40	
		Modified Urethane	Used, and have both material and construction specification available in the State's manual	25 mils		35	
4	**Iowa**[3]		No specification is provided in the Iowa DOT standard specifications				(Iowa DOT, 2015)
5	**Kansas**	Epoxy	Used both on asphalt and PCCP, and have both construction and material specifications	20 mils	25 lb./gallon	32	(KDOT, 2015)
6	**Minnesota**[4]	Epoxy	Slow curing epoxy is used in the State. However, in cold weather locations, fast curing epoxy is used.	20 mils	25 lb./gallon	50	(MnDOT, 2015)
7	**North Carolina**	Polyurea	Used, and have both material and construction specification available in the State's manual	30 mils on OGFC and 20 mils on all other surfaces	1 - 3 lb./gal	40	(NCDOT, 2018)
8	**Nevada**[5]	Polyurea	Used, and have both material and construction specification available in the State's manual	25 mils on OGFC and 20 mils on PCC	18 lb./gal	40	(NDOT, 2014)
		Epoxy	Used, and have both material and construction specification available in the State's manual	20 mils	18 lb./gal	50	
9	**North Dakota**[5]	Epoxy	Used, and have both material and construction specification available in the State's manual	20 mils	25 lb./gallon	50	(NDDOT, 2020)
10	**New York**	Epoxy	Used, and have both material and construction specification available in the State's manual	15 mils on all existing and 20 mils on new acc	20 lb./gal	50	(NYSDOT, 2002)
11	**Ohio** [7]	Epoxy	Used, and have both material and construction specification available in the State's manual		31 lb./ 100 sqft	50	(Ohio DOT, 2021)
12	**Oregon**	MMA	Used and have both material and construction specifications available in the State's manual. It is applied both by gravity and extrusion methods	90 mils - 120 mils			(Oregon DOT, 2021)

13	**Texas**	Multipolymers	Limited Use. No construction and material specifications are available in the TxDOT standard specifications in 2014. However, TxDOT Developed a special specification for this marking under item 6020 and item 6038.			(TxDOT, 2014 and 2004)
14	**Washington**	MMA	Used and identified as a type D marking in the State's manual.	Sprayed = 30 - 45 mils, Extruded = 90 mils on asphalt and pcc and 120 mils on OGFC	40	(WSDOT, 2021)
15	**Canada**	Epoxy	Very Limited Use.		50	(Transports Québec, 2019)
		MMA	Very Limited Use.		32	

Note:

[1] A survey participant from Colorado also confirmed that multi polymer marking is used in their State

[2] There are two types of reflective media for polyurea pavement marking. Polyurea Pavement Marking Type I uses glass beads as a reflective media while polyurea pavement marking type II uses a combination of composite reflective elements and glass beads as a reflective media.

[3] A survey participant confirmed that multipolymer pavement markings are used in the State. However, there is no construction and material specification regarding this marking in the state manual

[4] A survey participant confirmed that epoxy is used in the State. However, in the State's standard specifications, there is only construction and material specifications available for multi-component markings

[5] A survey participant from NVDOT Stated that Epoxy pavement markings are generally used for new project contract striping on both flexible and rigid pavements in both snowplow and no snowplow areas. Polyurea markings are used selectively in the Las Vegas area. The survey respondent also mentioned that in areas without snowplow use, these products generally last 1.5 to 2.5 years in urban environments with higher traffic volumes and 3 to 3+ years in rural environments with lower traffic volumes. In areas where snowplow use is prevalent, the service life is reduced as compared to where there is no snowplow use.

[6] A survey participant from NDOT mentioned that the State typically only specifies epoxy unless it's for product research and monitored for performance. NDOT has limited striping contractors, and some specialty markings lead to prohibitive bid pricing on certain markings that require modification to standard striping applicators.

[7] A survey participant from Ohio DOT stated that until recently, we were only using/allowing slow cure epoxy, which made installation times long and required MOT. We have just introduced an updated spec to allow fast dry epoxy, which we anticipate will help with this issue.

3.2.4.2 Polyuria

Polyuria is also a multipolymer pavement marking material that can be applied on new and existing asphalt and Portland cement concrete surfaces. According to TxDOT (2004), the main benefits of polyuria markings include color stability, resistance to abrasion, adhesion to all pavement surfaces, lower sensitivity

to pavement surface moisture and temperature, fast curing, and high durability, whereas requiring special striping equipment to apply the material is the main drawback. As polyuria is considered a low-profile marking whose usual thickness is 20 mils, it is suitable in areas with high snowplow exposure and limited accessibility (Needham, 2011). Based on the TxDOT (2014), no official material specification has been developed for this marking. Even though the TxDOT (2004) claimed that the durability of polyuria marking is more than five years, Cyrus & Frierson (2006), by performing comprehensive research, found that when using Type III beads based on retro-reflectivity, polyurea is not durable in locations with high traffic volume on both asphalt and concrete surfaces. However, when the material was tested on concrete with Type I beads, polyurea was still effective after 6 months, in terms of retro-reflectivity.

A few U.S. states incorporated the application procedure of polyurea in their standard specifications. These states include Michigan, Illinois, North Carolina, and Georgia (Nahrwold, 2012). The North Carolina Department of Transportation (NCDOT, 2018) emphasizes that the ambient temperature should not be less than 40 °F, and therefore polyurea should be applied from February 28 - November 15, with 20 mils on asphalt and concrete surfaces and 30 mils on textured surfaces such as OGFC. The NCDOT also noted that a thin layer of pavement marking paint at a thickness of 5 to 8 mils should be applied before installing the polyurea markings during the 15-day waiting period. Likewise, the IDOT (2016) also developed both construction and material specifications for polyurea material, in which it is noted that polyurea should be installed on a clean and dry road surface with a minimum wet thickness of 15 mils, based on the manufacturer's installation instructions. However, as per the manual, this minimum wet thickness should be 20 mils on new HMA surfaces. To install polyurea markings properly, the IDOT also recommends that the road surface be air blasted. Then, the resin should be mixed and heated according to the manufacturer's recommendations and sprayed onto the pavement surface. Further information regarding the usage and application of polyurea across several U.S. states is listed in **Table 28**.

3.2.4.3 Modified Urethane

Modified urethane is another multipolymer pavement marking type, classified as durable and having close characteristics to epoxy and polyurea. Modified urethane is comprised of two components. The first component consists of modified urethane resin and pigmentation, and the second component contains a curing agent (Abbas et al., 2009). The main advantages of modified urethane are high durability, fast curing time (less than 2 minutes), good ultraviolet color stability, and requiring the same application equipment as epoxy (2:1 mix ration, same as epoxy), and the ability to hold big beads and to bridge the cost and performance gap between fast dry epoxy and polyurea (Nahrwold, 2012; TxDOT, 2004). Although modified urethane is in the stage of experimental use in Texas and has no official specification in the TxDOT (2014) standard specification book, this marking is still used in several other states like Minnesota and Illinois (Nahrwold, 2012).

To install modified urethane marking material properly, the IDOT (2016) mandates that the marking be applied during conditions of dry weather and subsequently dry pavement surfaces at a minimum uniform wet thickness of 25 mils. At the installation time, the pavement surface temperature and ambient temperature should be 40 °F and 35 °F, respectively.

3.2.4.4 Methyl Methacrylate

After epoxy material and polyurea, methyl methacrylate (MMA) is the third most commonly used among multipolymer marking materials in the U.S. In some state manuals, it is also called "cold applied plastic." Like other multi-polymer marking materials, MMA is a durable marking that is comprised of two components. The first component is a resin that is combined with glass beads and fine aggregate to improve retro-reflectivity and skid resistance, whereas the second component consists of a liquid or powder catalyst to enhance bonding. The main advantages of MMA are durability, environmental friendliness, resistance to chemicals such as oils and antifreeze, strong adhesion to both concrete and asphalt, and suitability for the cold-weather climate. In contrast, the main drawbacks of this marking material are that it requires special equipment for the application, a slow curing time of 30

minutes, and a high initial cost (Abbas et al., 2009; TxDOT, 2004). According to Transports Québec (2019), MMA falls into two types of systems:

- A two-component system consisting of resin A and resin B. A solid benzoyl peroxide-based (BPO) catalyst is added to resin B. The two resins are then mixed in a 1:1 volume ratio.
- A two-component system consisting of resin A and a liquid benzoyl peroxide-based (BPO) catalyst. Each component is then mixed in a 98:2 volume ratio (A/BPO).

Although MMA is used as experimental material in Texas and no specific material specification is developed for this marking, many other states and countries have already developed both material and construction specifications for it and considered it as a strong marking material alternative to other durable marking materials. In creating both construction and material specifications, the CDOT (2021) recommends that MMA be applied by the sprayed method at a minimum rate of 26 sq ft/gallon with a minimum thickness of 60 mils. On the other hand, the ODOT (2021) indicates that MMA should be applied by a gravity and extrusion method, with a thickness of 90 mils to 120 mils, exclusive of projecting surface-applied reflective elements. Furthermore, Transports Québec (2019) mentioned that the application conditions of MMA are highly identical to those for the application of epoxy resin-based materials, although theoretically, MMA can be installed at a minimum ambient temperature of 32 °F. Further information regarding the usage and application of MMA across many U.S. states is listed in **Table 28** also.

As shown in **Figure 23**, most of the states studied (10 out of 14) use epoxy marking materials, while very few states (2 out of 14) use modified urethane marking materials. Furthermore, **Figure 24** shows detailed information regarding the curing time requirements of multipolymers (two-component marking materials).

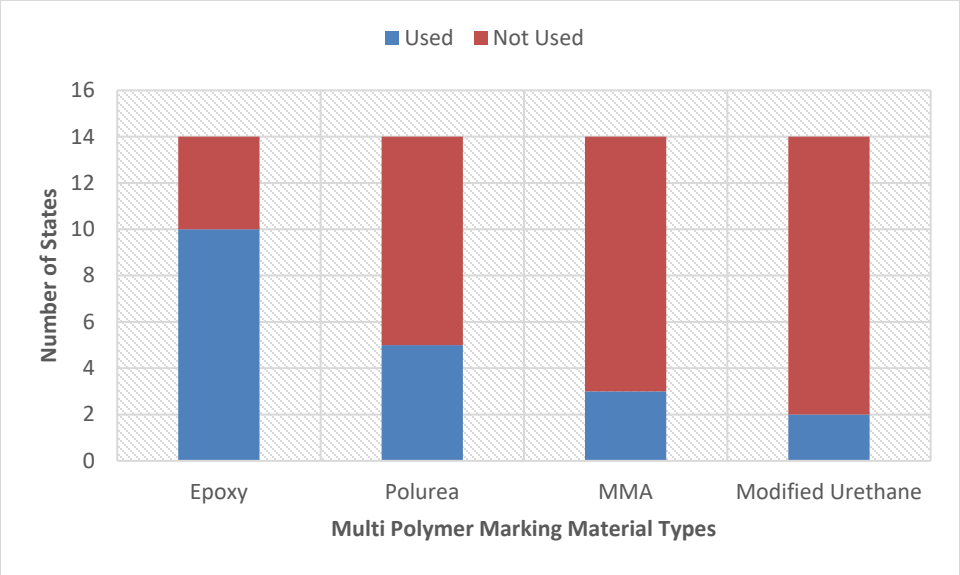


Figure 23 Multipolymer Marking Material Usage

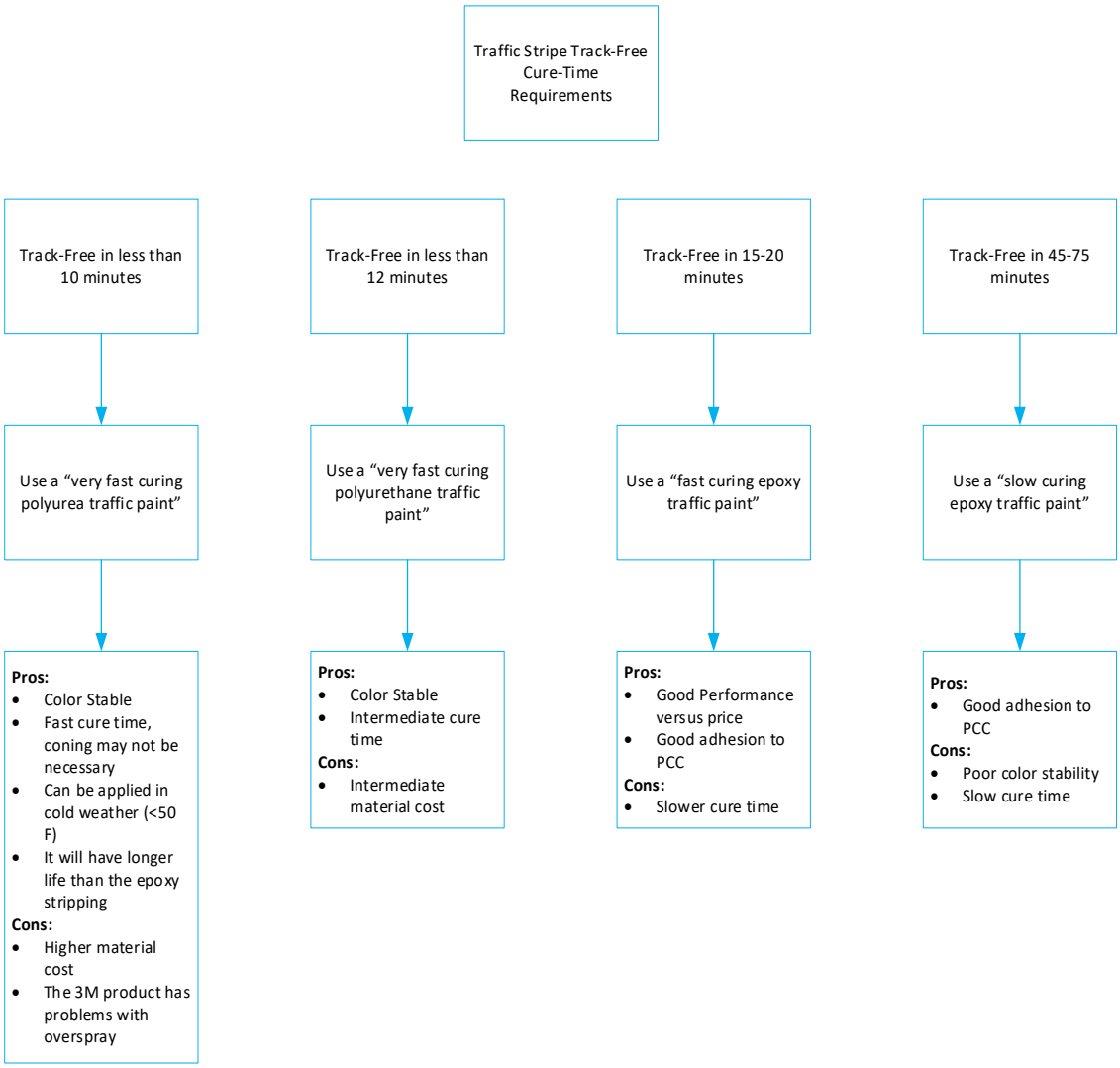


Figure 24 Two-Component Paint Traffic Stripes Curing Time Requirement (Caltrans, 2019)

3.2.5 Profiled Markings

A profiled marking is another type of durable marking material that provides high retro-reflectivity during wet night conditions and noise alert to avoid run-off-road collisions. Profiled markings are also known as "structured pavement markings." Thermoplastics and two-component marking materials, i.e., epoxy,

polyurea, modified urethane, and MMA, can be installed as profiled markings. However, in the State of Texas, considering the wide usage of thermoplastic and its cost, most of the profile markings are made of a thermoplastic material called "profiled thermoplastic." Profiled thermoplastic is used in several states. In our survey in Chapter 2, 10 participants confirmed that profiled thermoplastic is used in their state. In contrast, 12 participants mentioned that this marking is not used in their state. The main reasons this marking is not used in some states are its lower durability in snowplow areas and the problem associated with the uniform heating of thermoplastic material in track.

Profiled markings are applied in several ways. According to the TxDOT (2004), profiled thermoplastic markings are applied by two methods: as inverted-profile markings and as raised-profile markings. The pictures for inverted-profile markings and raised-profile markings are shown in **Figures 25** and **26.**

Figure 25 Typical Inverted Profile Thermoplastic Marking (Profile View)

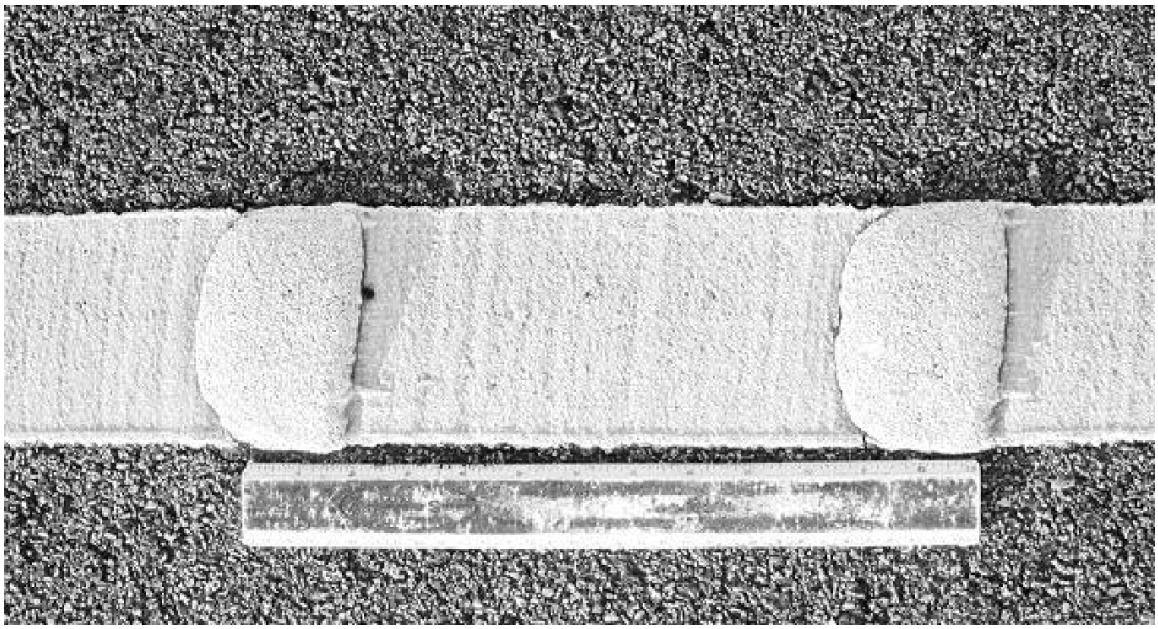


Figure 26 Typical Raised Profile Thermoplastic Marking (Overhead View)

On the other hand, based on BORUM (2021), the methods by which profiled markings are the applied include agglomerate application, rib line application, dot application, and extrusion application, which can be applied with multipolymers/two-component marking materials and thermoplastic materials, as shown in **Figures 27-31**. However, the rib line application can only be used with thermoplastic materials. In addition, the ranges of application thickness for rib line, agglomerate, extrusion, and dot application methods can be 118 - 160 mils, 160 mils, 315 - 470 mils, and 390 mils, respectively.

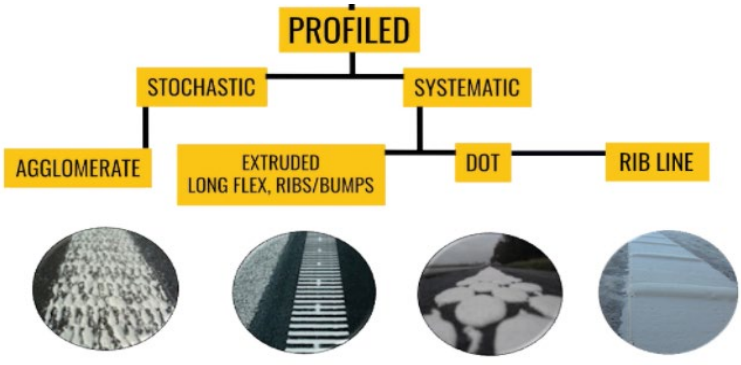


Figure 27 Four Different Methods of Profiled Markings Application (Source: BORUM, 2021)

Figure 28 Agglomerate Application Method

Figure 29 Rib Line Application Method

Figure 30 Dot Profile Marking Application Method

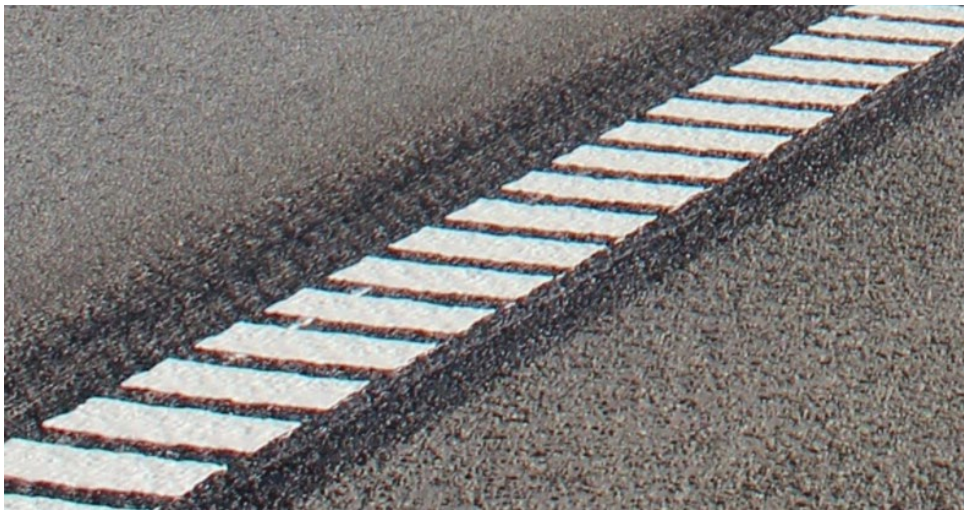


Figure 31 Extraction Profiled Marking Application Method-Long Flex Line

According to the Florida Department of Transportation (FDOT, 2021), the minimum application thickness of flat baselines of profiled thermoplastic markings is between 100-150 mils, while the thickness of raised bumps should be at least 450 mils. In addition, the baseline coverage dimension of the bumps should be at least 2.5 inches for both transverse and longitudinal directions.

3.2.6 New Marking Materials

Usually, the pavement marking marketplace is highly dynamic, and continuously, new materials are becoming available. To improve the overall durability and effectiveness of roadway markings, it is strongly recommended that TxDOT welcome the testing and evaluation of the newly available marking materials and ultimately use them if they are proven durable and cost-effective. To that end, in this section, the research team briefly introduces some of the marking materials with new features that have been made available recently.

3.2.6.1 All-Weather Thermoplastic Marking Materials

All-weather thermoplastics are designed to provide high night visibility in both dry and wet conditions. This marking material prolongs the retro-reflectivity long after other thermoplastics have become ineffective, dramatically enhancing

roadway safety, and minimizing traffic disruptions. TxDOT has developed a special specification under the name SS 8582. **Figure 32** shows the retro-reflectivity of all-weather thermoplastic pavement markings during the night. Meanwhile, **Figure 33** compares the visibility of all-weather thermoplastic with normal thermoplastic markings during wet and dry conditions. As is shown in **Figure 32**, the retro-reflectivity of normal thermoplastic material is highly reduced during wet conditions, while all-weather thermoplastic still produces night visibility.

Figure 32 All-Weather Thermoplastic Retro-reflectivity During the Night (*Source: Yeng Hsingh Co., Ltd, 2020*)

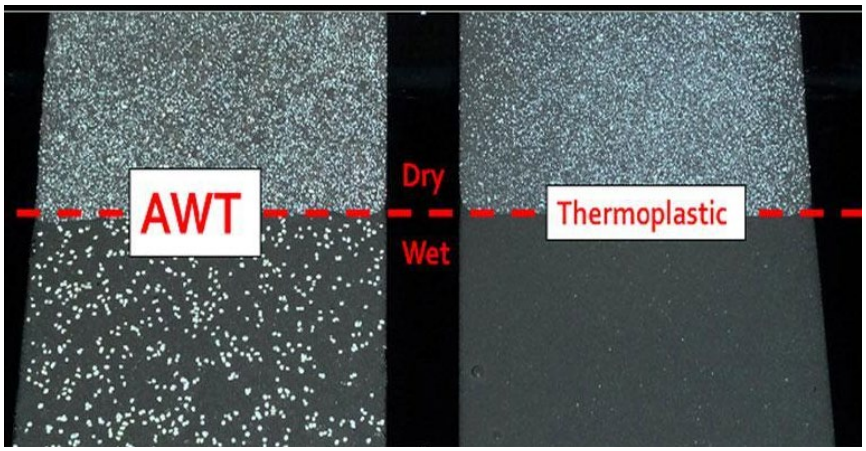


Figure 33 All-Weather Thermoplastic Versus Normal Thermoplastic Both in Dry and Wet Conditions (*Source: Yeng Hsingh Co., Ltd, 2020*)

3.2.6.2 Multi-Component Pavement Markings

Although several multi-component (multipolymer) materials, such as epoxy, polyurea, modified urethane, and MMA, were discussed in Section 3.2.4, a few other multipolymers that are relatively recently available on the market will be addressed in this section.

3.2.6.2.1 Modified Polyacrylate

Modified polyacrylate is a two-component material and falls under the category multipolymers. This marking is durable, 100% solid, highly resistant to abrasion, has high retro-reflectivity, and is applicable both on PCC and asphalt surfaces. Furthermore, this marking material can work as traverse and longline marking. Interestingly, modified polyacrylate can be applied using the same equipment for epoxy materials. According to Swarco (2021), modified polyacrylate has the following advantages:

- 100% solids chemistry
- Low viscosity for smooth application
- Rapid curing for less road-blocking
- Special chemistry for a rapid set at a wide range of temperatures
- Outstanding long-term abrasion and corrosion resistance
- Exceptional adhesion to a variety of substrates
- Protection against moisture penetration
- Good flexibility
- Excellent ultraviolet light stability
- High reflective qualities

Swarco (2021) specified a range for application thickness of modified polyacrylate between 15 mils and 25 mils, depending on the ADT and the type of roadway. The Iowa Department of Transportation (Iowa DOT, 2019) has developed a special specification under the name "multi-component liquid pavement markings," in which a minimum thickness of 20 mils and minimum glass bead application rate of

25 lb./gal. are mandated. Swarco (2021) indicates that ambient temperature while applying this marking type should not be lower than 35 °F. According to Iowa DOT (2019), there is one modified polyacrylate product available on the market, which is the 3180 Series MFUA-10 manufactured by SWARCO. Although this marking material seems to have promising durability and effectiveness, little field data is available to support its claimed advantages over other multipolymer markings.

3.2.6.2.2 Integrated Multipolymer System (HPS-8)

The integrated multipolymer system (HPS-8) is 100% solid and recently released for durable markings. It is comprised of pigments, glass beads, binder, and filler. Pigments provide opacity and color, fillers mainly made of calcium carbonate provide bulk, and binders comprised of plasticizers and resins provide toughness, flexibility, and bonding. This marking material is manufactured by Ennis-Flint, Inc. under the name of HPS-8. An integrated multipolymer system can be applied at thicknesses ranging from 60 to 120 mils by the same equipment as thermoplastic through the extrusion method. The service life of this marking is warranted by its manufacturer for 4 years. **Table 29** compared HPS-8 advantages to those of other marking types. Ennis-Flint (2020) listed the following benefits related to HPS-8 markings:

- Superior performance; abrasion-resistant for durability
- Extended retro-reflectivity results from both the advanced formula and a 50% intermix of Type I and Type III beads
- 4-year warranty is available for durability and retro-reflectivity
- Mechanically adheres to all asphalt pavements
- Formulated for quick dry of < 2 minutes at temperatures as low as 50 ºF
- Uses standard thermoplastic extrude equipment
- Engineered to minimize lane interruptions and closures
- May be applied using the extrude method in 60-120 mil thickness with double drop glass bead application

Table 29 Integrated Multipolymer System (HPS 8) Advantage vs. Other Marking Types

HPS-8 Advantage vs. Permanent Tape		
Similar	**Better**	**What this means to you**
Abrasion-resistant material		Comparable durability
	Easier and faster application	Use standard extrude thermo equipment; hand liner or truck mount
	Apply over previous thermoplastic	Do not have to remove and replace as with tape before new or refurbished application
	50% beads in the intermix: Type I and Type III	Sustained retro-reflectivity because beads are in the intermix and not simply sitting on the surface to be knocked off. As marking wears, new beads are exposed.
	Lower cost per running linear foot	Coverage rate combined with faster installation reflects more accurate cost per linear foot by true comparison
	Rolling work zone	Keep traffic moving with minimal delays
	Warranty supporting better performance available	4-year coverage with higher retro-reflectivity values; white and yellow
HPS-8 Advantages vs. MMA and Epoxy		
Similar	**Better**	**What this means to you**
Abrasion-resistant material		Comparable durability
	Easier and faster application	Use standard extrude thermo equipment; hand liner, or truck mount, whereas MMA and Epoxy may present equipment limitations and availability
	50% beads in the intermix: Type I and Type III	Sustained retro-reflectivity because beads are in the intermix and not simply sitting on the surface to be knocked off. As marking wears, new beads are exposed.
	Rolling work zone	Keep traffic moving with minimal delays
	Extended performance warranty	4-year coverage for retro-reflectivity
HPS-8 Advantages vs. Thermoplastic		
Similar	**Better**	**What this means to you**
	Abrasion-resistant material	Comparable durability
Easy application method		Use standard extrude thermo equipment; hand liner, or truck mount
	50% beads in the intermix: Type I and Type III	Sustained retro-reflectivity because 50/50 combination of beads is in the intermix; as marking wears, new beads are exposed.
	Extended performance warranty available	4-year coverage for retro-reflectivity

Source: Ennis-Flint (2020)

Table **29** compares the integrated multipolymer system advantages with other traditional marking materials.

Although integrated multipolymer system materials seem to have promising durability and effectiveness, it is difficult to find support for its advantages over other multipolymer markings due to a lack of field data.

3.2.6.3 Photoluminescent Road Marking

Photoluminescent road marking is an advanced material that is widely used in building pathways both in the U.S. and other countries. However, this material has also recently been utilized for roadway marking in some countries. The Netherlands is one of those countries already using the photoluminescent material for road marking. The U.K. is also looking at the new material by studying The Netherlands' approach (BBC News, 2014b; McGrath, 2014). The idea behind photoluminescent material is that it absorbs light during the day and reflects the absorbed light in darkness. The duration that this material continuously provides light in the darkness is estimated between 8 – 10 hours.

The installation of photoluminescent road marking materials reduces the chance of roadway incidents during the night, as it provides high retro-reflectivity. To achieve a more efficient glowing road marking, the disc component installed onto the road surface should be protruded by 1 mm to 2 mm to lower dirt built up on the disc (Star Path, 2018). The glow radiated by the material is more effective in exceptionally dark conditions. However, it should be noted that the existence of surrounding lights impedes the light transmitted to the driver. At the point when surrounding light arrives at a specific level, the material becomes insufficient.

Presently, the average life span of this material is estimated up to 10 years, even in severe weather conditions, compared to other traditional materials, which have a life cycle of about 3 to 5 years. The photoluminescent material also exhibits longevity and durability compared to thermoplastic material (Aexcel, 2021). The advancement of glowing or photoluminescent road marking is not as developed as first visualized. Notwithstanding, there is potential for the advancement of a road marking material utilizing comparable innovations. For road markings to be invented, they would need to be created and tested to demonstrate that they satisfy all safety guidelines. Thus, the material would need to show execution and solidness against each of the following criteria:

- Standards

- Performance - skid resistance, photo luminance, and vehicle headlamp reflections
- Durability - minimal level of maintenance and traffic volume durability level
- Sustainability - material and carbon footprints
- Cost of the material - life span

The review has synthesized information showing that, with the advancement in technological engineering and new materials in pavement road marking, further testing of the new material needs to be undertaken by TxDOT to assess the potential application of the material on roads using laboratory and trial sections to determine if the material meets its specifications and standards.

3.2.6.4 Nanocomposite Paints Marking

In recent times, the growth of technologies and research into new coating materials has led to the introduction of advanced marking materials like photoluminescent marking material with decorative and protective characteristics. With extreme climatic conditions and traffic volume, night visibility and durability on pavement become a major concern. Nanocomposite paint marking helps to increase wear and scratch resistance, and thus the service life of road markings. Nanostructure material adopts fillers into pavement marking material with polymeric nanocomposite, displaying good performance compared to the standard traffic paint.

Taheri et al. (2018) prepared and characterized the composition of acrylic/nano clay-resin as marking paint. The properties of the nanocomposite marking paint were evaluated based on retro-reflectivity dynamics, wear, and scratch resistance. Nano-titanium dioxide-silicon dioxide is a new organic-inorganic advanced material with additive properties to achieve a self-cleaning effect (Hatami et al., 2018).

The most significant benefit of this new material is its cost effectiveness; it is one of the most affordable traffic materials accessible. The cost of the nanocomposite paint is between $10.00 and $15.00 per gallon, and it is estimated to stripe about 250

to 300 linear feet per gallon for a 4" lane, while the cost for thermoplastic paint is between $0.0645 to $2.3476 per linear foot (Trusco Manufacturing Company, 2019). This will help provide a benchmark for TxDOT in terms of the cost difference.

Another benefit is that it does not need solvents for tidying up; it very well may be flushed out with water or ammonia mixture. Since it evaporates rapidly in ideal conditions and has a quick drying time, it is ideal for use on road jobs that require fast turnaround work. Above all, the new material is eco-accommodating. Applying the nanocomposite paint on a wet surface or another painted surface can disturb the drying and restoring process, resulting in the least durable markings. As suggested by manufacturers, applying this marking material to dry surfaces, when the region has not experienced quantifiable downpours for more than 24 hours and would not encounter downpours for 4 hours after application, gives the best outcome. In any case, since the climate is exceptionally inconstant, reasonable rules include:

- The material should be applied to dry surfaces, not on a wet surface
- Satisfactory time expected to dry no less than 60 minutes
- For appropriate drying and attachment to the surface, the material should be applied when the surface and air temperature are somewhere around 50 °F or higher

This new marking material is a practical answer for creating traffic markings on streets, parking areas, and other regions with exceptionally high traffic. The material should be applied and permitted to dry under favorable conditions to guarantee the sturdiness of the markings. However, further testing should be undertaken by TxDOT on the chemical composition of the new material to ascertain the durability, retro-reflectivity, and safety components. The average life span of this new material is between 0.7 to 2.5 years, subject to the traffic flow on such a network (Sathyanarayanan, 2007). The application of the wet film thickness is between 4 mils and 10 mils at not more than 100^{o} C/212^{o} F. The drying and cure time between individual coats for 4 mils thickness is 1-2 hours, depending upon humidity and air movement.

3.2.6.5 Translucent Concrete-Based Smart Lane Separator

Translucent concrete-based smart lane separator utilizes the planting of plastic optical fibers into the pavement surface in order to transmit colored light and pass on immediate information on traffic density, road blockage, lane saturation utilization, and road geometry dynamics (Saleem et al., 2017). The translucent smart lane separator introduces an appealing potential to cooperate with intelligent transport systems such as independent self-driving vehicles. Furthermore, the performance of the marking material was assessed based on a strength test, skid resistance test, and temperature test. The analysis and results showed that a translucent concrete-based smart lane separator was suitable for both flexible and rigid pavement (Saleem et al., 2017). **Figures 34-36** reveal further information about the translucent concrete-based smart lane separator.

Figure 34 Optical Fiber Tendon (A)

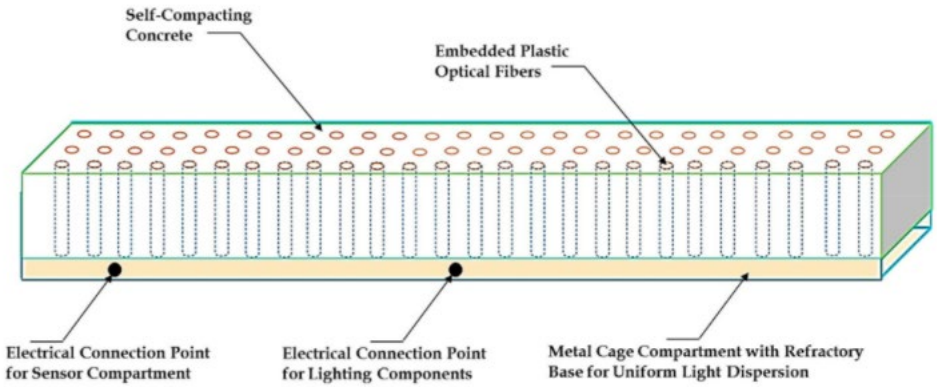


Figure 35 Smart Lane Separator with Detailed Function Description (B)

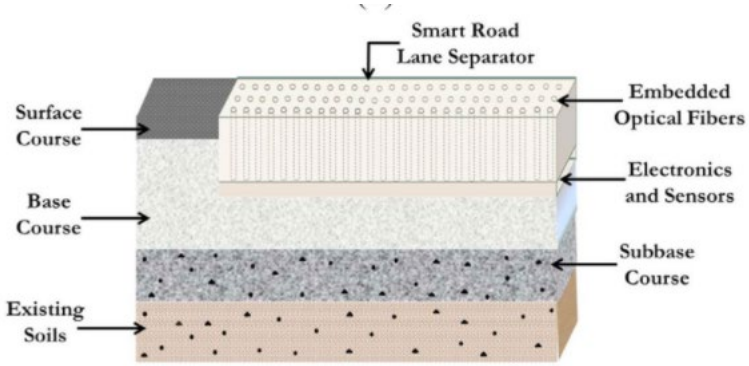


Figure 36 Layout of Smart Road Lane Separator with the Road Structure (C)

(Source: Saleem et al., 2017)

Current innovations in vehicles have advanced considerably since their creation; in many cases, the road infrastructure is comparatively slacking in any significant development concerning traffic safety. In such a manner, the introduced new material centers around developing and testing the translucent smart lane separator material, which can be installed on the road surfaces and can be utilized for dynamic observation and communicating valuable data to the road users to improve traffic safety and efficiency. The following can be deduced about the translucent smart lane separator:

- The developed material can send shaded light and is effective enough in compressive strength testing, temperature testing, and slide opposition testing.
- The created plastic-optical-fiber-based clear concrete has the option to support compressive stacking and thus can be utilized for adaptable and inflexible asphalts; for engineering and proper prerequisites, the plastic optical fiber ligament proportion can be expanded to build the light to move through the clear concrete.
- The ideal volume of the plastic optical fiber ligament can be presumed as 3% to limit the shortcoming in compressive strength owing to fiber substitution. Additionally, the interfacial connection between the plastic optical fiber

ligament and encompassing cement can be improved by roughing the outer layer of the plastic optical fiber ligament.

The new material has introduced an innovative way to deal with traffic safety issues and continues as a pilot examination for future investigation and recommendation. Utilizing the proposed translucent concrete base smart lane separator will make TxDOT a trailblazer in smart road infrastructure. The testing and evaluation should be based on compressive strength, translucency, temperature, flexural strength, and slide opposition testing.

3.2.7 Recommendations for New Pavement Marking Materials

The application of marking materials has contributed significantly to traffic safety and management. Marking material manufacturers and transportation agencies continue to advance the progression of materials and strategies, including thermoplastic marking materials, waterborne paint, and cold-plastic marking materials. Among them, the waterborne paints had been the viable answer to the more significant concerns of execution, climate, and health necessities. In the future, it is anticipated that waterborne paints will proceed to advance and obtain a bigger portion of the marking industry. The following are recommendations to TxDOT regarding pavement materials:

- The new marking materials, especially photoluminescent road markings and translucent concrete-based smart lane separators, still require detailed scrutiny to determine their practical applications.
- Further investigation is required to determine the minimum retro-reflectivity data for the new marking materials. Given the varying road geometry, vehicle mobility, and weather conditions, it is important to approve the suggestions through field tests to decide if the base level retro-reflectivity could give road users sufficient data.
- The new marking materials are eco-friendly materials that consider road users' health and environmental needs. Manufacturers of these materials may integrate technical expertise to enhance the durability of the new materials.

Also, TxDOT may develop its own durability standards with reference to field observation and conditions.

- The research should be relied upon to understand the inventive advancement of the new materials, for example, photoluminescent road marking nanocomposite paints and brilliant covering. Particularly, the photoluminescent material, as a cost efficient and inexhaustible light source, could upgrade traffic safety and the success of the marking framework. However, the application of these new materials still requires further investigation.
- In determining new marking materials and technologies in traffic safety, close attention needs to be given to real-world application situations. Installation and inspection managers should be equipped and able to ensure the advanced marking materials conform to requirements when adopted.

3.2.8 Marking Material Selection Process

3.2.8.1 Overview of Marking Material Selection Factors

The selection process of marking materials for a roadway project is one of the essential steps to be taken since it should determine the optimum suitability of a particular marking material type for a specific project. In this section, the research team has gathered important information from various sources and research papers to help answer critical questions, such as:

- Based on what criteria is the marking material selected?
- How do various transportation agencies' marking selection criteria differ from those in the TxDOT handbook?
- What other possible factors could be considered to enhance the TxDOT's marking material selection process?

Basically, many factors need to be considered in the selection of marking materials. These factors may include the following but are not limited to:

- Pavement surface
- Snow removal area

- Traffic volume (AADT or ADT)
- Type of street and highway
- Pavement condition
- Brightness benefit factor
- Speed
- Length of project

The NCHRP Synthesis 306 report showed the result of the survey that considered the parameters in the marking materials selection criteria by eight different state agencies. It concluded that the material selection process always leads to choosing between durable and paint markings. The most common factors are the type of line, pavement surface, traffic volume, and type of street and highway, while the service life of the remaining pavement is a less prevalent factor (Migletz and Graham, 2002).

3.2.8.2 Marking Material Selection Guide in Texas

For the selection of marking material type, the TxDOT (2004) considers three main factors: traffic characteristics (AADT), pavement remaining service life, and pavement types (HMAC, HCC, and surface treatments). As per the handbook, thermoplastic materials could be selected as the highest recommended material and alternative in all conditions set by TxDOT. **Tables 30-32** show the TxDOT marking material selection guideline.

Table 30 Pavement Marking Materials for Hot Mix Asphalt Concrete Pavements

Traffic Characteristic	**Pavement Remaining Service Life**		
	0 – 2 years	**2 – 4 years**	**>4 years**
AADT[2] < 1,000	*Thermo*, Water-Based Paint	*Thermo*, Water-Based Paint	*Thermo*, Water-Based Paint, Epoxy[3,4], Modified Urethane[4], Polyurea[4], MMA[4]
1,000 < AADT < 10,000	*Thermo*, Water-Based Paint	*Thermo*, Epoxy[3,4], Modified Urethane[4], Polyurea[4], MMA[4]	*Thermo*, Preformed Tape, Epoxy[3,4], Polyurea[4], Modified Urethane[4], MMA[4]
AADT > 10,000	*Thermo*, Epoxy[3,4], Modified Urethane[4]	*Thermo*, Preformed Tape, Epoxy[3,4], Polyurea[4], Modified Urethane[4], MMA[4]	*Preformed Tape, Thermo*, Epoxy[3,4], Polyurea[4], Modified Urethane[4], MMA[4]
Heavy Weaving or Turning	*Thermo*, Epoxy[3,4], Modified Urethane[4]	*Thermo*, Epoxy[3,4], Polyurea[4], Modified Urethane[4], MMA[4]	*Thermo*, Epoxy[3,4], Polyurea[4], Modified Urethane[4], MMA[4]

Notes:

[1] Source: (TxDOT, 2004). Materials may be used for short lines or longlines – except for two-component materials, which should only be used for longlines. Other materials may be used on an experimental basis with the approval of TRF or CST-MAT. Contrast markings may be used to improve visibility and safety as needed.
[2] AADT = Average Annual Daily Traffic.
[3] Epoxies are specially formulated as high-quality, high-durability permanent markings.
[4] Experimental materials.

Table 31 Pavement Marking Materials for Hydraulic Cement Concrete Pavement

Traffic Characteristic	**Pavement Remaining Service Life**		
	0 – 2 years	**2 – 4 years**	**>4 years**
AADT[2] < 10,000	*Thermo*[3], Epoxy[4,6], Modified Urethane, Water-Based Paint	*Epoxy*[4,6], *Thermo*[5] *(concrete formulation),* Modified Urethane[6], Water-Based Paint, Polyurea[6], MMA[6]	*Epoxy*[4,6], *Thermo*[5] *(concrete formulation),* Modified Urethane[6], Polyurea[6], Water-Based Paint, MMA[6]
10,000 < AADT < 50,000	*Thermo*[3], Epoxy[4,6], Modified Urethane[6], Water-Based Paint, Polyurea[6]	*Epoxy*[4,6], *Thermo*[5] *(concrete formulation),* Modified Urethane[6], Polyrea[6], Water-Based Paint, MMA[6]	*Epoxy*[4,6], *Thermo*[5] *(concrete formulation),* Preformed Tape, Polyurea[6], Modified Urethane[6], MMA[6]
AADT > 50,000	*Expoxy*[4,6], *Thermo*[5] *(concrete formulation),* Modified Urethane[6]	*Epoxy*[4,6], *Thermo*[5] *(concrete formulation),* Preformed Tape, Polyurea[6], Modified Urethane[6], MMA[6]	*Preformed Tape, Thermo*[5] *(concrete formulation),* Polyurea[6], Modified Urethane[6], Epoxy[6], MMA[6]
Heavy Weaving or Turning	*Epoxy*[4,6], *Thermo*[5] *(concrete formulation),* Polyurea[6], Modified Urethane[6]	*Epoxy*[4,6], *Thermo*[5], *(concrete formulation),* Preformed Tape, Polyurea[6], Modified Urethane[6], MMA[6]	*Epoxy*[4,6], *Thermo*[5] *(concrete formulation),* Preformed Tape, Polyurea[6], Modified Urethane[6], MMA[6]

Notes:
[1] Source: (TxDOT, 2004). Materials may be used for short lines or longlines – except for two-component materials, which should only be used for longlines. Other materials may be used on an experimental basis with the approval of TRF or CST-MAT. Contrast markings may be used to improve visibility and safety as needed.
[2] AADT = Average Annual Daily Traffic.
[3] Primer-sealer required prior to application of current TxDOT spec. Thermoplastic on concrete.
[4] Epoxies specially formulated for use as high-quality, high-durability pavement markings.
[5] See manufacturer's recommendations for use of primer-sealer.
[6] Experimental materials.

Table 32 Pavement Marking Materials for Surface Treatments

Traffic Characteristic	**Pavement Remaining Service Life**		
	0 – 2 years	**2 – 4 years**	**>4 years**
AADT[2] < 1,000	*Thermo*[3,4], Water-Based Paint	*Thermo*[3,4], Epoxy[5,6], Modified Urethane[6], Water-Based Paint	*Thermo*[3,4], Epoxy[5,6], Modified Urethane[6], Polyurea[6], Water-Based Paint
1,000 < AADT < 10,000	*Thermo*[3,4], Water-Based Paint, Epoxy[5,6]	*Thermo*[3,4], Epoxy[5,6], Modified Urethane[6], Polyurea[6]	*Thermo*[3,4], Epoxy[5,6], Polyurea[6], Modified Urethane[6]

AADT > 10,000	*Thermo*[3,4], Epoxy[5,6], Modified Urethane[6]	*Thermo*[3,4], Epoxy[5,6], Polyurea[6], Modified Urethane[6]	*Thermo*[3,4], Epoxy[5,6], Polyurea[6], Modified Urethane[6]
Heavy Weaving or Turning	*Thermo*[3,4], Epoxy[5,6], Modified Urethane[6]	*Thermo*[3,4], Epoxy[5,6], Polyurea[6], Modified Urethane[6]	*Thermo*[3,4], Epoxy[5,6], Polyurea[6], Modified Urethane[6]

Notes:

[1] Source: (TxDOT, 2004). Materials may be used for short lines or longlines – except for two-component materials, which should only be used for longlines. Other materials may be used on an experimental basis with the approval of TRF or CST-MAT. Contrast markings may be used to improve visibility and safety as needed.

[2] AADT = Average Annual Daily Traffic.

[3] If the bleeding or aggregate loss on a new surface treatment is common, consider the use of a temporary pavement marking (for example, paint or thin Thermo) prior to the standard thermoplastic application until the pavement surface has stabilized.

[4] For surface treatments with Grade 3 aggregates or larger, thermoplastic thickness greater than 100 mils may be necessary to achieve proper durability

[5] Epoxies specially formulated for use as high-quality, high-durability pavement markings.

[6] Experimental materials.

3.2.8.3 Marking Material Selection Guides in Virginia

Likewise, the VDOT (2019) uses pavement service life and roadway type as criteria to choose a particular marking material. The manual considers thermoplastic marking for pavement with all service life ranges. However, the VDOT (2019) recommends that the engineer's judgment should be used to select marking material for a particular roadway project.

3.2.8.4 Marking Material Selection Guides in Oregon

The ODOT (2021) suggests factors such as roadway surface type, traffic volume, the expected remaining service life of the pavement, future anticipated projects, pavement markings of adjacent sections, and available funding and ability to maintain should be considered during the selection process of marking materials to meet the performance requirements at the lowest cost.

3.2.8.5 Marking Material Selection Guides in California

Caltrans (2019) considered pavement surface type, snow removal area, wet night/fog area visibility concerns, and stripe durability requirements as major selection factors for pavement marking materials. Specifically, thermoplastic is considered when it comes to the elements like wet night/fog area visibility concerns, OGFC or bituminous seal surfaces, and PCC or HMA surfaces. According to the manual,

thermoplastic could be selected both for low and high durability requirements on OGFC or bituminous seal and PCC or HMA surfaces. For high, medium, and low durability, a thickness of more than 100 mils, 80 mils, and lower than 80 mils, respectively, are recommended (Caltrans, 2019). The interesting point regarding the California marking guidelines is that the application of thermoplastic is categorized based on pavement surface life surface. It could help to reduce the cost of the marking. The appendix of this report provides further information regarding the marking selection guidelines of Caltrans.

3.2.8.6 Marking Material Selection Guides in Wisconsin

The WSDOT (2019) developed a comprehensive policy for the selection of pavement marking materials. According to the WSDOT (2019) Traffic Engineering, Operations and Safety Manual, the pavement marking materials approved and used in the state include standard epoxy, grooved wet reflective epoxy, waterborne traffic paint, and permanent tape. To offer comprehensive guidance, the WSDOT developed two separate guidelines: one for roads which are marked for the first time, and another for roads that are required to be restriped. For the roads that need to be striped freshly, the Manuel considered several factors, including roadway type (conventional highways, freeways/expressways, and roundabouts), pavement surface type, pavement surface life, speed limit, and type of line. The same factors are considered for restriping/maintenance but with different guidelines. **Figures 37-42** reveal further information related to WSDOT marking selection policy.

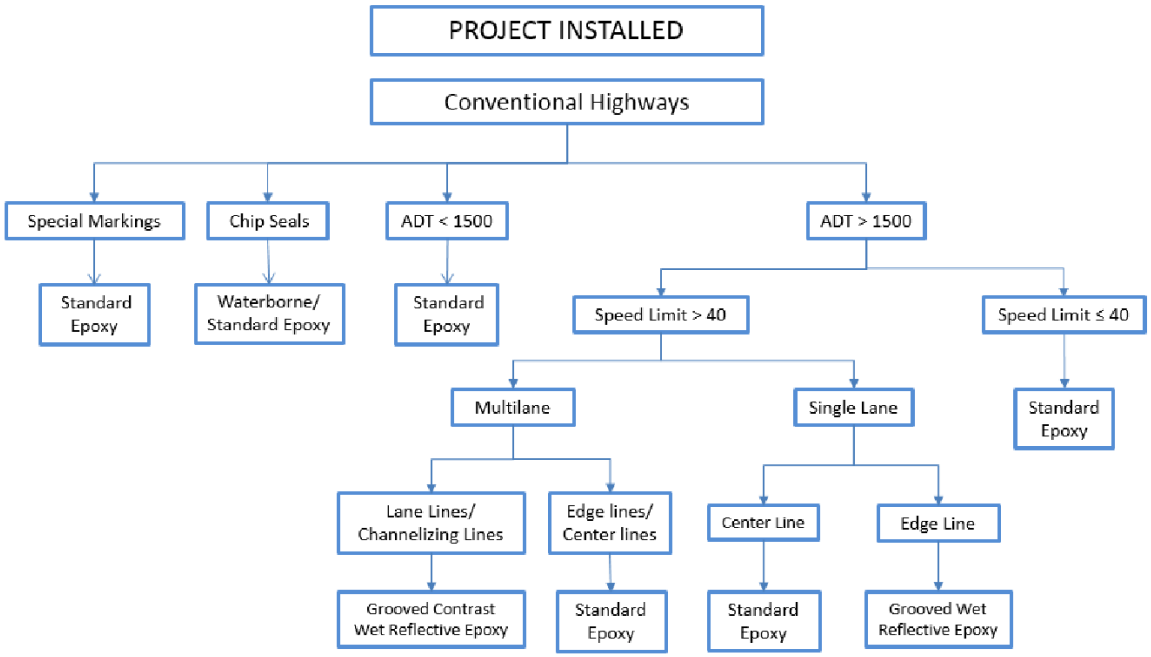


Figure 37 Conventional Highway Marking Selection Guideline (WSDOT, 2019)

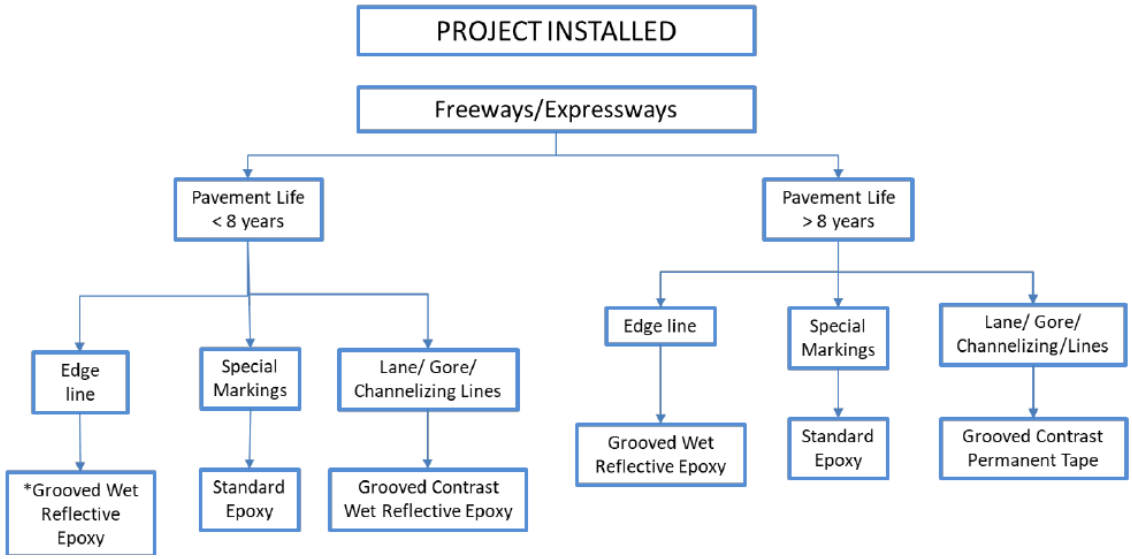


Figure 38 Freeway/Expressways Marking Selection Guide (WSDOT, 2019)

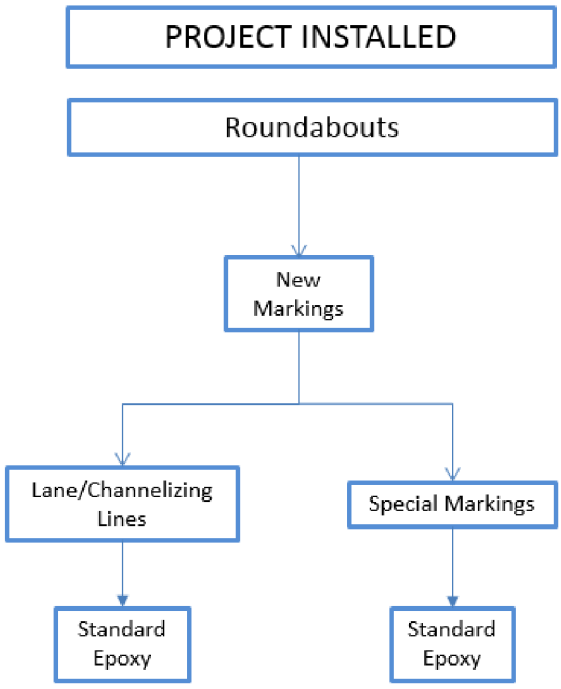
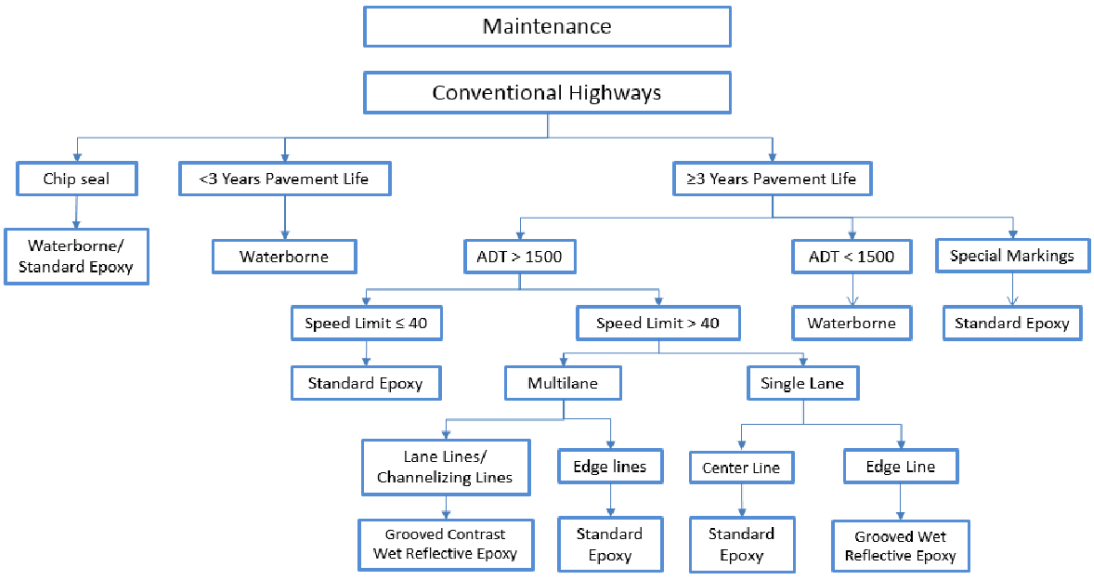


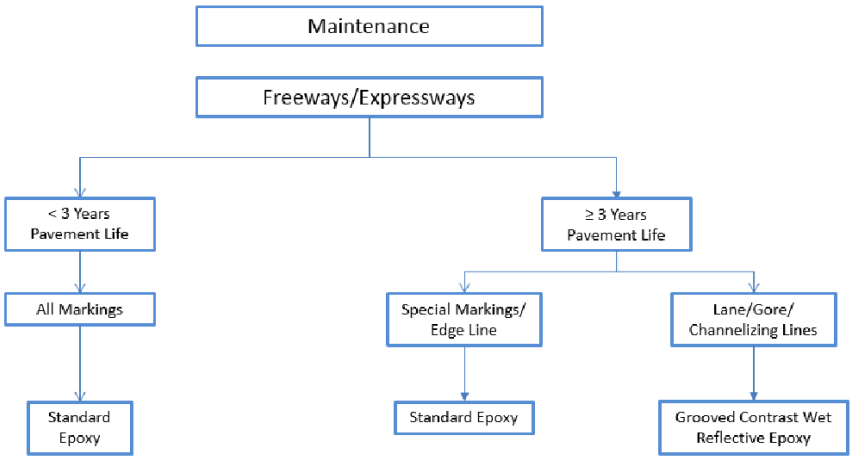
Figure 39 Roundabout Marking Selection Guideline (WSDOT, 2019)



NOTE:

- In areas where there is no groove, marking would be standard epoxy or waterborne.
- Where contrast epoxy already exists, retrace only the epoxy, not the contrast marking unless visually missing.
- Grooved Epoxy: Remarking within the existing groove, unless material is failing, then consider re-grooving.
- If thermoplastic is present, remove thermoplastic markings and replace with the correct product listed above. Retracing thermoplastic is NOT permitted.
- If tape is present and still bonding, retrace marking with the correct product listed above. If tape product is failing, remove tape and replace with epoxy.

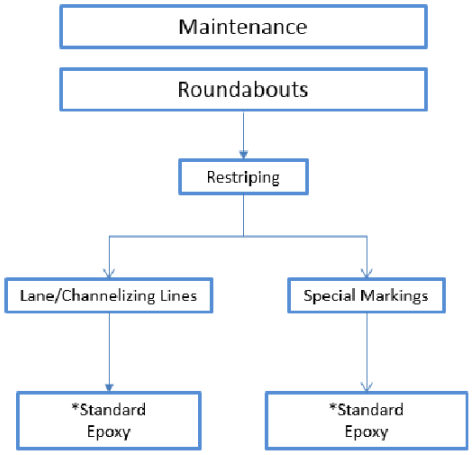
Figure 40 Maintenance-Conventional Highways Marking Selection Guideline (WSDOT, 2019)



NOTE:

- In areas where there is no groove, marking would be surface applied and not wet reflective.
- Where contrast epoxy already exists, retrace only the epoxy, not the contrast marking unless visually missing.
- Grooved Epoxy: Remarking within the existing groove, unless material is failing, then consider re-grooving.
- If thermoplastic is present, remove thermoplastic markings and replace with the correct product listed above. Retracing thermoplastic is NOT permitted.
- If tape is present and still bonding, retrace marking with the correct product listed above. If tape product is failing, remove tape and replace with epoxy.

Figure 41 Maintenance- Freeways/Expressways Marking Selection Guideline (WSDOT, 2019)



NOTE:

- Where contrast epoxy already exists, retrace only the epoxy, not the contrast marking unless visually missing.
- Grooved Epoxy: Remarking within the existing groove, unless material is failing, then consider re-grooving.
- If thermoplastic is present, remove thermoplastic markings and replace with the correct product listed above. Retracing thermoplastic is NOT permitted.
- If tape is present and still bonding, retrace marking with the correct product listed above. If tape product is failing, remove tape and replace with epoxy.

Figure 42 Maintenance- Roundabout Marking Selection Guideline (WSDOT, 2019)

3.2.8.7 Marking Material Selection Factors – From Survey in Chapter 2

In the survey in Chapter 2, one of the important questions that was asked was "What are the considered selection factors of this pavement marking?" In response, the respondents selected a broad range of factors that play a role in the selection of marking material. The responses are summarized in **Figure 13,** which shows that ADT, followed by pavement surface type, snow removal area, type of highways/roads, and remaining pavement service life, are selected by most respondents as the main factors that could affect the decision of road authorities in the selection of pavement marking materials. In addition, some of the participants selected "other" as a selection factor that is specified in the last three rows of **Table 33**.

Table 33 Responses on Pavement Marking Material Selection Factors- Survey in Chapter 2

Pavement Marking Type	Thermoplastic	Water-based Paint	Prefabricated	Multipolymer	Profiled thermoplastic
Pavement Surface Roughness	8	7	5	3	4
Roadway Surface Porosity	4	5	1	5	3
Heat Sensitivity	4	4	2	2	2
Traffic (ADT)	14	19	15	16	6
Environmental	4	7	2	2	1
Type of Line	5	5	13	6	4
Type of Street and Highway	7	9	6	10	4
Pavement Condition	8	6	9	5	3
Remaining Pavement Service Life	8	9	6	6	3
Area	0	1	3	2	1
Snow Removal Area	4	7	7	5	3
Brightness Benefit Factor	2	1	6	2	2
Speed	1	0	0	0	2
Length of Project	1	1	2	0	0
Others	7	12	5	6	3

Others - Specified by the respondents	Pavement age, pavement type, historically wet area so we use all weather thermoplastic. Cost	Used temporary. Used in rural areas. Used annually. Cost. Surface type.	Applied in places where durability matters	Used mostly in urban areas such as Las Vegas, Reno, Elko, as well as interstates and higher volume trafficked routes.	Dark, rural with high ROR/head on crashes w/ higher than 45 MPH posted speed. Safety
	TDOT is over 90% Thermoplastic on all types of pavements	Used for short term.	Type of surface	surface type, Final stripe applications	
	Permanent Stripe vs. Temporary	Temporary stripe	Do not use except temp. application		Accident reports and condition of existing stripe, and shoulder widen and pavement surface thickness
Answered	24	27	21	21	11
Skipped	10	8	14	14	24

3.2.8.8 Recommendations for TxDOT Marking Material Selection Guide

Based on the review of TxDOT's and several other states' marking selection guidelines and the survey responses, TxDOT marking selection guidelines may be improved by considering the following points:

- For thermoplastic, it is recommended that TxDOT consider various thicknesses based on the different situations. For instance, applying the same thermoplastic thickness may not be cost-effective for pavement with 0-2 years remaining service life and pavement with more than 4 years remaining service life.
- To select the most appropriate marking material for a particular project, factors such as roadway type and speed limit may also be considered in selecting marking materials since considering the roadway types and their speed limit would help engineers identify marking materials with appropriate retro-reflectivity based on the various conditions of roadways, i.e., weather condition, level of crashes, and so forth.
- To make TxDOT marking selection guidelines more comprehensive, the sub-classification of every marking material type may also be considered. For example, water-based paint has several sub-classifications, such as standard, all-weather, and high-build water-based paint, where each has different functionality and optimal application areas. The same is also true of epoxy

materials; there are various classifications of epoxy materials, including standard and modified epoxy.

- As the TxDOT Material Testing Division has already prequalified modified polyacrylate marking materials, it is recommended to consider this marking material in the marking selection guide as well.
- The research team recommends TxDOT develop a marking material selection tool to provide the engineers with appropriate marking material alternatives with all relevant information, including marking cost, based on the input parameters. This tool could be an Excel spreadsheet or software appropriately developed by a programmer.

3.3 Quality Control Approaches and Methods

Quality control is a crucial step that needs to be performed on behalf of the project owner to ensure that markings are installed by the pavement marking contractors based on the standards and specifications mandated by the state's manual and manufacturer's guidelines. Failure to fulfill the requirement of the standards and specifications may dramatically reduce marking service life, which may result in safety problems and financial losses. In this section of this report, the research team will evaluate the TxDOT marking quality control procedures based on the manual and specifications of other U.S. states and provide recommendations on the improvement of TxDOT quality control procedures.

3.3.1 Pre-installation Inspection of Pavement Markings

3.3.1.1 Pavement Surface Preparation and Checking for Moisture

Pavement surface preparation for markings is the first step that needs to be taken before applying pavement markings. TxDOT (2014) has developed separate specifications for the pavement surface preparation under Item 678. To effectively prepare pavement surface for marking installation, TxDOT recommends the following actions:

- Preparing enough pavement surface for the pavement markings or RPMs shown on the plans
- Removing all contamination and loose material
- Avoiding damaging the pavement surface
- Removing loose and flaking material when existing pavement markings are present

The TxDOT (2014) manual also approves four surface preparation methods: sweeping, air blasting, flail milling, and blast cleaning. For the air-blast method, the manual puts forward the below requirements:

- For concrete pavement surface, the air blast should be performed after removing contamination or old marking material just before the application of the pavement marking material.
- The air blasting equipment should generate compressed air at a minimum of 150 cu. ft. per minute and 100 psi using 5/16 in. or larger hosing.

According to TxDOT (2014) specifications, the inspector may allow the application of the marking if the contaminants up to 0.5 sq. in. to remain on the surface of the pavement after performing the following test, completed just before application of markings:

- Step 1. Air blast the surface to be tested to simulate blasting during the application of markings.
- Step 2. Firmly press a 10-in. long, 2-in. wide strip of monofilament tape onto the surface, leaving approximately 2 in. free.
- Step 3. Grasp the free end and remove the tape with a sharp pull.

TMR (2019) provides identical instructions to the TxDOT manual, stating that pavement surface area and the surrounding area of the marking must be dry and free of dirt, gravel, flaking pavement marking material, and other loose or foreign material. In addition, the manual mandates that, before applying markings on new

bitumen sealed surface, no volatile material and solvents should be present on it. The manual recommends that pavement marking construction be postponed if any of the following conditions are present.

- Where the existing material is flaking or chipping, is of a type or is in such a condition that adhesion of the new material to the road surface cannot be guaranteed for the required life of the marking, obtain the agreement of the principal to the proposed method of surface preparation and its extent.
- Where a pavement marking material is to be applied to a surface where it may be incompatible with the existing marking or surface, prepare the marking or surface suitably before applying the pavement marking material.
- Where a curing compound has been applied to a new rigid concrete pavement surface, remove the curing compound by physical abrasive means such as grinding or blasting from the areas where the pavement marking material is to be applied.

According to the TxDOT (2004) marking handbook, the pavement surface should be free of any moisture before applying the marking. The handbook suggests that the quality control engineer could verify the non-existence of moisture by the following two methods:

- *Asphalt or Concrete Surfaces* — Place a 12×12-inch square piece of plastic wrap on the pavement surface using duct tape to affix the edges. Let it stand approximately 15 minutes and check for moisture bubbles on the inside surface of the plastic. If moisture bubbles on the plastic are larger than a pencil eraser, then the pavement contains too much excess water. Notify the contractor of this condition and postpone all marking operations until the pavement is dry enough to prevent the large moisture bubbles from forming on the plastic.
- *Thermoplastic Applications on Asphalt Only* — Using roofing felt paper, place a 12×12-inch square of felt on the asphalt and install the thermoplastic material directly onto the felt paper. Let it cool for approximately 10 seconds, then lift

the paper to check for moisture on the backside. If moisture bubbles larger than a pencil eraser is present on the backside of the roofing paper, then the pavement contains too much excess water. Notify the contractor of this condition and postpone all marking operations until the pavement is dry enough to prevent the large moisture bubbles from forming on the back of the felt paper.

3.3.1.2 Weather Conditions and Pavement Temperature

Weather conditions and pavement temperature are other important parameters that need to be closely monitored by the quality control engineer during the application of pavement markings since most of the markings, including thermoplastics, are highly sensitive to the ambient and pavement temperature. According to TMR (2019), pavement markings must not be applied if rain, fog, and condensation may happen before curing the markings. The manual also states that wind movement affects the dispersion of glass beads, and therefore, it should be a reasonable condition during the application of markings, i.e., no wind more than 10 km/h for the application of glass beads or water-based paint. Based on the TxDOT (2004), an infrared thermometer is usually used to measure the pavement temperature.

Table 34 and **Figure 43** reveal the minimum ambient and pavement temperature requirements for various marking materials. As is shown in Figure 43, among all material marking types, thermoplastic is highly sensitive to ambient and surface temperature. On the other hand, low-VOC alkyd paint, followed by low-temperature waterborne paint and multipolymers, are the least susceptible to environmental and pavement temperatures.

Table 34 Ambient and Surface Temperature Requirement for Application of Various Marking Materials

Material Type	Sub-classification	Min. ambient and pavement temp (°F)	Min. Material Temperature (°F)	Source
Thermoplastics	Thermoplastic	55	410 - 430	(TxDOT, 2004 and 2014)

	Preformed Thermoplastic	55	302 - 356	(TMR, 2019)
	Profiled Thermoplastic	50	390	(Florida DOT, 2021)
Traffic Paint	Waterborne Paint	50		(Caltrans, 2018)
	Acetone-based Paint	40		
	high-build Waterborne Paint	45		(CDOT, 2021)
	Low-Temperature Waterborne	35		
	Low-VOC alkyd paint	32		(Transports Québec, 2019)
Multipolymers	Preformed Tapes	40		(Transports Québec, 2019)
	Slow curing Epoxy	50		(MnDOT, 2015)
	Polyurea	40		(NCDOT, 2018)
	Modified Urethane	35		(IDOT, 2015 and 2016)
	Fast curing epoxy	36		(Caltrans, 2018)
	Fast curing polyurea	36		
	Modified polyacrylate	35		(Swarco, 2021)
	Integrated Multipolymer System	50		(Ennis-Flint, 2020)

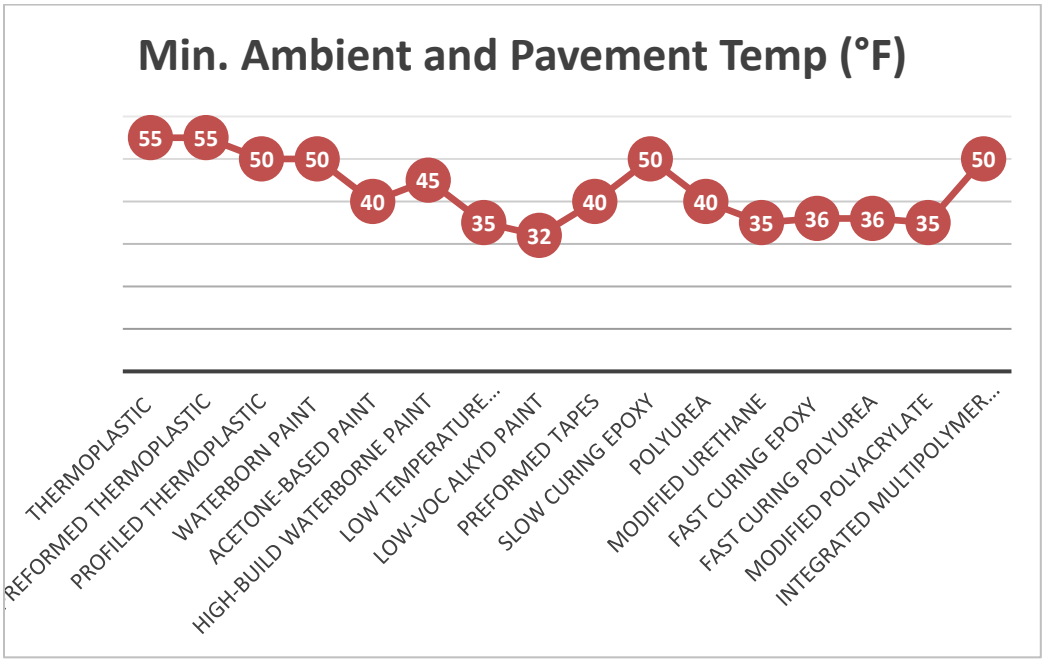


Figure 43 Minimum Ambient and Pavement Temperature (°F) Requirements for Various Marking Materials

3.3.2 Quality Control During the Installation of Markings

Monitoring the contractor's activities and determining whether the markings are applied sufficiently based on the pre-designated contract documents is a crucial

task. It could help fix problems associated with installing the markings and verify the contractor's payment. The essential elements required to be verified during the application of the markings are the thickness, width, color, glass bead application, and retro-reflectivity (nighttime appearance) of the markings.

3.3.2.1 Marking Thickness Inspection and Verification

One of the crucial elements that must be verified during the application of the markings is the thickness of the markings. As the thickness of the markings is directly proportional to durability, the person responsible for quality control must closely check to determine whether the marking is implemented based on specifications and standards. There are several ways to measure and verify the application of the markings, which are discussed in the subsequent sections.

3.3.2.1.1 TxDOT Method

According to TxDOT (2004), a special specification under Test Method Tex-854-B has been developed to measure the thickness of the markings. Using this method, a needlepoint micrometer is recommended to measure the marking's thickness with a maximum 2,000-foot sampling and three measurements diagonally across each sample. **Figure 44** shows the needlepoint micrometer measuring a thermoplastic sample. Section 4.3.1.1 in chapter 4 of this report provides further details on TxDOT method.

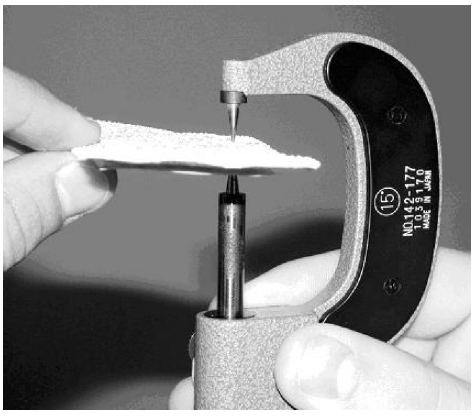


Figure 44 Needlepoint Micrometer Measuring a Thermoplastic Sample (*TxDOT, 2004*)

3.3.2.1.2 Marking Thickness Gauge Method

The marking thickness gauge is another device that can measure the thickness of the marking very quickly (*see* **Figure 45**). The instrument is a simple but efficient metric for ensuring the correct thickness of pavement stripes. Control measures can be necessary, particularly for thermoplastic stripes, where expensive material constitutes a significant part of the costs. This device can measure thicknesses ranging from -12.7 mm to +12.7 mm with a resolution of 0.01 mm and accuracy better than +/-0.02 mm (Delta and Forcetechnology, 2014). To check the accuracy, the readings made using this device can be compared with the theoretical usage rate specified in the Tex-854-B testing method.

Figure 45 Marking Thickness Gauge (Delta and Forcetechnology, 2014)

3.3.2.1.3 Methods Used in Maryland

The Maryland Department of Transportation (MDOT, 2013) has approved several methods to measure the thickness of paint, thermoplastic, and epoxy markings. For the measuring of the wet film thickness of paint and epoxy, MDOT uses a wet film thickness gauge device, which is calibrated in mils, as shown in **Figure 46.**

Figure 46 Wet Film Thickness Gauge

For measuring the dry film thickness of thermoplastic, MDOT recommends two methods: methods A and B. For method A, a shim, straightedge, and taper gauge are used to measure the marking thickness with the following procedure:

1. Place a shim on each side of the applied marking
2. Place the straightedge on top of the shims, leaving a small space between the marking and the straightedge
3. Measure the space between the straightedge and the marking material using the taper gauge or other equipment approved by the engineer
4. Determine the thickness of the marking by subtracting the space measured with the taper gauge from the shim thickness

For method B, the duct tape, shim, and straightedge are used to measure the thermoplastic marking thickness with the following procedure:

1. Apply the duct tape to the pavement perpendicular to and in the path of the pavement marking equipment
2. Apply the marking material across the tape
3. When the marking has dried, remove the duct tape
4. Place a shim in the void left by the duct tape

5. Place the straight edge on the top of the shims, leaving a small space between the marking and the straightedge
6. Measure the space between the straightedge and the marking material using the taper gauge from the shim thickness
7. Determine the thickness of the marking by subtracting the space measured with the taper gauge from the shim thickness

For both methods, it is recommended by MDOT to select the testing sites based on ASTM D3665. In addition, the manual suggests that measuring the marking thickness should be performed at a minimum rate of two sites per mile in each direction, for each color and line type; whereas for projects less than three miles in length, the test should be performed at a minimum rate of five sites per project. However, the ODOT (2021) mandates that the measurement of the thickness should be performed at 300-foot intervals, except for paint and tape applications.

3.3.2.1.4 Measuring Marking Thickness Using a Point Laser Device

Another method that can measure the thickness of thermoplastic is the usage of a point laser device mounted on a vehicle. According to Liu et al. (2006), this device is comprised of two parts: a hardware system to measure the pavement marking by using the laser triangulation technique and a software package to analyze and process the measured data, as shown in **Figures 47** and **48.** The research report conducted by Liu et al. (2002) reveals that point laser devices can effectively measure thermoplastic marking thickness at a satisfactory level of accuracy. The maximum measurement error of this device was estimated at 5 mils and 10 mils on smooth pavements (asphalt and concrete) and surface treatments, respectively.

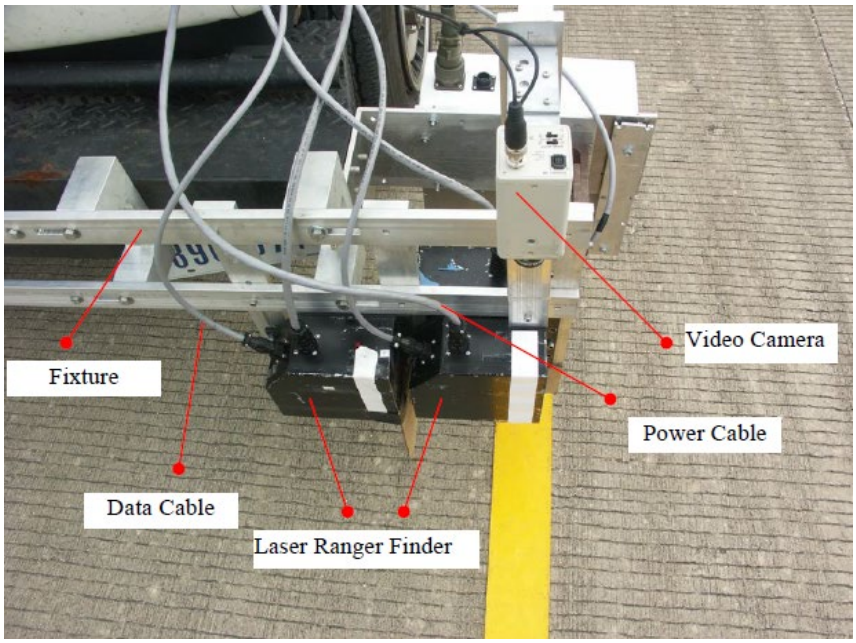


Figure 47 Vehicle Mounted Measurement System Component (*Liu et al., 2006*)

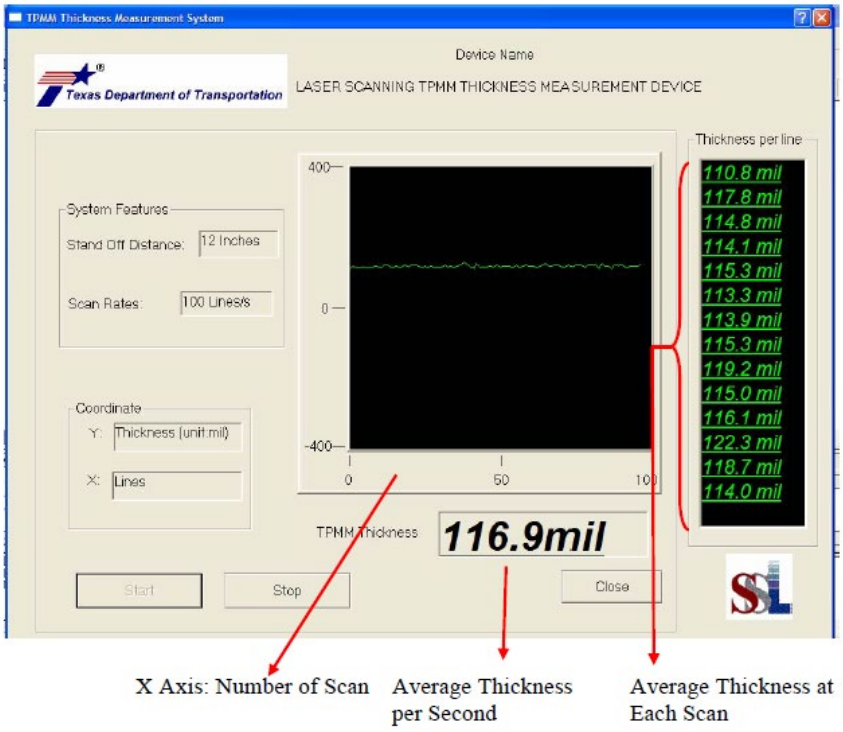


Figure 48 Thickness Information Display (*Liu et al., 2006*)

3.3.2.1.5 Survey Respondents on Measuring Marking Thickness

In the survey conducted in Chapter 2 of this research project, one of the main questions asked of the participants was "How would you verify the application rate of this marking in the field, i.e., thickness, volume, or rate, during your quality control procedure?" The research team received a broad range of responses, summarized in **Table 35**. In Chapter 4, the research team goes into detailed studies of various methods by which the measurement of marking thickness is performed.

Table 35 Survey Participants' Responses on Application Verification of Pavement Marking

No.	Water-based Paint	Thermoplastic	Prefabricated	Multipolymer	Profiled thermoplastic
1	Reading from on Board Computers.	TEM 350-8.4 - Data Logging System	Data Logging System attached to striping installation equipment	TEM 350-8.4 Data Logging System	N/A
2	Visual inspection, use tape and micrometer	Yield determination	visual inspection	Inspection	Micrometer
3	By taking measurements	Thickness using tape and micrometer	Inspect contractor while markings are being installed	Tape and micrometer	Thickness gauge
4	N/A - I'm guessing this is directed toward long liquid lines	Thickness verified by Nevada Test Methods T509B or T510A. Volume determined by quantity delivered to the job site.	thickness	For Epoxy applied on our contracts, the verification of the application rate is not mandatory since the contractor is normally subject to performance requirements. However, the supervisor can check the application rate using the wet film measurement method for verification purposes. The validation method based on the quantities in the tanks is more complex since there are two tanks on the stripping truck, one for each component.	Visual
5	Take sample mil checks	We have two main methods for verifying the application rates of Water-Based Paint Marking: the validation of quantities from the stripping truck tanks and the measurement of the wet film thickness with a paint thickness gauge.	We use prefab on stop bars, school zones, crosswalks, arrows, and words. Not really a rate on these types of applications.	Drawdown or Data Logging System files	Volume
6	Thickness	Drawdown and/or Data Logging System File	Adhesion test. Chisel test.	Thickness	Test sections prior to beginning
7	We only use preform	Verify with the contractor.	Check thickness before placement.	Mil plate and onboard computers	Thickness
8	Preformed Thermoplastic only for messages	Thickness	On-site inspections, mobile retroreflectivity/width inspections	Physical mil checks for the first mile, then KDOT uses a data logging system to verify mils and application rates.	
9	Mil checks are required. Mils are verified with calipers by inspector	Mil plates and on-board computer	Reflectivity and adhesion	Micrometer	

No.	Water-based Paint	Thermoplastic	Prefabricated	Multipolymer	Profiled thermoplastic
10	Micrometer	By number of feet painted and the gallons they use and convert them to mill thickness and to make sure it satisfies the spec.	Beginning and ending location	Footage & usage counters quality control strips	
11	On-site inspection and mobile retroreflectivity/width reviews	Data logger. Either Epic Solution or Skip line data logging equipment	Quantities	DLS, field inspection	
12	TEM 350-8.4 - Data Logging System According to C&MS Items 640, striping equipment for traffic paint, polyester, thermoplastic, epoxy, spray thermoplastic and work zone marking shall be equipped with a computerized Data Logging System (DLS). The data recording requirements depend on the material type and shall include the following information for long line markings only: 1. Measure and record application vehicle speed to the nearest 0.1 miles per hour. 2. Measure and record the weight and/or volume amount of material used by color. 3. Measure and record the weight or volume amount of material used by line type. 4. Measure and record the weight of glass beads. 5. Measure and record the weight of wet reflective optics 6. Measure and record the pavement surface temperature. 7. Measure and record the air temperature. 8. Measure and record the dew point (thermoplastic and spray thermoplastic not included) 9. Measure and record the humidity (thermoplastic and spray thermoplastic not included). 10. Calculate and record average materials application rates and	For maintenance operations, the TMA driver immediately behind the striper typically conducts the quality control at the beginning of a run, getting out of the truck, if possible, to make sure the line width is good and that the bead application rate and embedment is sufficient. We call for 60% bead embedment, mil thickness calibrations are the starting point, but bead embedment is used to adjust thickness for any given pavement surface. For contractor applied lines the specs call us for a minimum mil thickness, but also requires the contractor to increase mil thickness to achieve 60% bead embedment. Our inspectors typically do not inspect the embedment (although I know of one case where they have) so we rely on mobile retro readings to validate the quality of the line, but those readings are taken 30-45 days after the application to allow a poor application to become more evident by allowing more time for possible bead loss.	I may be misinterpreting what you mean by "prefabricated pavement markings" as this is not a term we use, but again assuming preformed thermoplastic or cold applied tapes since these are prefabricated in specific shapes and thicknesses the quality control is typically done through out materials lab certify the product meets specification upon award of a materials contract and quality assurance testing if there are any questions after the award.	Thickness by using Nevada Test Method T509B or T510A. Volume by amount of quantity delivered to job site.	

No.	Water-based Paint	Thermoplastic	Prefabricated	Multipolymer	Profiled thermoplastic
	film thickness over the section painted. 11. Measure and record temperature in the kettle and at the point of application (thermoplastic and spray thermoplastic only)				
13	Mil thickness gauged	On-site inspection	The thickness is set by the manufacturer. The volume is measured by how many sheets are used.	Spray a sign blank and test the mil thickness with a standard mill gauge card.	
14	Inspection	On board computers		Quantities	
15	We are using quantities	Wet film gauge		Not used	
16	Spot check thicknesses with tape and caliper	Data Logging System submittal, field inspection personnel		Mil gauge	
17	We make the contractor perform a test section prior to beginning the work.	Inspection			
18	I am unsure if we are doing this. Will check into it.	Yield based on volume and rate			
19	Thickness, rate	Mobile Reflectometer			
20	A micrometer is used to check thickness. The rate is figured by calculating how many tons are used per linear foot.	Rate. We check the gallons per mile on occasion if we see an issue with the look of the stripe. The speed of the paint truck is a factor as well.			
21		Mil gauge			
22		The volume is calculated by making sure they are using 20 gallons per mile.			
23	Duct Tape or AL Plate Placed prior to striping - verify striper speed, pull tape/plate and measure with caliper	Speed of striping rig, pavement absorption, bleed thru stripe and gallons per feet	Review material packaging		Measure in the field

3.3.2.2 Width Inspection

Pavement marking width is another component that must be inspected during marking application. According to the TxDOT (2004), TxDOT has not developed any testing method in the TxDOT Manual of Testing Procedures for measuring width, but it is mandated to be inspected at the minimum interval that is specified for marking thickness. TxDOT (2014) mentioned that marking lines should be installed with clean edges and a uniform cross-section with a minimum tolerance of ± 1/8 in. per 4 in. width. On the other hand, the MDOT (2013) requires the inspector to use a

straightedge for measuring the width of pavement markings. It is also noted that edge splatter should not be included in the width measurement.

3.3.2.3 Inspection of Glass Beads Application

Inspecting glass beads application is a crucial task that must be performed because improper application would adversely impact the retro-reflectivity of the roadway markings. Glass beads could be applied in two ways, either by spraying (pressure drop) or gravity drop onto the wet film marking material. There are various types of glass beads with different features and gradations. **Table 36** shows different kinds of glass beads based on federal specifications TT-B-1352B.

Table 36 Three Types of Glass Beads Based on Federal Specification TT-B-1352B

Properties	**Type I**	**Type II**	**Type III**
Refractive Index	Low: 1.50 -1.55	Medium: 1.65 - 1.75	High: 1.9 - 1.93
Appearance	Roundness-true spheres		
Weight Ratio	min 70% by weight	Min 70% by weight	min 75% by weight
Specific Gravity	2.30 - 2.50	2.80 3.20	4.00 - 4.50
Gradation	A or B	A	

Notes: Gradation A referred to the course for the drop on the application; Gradation B referred to the fine for premixing with the markings; All these types described above shall have enough resistance to calcium chloride, acids, and sodium sulfide without dulling effect on glass beads. Source: Xu et al., 2021

The efficiency of the glass beads is contingent on several components, including density and size, spherical defaults, and embedment (Xu et al., 2021). Likewise, TxDOT (2004) indicates that two critical components need to be closely monitored, including the amount and dispersion of exposed beads across a line and the depth of embedment of the beads, which will be discussed in the subsequent sections.

3.3.2.3.1 Amount and Dispersion of Glass Beads

There are several ways to check glass bead dispersion. MnDOT (2015) and TxDOT (2004) put forward two main methods to check the bead dispersion of the markings: the visual checking approach and the sun-over-shoulder method. For the visual checking method, the quality controller must verify whether the beads are dispersed uniformly on the surface of markings. If not, the quality controller should notify the contractor that his bead gun or pump is not functioning well. On the other

hand, using the sun-over-shoulder test method, the quality controller must ensure that the marking lines have a vibrant and steady glow. MnDOT (2015) and TxDOT (2004) suggest that this test should be performed when the sun is 20 to 80 degrees above the horizon with the following procedures:

- Select an area of roadway that contains the test line or message. It can be made of any material.
- When the sun is 20 to 80 degrees above the horizon, stand so that the sun is behind you.
- Adjust your distance from the stripe to where the shadow of your head touches the stripe area being observed.
- From this position, evaluate the retroreflective qualities of the stripe. You will be able to see whether the glass beads are evenly distributed over the line or message.

MDOT (2013) puts forward another procedure for bead analysis in which the equipment, such as magnifying lens, 2,400 ml capacity container, and stopwatch, have been used to complete the following steps:

- Determine the amount of glass beads being applied by securing the container under the bead gun and dispensing the dots for a predetermined time. Using the "Glass Bead Application Rate Tables," determine the application rate needed. The application rate can be determined in conjunction with the striping vehicle's speed and the material's width (e.g., 5 in. wide striping at 8 mph needs to yield 531 mL in 5 seconds to achieve 8 lb./100 ft^2). Compare the amount of collected beads to the required rate and adjust the number of beads and/or speed to ensure the proper number of beads is applied to the pavement surface. **Table 37** provides detailed information regarding glass bead application rate versus speed.
- After bead rate determination, apply the pavement marking and evaluate the beads' distribution, placement, and bonding using the magnifying lens.

a. The beads shall be uniformly distributed over the entire width of the marking material.
b. The beads shall be embedded into the marking medium 55 to 60%.

Table 1 Glass Beads Application Rate Equivalent Volume in Milliliters Per 5 Seconds Per 100 Square Ft

5 Inch Stripe							
SPEED mph	**WEIGHT OF BEADS, 1b**						
	6	**8**	**10**	**12**	**14**	**16**	**20**
10	500	688	844	1000	1168	1325	1668
9	438	594	750	875	1035	1162	1462
8	400	531	687	800	938	1068	1338
7	344	462	575	688	800	919	1150
6	300	400	500	593	694	793	1000
5	250	325	412	500	587	662	825
4	200	262	325	400	462	400	662
3	156	200	250	313	362	412	518
2	100	125	162	200	231	262	331
6 Inch Stripe							
SPEED mph	**WEIGHTS OF BEADS, 1b**						
	6	**8**	**10**	**12**	**14**	**16**	**20**
10	600	825	1012	1200	1402	1590	2003
9	525	712	900	1050	1230	1395	1755
8	480	638	825	960	1126	1282	1605
7	412	555	690	825	960	1103	1380
6	360	480	600	712	825	952	1200
5	300	390	445	600	705	795	990
4	240	315	390	480	555	480	795
3	187	240	300	375	435	495	622
2	120	150	195	240	278	315	398

3.3.2.3.2 Glass Beads Embedment Depth

Glass beads embedment depth is another component that must be checked by the quality controller since the lack of bead embedment directly reduces the retro-reflectivity of the markings. Generally, most of the states' manuals recommended that 60% of the glass bead's size should be embedded in the marking, and 40% should be exposed above the marking (Xu et al., 2021). Providing skid resistance on marking is another benefit of glass bead exposure above the marking. According to the TxDOT (2004), a close-up visual examination is recommended to inspect the glass beads embedment. The quality controller should notify the contractor if the beads appear to be too high or too low. **Figure 49** shows marking retro-reflective behavior given different depths of glass bead embedment.

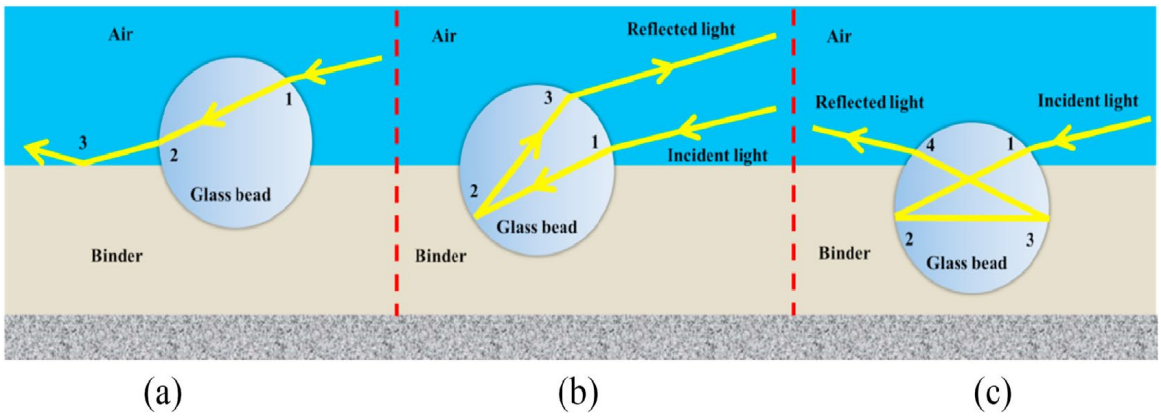


Figure 49 Retroreflection of Glass Beads in Pavement Markings: (a) Too shallow; (b) Suitable; (c) Too deep (Grosges, 2008)

3.3.2.4 Retro-Reflectivity Inspection

Inspection of retro-reflectivity is a critical requirement that needs to be precisely performed during the marking quality control procedures. Considering roadway safety importance for drivers traveling during the night, providing markings with high retro-reflectivity continuously remains a key concern of transportation authorities in the U.S. Retro-reflectivity indicates quantitatively the efficiency of marking material night visibility for drivers at a specified geometry. In general, retro-reflectivity is measured in units of millicandelas per meter squared per lux (mcd/ m^2/lux) using a standard 30m measurement geometry. **Figure 50** indicates the geometry of retroreflection.

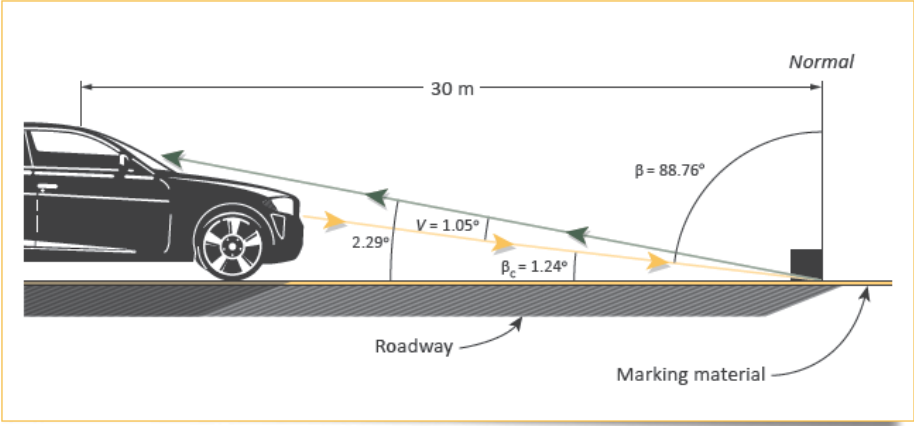


Figure 50 Geometry of Retroreflection (Transports Quebec, 2019)

There are several ways to measure and inspect the quality of pavement markings in terms of retro-reflectivity. TxDOT (2004) recommends two approaches for the evaluation of roadway marking retro-reflectivity: the sun-over-shoulder test and measuring the retro-reflectivity with the portable hand-held retro-reflectometer device and comparing its results to minimum specifications. The sun-over-shoulder test is the same method that has been discussed in Section 3.3.2.3.1. According to the TxDOT (2014), the portable retroreflectometer should fulfill the following requirements:

- Uses 30-meter geometry and meets the requirements described in ASTM E1710.
- Has either an internal global positioning system (GPS) or the ability to be linked with an external GPS with a minimum accuracy rating of 16 ft. 5 in., in accordance with the circular error probability (CEP) method (CEP is the radius of the circle with its origin at a known position that encompasses 50% of the readings returned from the GPS instrument).
- Able to record and print the GPS location and retro-reflectivity reading for each location where readings are taken.

In terms of usage, there are two types of retroreflectometers: hand-held portable and vehicle-mounted mobile. Hand-held is widely utilized for spot-checking markings, and a mobile retroreflectometer is used to take continuous readings while driving down the road at highway speeds. **Figures 51** and **52** show pictures of hand-held and mobile retro-reflectometers, respectively.

Figure 51 Hand-held Portable Retroreflectometer (Transports Quebec, 2019)

Figure 52 Mobile Retroreflectometer (Transports Quebec, 2019)

ASTM has separately developed specific procedures for measuring retro-reflectivity under ASTM E1710, ASTM E2177, and ASTM E2832 in dry, standard wetness (recovery), and continuous wetting, respectively (ASTM International, 2018, 2017).

ASTM E1710 gives the standard test for measuring pavement marking retro-reflectivity in dry conditions using a portable retroreflectometer. This test method requires the pavement marking to be clean and dry. As ambient temperature influences the retroreflectometer readings, ASTM E1710 mandates that the ambient

temperature should be more than 40 °F (Pike & Barrette, 2020). Based on this method, 30-m is the accepted standard for pavement marking retro-reflectivity measurement in all current retro-reflectometers, although other geometries, such as 12-m, and 15-m, have been used in the past (Pike & Barrette, 2020).

ASTM E2177 is another current standard for measuring pavement marking retro-reflectivity in a standard condition of wetness (ASTM International, 2018). The requirements of this test are identical to the testing conditions of ASTM E1710 except for the inclusion of requiring water to be considered in the testing process. Due to the inclusion of water consideration in the testing process, this test is often named the "recovery" or "bucket" method. Pike & Barrette (2020) explained the process of performing this testing as follows:

> "The wetting requirements for the test are 3 L of water poured from a bucket over the measurement area within a 3- to 5-second span of time. The retro-reflectometer is then placed on the marking, and a retro-reflectivity reading is measured 45 seconds after pouring the water. Dry and wet recovery readings should be recorded for each measurement area. Readings need to be made in areas where there is an adequate cross slope to facilitate drainage of the pavement markings."

ASTM E2832 is another currently practiced standard for measuring roadway marking retro-reflectivity in a continuous wet condition (ASTM International, 2017). This method has several requirements that differ from the methods discussed in the previous paragraphs. One of its main differences from other retro-reflectivity measurements is the inclusion of continuous spray box requirements. This box provides constant rain on the testing site at an intensity of 2 in/h (Pike & Barrette, 2020). This ASTM specification detail further discussed the process and procedures on how to perform this testing method. Figure 53 compares the different ASTM test methods under dry and wet conditions.

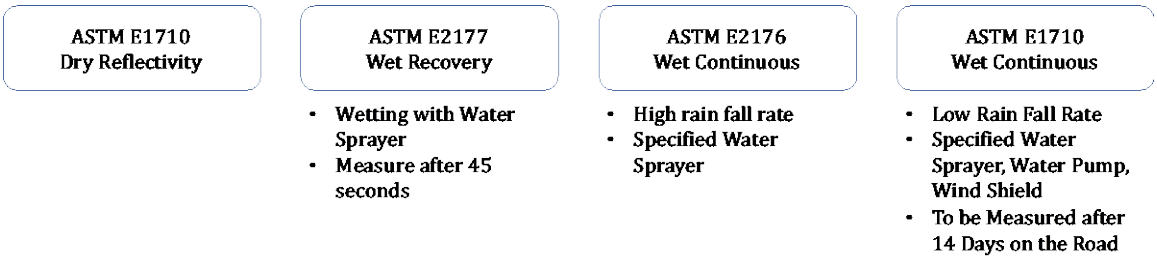


Figure 53 American Society for Testing and Materials (ASTM) Test Methods

According to TxDOT (2014), after completing the retro-reflectivity measurement test, the quality controller should compare the readings from the test with the minimum retro-reflectivity requirement specified in the standard specifications. All the readings must meet the minimum retro-reflectivity requirements at least for 30 calendar days. **Table 38** indicates minimum retro-reflectivity requirements for TxDOT.

Table 38 Minimum Initial Retro-Reflectivity for TxDOT (mcd/m^2/lux)

Type of Markings	Conditions	White	Yellow
All-weather thermoplastic	Dry (ASTM E1710)	400	325
	Wet continuous (ASTM E2832)	150	125
All-weather paint on the smooth surface	Dry	350	275
	Wet recovery (ASTM E2177)	350	275
	Wet continuous (ASTM E2832)	100	75
All-weather paint on the rough surface	Dry	250	200
	Wet recovery (ASTM E2177)	250	150 (Direction of striping) 125 (Opposite direction of striping)
	Wet continuous (ASTM E2832)	75	75
Type I- hot-applied thermoplastic	Not specified	250	175

3.3.3 Recommendation on TxDOT Marking Quality Control Procedure

Following review of TxDOT quality control procedures (TxDOT Pavement Marking Handbook, 2004), TxDOT Standard Specifications (2014), TxDOT's other special specifications, and several other states' quality control approaches, the research team concluded that the TxDOT has developed state-of-the-art procedures for the quality control of pavement markings. However, in order to make further

improvements to the TxDOT's quality control procedures, the research team has made the following recommendations:

- It is recommended that TxDOT conduct a comprehensive study on the viability of every approach practiced in the U.S. and other countries in determining marking material thickness. This study may evaluate various parameters involved in marking thickness measurement methods, including accuracy, time, cost, and so forth. It seems the TxDOT method for the measurement of road marking thickness using a needlepoint micrometer is time-consuming. Some other techniques, such as the marking thickness gauge device, may be less time-consuming.
- As TxDOT does not have any specifications for measuring marking width, it is recommended that the straightedge tool be used for measuring the width of the roadway markings.
- It is recommended that the TxDOT, based on the ASTM E1710, ASTM E2177, and ASTM E2832, adopt its own procedure for the testing of marking retro-reflectivity in different conditions such as dry, standard wetting, and continuous wet for all marking types that are used within the state. As per TxDOT standard specifications (2014), there is a minimum retro-reflectivity requirement only for Type I markings, while no retro-reflectivity requirement is mentioned for other types.

Chapter 4: Identify Types of Specifications and Application Rate Verification

4.1 Overview

Chapter 4 aims to identify various specifications and different approaches to application rate verification of pavement markings in Texas and other states. The research team reviewed and synthesized a variety of documents from several U.S. DOTs and other transportation agencies. In addition, the research team investigated issues and problems associated with each specification of marking types and the respective application rate verification. The research team investigated the following aspects:

(1) **Identified Types of Specifications Used and Recommended Language on:**

- How each transportation agency implements specifications on pavement marking materials and pavement marking constructions
- How material specifications are categorized for different types of pavements
- Construction specifications throughout the United States and other countries
- The warranty specifications of pavement markings in the U.S. and other countries

(2) **Application Rate Verification in the Field on:**

- How each state transportation agency (in and outside Texas) verifies the application in their quality control procedures
- How the application rate is checked
- How Texas, other states, and countries identify problems that have been encountered with the use of paint as a striping material, and their suggestions to solve such problems

- Tips and solutions of other states and countries based on their best-case examples
- Investigation applicability and testing in Texas
- A list of successful approaches to verify the application rate in the field regarding the thickness, volume, and rate, including the pros and cons of each approach.

4.2 Pavement Marking Specifications

Specifications are the most critical component of road marking practices as they determine all the requirements needed for developing and applying marking materials. There are various categories of pavement marking specifications, including marking material specifications, marking construction specifications, and warranty specifications. Each of these categories of marking specifications will be thoroughly discussed in the subsequent sections. **Figure 54** indicates different types of marking specifications with their relevant definitions.

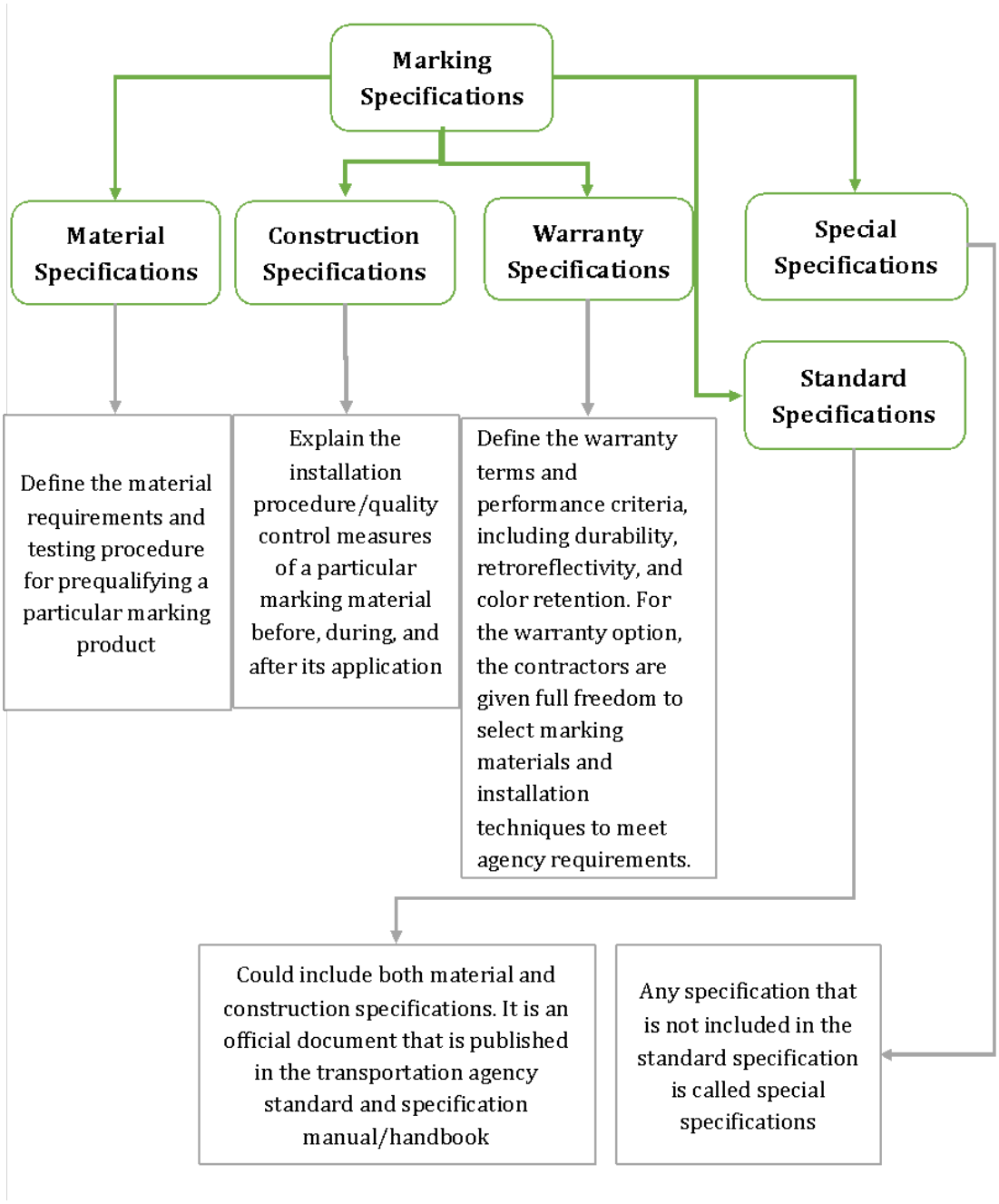


Figure 54 Different Categories of Pavement Marking Specifications

4.2.1 Pavement Marking Material Specifications

Pavement marking material specifications determine all features and requirements of a particular marking material so that it shows a high performance when applied in the field. In addition, the primary purpose of developing material

specifications is to describe the prequalification procedure for marking material products. Those products which are deemed prequalified are not required to undergo further testing prior to use. However, sometimes state Departments of Transportation (DOTs) also reserve the right to test the prequalified material based on the judgment of material engineers. Considering the importance of material specifications, most state DOTs developed material specifications for each type of marking material. For instance, the Texas Department of Transportation (TxDOT) has developed a unique material specification for traffic paint and hot-applied thermoplastic under DMS-8200 and DMS-8220, respectively. Although the state DOTs have developed their own marking material specifications, it is essential to note that manufacturers also create material specifications for the marking materials they produce. Hence, most states' marking manuals also recommend considering the manufacturers' recommendations if they are aligned with the agency's prequalification requirements.

4.2.1.1 Material Specifications for Thermoplastic

Thermoplastic has been the most used marking material in the U.S. for the past 60 years, and most U.S. states have developed material specifications for thermoplastic. Based on the research team's investigation across 10 states with regards to thermoplastic material specification development, it shows that five states have developed material specifications for thermoplastic while the other five states have not developed any specification for it. **Table 39** shows a summary of our reviews regarding the material requirements and testing methods for prequalification of the thermoplastic products and the source from which that data was retrieved.

Table 39 Thermoplastic Plastic Material Specifications in Various States

No	States	Thermoplastic Material Specification	Requirements Definition	Testing Method	Sources
1	**California**	Developed material specification under the name of the California Department of Transportation Specification for Thermoplastic Traffic Striping Material, Alkyd Resin Binder, White, and Lead-Free Yellow with spec.# PTH-02ALKYD	The specifications set 6 requirements, which include composition, form, application type/viscosity, characteristics of the finished thermoplastic, manufacturer QA program, and other requirements (Melting and Applicability, Workmanship, Shelf Life, Air Pollution Compliance)	1) California Test Methods CT 423 and CT 660. 2) (Caltrans), Standard Specifications. 3) AMS-STD-595A, color 33538. 4) the U.S. EPA, SW-846, Methods 3052 and 6010B. 5) AASHTO Designation: M 247. 6) ASTM Designations; D 476, D 2794, D 3335, D 3718, D 5380, D 5381, D 6628, E 11, E 28, E 313, E 1621, E 1710 and G 154. 7) Commission International de l'Eclairage (C.I.E.) 1931 Chromaticity Diagram. 8) California Code of Regulations: Title 22.	(CADOT, 2022)
2	**Colorado**	No thermoplastic material specification is developed			(CODOT, 2020)
3	**Illinois**	A general material specification is developed in the standard specification under the section of SECTION 1095	The specification has set 11 requirements for the feature of thermoplastic which include form, temperature, color, daylight reflectance and color, gravity, water absorption of plastics, softening point, tensile bond strength, yellowness index, accelerated weathering.	1) for specific gravity: ASTM D153; 2) for water absorption of plastic: ASTM D570; 3) for tensile bond strength: ASTM D 4796; 4) for yellowness index: ASTM D 1925; 5) for accelerated weathering: ASTM G 53	(ILDOT,2015)
4	**Iowa**	No thermoplastic material specification is developed			(IA, 2015)
5	**Kansas**	A general material specification is developed under the SECTION 2211 of Kansas DOT standard specification	The specification has set 6 requirements for the qualifying thermoplastic material, including general thermoplastic material, premix beads, glass beads for drop-on application, binder-sealer, color, and retro reflectivity.	The testing method for verifying thermoplastic include1) AASHTO T 250, plus, (2) Verify the material is alkyd using KTMR-6, Determination of Alkyd Base in Thermoplastic Material. (3) Glass Bead Content. ASTM D 4797. (4) Titanium Dioxide. ASTM D 1394, Aluminum Reduction Method. (5) Specific Gravity. AASHTO T 228.	(KS, 2015)
6	**Minnesota**	No thermoplastic material specification is developed			(MNDOT, 2015)
7	**Nevada**	No thermoplastic material specification is developed			(NV, 2014)

8	**North Dakota**	No thermoplastic material specification is developed			(ND, 2020)
9	**Ohio**	A general material specification is developed for thermoplastic pavement marking under the section 740.10 of Ohio DOT standard specification	The specification has set 10 requirements for the qualifying sprayed thermoplastic material, including composition, binder, pigment, filler, color, specific gravity, softening point, bond strength, impact resistance, and indentation resistance.	The Ohio DOT uses the following testing method to verify the thermoplastic materials: 1) for pigment - AMS-STD-595A Color No. 13538; 2) for color - ASTM 4960 and E 313; 3) for softening point- ASTM E28; 4) For bond strength -ASTM D 4796; 5) for impact resistance- ASTM D 2794; 6) for indentation resistance- ASTM D2240 have been adopted.	(OH, 2021)
10	**Texas**	A general material specification is developed for thermoplastic material under the name of DMS-8220 - Hot-Applied Thermoplastic	The specification has set 8 requirements for the qualifying for sprayed thermoplastic material, including general requirements, pigment, filler, binder, silica, color, uniformity, and formula.	The Texas DOT uses the following testing method to verify the thermoplastic materials: 1) for pigment, Tex-863-B and ASTM D 476; 2) for color, ASTM E 1710, and ASTM G 155; 3) for Tex-862-B, Tex-862-B have been recommended 4) AASHTO M249	(TxDOT, 2016)

As shown in **Table 39**, TxDOT (2016) has set eight requirements for the prequalification of thermoplastic materials in DMS-8220. These requirements include general requirements (meeting the requirements of AASHTO M249 with additions of some terms and conditions), pigment, filler, binder, silica, color, uniformity, and formula. The most important requirement of TxDOT's thermoplastic material specification is the use of AASHTO M249. This requirement is also set by other state DOTs, including those of Ohio, Kansas, and New York.

Some requirements are mandated in other states' specifications but not available in the TxDOT specifications. These requirements include water absorption of plastics, tensile bond strength, and accelerated weathering. For water absorption of plastics, the Illinois Department of Transportation (ILDOT 2015) states that "The material shall have not more than 0.5 percent by weight of retained water when tested by ASTM D 570, in 'Water Absorption of Plastics' Procedure (a)." Similarly, regarding the tensile bond strength, it is mentioned that "After heating the thermoplastic material for four hours ± five minutes at 425 ±3 °F (218.3 ±2 °C), the tensile bond strength to unprimed, sandblasted Portland cement concrete block,

0.0625 in. (1.587 mm) thick film drawn down at 425 °F (218.3 °C), tested at 75 ±2 °F (23.9 ±1 °C) shall exceed 150 psi (1,030 kPa) when tested according to ASTM D 4796." Likewise, for accelerated weathering, ILDOT (2015) points out that the thermoplastic material shall be applied to a steel wool abraded aluminum alloy panel at film thickness of 30 mils after heating the material for four hours ± five minutes at 425 ± 3 °F (218.3 ± 2 °C), which is then allowed to cool for 24 hours at room temperature. After that, the coated panel should be subjected to accelerated weathering using the light and water exposure apparatus (fluorescent UV - condensation type) for 75 hours according to ASTM G 53 (equipped with UVB-313 lamps).

In contrast, there are a few requirements that are made by AASHTO M249 but not in other investigated manuals. One of these requirements is flowability. AASHTO M249 (2008) states: "After heating the thermoplastic material for 240 ± five minutes at 425 ±3 °F (218.3 ±2 °C) and testing for flowability, the white thermoplastic shall have a maximum percent residue of 18, and the yellow thermoplastic shall have a maximum percent residue of 21."

4.2.1.2 Material Specifications for Preformed Thermoplastic

Preformed thermoplastic is a sub-category of a thermoplastic material that is commonly manufactured in sheets, normally 23.62 inches ×35.43 inches. The application procedure of preformed thermoplastic is that it is first fixed to its final position on the pavement surface; then, it is re-heated with the flame of a blow torch (150 °C – 180 °C) with a dry film thickness of 2 mm. Although the preformed thermoplastic material specifications are mostly the same as hot-applied thermoplastic ones except for the relevant differences due to the material being supplied in a preformed state, several state DOTs developed separate specifications for preformed thermoplastic. Based on our investigation, these states at least include Kansas, New York, Colorado, Illinois, Minnesota, and Nevada. **Table 40** indicates a summary of our reviews regarding the material requirements and testing methods/references for prequalification of the preformed thermoplastic products and the source from which that data was retrieved.

Table 40 Preformed Thermoplastic Material Specifications Across Various States

No	States	Preformed Thermoplastic Material Specification	Requirements Definition	Testing Method/ references	Sources
1	**California**	No preformed thermoplastic material specification is developed			
2	**Colorado**	A general material specification is developed for preformed thermoplastic pavement marking under the section 713.14 of Colorado DOT standard specification	Conforming with AASHTO M249 except for the difference due to being in a preformed state is the first requirement. The other requirements include graded glass beads, pigments, skid resistance, thickness, and environmental resistance.	1) AASHTO M249 2) ASTM E303	(CODOT, 2020)
3	**Illinois**	A general material specification is developed for preformed thermoplastic pavement marking under the section 1095.05 of Illinois DOT standard specification	The specification has set 11 unique requirements for the defining feature of preformed thermoplastic.	1) for skid resistance: ASTM E 303-74 recommended	(ILDOT,2015)
4	**Iowa**	No preformed thermoplastic material specification is developed			
5	**Kansas**	A general material specification is developed for preformed thermoplastic pavement marking under the section 2212 of Kansas DOT standard specification	Conforming with AASHTO M249 except for the difference due to being in a preformed state is the first requirement. The other requirements include general requirements, color retro reflectivity, pigments, and glass beads for drop-on application.	1) AASHTO M 249 2) AASHTO T250 3) ASTM D 6628	(KSDOT, 2015)
6	**Minnesota**	A general material specification is developed for preformed thermoplastic pavement marking under the section 3356 of Minnesota DOT standard specification	The specification has set 6 unique requirements for the defining feature of preformed thermoplastic. These requirements include general requirements, retro reflectivity, color, glass beads, skid resistance, and thickness.	1) for retro reflectivity: ASTM E1710; 2) for color: AMD-STD-595A and ASTM D6628 3) for glass beads: AASHTO M 247 4) for skid resistance: ASTM E303 haven recommended	(MNDOT, 2015)
7	**Nevada**	A general material specification is developed for preformed thermoplastic pavement marking under the section	For material composition, AASHTO M249 except for the relevant differences due to the material being	1) for composition: AASHTO M249 2) for glass beads: AASHTO	(NVDOT, 2014)

		732.03.03 (b) of Nevada DOT standard specification	performed is recommended. In addition to that, 15 unique requirements have been set.	M247 3) skid resistance: ASTM E303 4) for tensile strength: ASTM D638 5) for bond strength: ASTM D4796
8	**North Dakota**	No preformed thermoplastic material specification is developed		
9	**Ohio**	No preformed thermoplastic material specification is developed		
10	**Texas**	No specific preformed thermoplastic material specification is developed		

As **Table 40** indicates, TxDOT did not develop any material specifications for preformed thermoplastic even though this material is used for symbols and transverse markings in Texas. Although preformed thermoplastic material is highly identical to hot-applied thermoplastic, it is better to have specific specifications to provide a clear reference for the manufacturers, engineers, and contractors.

4.2.1.3 Material Specifications for Water-Based Paint

Water-based paint, as investigated in Chapter 3, is the most widely used marking material in the U.S. and other countries due to its exceptionally low cost. Therefore, most state DOTs have developed the material specifications for water-based paint. As per the research team's investigation across 10 state DOTs, all of them have developed the specifications for water-based paint. **Table 41** indicates a summary of our reviews regarding the material requirements and testing methods/references for water-based paint and the source from which that data was retrieved.

Table 41 Water Based Material Specifications Across Various States

No	States	Water-Based Paint Material Specification	Requirements Definition	Testing Method/references	Sources
1	**California**	Developed material specification under the name of the California Department of Transportation Specification for paint, rapid dry waterborne traffic line, White, Yellow, and Black with spec.# PTWB-01R2	The specifications set 3 requirements, including general requirements, composition, and characteristics of the finished paint.	1)ASTM Designations: D93, D476, D522, D562, D711, D869, D1210, D1475, D1640, D2369, D3168, D3335, D3718, D3723, D3960, D4563, D5380, D6628, D7585, E70, E313, E1710 and G154. 2) Federal Specification 595b, Color #33538 and #37038. 2) EPA Method 24 3) Code of Federal Regulations, Title 49. 4) California Code of Regulations, Title 22, Division 4. 5) California DOT, Test Method No. 660.	(Caltrans, 2019)
2	**Colorado**	A general material specification is developed both for low-temperature acrylic waterborne paint and high build acrylic waterborne paint pavement marking under the section 708.05 of Colorado DOT standard specification	The specification has set 7 unique requirements for the defining feature of water-based traffic paint.	1)ASTM E313 2) ASTM D2205 3) ASTM D4451 5) ASTM D3723 6) ASTM D5381 7) ASTM D4758 8) ASTM D2205 9) ASTM D562 10) ASTM D2243 11) ASTM D1210 12) ASTM D2486 13) ASTM E1347 14) ASTM D2805	(CODOT, 2020)
3	**Illinois**	A general material specification is developed for preformed thermoplastic pavement marking under the section 1095.02 of Illinois DOT standard specification	The specification has set 18 unique requirements for the defining feature of traffic paint.	1) for ingredient materials: ASTM D 476, ASTM D 1199, ASTM D 1152 - 2) For paint properties: ASTM D 3960, ASTM D 2369, Federal Specification TT-P-1952D	(ILDOT,2015)
4	**Iowa**	A general material specification is developed both for waterborne and high-build water borne paint marking under the section2527.02 (2) of Iowa DOT standard specification			(IADOT, 2015)
5	**Kansas**	A general material specification is developed for paint pavement marking under the section 2215 of Kansas DOT standard specification	The specification has set 6 unique requirements for the defining feature of traffic paint.	1) For dry opacity: ASTM D 2805 - 2) Daylight reflectance: ASTM E 1347 3) Bead Embedment: AASHTO M 247	(KSDOT, 2015)
6	**Minnesota**	A detailed material specification is developed for water-based traffic paint pavement marking under the section 3391 of Minnesota DOT standard specification	It has various requirements; please refer to the specifications.	ASTM D1475 - ASTM D562 - ASTM D1210 - ASTM D2369 - ASTM D2371 - ASTM D711 - ASTM D711 - ASTM E1349 - ASTM E1349 - ASTM D2805 -	(MNDOT, 2015)

7	**Nevada**	A detailed material specification is developed for water-based paint pavement marking under the section 729.03.04 of Nevada DOT standard specification	Various requirements were developed; please refer to the material specification	ASTM D3335 - ASTM D 3718 - ASTM 1849 - ASTM D522 - ASTM D2243 - ASTM D2244 - ASTM E1347 -ASTM D1729 - ASTM D1640 - ASTM 968	(NVDOT, 2014)
8	**North Dakota**	A general material specification is developed for water-based paint pavement marking under the section 880.01 of North Dakota DOT standard specification	Various requirements were developed, including general requirements, composition, dry through time, water resistance, freeze-thaw stability, color, contrast ratio, reflectance, durability, retro reflectivity	ASTM D 3960 - ASTM D 562 - ASTM D 1210 - ASTM D 711 - ASTM E 1349 - ASTM D 2805 - ASTM E 1710	(NDDOT, 2020)
9	**Ohio**	A general material specification is developed for traffic paint pavement marking under the section 740.02 of Ohio DOT standard specification		ASTM D 2369 - ASTM D 1394 - ASTM D 3723 - ASTM D 1475 - SS 1047 ASTM D562 - ASTM D711	(OHDOT, 2021)
10	**Texas**	A detailed material specification is developed for water-based paint pavement marking under the name of DMS-8200 "traffic paint" in TxDOT standard specification	Various requirements were developed; please refer to the material specification	ASTM D476 - ASTM D1199 - ASTM D1152 - (Tex -806 -B) - (Tex - 811 - B) - ASTM D711	(TxDOT, 2017)

As shown in **Table 41**, almost all state DOTs have developed material specifications for water-based paint pavement marking. For paint testing, ASTM testing procedures are utilized as a reference by all states. However, in addition to using the ASTM procedure, several states have developed their own methods for testing paint marking materials. For instance, the TxDOT developed Tex-806-B and Tex-811-B to verify the grind and skinning features of the furnished paint, respectively. Similarly, the Caltrans developed Test No. 660 for evaluating marking material color based on its chromaticity coordinates.

4.2.1.4 Material Specifications for Preformed Tapes

Generally, the preformed tape is a urethane or pliant polymer film with glass beads embedded on the surface for improvement of its retro-reflectivity and skid resistance. Preformed tapes are supplied in continuous rolls of various widths and lengths and available in sheeting form, which can be cut into different words and

symbols. Based on the research team's investigation across 10 states regarding preformed tape material specification development, eight states have developed material specifications for preformed tapes while the other two states have not developed any specifications for it. **Table 42** indicates a summary of our reviews regarding the material requirements and testing methods for prequalification of the preformed tape products and the sources of citations.

Table 42 Preformed Tape Material Specifications Across Various States

No	States	Preformed Tape Material Specification	Requirements Definition	Testing Method/references	Sources
1	**California**	No preformed tape material specification is found			
2	**Colorado**	A general material specification is developed for preformed plastic tape pavement marking under the section713.13 of Colorado DOT standard specification	The specification has set 7 unique requirements for the preformed tape.	ASTM D6628; ASTM D4505; ASTM D4505; ASTM Test Method 1000;	(CODOT, 2020)
3	**Illinois**	A general material specification is developed for preformed thermoplastic pavement marking under the section 1095.03 of Illinois DOT standard specification	The specification has set 14 unique requirements for the defining feature of preformed tape.	1) For skid resistance: ASTM E303 - 2) for tensile strength: ASTM D 638-76	(ILDOT,2015)
4	**Iowa**	A very general material specification for regular preformed tape is developed			(IADOT, 2015)
5	**Kansas**	A general material specification is developed for cold plastic (preformed tape) marking the under the section 2207 of Kansas DOT standard specification	Conforming with ASTM D 4505 is the base requirement.	1) ASTM D 4505	(KSDOT, 2015)
6	**Minnesota**	A general material specification is developed for preformed tape pavement marking under the section 3354 of Minnesota DOT standard specification	The specification has set 7 unique requirements for the defining feature of preformed tape. These requirements include general requirements, retro reflectivity, color, tensile stress, elongation, skid resistance, and thickness.	1) for retro reflectivity: ASTM E1710 - 2) for color: AMS-STD-595A and ASTM D6628 -3) for tensile stress: ASTM D638 - 4) for elongation: ASTM D638- 5) for skid resistance: ASTM E303 are recommended	(MNDOT, 2015)
7	**Nevada**	No preformed tape material specification is developed			
8	**North Dakota**	A general material specification is developed for preformed tape pavement marking under the section 880.03 of North Dakota DOT standard specification			(NDDOT, 2020)

9	**Ohio**	A general material specification is developed for various types of preformed tape pavement markings under the section 740.05 of Ohio DOT standard specification	Various requirements were developed; please refer to the material specification		(OHDOT, 2021)
10	**Texas**	A general material specification is developed for preformed tape pavement marking under the name of DMS-8240 "permanent prefabricated" in TxDOT standard specification	Various requirements were developed, including general requirements, composition requirements, dimensional tolerance, and color.	Tex-888-B; Tex-863-B; Tex-732-I; Tex-839-B; ASTM G155	(TxDOT, 2016)

As indicated in **Table 42**, most state DOTs have developed material specifications for preformed marking materials. TxDOT has also developed general material specifications for this marking material. The main difference between the specifications of the TxDOT and other states is that the TxDOT have used the term "prefabricated" for this particular marking material, while all other state DOTs use the term "preformed". Another difference that can be observed is that the TxDOT developed very general specifications for this material while several other states made a very detailed set of requirements. As an example, ILDOT developed a wide variety of requirements, including skid resistance, tensile strength, elongation, plastic pull test, and reflectance, while none of these requirements are included in the TxDOT specifications.

4.2.1.5 Material Specifications for Multipolymers

Multipolymers marking materials, such as epoxy, polyurea, modified Urethane, and methyl methacrylate are not extensively used in most U.S. states. The reasons for the restricted usage of the multipolymers are not limited to their high cost, durability concerns, and difficulties in finding contractors to install and implement this type of marking materials in various states. **Table 43** illustrates a summary of our review regarding the material requirements and testing methods for the prequalification of multipolymer material specifications in some state DOTs.

Table 43 Multipolymer Material Specification Across Various States

No	State	Multipolymer Types	Material Specification	Requirement Definitions	Test Methods	Source
1	California	Epoxy Polyurea	Material specifications are developed under the name of "integrated multipolymer materials" section 84-2-02F	The specifications contain five material requirements including glass sphere, titanium dioxide, organic yellow, resin polymer content, and inert filler	ASTM D4797	Caltrans 2018
2	Florida	Integrated Multipolymer	Developed material specification under pavement marking materials-Integrated Multipolymer Material section 971	The specification has set 5 requirements which include pigments, resin, polymers (adhesive constituent), glass beads, and fillers	Accordance with ASTM D7307 & ASTM D7308 (1) Bond strength. ASTM C321 (2) Low-temperature stress AASTHO T250 (3) Gardner impact ASTM D5420 (4) Tensile Elongation ASTM D638 (5) Taber Abrasion ASTM D4060 (6) Flash point ASTM D92 (7) Specific gravity: Water displacement	FDOT, 2020
3	Illinois	Epoxy Polyurea Modified urethane	Developed a general material and construction specification available in the State's manual under pavement marking section.	The specifications have nine set of requires include: ambient temperature, wet film thickness, material temperature. small glass beads application rate, large glass beads application rate retro reflectivity, pavement edge, lateral deviation, and marking width	AASHTO M 284, Tex-828-B	IDOT, 2013
4	Iowa		No specification is provided in the Iowa DOT standard specifications			

5	Kansas	Epoxy	A special provision to the standard specification under section 1808	The specifications have three material requirements: rust penetrating sealer, spot primer, and topcoat	ASTM D1644 ASTM D5894 ASTM D1654	KDOT, 2015
6	Oklahoma	Multipolymer	Developed a special provision for traffic stripe (multi-polymer) under section 856	The specifications have set four material requirements for the qualifying for multipolymer, which include: color, multipolymer composition, sampling and certification, and non-reflectorized contrast or shadow marking	The testing method for pigment composition (1) Titanium Dioxide Rutile ASTM D476, type III, 94% minimum for white (2) for yellow Titanium Dioxide ASTM D476, Type III	Oklahoma, 2017
7	Nevada	Polyurea Epoxy	Under the advancing durable pavement marking material specification	The specification has set 3 unique requirements of retro reflectivity, color, and durability.	ASTM D 6628 ASTM D 6359 ASTM E 1710	NDOT, 2014
8	New York	Epoxy	Standard specification for Pavement marking materials under section 685 epoxy reflectorized pavement markings.	Having two-components (part A and B) of color, directional reflectance, drying time (laboratory and field), hardness, infrared spectrophotometer analysis	ASTM D1535 ASTM E1347 ASTM D711 ASTM D2240 ASTM D2621 AASHTO T-250	NYSDOT, 2002
9	Oregon	MMA	For Longitudinal Durable Pavement Markings Section 00865.00 method A and B		Application and testing method is extruded and spray	
10	Texas	Multipolymers	Developed a special specification under the section 6279-Multipolymer Pavement Markings (MPM)	The specifications have set three performance requirements for the prequalification of multipolymer pavement marking on pavement surfaces including: color, durability, and retro reflectivity.	(1) measured by 45 degrees/ 0-degree geometry CIE (2) 2-degree standard observation angle ASTM E1347, E1348 or E1349 (3) Retro reflectometer ASTM E1710 (4) Durability ASTM D913	TxDOT, 2004

As shown in **Table 43**, the TxDOT (2004) has set three performance requirements for the prequalification for multipolymer materials in its special specification 6279. These performance requirements include color, durability, and retro reflectivity requirements. The Caltrans specifications are on the five-material

requirements of glass beads, resin polymer, titanium dioxide, organic yellow and inert filler for the epoxy, polyurea, and methyl methacrylate uses. The New York DOT uses the color directional reflectance, drying time, hardness, and infrared spectrophotometer for it epoxy material. The Illinois DOT addresses its uses of epoxy, polyurea, and modified urethane on nine set of material requirements for the multipolymers materials. However, the TxDOT Tex-826-B method is employed to assess retroreflective properties, which are the same as the Illinois DOT's. The Florida DOT includes some conditions that are not available in the TxDOT specifications like the specific gravity, Gardner impact, bond strength, low-temperature stress, and Taber abrasion. The Oklahoma DOT material specification focuses on color requirements for its white and yellow titanium dioxide.

4.2.1.6 Material Specifications for Profiled Markings

This type of marking consists of a baseline thickness and a profiled thickness which is part of the pavement marking line that is installed at a greater thickness than the baseline thickness. Profiled marking is usually applied by the extrusion method in the same application as the baseline. According to the survey conducted in Task 2, the non-usage of profiled marking in many state DOTs is because of not obtaining satisfactory results during the testing process, challenges in heating thermoplastic material, and not being durable in states experiencing snowfall. **Table 44** illustrates the synthesized summary of profiled marking material specifications in some state DOTs.

Table 44 Profiled Marking Material Specifications Across Various States

No	States	Profiled Marking Specification	Requirements Definitions	Testing Method	Source
1	Washington	No profiled marking specification is developed			(WSDOT, 2021)
2	Florida	Developed a general material specification for pavement marking materials under section 971	The specification has set 7 requirements for the qualifying for profiled thermoplastics marking, which include binders, Titanium Dioxide, type II Rutiles, Reflective elements, yellow	The testing method shall be in accordance with (1) Bond strength. ASTM C321. (2) Low temperature stress AASTHO T250 (3) Softening point ASTM D36 (4) Indentation resistance ASTM D7735	(FDOT, 2016)

			pigments, calcium carbonate, and inert filler	(5) Impact resistance ASTM D256, Method A (6) Flash point ASTM D92 (7) Specific gravity: Water displacement (8) water absorption ASTM D570 (9) Reflective element AASTHO T250 (10) Titanium Dioxide ASTM D476	
3	Illinois	No profiled marking specification is developed			(IDOT, 2015)
4	Iowa	No profiled marking specification is developed			(IOWA, 2019)
5	Tennessee	Developed a special provision regarding profiled thermoplastic pavement marking audible system (SP716PTA)	The specification for raised profile system shall meet the department sampling and testing guide and glass beads drop-on application. for inverted profile system has set 4 material requirements for the qualifying, which include composition, glass beads, intermix glass beads, and double drop system	The testing and measurement are done on linear miles, complete in place, and accepted raised or inverted audible system.	(TDOT, 2021)
6	South Carolina	Developed a supplemental specification for profiled road marking system	The specification shall meet the requirement for appearance: base line, raised shapes, integrally formed ribs, drop-on /preformed disc or hot extruded shape.	The testing method for profile marking (1) Titanium Dioxide Rutile ASTM D476, Type II rutile (2) intermixed beads AASTHO M247-type I (3) Pigment titanium dioxide ASTM D476-Type II Rutile (4) yellowness index AASHTO M249 (5) Softening point AASTHO T-250 (6) impact resistance AASTHO T-250 (7) flash point ASTM D92 (8) color ASTM D4960	(SCDOT, 2011)
7	Minnesota	No profiled marking specification is developed			(MnDOT, 2015)
8	Nevada	No profiled marking specification is developed			(NDOT, 2014)
9	Indiana	No profiled marking specification is developed			(IDOT, 2012)
10	Texas	Developed a special specification 6085 for Inverted profiled Pavement Markings (audible)	The specification has set 5 material requirements for the qualifying for inverted profiled marking (audible) which include: composition, pigment, beads, resin, and filler uniformly blended.	The Texas DOT uses the following testing method to verify profiled pavement marking: (1) Titanium dioxide ASTM D476-Type II (2) Glass beads ASTM D1155 (3) color ASTM 1925 (4) reflectivity ASTM E1710	(TxDOT, 2004)

	(5) Indentation resistance ASTM D2240

As shown in **Table 44**, TxDOT has set five material requirements for inverted profiled marking, including composition, pigment, beads, resin, and fillers applied uniformly, which corresponds to other state specifications for the use of profiled markings. South Carolina's material requirements focus on the baseline, raised shape, integrally formed ribs, and drop-on disc. The Florida DOT's material requirements include titanium dioxide, reflective elements, yellow pigment, calcium carbonate, and inert filler. The state of Tennessee's material requirements includes the use of glass beads, composition, intermixed glass beads, and a double drop system. The testing methods from other states are quite different from the TxDOT's testing method, however. For instance, the Florida and South Carolina DOTs use flash point ASTM D92, softening point AASTHO T250, yellowness index AASTHO M249, specific gravity, and bond strength for testing profiled marking.

4.2.1.7 Material Specifications for New/Advanced Marking Materials

In the U.S., most pavement material specifications are developed using the AASTHO or ASTM standards. To date, state DOTs have not developed any material specification for new/advanced marking materials, such as the photoluminescent road marking, nanocomposite paint marking, and the translucent concrete-based smart lane separator. In 2004, the AASTHO, FHWA, and the Scan Implementation Specialists met in Europe to address superior material advanced test methods and specifications and developed a strategic framework for the implementation of these superior materials in the United States and Europe, with support from the British Highway Authorities Products Approval Scheme (HAPAS), the European Union, and the French Charter for Innovation. Although the U.S. is considering performance as a criterion for adopting the superior marking materials, no formal national process is in place to coordinate and manage such transition of the translucent smart lane separator.

Material specifications for the Nanocomposite traffic marking paint focus on wear resistance, improving longevity and durability of the paint (Taheri et al., 2018). Clay/acrylic resin nanocomposite is incorporated using Cloisite 30B with different scales of resin, solvent, filler pigment, and a dispersing agent. Some vendors/manufacturers are developing their own specifications for their products. One such vendor, Carbit Paint Company, develops its system specifications for photoluminescent road marking. Its specifications cover the number of coats, minimum dry film thickness measured in mils, and dry time for its products. The major issue with the advanced marking material is how specifications can be modeled to ensure vendors/manufacturers produce superior materials. Vendor contributions to the development of the material specifications for its photoluminescent road marking and nanocomposite paint marking also come into play.

4.2.1.8 Pavement Marking Color Specifications

4.2.1.8.1 Pavement Marking Color Specifications In Different States

Thomas-Meyers et al. (2003) proposed a specific color recommendation for the current color specification by the MUTCD, which recommends specifying a range of chromaticity allowable for pavement markings to produce good day and nighttime visibility on the different pavements that can be admissible. The color specifications make up for the daytime and nighttime color of retroreflective asphalt marking materials and images on pavement surfaces. Primarily, most state DOTs use the white and yellow color specifications in the MUTCD.

The California DOT (Caltrans 2019) requires that the yellow color shall comply with AMS–STD–595, color 33538, and will lie within the chromaticity limit. The BYK Gardner "color gauge" spectrophotometer is used to measure the color application after 60 days using the manufacturer's guide. The yellow color reflectance is to be within 47 to 60, and for white color 80 minimum matching with a DSM-STD-595 chromaticity limit.

The Missouri DOT (MDOT) uses the Federal Standard 596B color specifications. Color selection is guided by the material marking and daytime brightness that support chromaticity appearance limits. For liquid marking material, color choices may be made on the black portion of the marking for at least 24 hours after application of a 15-mil wet film. The ASTM E1349 is used, requiring chromaticity appearance limit and standard observer and illuminant D65 for color reading.

The New York State DOT's (NYDOT, 2002) color specifications for reflectorized thermoplastic pavement markings entail white and yellow marking materials, applying the extruded and molten state on the pavement. The glass bead is then applied at normal temperature, which the specifications put at greater than 205^{o}c. The white thermoplastic color is to be free from dirt according to the color chip in the Material Bureau Handbook, and yellow thermoplastic color is to be free from dirt and sufficiently visible to Munsell Book Notation (ASTM D1535). Curing time is 10 minutes at 3mm and 5mm thickness. The white thermoplastic will not exceed a yellowness index of 0.12 when tested in accordance with AASHTO designation T- 250.

Taking an example from Canada, the Ontario Provincial Standard Specification (OPSS, 1991) conforms to the color requirements of white and yellow thermoplastics marking material. CGSBI-GP-12C white and 513-301 yellow thermoplastic material matching the color chip of the ministry of transportation or United States federal code 595B. OPSS calculates the color tolerance by the uniform color space and color difference using the ASTM D2244. MUTCD color specifications are used mainly for design purposes for sign sheeting and pavement marking materials. The MUTCD specifications were last revised in 2002, adding new specifications for three new colors.

4.2.1.8.2 Range of Chromaticity of Pavement Marking Colors

The Florida DOT (FDOT, 2021) manual requires white-colored marking material to meet the initial daytime chromaticity specifications and yellow-colored marking materials to conform with performance rating requirements (**Table 45 and 46**).

Table 45 Daytime and Nighttime Chromaticity Coordinate for Yellow Colored Marking Material

Color	Day Chromaticity Coordinate		Night Chromaticity Coordinate	
	x	*y*	*x*	*y*
1	0.530	0.456	0.575	0.425
2	0.510	0.485	0.508	0.415
3	0.455	0.444	0.473	0.453
4	0.472	0.400	0.510	0.490

Source: FDOT Section 971 Pavement Marking Material

The Minnesota DOT (MnDOT, 2014) requires color determination to be made for marking material with the daytime color conforming to the CIE chromaticity coordinate limit. Reading of the color shall be achieved using ASTM E1349, CIE 1931 2^0 standard observer, and CIE standard illuminant D65.

Table 46 CIE Chromaticity Coordinate Limit for MnDOT

Color	1		2		3		4	
	x	*y*	*x*	*y*	*x*	*y*	*x*	*y*
White	0.334	0.357	0.334	0.317	0.297	0.357	0.297	0.317
Yellow	0.531	0.483	0.531	0.429	0.471	0.483	0.471	0.429

Source: MnDOT (2014) CIE Chromaticity Coordinate Limit (initial)

The Caltrans (2020) requires that daytime color reflectance is applied to white and yellow thermoplastics materials. The yellow color shall match the ASM-STD 595 chromaticity limit, and the reflectance shall be between 47-60 min for yellow color thermoplastic and 80 min for white thermoplastics.

The TxDOT (2014) uses white and yellow for daytime and nighttime CIE chromaticity coordinate corner points. The white material is put at 70 hours and 1,000 hours for the yellow material of Weather-odometer in accordance with ASTM G 155. The nighttime CIE chromaticity coordinate for yellow thermoplastic material is measured using retro reflectometer in accordance with ASTM E 1710. The daytime CIE chromaticity coordinate materials is sampled in accordance with Tex-839-B. The TxDOT and FDOT employ the use of daytime and nighttime CIE chromaticity coordinates to determine the range chromaticity compared to other states like Minnesota and California that rely on color for their specifications.

4.2.2 Pavement Marking Construction Specifications

4.2.2.1 Standard Specifications Preparations

The U.S. DOT has adopted the Standard Specifications for the Construction of Roads and Bridges on Federal Highway Projects (F.P.) cited in "FP-14" showing "Federal Project" standard specifications of 2014 and containing both U.S. customary and metric units of measure. This is designed to help the state DOTs develop construction specifications for pavement markings across the U.S. white color lines (double, single, broken), yellow color lines (solid or broken), and black color lines are used in pavement marking construction.

4.2.2.2 Special Specifications Preparations

There are some marking materials that are not incorporated into the state standard specifications, but they are used in the field by state DOTs. Therefore, in order to install such materials properly, many states have developed their own special specifications that cover the various marking materials, such as thermoplastics, water-based paint, prefabricated thermoplastic, multipolymers, and profiled thermoplastic pavement markings. Based on the survey results in Task 2, engineers responded to the use of other special specifications for Thermoplastic Pavement Marking. **Table 47** summarizes the various comments received from engineers regarding the special specifications in the survey conducted in Task 2.

Table 47 Engineers Responses to the Special Specifications

	Thermoplastic	**Water-Based Paint**	**Prefabricated**	**Multipolymers**
PennDOT	Specification in PennDOT publication 408, section 960	PennDOT publication 408, section 962	PennDOT publication 408, section 965 for preformed plastic and special provision for preformed striping tape	
KDOT	KDOT specification 806-durable pavement marking	KDOT specification 807-painted pavement marking		KDOT specification 2200
IOWA DOT		Iowa DOT standards and specifications	Iowa DOT standard and specifications	Most be evaluated by NTPEP

NDOT		NDOT standard specifications for road and bridges construction section 632, 729, and 730 along with associated sheet changes since original publication of the manual.		
CDOT	CDOT standard specifications		CDOT specifications and standard	Manufacturer recommendations are used

4.2.2.3 Surface Preparation

As part of the standard specifications, surface preparations are carried out on new and existing pavements. For new pavement, it shall be well cured, and meanwhile, it should be air blasted to remove contaminants or loose materials. For existing pavement, the existing markings should be removed according to the recommendations of the manufacturer of the new pavement markings. The activity of cleaning and removing loose materials should not damage the pavement surface. Grinding is not allowed for Portland Cement Concrete (PCC). Temporary pavement markings, if any, should be removed the same day the durable pavement markings are applied.

4.2.3 Pavement Marking Warranty Specifications

Warranty specifications are a sort of specifications that guarantees the integrity of an item and allot liability for the maintenance or substitution of imperfections to the contractor (NCHRP Synthesis 408, 2010). The specifications provide an update on the use of pavement marking warranties by various transportation agencies. The benefits of sourcing warranty specifications for pavement marking are to ensure safety and speed (mobility), general performance, and cost-effectiveness of the pavement marking materials. A pavement markings warranty plays a significant role in decreasing congestion and further enhancing safety by directing traffic streams, providing modular partition, raising the

consciousness of drivers, and providing data that facilitates protected and smooth vehicular and pedestrian traffic.

4.2.3.1 Pavement Marking Construction Warranty Specifications

A pavement construction warranty covers pavement marking warranties. A construction warranty moves the risk burden associated with developing and maintaining asset execution to a private organization (i.e., the material manufacturer), in return for a possibly higher bid. Furthermore, it might take care of warranty use, particularly through improved product quality and performance. Other transportation agencies may consider using pavement marking warranties to attract extra benefits for using a particular marking material. These benefits include high performance, requiring less staff for inspection and cost in the material life cycle, as well as the opportunity for more innovations in pavement markings. There are various types of warranty specifications, including method-based, performance-based, and observation period. Each of these warranty specifications shall be discussed in the following sections.

4.2.3.2 Method-Based Warranty Specifications

This type of specification puts the responsibility in the hands of the project managers for adjusting and rectifying poorly executed specifications or deformation of the marking according to the standards of the project manager within the period of warranty. In response to the materials and workmanship warranty, the various state DOTs oversee the structural design for the pavement. The project manager is not liable for the deformation of the pavement marking material resulting from pavement design as some responsibility is shifted from the state transportation department to the project manager for materials selection and workmanship (NCHRP Synthesis 408, 2010).

4.2.3.3 Performance-Based Warranty Specifications

This type of specification holds the project managers entirely liable for project execution during the period of warranty. The project managers ensure that the pavement performance is excellent and durable. The project managers demand some

degree of obligations on a particular task and for the structural pavement design (NCHRP Synthesis 408, 2010).

4.2.3.4 Observation Period Warranty Specifications

The Maryland, Nebraska, and South Carolina DOTs use the observation period warranty specifications for their durable pavement markings warranty specification covering a period of 180 days after the application of initial material to determine if the pavement markings conform with project construction specifications for the beginning phase of performance.

4.2.3.5 Performance Period Warranty Specifications

The performance period warranty specifications use a period that follows the beginning acknowledgment of the pavement markings to further assess the marking material and installation. However, prior to the beginning of the preparation of the warranty information, this type of warranty specification is practiced and adopted by the TxDOT and the Delaware DOT (DelDOT).

4.2.3.6 Warranty Period Specifications

This refers to a kind of warranty period after project acceptance during which the arrangement of the warranty specification applies. It applies for a period of one to six years and covers extreme weather conditions for traffic paint, after which the responsibility for the performance of the pavement markings is shifted from the project managers. **Table 48** shows the warranties specifications in different jurisdictions across the United States.

Table 48 Warranties Specifications in Different Jurisdictions

State, Province, Territory	Materials or Performance Covered	Warranty Period	Examples of Types of Markings Covered
Alaska	Methyl methacrylate pavement markings (MMA)	2 years	Longitudinal and transverse markings, symbols, markings at roundabouts and gores
Arizona	3M 380 Tape Retroreflective Raised Pavement Markers (RRPM)	4 years 2 years 1 year	Longitudinal markings Symbols and legends Longitudinal markings*
Arkansas	Option 1: Inverted profile thermoplastic	4 years 4 years	Longitudinal markings only

	Option 2: High-performance marking tape (or, for center and skip lines on Portland cement concrete pavements, high-performance contrast marking tape)		
British Columbia	Paint with glass beads	Calendar based following application	Longitudinal markings only
Delaware	Retroreflective preformed patterned pavement marking	1-year performance period + 4-year warranty 1-year performance period + 2-year Warranty	Longitudinal markings Symbols and legends
Idaho	Performance of recessed durable pavement Markings Materials submitted to date under the 2-year performance specification includes polyurea, epoxy, and Hi-Build Waterborne paint Performance of recessed durable pavement Markings Materials submitted to date under the 4-year performance specification includes inlaid high-performance tape and MMA	2 years 4 years	Longitudinal markings only, including curves and tapers, edge lines, skip lines, centerlines, interchange gore lines, intersection channeling, and bicycle lane lines Same as above
Illinois	Thermoplastic, paint, preformed plastic, epoxy, preformed thermoplastic, and compatible glass beads	180 days through a winter	Longitudinal and transverse markings, words, and symbols
Indiana	Durable pavement marking materials: Thermoplastic, preformed plastic, and epoxy	180 days through a winter	Longitudinal, transverse, and intersection markings
Maryland	Inlaid pavement striping tape	180-day observation only period + 5-yr warranty period	Longitudinal markings only
Missouri	Retroreflective pavement marking tape Performance of durable permanent pavement markings	4 years 4 years	Longitudinal markings only Mainline and ramp markings, mainline turn lanes, and crossovers and signalized intersections on the mainline (i.e., all long-line markings within and approaching an intersection, but excluding any markings on the side street approaches, and excluding intersection markings such as stop bars, turn arrows, and hash marks)
Nevada	General warranty requirement covering specified materials	2 years	General—for pavement markings specified in a project
Northwest Territories	Paint with reflecting beads	1 year	Longitudinal single and double lines, solid and broken directional dividing lines, edge

			lines, lane lines, continuity lines, arrows, gore areas, stop lines, crosswalk areas, railroad crossings, and lines and legends at ferry approaches
Oregon	Durable marking materials: Surface-mounted thermoplastic Other materials and methods including various types and applications of thermoplastic, MMA, and pavement marking tape. High-performance marking materials: Modified urethane, sprayed (25 mils) or protected inlaid Durable marking materials: Liquid, hot-laid thermoplastic. preformed, fused thermoplastic films; cold-applied plastic film (tape); and MMA	 3 years 4 years 1 year 18 months	Long lines Long lines Legends, stop bars, and crosswalk bars
Texas	prefabricated pavement markings Multipolymer pavement markings Raised pavement markers	6 years 3 years 1 year	Longitudinal markings only Longitudinal markings only Longitudinal markings*
West Virginia	Performance of medium-life pavement marking system	1 year	Longitudinal markings only

*Specifications do not explicitly mention a particular type of pavement marking, but longitudinal markings are a reasonable presumption and likely the dominant if not the only use.
Note: Table is intended as a summary comparison only. Source: NCHRP Synthesis 408 (2010)

Table 48 shows the warranty period specifications in different state DOTs. Each state has different warranties for materials and the type of marking it covers. The Illinois DOT material covers thermoplastic, paint, preformed plastic, epoxy, preformed thermoplastic, and compatible glass beads having a six-month (180 day) warranty period for longitudinal and transverse marking. The Nevada DOT warranty specifications recommends two years for general pavement marking covered in its projects. The Indiana DOT material covers a thermoplastic, preformed thermoplastic, and epoxy warranty period of 180 days for longitudinal, transverse, and intersection marking. The TxDOT warranty period specifications for polymer pavement marking suggest three years for longitudinal marking only and six years for longitudinal prefabricated pavement markings.

4.2.4 Issues and Problems with Marking Specifications in Texas

Currently, there are some issues with marking specifications in the 2004 TxDOT manual. Some of the issues with marking specifications include:

- The responses of engineers who participated in the survey conducted in Task 2 showed that the TxDOT and other state DOTs do not have challenges in implementing marking specifications for thermoplastics. However, challenges in the marking applications include seasonal installations of thermoplastic, humidity/wetness testing in cold/freezing temperatures and/or without sun, and difficulty in attaining reflectivity due to the bead types available.
- Surface characteristics and AADT display a significant role in the longevity of water-based paint. Marking installation in the spring cannot be commenced until the roads are washed and are free from chemicals after light rains. Importantly, temperature condition is a defining factor in pavement marking specifications.
- Poor performance of the preformed thermoplastic in some areas is widely restricting the use of the material. Its poor performance could be attributed to its improper application and installation, which is a common challenge for the TxDOT engineers in the field.
- For multipolymer pavement marking specifications, the slow curing time, especially with the epoxy, has made installation very problematic. The challenging issues of cost and availability of the material are reasons that the epoxy is not commonly used. Verification of the thickness and constant doming of the marking results from incorrect application temperature and equipment.
- Profiled thermoplastic has issues with the embedding beads in the surface top, and the bump thickness is a source of concern to the TxDOT and its engineers in the field.

4.2.5 Recommendations on TxDOT Marking Specifications

Regarding the 2004 TxDOT pavement marking handbook (TxDOT, 2004), the 2014 TxDOT standard specifications (TxDOT, 2014), and the review of other state manuals, the research team has made the following recommendations on TxDOT marking specifications.

- Certifying pavement marking installers and inspectors shall be considered, if not already in place, through in-house certification on pavement marking specifications to enhance skills and competence for the job.
- Material specifications for preformed thermoplastic should be developed as this would provide a clear reference for engineers and contractors when it comes to using this material.
- The marking material specifications from other states, such as California and Illinois, should be carefully reviewed to include some requirements that are not anticipated in the current TxDOT specifications.
- Field practices could be evaluated during the decision-making process under a common standard for efficacy and quality if the application of pavement markings cannot be independently guaranteed.

4.3 Marking Application Rate Verification

Monitoring the contractor's activities to determine whether the markings are applied sufficiently based on the pre-designated contract documents is a crucial task that must be accomplished. This is because it directly affects the marking durability and could help fix the problems associated with installing the markings and leading to verifying the contractor's payment release. The marking application rate could be verified either by measuring thickness or checking the quantity of the material used in the marking.

4.3.1 Application Rate Verification Practices Across U.S. States

In the U.S., there is no unified approach for verifying marking applications in the field. Every state has developed its own method. Therefore, to comprehend and

evaluate every approach practiced across the U.S., the research team has reviewed the pavement marking documents from various states and synthesized them in the subsequent sections.

4.3.1.1 The TxDOT Approaches

4.3.1.1.1 Application Rate Verification in Texas

According to TxDOT (2014), a special procedure under the name of "Tex-854-B" has been developed to measure the thickness of the thermoplastic stripe. Based on the specifications, two parts are described: Part I - measuring the thickness of a thermoplastic stripe mechanically, and Part II - determining stripe thickness from thermoplastic usage rates. In part I, a needlepoint micrometer is recommended to measure the markings' thickness with a maximum 2,000-foot sampling and three measurements diagonally across each sample. In addition to the micrometer, the necessary equipment for measuring the thermoplastic thickness includes duct tape or metal plates and a knife. As shown in Figure 45, needlepoint micrometer is used. **Figure 55** shows a different equipment required for measuring the thermoplastic thickness in the field as per the TxDOT method.

Figure 55 Duct Tape and Knife

For part II, Tex-854-B (2014) recommends a special procedure to obtain the thickness of thermoplastic from usage rates. This procedure is summarized in the following steps.

- Determine the amount of thermoplastic and beads the applicator has on hand at the beginning of striping operations.

- Determine the amount of material the applicator has on hand at the end of striping operations.
- Subtract the final quantities from the initial quantities to determine the number of materials used.
- Determine the linear footage of stripe applied and obtain this quantity from the applicator or from direct measurements.
- Divide the quantity used by the linear footage applied and compare the value to the theoretical usage rate.
- Calculate the theoretical usage rates by the following formula:

  Linear Footage × lb. per ft. = Min lb.

Table 49 details the usage rates required to produce a solid 100-mm (4-in.) wide stripe. For a 200-mm (8-in.) wide stripe, the usage rate shall be multiplied by two.

Table 49 Theoretical Usage Rates

Specification Thickness		**Minimum Pounds of Thermoplastic**			
Mils	Micrometers	Pounds per Mile	Kilograms per Kilometer	Pounds per Foot	Grams per Meter
60	1,500	1,000	282	0.189	282
75	2,250	1,300	366	0.246	366
100	2,500	1,800	507	0.341	507

Source: Tex-854-B (2014)

4.3.1.1.2 Texas Survey Respondents' Input on Marking Application Rate Verification

Several Texas respondents in the survey conducted in Task 2 answered the question: "How would you verify the application rate of this marking in the field, i.e., thickness, volume, or rate, during your quality control procedure?" For thermoplastic and multipolymers application rate verification, most participants indicated that they commonly verify the thickness of thermoplastic marking by using a micrometer and tape and performing a visual inspection. However, one of the participants mentioned that they require the contractor to perform a test section prior to beginning the work. For traffic paint, a participant said they check its application by verifying the rate of traffic applied in the field. Specifically, he said: "We check the gallons per mile on occasion if we see an issue with the look of the stripe. The speed of the paint truck is a factor as well." For prefabricated marking, most of the respondents mentioned that

they check the thickness before placement and inspect the contractor while markings are being installed.

4.3.1.2 The Nevada DOT Approaches

The Nevada DOT uses the same approach as TxDOT for verifying the dried film thickness of epoxy and water-based pavement marking. As per T510A, Nevada has adapted ASTM D 1005-95, where a hand-held micrometer is recommended. In addition, Nevada has developed another testing method for field verification of spray-applied paint film thickness under the name of "T509B". In this method, instruments such as steel plate, micro test coating thickness gauge-model, and calibration shim set have been recommended. As per the survey conducted in Task 2, a participant mentioned that the volume of marking is determined by the quantity of the material delivered to the job site.

4.3.1.3 The Colorado DOT Approaches

The Colorado DOT recommends several approaches for verifying the application thickness of pavement markings (Colorado DOT, 2020). These methods include the following:

- **Mil Thickness Plate Test.** This method is proposed by most of the state DOTs. The procedure of this approach is that small sheets of aluminum are placed across the pavement marking line, and then the paint is applied on the sheets without bead application. After applying the marking material on the sheets, a comb gauge is directly inserted into the paint at a perpendicular angle to the plate and observed where paint is visible on the gauge. It is highly recommended that measurement be made immediately after the application to an accurate reading since the paint starts to dry right after its application, which makes the paint decrease its wet film thickness.
- **Tank Stabs.** Tank stabs is another method that the Colorado DOT practices verifying the marking material's application rate by calculating the volume of material used over the corresponding application area. The procedure of this method is that the paint tank level is recorded at the start of the work and at

the end of the work when the truck is refilling. Then the measurement is taken from a fixed point to the top of the fluid level. After that, the area of applied pavement markings is divided by the total volume applied to calculate the application rate. For verifying the multipolymer marking material application rate, it is recommended that tank stabs be recorded for each tank and the volumes combined because this marking material works as a combination of resins and catalyst from separate tanks.

- **On-Board Computers.** The third method that Colorado DOT uses for application verification of pavement marking is the use of on-board computers installed on the paint trucks. This computer provides updated information relating gallons used and mill thickness applied to the driver based on the material weight in the tank and the average truck speed at every 300 ft. **Figure 56** show an example report of the on-board computer.

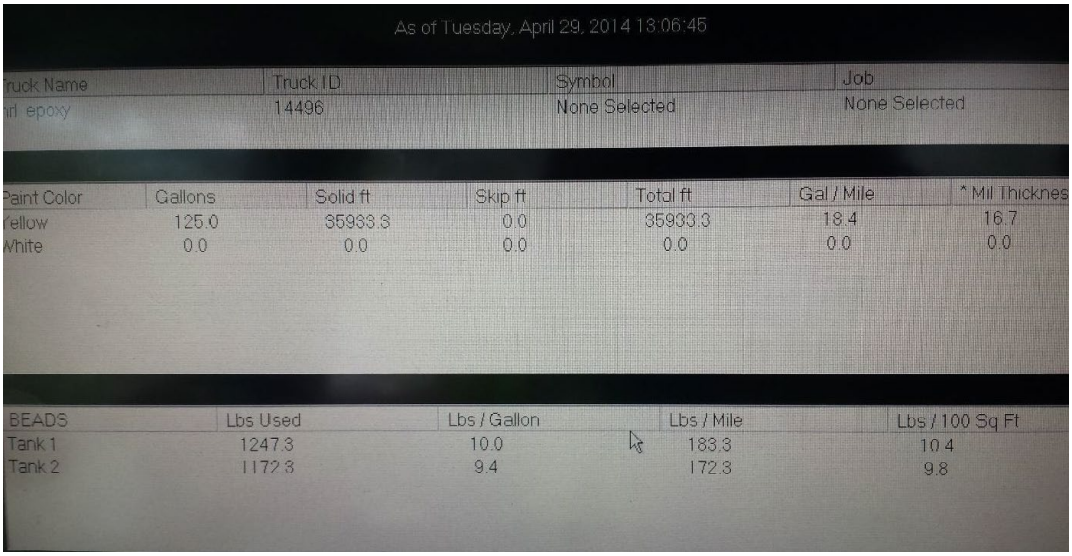


Figure 56 Example Report from an On-Board Computer

4.3.1.4 The Kansas DOT Approaches

For verification of thermoplastic application rate, the Kansas DOT checks thermoplastic thickness by either a micrometer or vernier calipers instrument. Its process is such that the metal plates are placed in a 3-foot section along the application path at 2 to 3 locations. After applying the thermoplastic material, the samples are cut free. Then thickness is measured in each location, and the average of

readings is recorded. According to the Kansas DOT (2015), the measurement of marking thickness is practiced every 1760 ft for each color and each stripe width. However, after establishing a pattern of compliance, the measurement of thickness could be performed once each 1-mile section.

A survey respondent (conducted in Chapter 2) from the Kansas DOT also confirmed that the application rate of thermoplastic marking material is verified by calipers. For verification of traffic paint, the respondent stated the Kansas DOT is using a data logging system installed on the striping truck. For multipolymers, the survey participant mentioned that "Physical mil checks are performed for the first mile, then KDOT uses data logging system to verify mils and application rates."

4.3.1.5 The Maryland DOT Approaches

The Maryland DOT (MDOT, 2013) has approved several methods to measure the thickness of paint, thermoplastic, and epoxy markings. Maryland DOT approaches are fully described in section 3.3.2.1.3 in Chapter 3 of this report.

4.3.2 Practices in Quebec, Canada

According to the Quebec Ministère des Transports (2019), there are two methods for verification of marking the application rate in the field: validation of quantities from the tanks of the striping truck and measurement of the wet film thickness. For validation of the quantity of materials from the tanks of the striping truck method, the application rate of traffic paint is determined by matching the paint quantities spent from the stripe tanks and calculating the quantity of paint applied according to the number of kilometers of lines striped. The Quebec Ministère des Transports (2019) follow the following procedure:

- The contractor must provide the Ministère with a means of knowing the precise amount of paint and glass microbeads in the striping truck's tanks. Generally, a schematic plan of the tanks is submitted.
- Before starting work, the level of the marking material in the tanks (initial paint level) must be measured.

- Measurements must be taken during the work and before any of the tanks are refilled to determine, using the tank diagram provided, the number of liters of paint applied (the difference between the second measurement and the initial measurement).
- Using the number of kilometers traveled between the two measurements, the application rate (L/km) can be calculated.

For measurements, a ruler or a laser device can be used, but the same reference point must be taken in the striping tank in all measurements. **Figure 57** show taking appropriate reference points in the striping tank.

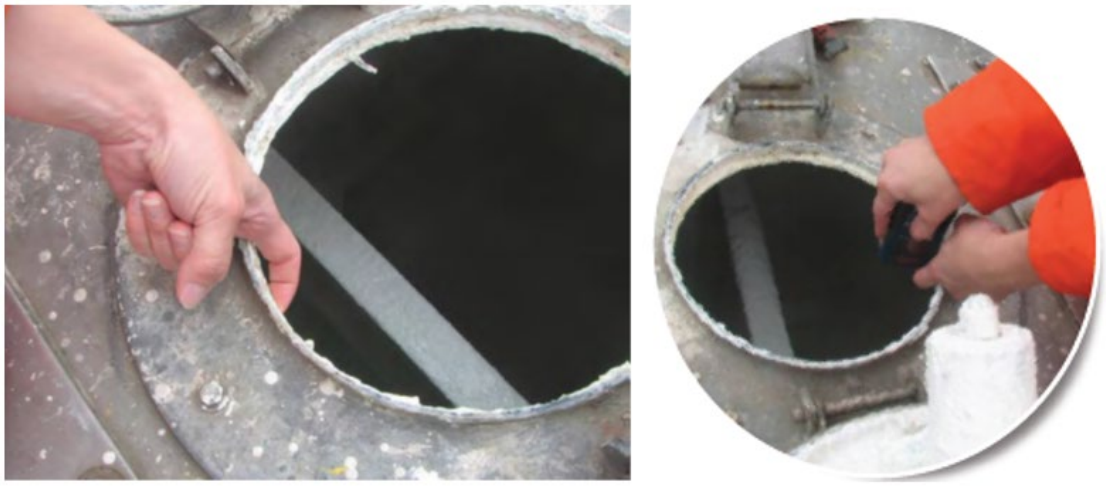


Figure 57 Right: Example of Reference Point for Taking Measurement, left: Taking Measurements, Using the Reference Point (*Quebec Minitere des Transports, 2019*)

For determining the number of kilometers of marking line striped, the Quebec Ministère des Transports (2019) recommends the odometer of the striping truck or any other vehicle to be utilized. The striped marking line's length must be checked to make sure that it is calibrated.

For the measurement of the wet film thickness method, the Quebec Ministère des Transports (2019) recommends the thickness gauge to be used for verifying the

application thickness of liquid paint. This method is the same as the Maryland method that was discussed in the previous section.

In the survey stated in Chapter 2, a participant from Quebec indicated that "For epoxy applied on our contracts, the verification of the application rate is not mandatory, since the contractor is normally subject to performance requirements. However, for verification purposes, the supervisor can check the application rate using the wet film measurement method. The validation method based on the quantities in the tanks is more complex since there are two tanks on the stripping truck, one for each of the components."

4.3.3 New/Advanced Technologies Available for Measuring Marking Verifications

4.3.3.1. Data Logger System (DLS) for Recording Liquid Pavement Marking Data

A data logging system is a computerized tool that can be connected to pavement marking equipment. Many U.S. state DOTs, including Ohio, Minnesota, Kentucky, and North Dakota, have already mandated that striping equipment should be equipped with a computerized Data Logging System (DLS). The good thing about the data logger system is that it can collect various data regarding the application of liquid pavement markings (traffic paint and multipolymers) in real-time. According to Ohio DOT (2021), during the installation of pavement markings, the data logging system measures, and records various data, including but not limited to:

- Application vehicle speed to the nearest 0.1 miles per hour.
- The weight and/or volume amount of material used by color.
- The weight or volume amount of material used by line type.
- The weight of glass beads.
- The weight of wet reflective optics
- The pavement surface temperature.
- The air temperature.
- The dew point (thermoplastic and spray thermoplastic not included)
- The humidity (thermoplastic and spray thermoplastic not included).

- Average materials application rates and film thickness over the section painted.
- Temperatures in the kettle and at the point of application (thermoplastic and spray thermoplastic only).

Data collected by the data logger system can be reported daily to the quality controller engineer as an Excel spreadsheet. This spreadsheet may include route, line type, line width, line color, the direction of application, weight of the material, scaling factors, marking film thickness, marking application rate, bead application rate, material temperature, ambient temperature, pavement temperature, and vehicle speed.

4.3.3.2 Marking Thickness Gauge Method

As stated in Section 3.3.2.1.2, marking thickness Gauge is another device that can measure the thickness of the marking very quickly as shown in (Figure 45). Section 3.3.2.1.3 in chapter 3 of this report provides further information on this device. 4.3.4.3. StripeScan retro reflectometer

StripeScan retro reflectometer (**Figure 58)** is another device that can measure the thickness of roadway markings when mounted on a line marking machine. According to Delta and Force Technology (2014), this device is "mounted after application and will allow the applicator via integration in the line marking machine software to know the actual thickness of the applied line."

StripeScan works based on a laser sensor with near-infrared radiation invisible to the eye. The configuration must be mounted at a distance above the road surface, allowing it to measure a width of 36 cm (14.3 in) while maintaining a height resolution of ±0.1 mm. If markings are wider than 30 cm (12 in) – the device needs a few centimeters of the road surface to make correct calculations – it will still be possible for the LTL Stripe Scan to measure the markings, but not in the full width (Delta and Force technology, 2014).

StripeScan is designed to automatically locate the road marking and deliver the height, width, and cross-section of the road marking over the CANbus. The system can generate a full 2D profile 45 times per second, so the resolution is determined by the speed at which the line marking machine is traveling. The system uses the 2D profile to locate a baseline for the road and measure the difference in height between the road and the road marking. Therefore, the system can measure the thickness, even if the marking is on a tilted surface.

Figure 58 StripScan Retro-reflectometer

4.3.4.4 Measuring Marking Thickness Using Point Laser Device

Another method that can measure the thickness of thermoplastic is the usage of a point laser device mounted on a vehicle. Section 3.3.2.1.4 in Chapter 3 of this report further details on this device.

4.3.4 Marking Application Rate Verification from Survey

Section 3.3.2.1.5 summarized the survey responses on marking application rate verification as is summarized in Table 35, which includes information from 23

engineers in and outside Texas. The involved materials include: water-based paint, thermoplastic, prefabricated, multipolymer, and profiled thermoplastic. Those information covers the thickness, volume, or rate during the quality control procedure per each engineer's practices.

4.3.5 Issues and Problems with Marking Application Rate Verification in Texas and the Other States

As stated previously, marking application rate verification is highly crucial because it directly affects the durability of pavement markings. To verify dried film thickness, TxDOT uses a needlepoint micrometer, which is also practiced by some other states, such as Nevada and Kansas. However, European countries developed several new technologies to quickly measure the dry film thickness of pavement thermoplastic marking materials. These technologies include the Marking Thickness Gauge and StripeScan retro reflectometer, both of which are manufactured by Delta and Force technology. As per their manufacturer, these instruments possess high precision in measuring marking thickness and can measure it much faster than the TxDOT approach. Therefore, these could be a potential alternative to the micrometer, which is currently utilized by the TxDOT and other states. Another alternative for verifying the marking application rate could be the verification of material quantity by calculating the marking material used during the application of markings. This method is also known as tank stabs, which is currently practiced in Colorado, Tennessee, Utah, and Quebec.

For the verification of liquid marking application, i.e., traffic paint and multipolymers, no method is specified in the TxDOT pavement marking-related documents. However, as discussed in the previous sections, there are several ways to measure and verify the application rate of liquid pavement markings. One of the most prominent approaches that some of the U.S. state DOTs follow is the use of data logging systems which can be installed in the striping truck and provide a broad range of information, including marking application rate, marking application thickness, moisture, ambient temperature, and so forth. As per the survey that was conducted

in Task 2, this system is also used for application rate verification of the thermoplastic material in Ohio and Colorado. In addition to the logging system, a wet film thickness gauge is another instrument for measuring wet thickness widely practiced across the United States. Various approaches for marking application rate verification which were discussed in previous sections, are summarized in **Figure 59.**

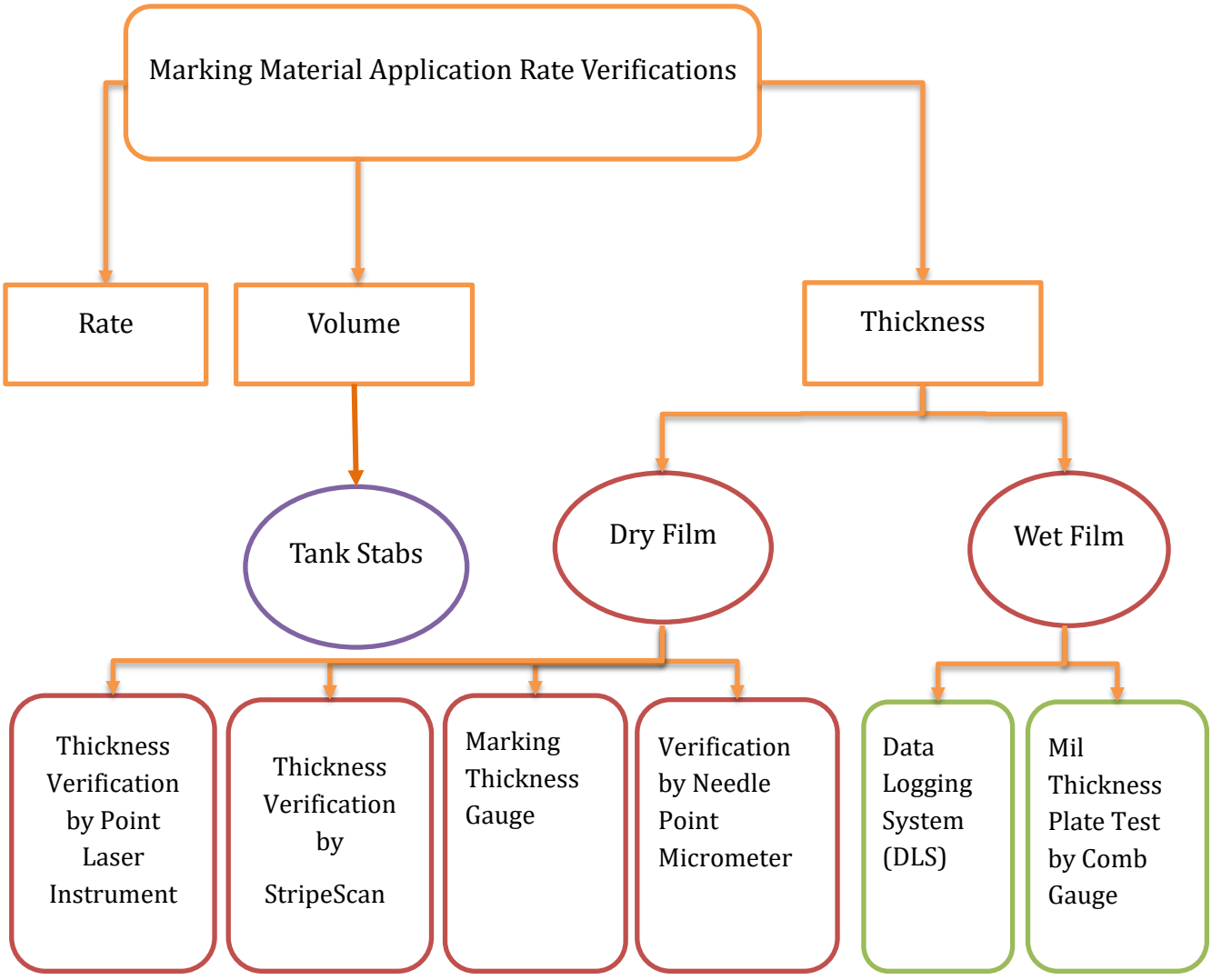


Figure 59 Summary of Different Approaches for Marking Application Rate Verification

4.3.6 Recommendations on TxDOT Marking Application Rate Verification Methods

Following our review of TxDOT marking application rate verification procedures in the 2004 TxDOT Pavement Marking Handbook (TxDOT, 2004), the 2014 TxDOT Standard Specifications (TxDOT, 2014), and the TxDOT's other special specifications, as well as the approaches of several other U.S. states and countries, the research team concluded that the TxDOT could improve its marking application rate verification by considering the following points:

- For thermoplastic and solid pavement marking materials, it is recommended for the TxDOT to conduct a comprehensive study on the viability of every approach practiced in the United States and other countries in determining marking material thickness. This study may evaluate various parameters involved in marking thickness measurement methods, including accuracy, time, cost, and so forth. While the TxDOT method for measuring thermoplastic marking material thickness using a Needlepoint micrometer is time-consuming, other techniques, such as the Marking Thickness Gauge device and StripeScan retro reflectometer, may be less time-consuming.
- For liquid marking materials, such as traffic paint and multipolymers (epoxy, polyurea, MMA), in addition to utilizing a wet film thickness gauge, the research team recommends for TxDOT to mandate that contractors equip their striping trucks with a data logging system. Currently, this system is not mentioned as a required equipment in the 2014 TxDOT Standard Specification (TxDOT, 2014). A data logging system has already been used by several other state DOTs and can provide valuable real-time data regarding the application thickness, ambient temperature, and so forth.
- As the TxDOT does not have any specification for measuring marking width, it is recommended that the Straightedge tool be used for measuring the width of the roadway markings.

Chapter 5: Identify Equipment Ability and Markings Payment Base

5.1 Overview

Chapter 5 aims to identify the ability of equipment to measure the quality of marking materials and recommend possible modifications to existing equipment use in Texas. The research team synthesized a variety of documents from various U.S. DOTs and other transportation agencies and investigated pavement marking payment base calculation practices in certain U.S. states and other countries. The research team investigated:

(1) **Assessed the ability of equipment to measure quantity and quality, and evaluated potential modifications to existing equipment**

- An examination of the ability of available equipment used in Texas and other states regarding quality measurement at different speeds and under different ambient environments
- What factors should be taken into consideration to meet the minimum retro-reflectivity requirement
- Whether the existing equipment can successfully measure the quantity (retro-reflectivity) of marking materials applied
- What modifications, if any, should be proposed for existing equipment to improve quality and quantity measurement methods of pavement markings

(3) **Identified Pavement Markings Payment Base**

- How the payments for various pavement markings are calculated in Texas, other states, and other countries
- Whether the price in other states and other countries is full compensation for the application of pavement markings, materials, equipment, labor, tools, and incidentals
- Whether there are any other direct/indirect payments

- How the surface preparation of all other asphalt and old concrete pavement, except for sealing, are paid for (directly or indirectly to a subsidiary)
- How payments for work zone pavement markings (Type II, paint, and beads) used as a sealer for Type I markings (thermoplastic) are determined
- How payments for the repair or replacement of markings damaged by inclement weather are determined

5.2 Identify Equipment Ability to Measure Quantity, Quality, and Modification to Existing Equipment

5.2.1 Equipment Required for the Surface Preparation of Pavement Marking

In the United States, state level DOTs do not use uniform equipment for surface preparation for pavement marking. Every state DOT has adopted its own equipment standards for surface preparation for pavement marking. Therefore, to comprehend and evaluate the equipment use across the country, the research team reviewed various documents from different states related to the equipment required for surface preparation for pavement marking. **Table 50** shows the types of equipment required for surface preparation by various state DOTs, their specifications, and sources from which the information was retrieved.

Table 50 Equipment Usage from Various States DOTs

State	Equipment Usage	Specifications	Source
New York	Power brooming or manual brooming is used	In accordance with S685-03.03	NYSDOT, 2015
North Carolina	Compressed air equipment is used to blow the pavement surface clean and remove residue or debris.	Pavement marking general requirement, section 1205	NCDOT, 2018
Kansas	Use of scarifies and scramblers as approved by Engineer.	Special provision to the standard specifications section 729	KDOT, 2015
Ohio	A power broom is used to clean the surface where gore marking is to be applied.	Pavement marking general specification, item 641	ODOT,2008
Texas	A broom truck to clean the pavement surface before installing actual striping is used.	TxDOT specification item 678	TxDOT, 2004

As shown in **Table 50**, the New York, Ohio, and Texas DOTs use brooming trucks for surface preparation for pavement marking. Such deployed equipment is

efficient and saves time in preparing pavement surfaces for the installation of pavement markings. The Kansas DOT uses sandblasting equipment, scarifies, and scramblers for its surface preparation. The use of sandblasting equipment is a very safe, efficient, and time-saving method. It is also easy to maneuver in pavement corners and tight geometrical areas with little effort. The disadvantages of using this equipment are that the residual dust remnants can cause air pollution, it is not economical for small projects, and high precautionary measures are needed by operators. The North Carolina DOT recommends using compressed air equipment to remove debris or residue from pavement surfaces. The advantages of using compressed air equipment are that it is easy to use, has low operating costs, and has a cheap power source. The disadvantages of the equipment are that leaks, and poor maintenance, planning, and control of the equipment can be very wasteful. Additionally, air blowing from a compressed air system into the mouth might cause a serious health risk such as a rupture in the lungs. **Figures 60-62** shows the typical equipment used for surface preparation for pavement marking.

Figure 60 A Typical Broom Truck for Surface Preparations in Texas, New York, and Several Other States.

Figure 61 Surface Preparation Equipment (Hog Technologies)

Figure 62 Sandblasting Equipment for Surface Preparation

5.2.2 Equipment Required for the Installation of Pavement Markings

The installation equipment is very important in achieving durable markings on pavement surfaces. The requirements for installation equipment in different state DOTs guide engineers in the field to install durable marking materials on pavement surfaces. High-quality installation equipment can often be credited for a well-prepared roadway surface. The performance of pavement markings on either concrete or asphalt surfaces is most often influenced by the quality of the bonding to

the pavement surfaces. Therefore, using the required equipment for installing pavement markings is crucial. Some common types of installation equipment include self-propelled ride-on line stripers, striping trucks, heat torch, and spray guns. **Table 51** presents a summary of equipment required for the installation of different pavement marking types from each state DOT and the source from which the information was obtained.

Table 51 Equipment Required by Various States for The Installation of Pavement Markings

State	Thermoplastic	Water-Based Paint	Prefabricated	Multi-Polymers	Profiled Thermoplastic	Source
Indiana	A Kettle for melting and applicator is used.	Spray equipment with an air blast, a guide pointer, spray guns, paint agitators, a control device, automatic bead dispenser are used.	A portable hand-propelled equipment, a guide pointer, guide roller and pressure roller, and a hand roller for symbol are used.	A high-pressure water blast equipment, a guide pointer, spray gun, automatic glass bead dispenser equipment is used.		INDOT, 2012
Nebraska	A full-sized spray truck-mounted unit is used for large projects. A hand-operated or small riding equipment is used for a small project.	A self-propelled, riding line striper with a glass bead nozzle mounted directly behind the paint applicator is used.				Nebraska DOT, 2021
Maryland	A spray gun, screed/extrusion shoe, and ribbon gun are used.	Airless spraying, conventional spraying, and air jets equipment are used.	A Roller applicator for preformed tape is used.	Epoxy Truck. An airless gun for polyester is used.	A Propane-fuel heat torch is used.	MDOT, 2019
Texas	A hot sprayed truck is used.	A striping truck is used.		Epoxy Truck polyurea-epoxy truck modified urethane-standard epoxy truck is used.	A spray gun is used.	TxDOT, 2014

Ohio	A-Data Logging System with a cab mounted to show the actual material application rate and film thickness	A striping truck with Data Logging System is used.		A Data Logging System equipment with a cab mounted to show the actual material application rate and film thickness for epoxy and polyester marking is used.		ODOT, 2010
Minnesota		Water-based Striper Truck is used.	Roller Applicator for Preformed Tape is used.	Epoxy Striper Truck	Heat Torch	MnDOT, 2015
New York	Mobile applicator or portable applicator for project less than 20,000 m is used.	Mobile or portable striping equipment is applied with airless striping equipment.	Manual (hand) or portable applicator for longline tape is used.	Mobile striping equipment with manual spraying capability, and an air blast gun mounted in front of the spray gun are used.		NYSDOT, 2002

As highlighted in **Table 51**, The Ohio DOT used the Data Logging System (DLS) mounted on a cab when installing Thermoplastic markings. The Nebraska and New York DOTs normally use a mobile truck-mounted unit for the installations and a hand-operated riding spray applicator for small projects. The Maryland DOT uses a combination of equipment such as a spray gun, screed/extrusion shoe, and ribbon gun for installing thermoplastic pavement markings, while TxDOT uses a hot spray truck. For Water-based paint, the Minnesota, New York, and Indiana DOTs use similar mobile or portable equipment with airless spraying and air jets equipment for the installations, while TxDOT uses the striper truck.

State DOTs such as Maryland, Minnesota, New York, and Texas used the mobile striping truck for the installation of multi-polymer marking materials, while the Ohio DOT uses the Data Logging System (DLS), including a cab-mounted display component, which shows the real material application rate and film thickness. For Profile Thermoplastic, the Minnesota and Maryland DOTs use a heat torch equipment,

while TxDOT uses a spray gun. **Figures 63-67** shows various installation equipment that is currently in use.

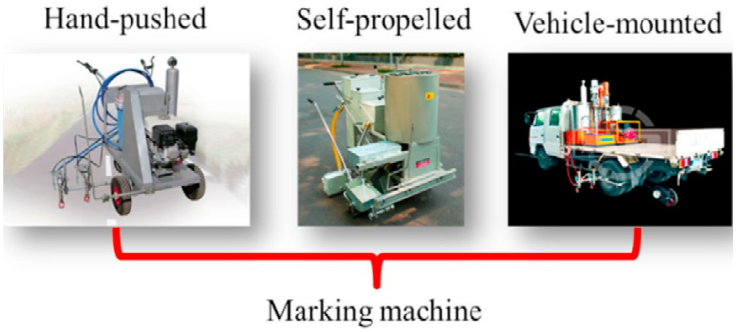


Figure *63* Equipment Required for Paint Material (Xu et al., 2021

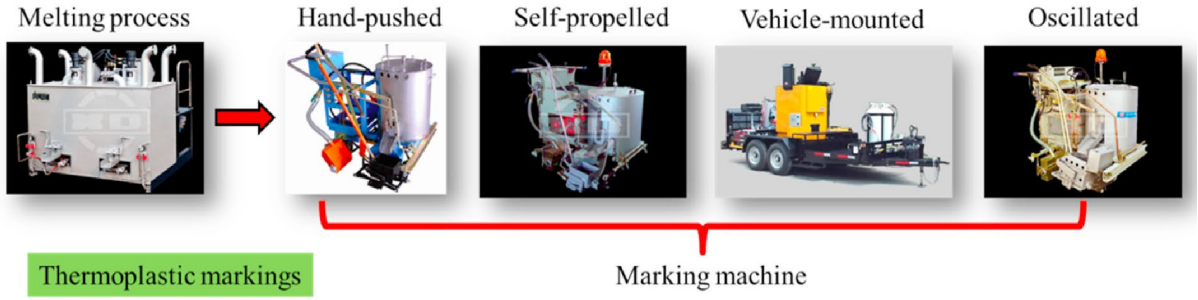


Figure 64 Equipment Required for Thermoplastic Marking (Xu et al., 2021)

Figure 65 Water Based Striper Truck (MnDOT, 2015)

Figure 66 Epoxy Striper Truck (MnDOT, 2015)

Figure 67 Arrow Symbol Being Applied by the Heat Torch (MnDOT, 2015)

5.2.3 Equipment Ability to Measure the Quality of Pavement Markings in Texas and Other States

5.2.3.1 Equipment Ability to Measure Retro-reflectivity of Pavement Marking in Texas and Other States

Currently, there are two main ways that pavement marking retro-reflectivity can be determined in the field, using: (1) hand-held retro-reflectometer, and (2)

mobile retro-reflectometer equipment. The hand-held retro-reflectometer equipment demands that the instrument be set on the pavement markings while the mobile retro-reflectometer instrument is attached to a vehicle and measures the pavement marking retro-reflectivity as it passes at a particular speed. The Manual on Uniform Traffic Control Devices (MUTCD) requires pavement markings to meet the minimum retro-reflectivity level of 30-meter geometry as described in its specification manual. Measuring pavement marking retro-reflectivity is used to ascertain compliance with the MUTCD minimum level for pavement markings. **Table 52** shows a summary of equipment ability to measure retro-reflectivity of pavement markings from different state DOTs in the U.S.

Table 52 Equipment Ability to Measure Retro-reflectivity of Pavement Marking Across the U.S. States DOTs

No	States	Equipment Use	Retro-reflectivity Requirements	Source
1	Florida	Mobile Retro-reflectivity Unit (MRU) and vehicle data collection software (computer and software) A hand-held Retro-reflectometers (Stripe Master, LTL- X)	In accordance with the Florida Test Method for Measuring Retro reflectivity of Pavement Marking Materials Using a Mobile Retro reflectivity Unit (FM5- 600) and all retro reflectivity data is required in FDOT Form 675-060-05.	FDOT, 2017
2	North Carolina	Hand-held Retro-reflectometer LTL-X	NCDOT pavement marking certification under section 1205 of NCDOT standard specification.	NCDOT, 2022
3	New York	Portable hand-held Retro-reflectometer	Item 685.30000008: epoxy reflectorized pavement testing equipment portable, hand-held retro reflectometer for pavement marking	NYSDOT, 2021
4	Maryland	Hand-held Retro-reflectometer	A 30-meter geometry retro reflectometer and manufacturer-supplied calibration standard	MDOT, 2013
5	Minnesota	Uses a hand-held Reflectometer LTL-X and LTL-2000 Laser Lux	A 30-meter geometry retro-reflectometer	MnDOT, 2015
6	Virginia	Mobile and handheld Retro-reflectometer	Use retro reflectometer with a 30-meter geometry.	VDOT, 2011
7	Colorado	Hand-held Reflectometer	Retro-reflectivity readings may be required as a quality assurance check in accordance with section 105.03 of the CDOT Standard Specifications for Road and Bridge Construction	CDOT, 2020
8	Missouri	Use a Laser Lux Retro-reflectometer	MoDOT standard specification for highway construction	MoDOT, 2020
9	Texas	Uses a mobile and a portable Retro-reflectometer	Approved by the Construction Division and certified by the Texas A&M Transportation Institute	TxDOT, 2004

	Mobile Retro-reflectometer Certification Program. Uses 30-meter geometry and meets the requirements described in ASTM E1710

According to **Table 52**, the Texas, Virginia, Minnesota, Maryland, Colorado, and New York DOTs use the same mobile and hand-held portable retro-reflectometers of 30-meter geometry to measure the retro-reflectivity of pavement markings. The Florida DOT uses the Mobile Retro-reflectometer Unit (MRU) with its data collection software for the measurement of retro-reflectivity of pavement markings. The MRU is capable of measuring stripes at a minimum of 20 inches on either side of the center position at the proper geometry and 40 inches for longitudinal variations. This equipment provides a more precise and accurate reflectivity measurement of pavement markings**. Figures 68-71** show a list of retro-reflectometers in use at selected DOTs.

Figure 68 MnDOT LaserLux Outboard Unit

Figure 69 FDOT Test Instruments: Handheld Retro-reflectometers and Mobile Retro-reflectivity Unit (MRU)

Figure 70 Examples of Portable Retro-reflectometers in TxDOT

Figure 71 A Typical Pavement Marking Retro-reflectivity Measurement Device by FHWA

5.2.3.2 Equipment Ability to Measure Color of Pavement Markings in Texas and Other States

Color equipment includes devices that are used to measure the color of pavement markings. These can measure the daytime and nighttime colors on pavement surfaces. The daytime color measurement of pavement marking materials is ordinarily utilized for quality control and material acknowledgments. The color equipment can measure the daytime luminance coefficient estimated at 30-meter geometry, which is utilized by the European Union to depict executions. The nighttime color measurement is restricted to the laboratory climate. **Table 53** shows the equipment used by some state DOTs for color measurements.

Table 53 Equipment Uses for Color Measurement

No	State	Equipment Uses	Color Requirements	Source
1	Texas	Colorimeter	Provide a colorimeter using 45°/0° geometry CIE, D65 Illuminant, 2° standard observation angle meeting the requirements of ASTM E1347, E1348, or E1349.	TxDOT, 2004
2	Maryland	Colorimeter or color chart	Placed on the pavement marking to determine acceptability for Traffic paint, thermoplastic, epoxy, and tape	MDOT, 2013
3	California	Spectrophotometer (Color gauge)	The color application after 60 days using the manufacturer's guide. The yellow color reflectance is to be within 47 to 60, and for white color 80 minimum matching with an AMS-STD-595 chromaticity limit	Caltrans, 2019
4	Florida	Mobile Retro-reflectivity Unit (MRU) and data collection software	MRU must meet the criteria described in the Project Level Quality Assurance. These field tests shall be conducted once every 365 days or as deemed necessary.	FDOT, 2017

In **Table 53**, the Texas and Maryland DOTs use colorimeters to measure the color of pavement markings. The colorimeter has unique requirements for measurement, having a $45^0/0^0$ geometry CIE, D65 Illuminant, and 2^0 standard observation angle, meeting the ASTM E1347, E1348, or E1349 requirements. California uses the "Color-Guide" spectrophotometer to measure the color of pavement markings. There are different reflectance levels for yellow (47 to 60) and white color (80 minimum) with AMS-STD-chromaticity limit for markings. Florida uses the MRU to measure the color of pavement markings, which meets the requirements described in the contract on quality assurance. The color measurement of pavement markings is often carried out once annually or when required.

A field instrument such as the Spectro2guide 45/0 color hand-held spectrophotometer offers the capacity to gauge the nighttime color of pavement markings. This kind of color spectrophotometer utilizes imaginative and elite execution LED innovations as a light source. The temperature stability (short-term and long-time) as well as a uniform color are associated with superior quality. The long-life nature of the LEDs, ensured for quite some time, guarantees low maintenance (no light substitution is required). This instrument consolidates a spectrophotometer with a fluorimeter in one convenient gadget with several features, such as (1) color, gloss, and new fluorescence measurement in one, (2) exchange of digital standards due to excellent inter-instrument agreement, (3) balanced and direct design with a large color touchscreen, (4) smart docking station with intelligent auto diagnosis to indicate when to calibrate, (5) live preview of the measurement spot with an integrated camera, (6) smart high-tech LED illumination for excellent short-term and long-term temperature stability, (7) 10-year warranty on the LED light source – no lamp change needed, and (8) professional data analysis with smart chart combined with Wi-Fi or USB data transfer. **Figure 72** show the outlook of a Spectro2guide color hand-held spectrophotometer.

Figure 72 Spectro2guide 45/0 Color Spectrophotometer (BYK-Gardner Instrument)

5.2.4 Equipment Required for the Removal of Pavement Markings

The use of equipment to remove old pavement markings generally occurs at the end of the lifespan of any marking. It is also popular to use relevant equipment to remove pavement markings due to construction work needing line diversions or changes in the traffic flow within work zones. If the equipment cannot remove the old pavement markings properly, there could be several serious consequences generated, such as (1) confusion to motorists, which in turn creates dangerous driving conditions, and (2) pavement scars or surface discolorations. **Table 54** shows various approaches by different state DOTs regarding equipment required for the removal of pavement markings in the U.S.

Table 54 Equipment Required in Different States DOTs for Removal of Old Pavement Markings

States	Equipment Function	Removal Specifications	Source
California	Grinding	The pavement marking image shall be removed by grinding a rectangular area. The minimum dimensions of the rectangle shall be the height and width of the pavement marking.	Traffic Stripes and Pavement

		Traffic stripes shall be removed before any change is made in the traffic pattern.	Markings 15-2.02B
Idaho	Not specified	Removal of painted pavement markings, plastic pavement marking tape, thermoplastic pavement markings, and raised pavement markings shall be with a method that completely removes old marking material and leaves minimal pavement scars or surface texture differences that could be confused with pavement markings regardless of road conditions	Pavement Marking Removal 203.04.
Illinois	Mechanical device	The existing pavement markings shall be removed from the pavement by a method that does not materially damage the surface or texture of the pavement or surfacing. Very small particles of tightly adhering existing markings may remain in place if, in the opinion of the Engineer, complete removal of the small particles will result in pavement surface damage.	Removal of Conflicting Markings 783.03.
Missouri	Mechanical device, High temperature burning with excess oxygen, Sand blasting	The use of asphalt or black paint to cover conflicting markings shall not be allowed. All removal methods must comply with EPA and MDNR regulations concerning air quality and material disposal.	Obliteration of Pavement Markings 620.1.13
Nevada	Water blasting	Perform removals on all other surfaces by approved methods. Much care to prevent damage to pavement surfaces, joint material, and bridge joints. Remove temporary pavement striping immediately after traffic has been re-routed and the temporary pavement striping is no longer required	Standard Specification 2001
Oregon	Hydro blasting for non-durable pavement marking and steel shot blasting or grinding for durable pavement marking.	Remove durable marking by steel shot blasting or grinding the pavement surface to a depth no greater than 1/8 inch, creating a smooth, flat slot of uniform depth. Remove pavement markings the same day permanent markings are applied. Use vacuum shrouded equipment or other equally effective containment procedures. Dispose of all waste materials according to 00290.20.	General Oregon DOT Specification Book 00851.4
South Carolina	Concrete surface: Sand blasting using air or water, High pressure water, Steam of superheated water, or Shot blasting. Asphalt surface: Sand blasting using air or water, high pressure water, steam of superheated water, shot blasting, and grinding.	Use grinding for pavement marking removal on asphalt pavement courses only. Do not use grinding for the removal of pavement markings from a concrete pavement course. Do not apply a black paint or any other color of paint or type of paint over pavement markings designated for removal as a singular method of removal of pavement markings. Remove the residue from a blast cleaning method i.e., sand, water, or shot when operating within 10 feet of a travel lane open to traffic.	Removal of Pavement Markings 609.4.1.2
Tennessee	Sand blasting, water blasting or grinding equipment method	Conflicting pavement markings must be removed to prevent confusion for motorist. Pavement marking removal shall be accomplished by the contractor in a manner acceptable to the Engineer.	Pavement Marking Removal.

Texas	Surface treatment, Burning, Blasting, Mechanical removal	Eliminate existing pavement markings and markers on both concrete and asphaltic surfaces in such a manner that color, and texture contrast of the pavement surface will be held to a minimum. Repair damage to asphaltic surfaces, such as spalling, shelling, etc., greater than 1/4 in. in-depth resulting from the removal of pavement markings and markers. Dispose of markers in accordance with federal, state, and local regulations.	2004 Specification Manual Under 677.4. Construction.
Utah	High-pressure water spray, sand blasting, shot blasting, grinding	Grinding is not allowed on the final surfacing unless the Engineer grants prior written approval. The Engineer may grant prior written approval for the use of black paint or other obscuring material for work durations shorter than "long term stationary" as defined in the Temporary Traffic Control section of the MUTCD. Use equipment specifically designed for the removal of pavement marking material.	Remove Pavement Markings 3.4

Source: (NCHRP Report 759, 2013)

From **Table 54**, it is shown that the California, Illinois, and Nevada DOTs use one type of equipment for the removal of pavement markings; a grinding device is used by California, a mechanical device is used by the Illinois DOT, and hydro or water blasting equipment is used by the Nevada DOT. TxDOT uses surface treatment, burning, blasting, and mechanical removal, while Utah and Tennessee use equipment with the functions of high-pressure water spraying, sandblasting, shot blasting, and grinding, as listed in Table 55. These types of equipment help in the efficient removal of the old markings with the least damage on pavement surfaces. South Carolina separates its equipment for use on asphalt and concrete surfaces, with the addition of grinding equipment to asphaltic surfaces, while Missouri has a combination of the mechanical equipment listed alongside high temperature burning with excess oxygen and sandblasting equipment. **Figures 73-75** shows several types of equipment for the removal of pavement markings.

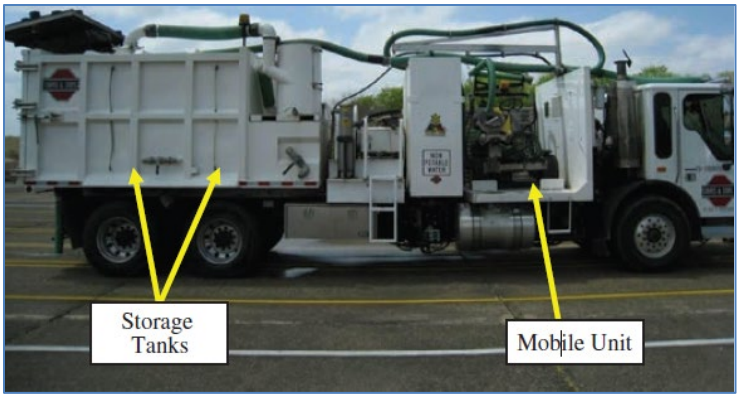


Figure 73 High-Pressure Water Blasting Removal Truck

Figure 74 Water Blasting Paint Removal Equipment

Figure 75 Stripe Hog for Roadway Marking Removal (Hog Technologies)

Each of the removal equipment methods listed in **Table 54** has its own reported advantages and disadvantages. The advantages and disadvantages were obtained from the NCHRP Report 759 (2013). **Table 55** provides the advantages and disadvantages associated with equipment used in different pavement marking removal methods.

Table 55 Advantages and Disadvantages of Equipment with Different Pavement Marking Removal Methods

No	Removal Method	Advantages	Disadvantages
1	High-Pressure Water	● Byproduct does not create dust and is contained within the equipment. ● Little to no scarring on PCC. ● Apart from drying time, the pavement surface is prepped for pavement marking reinstallation. ● Relatively fast for a blasting method. ● Large vehicle mobile systems are available with additional utility carts for smaller nearby areas.	● Limited to above-freezing conditions. ● May polish surface aggregate and/or clean the surrounding pavement, creating a color contrast. ● May remove some surface asphalt and fines that could lead to water penetration. ● Potential for damage to pavement joints. ● Currently not widely available, higher costs. ● Proper equipment operation critical to achieve good results.
2	Grinding	● Fast and economical. ● Depending on the system configuration (effective vacuum system installed to remove dust), dust created by removal can be contained. ● High availability.	● Damage to pavement surface. ● Scarring with full marking removal, minimizing damage to roadway may leave marking material behind. Orbital flailing may result in less noticeable scarring than drum flailing due to tapered edges. ● Non-vacuum systems can create dust clouds and be hazardous.
3	Sand Blasting	● Minimal pavement degradation. ● Little to no scarring. ● Hand-operated precision.	● Creates considerable byproduct. ● Creates considerable dust. ● No current large vehicle mobile system, therefore slower than mobile methods. ● Health hazards depending on blast media.
4	Shot Blasting	● Minimal byproduct. ● Byproduct does not create dust and is contained within the equipment. ● Minimal pavement degradation. ● Little to no scarring.	● Shot recovery can be problematic especially on uneven surfaces. ● Cannot be used in wet conditions. ● Can be slow especially for thicker markings. ● Can cause pavement damage on non-smooth surfaces. ● Limited availability of equipment.
5	Soda Blasting	● Minimal pavement degradation. ● Little to no scarring. ● Hand-operated precision.	● Creates a moderate amount of byproduct. ● Creates considerable dust. ● No current large vehicle mobile system. ● Can be slow especially for thick markings. ● Only useful on some markings.
6	Hydro Blasting	● Similar advantages to high-pressure water and sand blasting. ● Minimal pavement degradation. ● Limited scarring.	● Similar disadvantages to high-pressure water and sand blasting. ● Creates considerable byproduct. ● No current large vehicle mobile system. ● Limited to above freezing conditions.

7	Excess-oxygen Burning	● Minimal pavement degradation.	● Requires at least one additional pass to remove residue. ● Slow. ● No current large vehicle mobile system. ● Only useful on some markings.
8	Hand Removal	● Detailed removal.	● Slow. ● Typically, only for removable tapes.
9	Dry Ice Blasting	● Minimal environmental concerns with respect to debris generated. ● Minimal pavement degradation. ● Marking can be completely removed. ● Hand-operated precision.	● Dry ice is a difficult medium to handle and store. ● Very noisy. ● Slow. ● No current large vehicle mobile system. ● Only useful on some markings.
10	Masking	● No damage to road surface. ● Existing markings can be temporarily covered with tape that matches the road surface color and texture, and later reused when the tape is removed. ● Removed areas can be masked to help blend in scarring or surface color changes. ● Can be used in lane-shift areas to reduce driver confusion due to ghost markings or scarring.	● Can be expensive. ● Material may wear away exposing the markings being covered. ● Difficult to match color and texture with tape. ● Tape is for temporary purposes only. ● Cannot use marking materials other than tape to cover a marking.
11	Chemical	● Byproduct does not create dust. ● Can get complete removal without scarring.	● Potential to damage pavement surface if incorrect removing agents are used. ● Requires at least one additional pass to remove residue. ● Slow, need to wait for chemical to react then proceed with removal. ● No current large vehicle mobile system. ● Only useful on some markings.
12	Laser	● Non-contact and should have little to no wear, which reduces maintenance costs. ● Minimal pavement degradation. ● Minimal environmental concerns.	● Slow. ● Requires at least one additional pass to remove residue. ● No current large vehicle mobile system. ● Only useful on some markings.

Source: (NCHRP Report 759, 2013)

5.2.5 Issues and Problems Associated with Pavement Marking Equipment

There are some issues and problems associated with pavement marking equipment that have been noted in Texas and other states, which include:

- The use of equipment for surface treatment might result in reflective cracking of pavement surfaces due to high friction.
- Measurement bias, repeatability, and reproducibility issues with hand-held retro-reflectometer equipment can be time-consuming and expensive for large projects compared to the usage of the mobile one (i.e., the MRU), which is employed by many state DOTs.

- The capacity of color equipment to gauge the nighttime color of pavement markings presents a challenge because the nighttime color measurement is currently limited to laboratory settings.
- If the removal equipment cannot properly remove the old pavement markings, a source of distraction will be created for drivers, resulting in dangerous driving conditions. The incomplete removal of pavement markings may suggest that the original travel path or marking is still valid.
- If the equipment for removal of pavement markings is not operated properly, scars and/or discoloration of the pavement surface will result, which will contrast with the existing surface.
- The use of mechanical equipment alone for the complete removal of pavement markings may result in damage to pavement surfaces.

5.2.6 Recommendations to TxDOT on Equipment Measures

The research team has made the following recommendations to TxDOT on equipment measures, which include:

- The use of marking equipment such as Hog Technologies Truck is recommended for the marking surface preparation and removal of existing markings because such equipment could substantially reduce scarring or discoloration of pavement surfaces.
- It is recommended that the installation equipment, such as the striping trucks for thermoplastics or epoxy and water-based materials trucks, shall be equipped with the Data Logger System to show the actual material application rate and film thickness.
- The use of the MRU that incorporates data collection software for the installation of pavement markings is recommended.
- A combination of removal techniques such as flailing and high-pressure water blasting is recommended for thermoplastic pavement marking removal on asphalt and concrete surfaces.

- Training on the use of equipment should be required for personnel who are to use the relevant equipment for surface preparation, installation, retro-reflectivity, color measurement, and removal of old pavement markings.
- For the selection of removal equipment for pavement markings, certain factors need to be considered, such as:
    - Which marking material(s) shall be removed?
    - What pavement surfaces are the marking materials on?
    - What are the reasons for the removal?
    - Which removal equipment is accessible, and at what cost?

5.3 Identifying a Pavement Markings Payment Base

Determining a pavement marking payment base is an important element that is required to be rigorously set up and monitored because it will affect the cost and the durability of the markings. Pavement marking costs could be paid in various ways, including determination by subsidiary, volume, and length. However, understanding how the payment of various markings, such as surface preparation, installation material, and repairing or replacement, is handled is quite essential. In the subsequent sections, all issues, unit prices of various marking types, and payment approaches in different state DOTs will be discussed thoroughly.

5.3.1 Pavement Markings Payment Bases in Texas and Other States

According to TxDOT (2014), the payment for pavement marking in Texas is made under different categories, such as (1) work zone pavement markings, (2) reflectorized pavement markings, (3) prefabricated pavement markings, (4) eliminating existing pavement markings and markers, and (5) pavement surface preparation for markings. For work zone pavement markings, it is mentioned that the pavement marking costs are paid based on the length, word, shape, symbol, or temporary and flexible reflective roadway marker tap. This price includes full compensation for furnishing, placing, maintaining, and removing work zone

pavement markings, as well as materials, equipment, labor, tools, and incidentals. The same methodology is stated for retro-reflectorized pavement markings. Specifically, it is stated, "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 'Pavement Sealer' of the size specified, 'Retro-reflectorized Pavement Markings' of the type and color specified and the shape, width, size, and thickness specified as applicable, 'Retro-reflectorized Pavement Markings with Retroreflective Requirements' of the types, colors, sizes, widths, and thicknesses specified or 'Retro-reflectorized Profile Pavement Markings' of the various types, colors, shapes, sizes, and widths specified." In addition, it is worth mentioning that the cost for repairing or replacement of markings damaged by inclement weather could be charged to the project client if the installation of the marking was permitted in such environmental conditions by engineers.

According to TxDOT (2014), prefabricated pavement markings also could be paid for on a length basis or by the word, shape, or symbol. The unit price includes cleaning the pavement by any means other than required abrasive or water-blast cleaning or milling; furnishing and placing materials; and equipment, labor, tools, and incidentals. TxDOT pays for the removal of existing pavement under a separate item named "Item 677 – Eliminating Existing Pavement Markings and Markers." The unit price includes the total compensation for the elimination method used and materials, equipment, tools, labor, and incidentals. In addition, per TxDOT (2014), the payment for surface preparation is also made under a different item named "Item 678." Its payment is made on a length basis for each width specified, by each word, shape, symbol, or other units, except a lump sum.

MnDOT (2015) states that costs for marking lines are paid by length, while those for crosswalks and pavement messages are paid by square feet. The unit price for MnDOT includes the costs associated with installation, pavement marking installation records, traffic control, surface preparation, and primers, as required by the contract. However, the cost for measuring retro-reflectivity of pavement marking is deemed to be paid under a separate item. As per MnDOT, it is stated that the

contract unit price for the mobile retro-reflectometer measurements (MRM) includes all costs incurred in materials, equipment, labor, traffic control, and time, as required by the contract. Its payment condition is such that 50% of the payment for pavement markings will be retained until the evaluation of retro-reflectivity is complete and the engineer accepts the work. It is also noted that MnDOT may apply monetary deductions if the field marking retro-reflectivity reading is less than 20% of what is specified in the retro-reflectivity requirement. The amount of reduction would be in correlation with the percent of retro-reflectivity deficiency.

Similarly, according to the Nevada DOT (2014), the payment of pavement marking tape and thermoplastic marking is based on either linear feet/linear meters or square feet/square meters basis. It is important to note that the Nevada DOT considers the double solid and broken w/solid lines as a single line when measured for payment. Therefore, gaps in broken and dotted lines will be included in the linear measurement. In summary, the Nevada DOT considers the payment of pavement marking based on the criteria noted in **Table 56**.

Table 56 The Nevada DOT Payment Basis

Pay Item	Pay Unit
Pavement Marking Tape (type) (Varies)	Square Meter (Square Foot)
Pavement Marking Tape (type) (*)	Linear Meter (Linear Foot)
Pavement Marking Tape (type) (*)	Kilometer (Mile)
Thermoplastic Pavement Marking (Varies)	Square Meter (Square Foot)
Thermoplastic Pavement Marking (*)	Square Meter (Square Foot)
Thermoplastic Pavement Marking (*)	Kilometer (Mile)
Temporary Striping Tape (type)	Linear Meter (Linear Foot)
Temporary Painted Striping (**)	Linear Meter (Linear Foot), or Kilometer (Mile), or Square Meter (Square Foot)

*Width, pattern, or color as indicated in the proposal.
** color and type (solid or broken) as indicated in the proposal.

Table 57 provides further information regarding the payment basis, payment of surface preparation, issues, and sources from which the data were retrieved for various states.

Table 57 Payment Basis in Various States

No	States	Payment Basis	Payment for surface preparation	Issues	Sources

1	**California**	By length - Linear feet (LF)	Payment for removal of marking is considered separately	Striping along the line of the traffic stripe is measured without deductions for gaps	(Caltrans, 2019)
2	**Illinois**	By length - Linear feet (LF) with consideration of the width		Payment for removal of marking is considered separately, and it is measured in square feet	(IL DOT, 2015)
3	**Iowa**	Per station placed, and each for symbols and words	Included in the unit price	Payment includes cleaning and surface preparation, maintenance, removal, installing or removing temporary delineators, furnishing all materials, equipment, and labor, and disposal of material generated from the removal operations.	(IA DOT, 2015)
4	**Kansas**	By length or each word, symbol, and shape		90% of the payment is paid right after the work completion, while 10% is released after 180-day observation period. The removal of the pavement is paid for by the linear foot	(KSDOT, 2015)
5	**Minnesota**	Lines are paid by length, and crosswalks and pavement messages are paid by square feet	Included in the unit price	Contract unit price for pavement markings include the costs of materials, collection of survey data, marking of spot locations, initial pavement marking retro-reflectivity, installation, pavement marking installation records, traffic control, surface preparation, and primers	(MNDOT, 2015)
6	**Nevada**	Either by length or by square meter, accepted		Double solid and broken w/solid lines will be considered as a single line when measured for payment. Gaps in broken and dotted lines will be included in the linear measurement.	(NV, 2014)
7	**New York**	By length - Linear feet (LF)	Not included in the unit price	The cost includes furnishing all labor, materials, and equipment and maintaining and protecting traffic during the marking operations. The cost of removal of concrete curing compounds, removing existing marking, and surface preparation are being paid separately.	(NYDOT, 2002)
8	**Ohio**	By length - Linear feet (LF)		Payment for removal of marking and surface preparation is considered separately, and it is measured in square feet.	(OHDOT, 2021)
9	**Oregon**	By length - Linear feet (LF)		Measurement will be the actual stripe. Gaps between skip stripes will not be measured. Payment for work done will be limited to 75 percent of the amount due until the agency has received the signed warranty. The warranty period is 3 years for surface mounted thermoplastic, and 4	(ORDOT, 2021)

				years for all other methods and materials	
10	**Texas**	By length or each word, and shape or any other unit shown on the plans	It is not included in the unit price of pavement marking, and it is paid separately under " pavement surface preparation for markings." However, for Retro-reflectorized Pavement Markings, it is noted that surface preparation of all asphalt less than three years old and old concrete, except for sealing, will not be paid directly but is subsidiary to this item.		(TxDOT, 2014)
11	**Washington**	By length or each symbol and square foot for painted crosswalk line	Included in the unit price	All costs associated with surface preparation and installation of markings are included in the contract	(WSDOT, 2021)

As shown in **Table 57**, all investigated states make the payment of pavement marking costs by measuring the length of marking lines or by counting symbols, words, and shapes. For crosswalk pavement markings, several states, such as MnDOT, NDOT, and WSDOT, pay based on square meters/square feet. Another important issue to highlight is that none of the investigated states pay for marking services based on the volume of marking materials. In addition, it is also critical to note that, except for MnDOT, none of the investigated states have predicted the payment of mobile retro-reflectometer measurements. As checking the retro-reflectivity of new marking is essential in ensuring that the retro-reflectivity of newly installed markings meets the standard requirements, it is a noteworthy idea to include its payment base in the specification.

As highlighted in **Table 57,** Caltrans (2019) and NDOT (2014) consider gaps in broken and dotted lines in their measurement and will not deduct any amount for

gaps, whereas ORDOT (2021) does not include them in the measurement for its payment purposes. In contrast, TxDOT (2014) does not clarify whether the gaps in broken and dotted lines should be included in the measurement or not.

Similarly, the removal of existing pavement markings is another important issue that needs to be addressed. Almost all the investigated states do not include payment for this item in the marking installation unit price and pay it separately under a different item. Some of the states, including Kansas and Texas, consider the removal of existing markings payment basis the same as marking installation, which is by length, symbol, shape, or word, while some other states, such as Ohio and Illinois, make its payment based on square feet/square meters.

5.3.2 Pavement Markings Payment Schedule

The schedule and condition of pavement marking cost payment is a critical component of standard specification, as it determines when the contractor is eligible to be compensated for the work performed. According to TxDOT (2014), it is mandated that "all marking must meet the requirements of the specification for at least 30 calendar days after installation." However, TxDOT (2014) does not specify the percentages they would retain until the final approval of the work.

On the other hand, KDOT (2015) stated that the contractor will be paid for 90% of the completed road right after the completion of all work, while the remaining 10% could be released upon the acceptance of the work following the 180-day observation period. Similarly, ODOT (2021) has limited the release of payment to 75% of the amount due until the agency has received the signed warranty. The warranty period is 3 years for surface-mounted thermoplastic, and 4 years for all other methods and materials.

Likewise, ILDOT (2015) also finalizes their inspection following 180 days of installation of pavement marking as a performance period. Specifically, it is stated that "upon completion of the final performance inspection, or after satisfactory completion of any necessary correction, the Engineer will notify the contractor, in

writing, of the date of such final performance inspection and release him/her from further performance responsibility. If this inspection discloses any work, in whole or in part, which does not meet the inspection requirements, the contractor shall, within 30 calendar days, completely repair or replace such work to the satisfaction of the Engineer."

5.3.3 Pavement Markings Payment Bases in Foreign Countries

5.3.3.1 Pavement Marking Payment Base and Process in Canada

According to the Ministry of Transportation and Infrastructure (2019), in British Columbia, Canada, the provincial government announces a Request for Quotation (RFQ) for contractors to provide annual and multi-year pavement marking services, and those services include labor, materials, and equipment to the province, on or in respect of all highways within the pavement marking service area, per the terms and conditions of the agreement. The contract documents specify the annual line kilometers to be painted for various types of pavements marking services. The pavement marking services are comprised of the following four general groups of pavements marking activities to be performed by the contractor to facilitate the safe and efficient movement of traffic on highways using pavement markings:

- Routine pavement marking services
- Second coat application pavement marking services (to be painted a second time within a calendar year)
- Quantified pavement marking services
- Additional pavement marking services

Once the contractor performs all pavement marking services except additional ones in a manner that meets or exceeds the specifications, the contractors are paid for the core services except additional pavement marking services during each applicable contract year and payable in 12 installments. Moreover, the contractors will receive the holdbacks retained by the client once they are satisfied with the services performed by the contractors. The unit of measurement for longitudinal pavement and transverse markings is the linear kilometer and square meter (m^2),

respectively. In addition, each is used separately and counted for the Delta Island markings and others. **Table 58** shows the pavement marking payment basis calculation in Canada.

Table 58 Pavement Marking Payment Basis in Canada

Items	Unit of Measurement	Year 1 Unit Prices
Longitudinal Pavement Markings (Paint & Repaint)	line km	$@@@
Painted Transverse Markings (Paint & Repaint)	M2	$@@@
Thermoplastic Transverse Markings (Application)	M2	$@@@
Layout of Longitudinal Line	Line km	$@@@
Layout of Delta Island	Ea.	$@@@
Layout of Transverse Markings	Ea.	$@@@
Grinding for inlaid markings	Cost-plus markup	

5.3.3.2 Pavement Marking Payment Base and Process in Australia

According to Transport for New South Wales – Australia (2020), the payment for pavement marking incorporates all costs associated with completing the work detailed in specifications according to each specified pay item in the contract agreement. Specifications are developed as a performance-based specification type, setting out the pavement marking initial, medium-term, and long-term performance requirements. It should be noted that, in the performance-based specification type, the contractor is responsible for choosing the appropriate pavement marking material that will satisfy the performance requirements for any marking application. The contractor must perform field testing after opening to traffic. After that, it is mandated that subsequent tests are conducted at least once every 12 months unless specified otherwise in the contract documents. The client may carry out field testing of the pavement marking for any or all the set performance criteria. The client will use the result of this testing to decide if any pavement marking needs to be remarked. The unit of measurement used for longitudinal lines is the linear meter for each line type and the square meter for transverse lines and other markings. Moreover, the payment for the removal of existing pavement markings can be paid under a separate item, which is measured by square meter.

5.3.3.3 Pavement Marking Payment Base in South Africa

According to the Department of Transportation KwaZulu-Natal Province - South Africa (2021), the payments to contractors are made based on the contract agreement, and the contracts are like other construction contracts. The unit of measurement for white and yellow broken or unbroken lines is the kilometer. The unit of measurement for transverse lines, painted islands, and arrestor bed markings is the square meter. The unit of measurement for white and yellow paint is the liter.

5.3.4 Payment for Surface Preparation

Surface preparation is another crucial task that needs to be carefully performed, as it directly affects the bonding of marking materials to the surface of the pavement. Surface preparation involves a range of activities, including sweeping, air blasting, flail milling, and blast cleaning. As indicated in **Table 58** above, some U.S. states, such as Texas, California, and New York, pay for surface preparation under a separate item, while other states, such as Iowa, Minnesota, and Washington, include its cost in the unit price of marking installation. It is concluded that it is better to consider surface preparation as a separate item because it would provide more clarity on the price of various pavement marking tasks, and at the same time, it would make it possible for the agency to hire multiple contractors concurrently for performing different marking jobs.

5.3.5 Key Takeaways of Studying Pavement Marking Payment Base

The followings are the key takeaways that can be made from the study of pavement marking payment base in this section:

- Identification, understanding, and improvement of pavement marking payment basis is important, as it directly affects the cost and durability of pavement markings.
- Payment for pavement marking services in Texas is made under five categories.

- All states investigated paid pavement marking costs based on length or area; none paid services based on volume.
- None of the state DOTs, except for MnDOT, has predicted the payment of mobile retro-reflectometer measurements.
- Inclusion of the mobile retro-reflectometer in the payment marking basis is a worthwhile consideration.
- Payment for the removal of existing pavement marking is considered separately.
- Pavement marking payment schedules vary from state to state, with states retaining varying amounts for work acceptance.
- Several states include the gaps in broken and dotted lines in their measurement, while some states do not pay for it. TxDOT does not clarify whether the gaps in broken and dotted lines should be included in the measurement or not.
- The determination of the marking payment cost basis in foreign countries, such as Canada, Australia, and South Africa, is identical to the practice in the U.S.

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Appendixes

Appendix A Microsoft Version of the Survey Form

Dear Respondent,

You are invited to take this survey, which is designed to collect information on the needs, concerns, and expectations regarding the types of pavement markings on roadways. The purpose is to understand the existing technologies and materials that are using in practices; as well as the performances, and practical and specific issues encountered in relevant areas. This questionnaire is administered strictly by Texas Department of Transportation (TxDOT) and performed by Texas Southern University (TSU) through the research project 0-7135.

You are selected as we believe that you are in charge of or related to pavement markings practices and/or studies. Please kindly respond based on your experience in design, selection, and maintain roadway pavement markings for roadways in your district/area.

Should there be any technical questions, please contact Dr. Fengxiang Qiao at fengxiang.qiao@tsu.edu at TSU.

Thank you in advance for your participation!

Fengxiang Qiao, Ph.D.
Supervisor of TxDOT project 0-7135, and
Professor in Texas Southern University
fengxiang.qiao@tsu.edu

Part I: Basic Information

A. Your Contact Information (for the benefit of further contact of this project).

_____

- District /Division

_____

- Name

_____

- Title

_____

- E-mail

_____

- Phone Number

_____

B. What TxDOT district are you currently located in?

C. How do you rate the overall performance of pavement markings in your area?

   a. Poor

   b. Below Average

   c. Fair

   d. Above Average

   e. Outstanding

D. Which of the following pavement markings are mostly used in your area?

   a. Thermoplastic

   b. Water-Based Paint

   c. Preformed Tapes

   d. Multipolymer (Epoxy, Polyuria, Modified Urethane, Methyl Methacrylate, etc.)

   e. Profiled Thermoplastic

   f. Other (please specify)

Part II: Pavement Markings Evaluation

(When this survey form is been uploaded on the website in SurveyMonkey.com, the TSU team will use pull-out windows for the options in the following tables.)

Table 1. Pavement Types*

1. Flexible Pavement	2. Perpetual Pavement	3. Rigid Pavement	4. Concerete Older than Three years
5. Concrete Less than Three Years	6. Composite Pavement	7. Other Pavement Types (please specify)	

* For Details, please refer to the link for TxDOT Pavement Manual (2016), https://ftp.txdot.gov/pub/txdot-info/cst/pavement-manual-0516.pdf

Table 2. Performance Influencing Factors

1. Pavement surface	2. Traffic volume (aadt or adt)	3. Type of street and highway
4. Pavement condition	5. Snow removal area	6. Brightness benefit factor
7. Designed Speed Limit	8. Length of the project	9. MIL Thickness
10. Environment	11. Type of lines	12. Age of the pavement

13. Other (please specify)

Table 3. Performance Rating

1. Poor	2. Below Average	3. Average	4. Above Average	5. Outstanding

Table 4. Material Selection Factors

1. Surface Roughness	2. Heat Sensitivity	3. Surface Porosity	4. Traffic	5. Environmental	6. Other (please specify)

Table 5. Pavement Marking Maintenance Methods

1. Visual Nighttime Inspection Methods	2. Measured Retroreflectivity Method	3. Expected Service Life Method	4. Blanket Replacement Method	5. Sun Over the Shoulder Technique
6. Comparison Panel Technique	7. Lane Line Count Technique	8. Control Markings Technique	9. Windshield Marking Technique	10. Comparison Light Box Technique
11. Other (please specify)				

* For Details, please refer to the link for the Methods for Maintaining Pavement Marking Retroreflectivity (2014), https://safety.fhwa.dot.gov/roadway_dept/night_visib/fhwasa14017/fhwasa14017.pdf

Table 6. Marking Considerations (Material, Installation and Application)

1. Material Selection-Roadway Surface Characteristics	2. Material Selection-Traffic	3. Material Selection-Environmental	4. Installation-Surface Moisture
5. Installation- Dirt and Debris	6. Installation- Air and Pavement Temperature	7. Installation-Material Temperature	8. Installation-Traffic Control
9. Application-Thickness	10. Application-Width	11. Application-Color	12. Application-Nighttime Appearance

13. Application-Material Disposal	14. Other (please specify)		

Table 7. Marking Payment

1. Subsidiary	2. By volume	3. By length	4. Other (please specify)

A. Thermoplastic Pavement Marking

1) What pavement type(s) is (are) this marking used for? (Refer to Table 1)

_____

2) Is this marking used in your district (Y/N)? If it is not used or its use in your district has been significantly reduced, please explain why.

_____

3) What is the life expectancy of this marking in your district?

_____

4) What is (are) the most significant performance influencing factor(s) of this marking? (Refer to Table 2)

_____

5) What is the performance rating of this marking? (Refer to Table 3)

_____

6) What material factors are most considered in the section of this marking? (Refer to Table 4)

_____

7) What is the most common marking thickness used in your district (mils)?

_____

8) Is special equipment required for installing, maintaining, and measuring this marker (Y/N)? Please specify.

_____

9) What is (are) the typical maintenance method(s) for this marking? (Refer to Table 5)

_____

10) What material, installation and application considerations are used in the determinator to select this marking? (Refer to Table 6)

11) what type of material, construction specifications do you use for this marking? Please provide a reference for the specification you use.

12) Do you use any other special specification for this marking (Y/N) if yes, please specify.

13) Do you face any challenges with implementing the specifications you are using for this marking (Y/N)? If yes, please specify.

14) How would you verify the application rate of this pavement marking in the field, i.e., thickness, volume, or rate, during your quality control procedure?

_____

15) How is this type of marking being paid? (Refer to Table 7)

_____

16) Do you have any comments and improvement suggestions on this marking?

_____

B. Water-Based Paint

1) What pavement type(s) is (are) this marking used for? (Refer to Table 1)

_____

2) Is this marking not been used or extensively used anymore (Y/N)? Why?

_____

3) What is the life expectancy of this marking?

_____

4) What is (are) the most significant influencing factor(s) of this marking? (Refer to Table 2)

_____

5) What is the performance rating of this marking? (Refer to Table 3)

_____

6) What is (are) the most considered selection factor(s) of this marking? (Refer to Table 4)

_____

8) Is special equipment required for installing, maintaining, and measuring this marker (Y/N)? Please specify.

_____

9) What is (are) the typical maintenance method(s) for this marking? (Refer to Table 5)

_____

10) What specifications are considered for this marking? (Refer to Table 6)

_____

11) How is this type of marking been paid? (Refer to Table 7)

_____

12) Do you have any comments and improvement suggestions on this marking?

_____

C. Preformed Tapes

1) What pavement type(s) is (are) this marking used for? (Refer to Table 1)

_____

2) Is this marking not been used or extensively used anymore (Y/N)? Why?

_____

3) What is the life expectancy of this marking?

_____

4) What is (are) the most significant influencing factor(s) of this marking? (Refer to Table 2)

_____

5) What is the performance rating of this marking? (Refer to Table 3)

_____

6) What is (are) the most considered selection factor(s) of this marking? (Refer to Table 4)

_____

7) Is special equipment required for installing, maintaining, and measuring this marker (Y/N)? Please specify.

_____

8) What is (are) the typical maintenance method(s) for this marking? (Refer to Table 5)

_____

9) What specifications are considered for this marking? (Refer to Table 6)

_____

10) How is this type of marking been paid? (Refer to Table 7)

_____

11) Do you have any comments and improvement suggestions on this marking?

_____

D. Multipolymer (Epoxy, Polyuria, Modified Urethane, Methyl Methacrylate, **etc.)**

1) What pavement type(s) is (are) this marking used for? (Refer to Table 1)

_____

2) Is this marking not been used or extensively used anymore (Y/N)? Why?

_____

3) What is the life expectancy of this marking?

_____

4) What is (are) the most significant influencing factor(s) of this marking? (Refer to Table 2)

_____

5) What is the performance rating of this marking? (Refer to Table 3)

_____

6) What is (are) the most considered selection factor(s) of this marking? (Refer to Table 4)

_____

7) Is special equipment required for installing, maintaining, and measuring this marker (Y/N)? Please specify.

_____

8) What is (are) the typical maintenance method(s) for this marking? (Refer to Table 5)

_____

9) What specifications are considered for this marking? (Refer to Table 6)

_____

10) How is this type of marking been paid? (Refer to Table 7)

_____

11) Do you have any comments and improvement suggestions on this marking?

_____

H. Profiled Thermoplastic

1) What pavement type(s) is (are) this marking used for? (Refer to Table 1)

_____

2) Is this marking not been used or extensively used anymore (Y/N)? Why?

_____

3) What is the life expectancy of this marking?

_____

4) What is (are) the most significant influencing factor(s) of this marking? (Refer to Table 2)

_____

5) What is the performance rating of this marking? (Refer to Table 3)

_____

6) What is (are) the most considered selection factor(s) of this marking? (Refer to Table 4)

_____

7) What is the normal marking thickness (mils)?

_____

8) Is special equipment required for installing, maintaining, and measuring this marker (Y/N)? Please specify.

_____

9) What is (are) the typical maintenance method(s) for this marking? (Refer to Table 5)

_____

10) What specifications are considered for this marking? (Refer to Table 6)

_____

11) How is this type of marking been paid? (Refer to Table 7)

_____

12) Do you have any comments and improvement suggestions on this marking?

_____

Part III: New Technology and Materials.

A. Do you know some of the new technologies and materials used as pavement markings? (Y/N)

_____

B. If Yes for the previous question, please specify.

_____

C. Under what circumstances the new technologies and materials can be used?

_____

D. Please provide references/specifications on these new types of pavements marking materials.

E. Do you have any recommendation on improvement of the TxDOT manuals on pavement marking? For Details, please refer to the link for TxDOT Pavement Marking Handbook (2004), http://onlinemanuals.txdot.gov/txdotmanuals/pmh/pmh.pdf

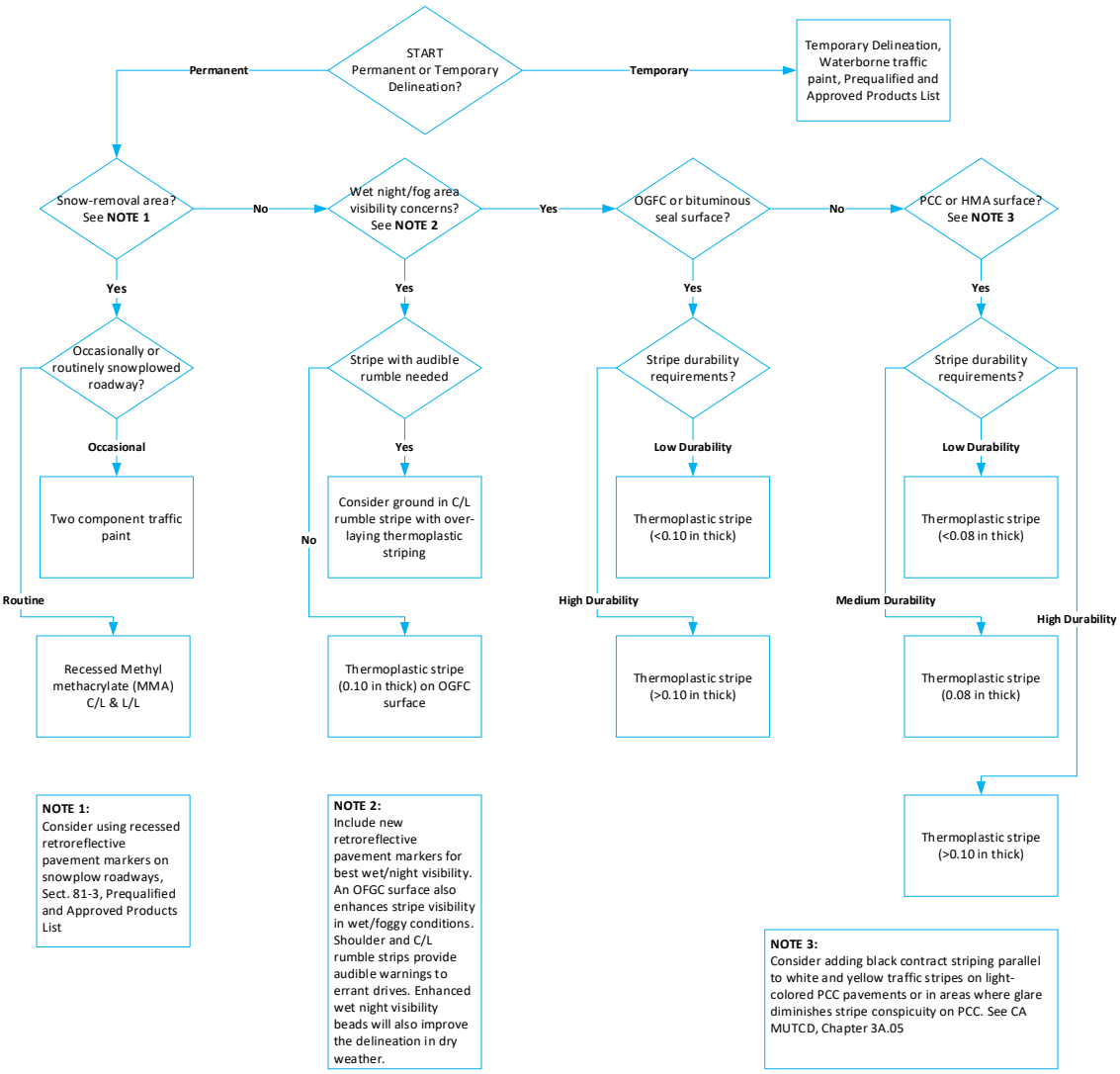
_____

Appendix B List of Responders

No.	Name	Email Address	Title	Division	State/ province	Country
1	Trace Eberhardt	Trace.Eberhardt@dot.ohio.gov	Transportation Engineer 1	Central Office	Ohio	United States
2	Patrick Galarza	patrick.galarza@dot.ny.gov	PE 1	NYSDOT: Materials	New York	United States
3	Rebecca Wells	rebecca.wells@txdot.gov	Director of Transportation Operations	Atlanta	Texas	United States
4	Gayle Maurer	gmaurer@dot.nv.gov	Senior Materials Engineer	Nevada DOT	Nevada	United States
5	Frédéric Boily	frederic.boily@transports.gouv.qc.ca	Chemist	Ministère des Transports du Québec (MTQ)	Quebec	Canada
6	Mohamad Kaddah	mohamad.kaddah@khatibalami.com	Senior Project Manager - Infra	Supervision		Lebanon
7	Hussain Moussa	hussain.moussa@khatibalami.com	Senior Project Engineer	Riyadh	Riyadh	Saudi Arabia
8	Ethan Peterson	ethan.peterson@state.mn.us	Pavement Marking and Crashworthy Engineer	Central Office, MnDOT	Minnesota	United States
9	Shon Crouch	shon.crouch@txdot.gov	Transportation Specialists	Childress	Texas	United States
10	Justin Smith, PE	jussmith@pa.gov	Civil Engineer Manager	Bureau of Maintenance and Operations	Pennsylvania	United States
11	Esayas Butta	Esayas.butta@state.co.us	PE	HQ	Colorado	United States
12	Zena Hailu	zena.hailu@txdot.gov	Transportation Engineer	Houston	Texas	United States
13	Abdul Wakil	awakil@utah.gov	Asset engineer for maintenance	Central Maintenance	Utah	United States
14	Jonny Madrid	jonny.madrid@ks.gov	Engineering Technician Specialist	Bureau of Traffic Engineering	Kansas	United States
15	Tom Honich	thomas.honich@modot.mo.gov	Traffic Liaison Engineer	Highway Safety and Traffic Division	Missouri	United States
16	David Morren	David.Morren@txdot.gov	District Maint Engr	Dallas	Texas	United States
17	Matt Springer	mspringer@ncdot.gov		NCDOT	North Carolina	United States

No.	Name	Email Address	Title	Division	State/ province	Country
18	Esayas Butta	Esayas.butta@state.co.us	PE	HQ	Colorado	United States
19	Dr. Doc Tisdale	dtisdale2@mdot.maryland.gov	Assistant Division Chief -Pavement Markings	MDSHA/OMT/ SMPMD	Maryland	United States
20	Jon Stork	jstork@nd.gov	Research and Pavement Engineer	Materials & Research	North Dakota	United States
21	Karen Byram	karen.byram@dot.state.fl.us	State Product Evaluation Administrator	FDOT	Florida	United States
22	Kevin Wray	kevin.wray@nebraska.gov		Traffic	Nebraska	United States
23	Clayton Burke	clayton.burke@iowadot.us	Work Zone Traffic Safety Engineer	Operations	Iowa	United States
24	Brandon Bilbrey	brandon.bilbrey@txdot.gov	Engineering Assistant IV	Amarillo/Traffic	Texas	United States
25	Danny Lane	danny.lane@tn.gov	Assistant Director	TDOT Materials and Tests	Tennessee	United States
26	Chris Pruitt	chris.pruitt@txdot.gov		Waco	Texas	United States
27	Eduardo Villalon	eduardo.villalon@txdot.gov	SAT District Traffic Engineer	SAT - 15	Texas	United States
28	Chad Ingram	chad.ingram@txdot.gov	Director of Construction	01	Texas	United States
29	Chris Graf	Chris.Graf@txdot.gov	Director of Construction	Brownwood	Texas	United States
30	Daniel Garcia	Daniel.Garcia2@txdot.gov	Director of Construction	21	Texas	United States
31	Shannon Ramos	shannon.ramos@txdot.gov	Director of Construction	11-LFK	Texas	United States
32	Don Maddux	donald.maddux@txdot.gov	Traffic Systems Administrator	LFK	Texas	United States
33	Oak Metcalfe	rmetcalfe@mt.gov	State Materials Engineer		Montana	United States
34	David Valdez	david.valdez@txdot.gov	Transportation Engineer	TRF	Texas	United States
35	Jaunita Daniels	Juanita.danielswest@txdot.gov	Director of Trans. Ops.	Tyler/10	Texas	United States

Appendix C New pavement delineation selection guide - (Caltrans, 2019)



Appendix D Pavement marking application chart (NYSDOT, 2002)

Appendix								
Pavement Marking Application Chart								
					Application Factor			
New Marking	**Uses**	**AADT**	**Cost[1] Per Meter @ 100 mm ($)**	**Life[2] (Yrs)**	**Temp**	**Thickness[3] (mm)**	**No-Track Time (minutes)**	**Reflective Spheres**
Traffic Paint	Longline	<5000	0.18 to 0.53	0.5 to 1	Air and Pvt >= 10°C and Rising	0.38 (existing and new pcc) 0.51 (new acc) 0.75 (og or pp)	3	0.75 kg/l
Epoxy	Longline Intersections Hatch	All	0.26 to 0.33	2-3 (acc) 1.5-2 (pcc)	Air and Pvt >= 10°C and Rising (Not Damp)	0.38 (existing and new pcc) 0.51 (new acc) 0.75 (og or pp)	30 (reg @ 25°C) 60 (slow @25°C)	2.4 kg/l or 1.2 kg/l Type 1 plus 1.2 kg/l Type 2
Polyester	Longline	<5000	0.23	2 (acc) NR (pcc)	Air and Pvt >= 10°C and Rising (Not Damp)	0.38 to 0.51 (acc)	30 (@25°C)	2.4 kg/l or 1.2 kg/l Type 1 plus 1.2 kg/l Type 2
Thermoplastic	Longline Hatch	All	High	3-5 (acc) NR (pcc)	Air >= 9.5°C Pvt > = 10°C and Rising (Not Damp)	3.2 - 4.8 (acc)	10 (@21°C)	0.25 kg/m^3
Performed Tape	Intersections	All	High	3	Air >= 15.5°C Pvt > = 21°C (Not Damp)	-	10 (@21°C) for primer/adhesive	-

NOTES: 1. Upstate, without wet-night visibility spheres. Where/when contracts, add 30%.

2. Factors are for recommended uses and pavement/substrate condition. (See Appendix C.)

3. Og = open graded. Pp = paver placed.