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FINAL REPORT

DEVELOPING A GDOT PAVEMENT MARKING HANDBOOK USING FIELD TEST DECK EVALUATION AND LONG-TERM PERFORMANCE ANALYSIS

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Final Report

DEVELOPING A GDOT PAVEMENT MARKING HANDBOOK USING FIELD TEST DECK EVALUATION AND LONG-TERM PERFORMANCE ANALYSIS

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16. Abstract:
This research project comprehensively reviewed the state departments of transportation's (DOTs) practices on selecting and inspecting pavement marking materials (PMMs) and evaluated pavement marking retroreflectivity data collected on the Georgia Department of Transportation (GDOT) Test Deck and the National Transportation Product Evaluation Program (NTPEP) test decks. A methodology was developed to enhance the reliability of pavement marking retroreflectivity analysis by systematically identifying and removing retroreflectivity data with irregular variability, such as inconsistent retroreflectivity along the same section, as well as irregular temporal jumps in retroreflectivity. Statistical models were further developed to predict the retroreflectivity and expected service life of selected PMMs. Life-cycle cost analysis (LCCA) was then conducted to calculate the expected life-cycle cost of each type of material. Results of the comprehensive review and data analysis were finally integrated into a Pavement Marking Handbook for GDOT to have a standardized and consistent reference for selecting and inspecting PMMs. An interactive tutorial was also developed to enhance the content of the Handbook through interactive means such as images, videos, and user inputs.

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EXECUTIVE SUMMARY

In this study, a pavement marking handbook was developed to support the Georgia Department of Transportation's (GDOT) decision-making and training on the use of pavement marking materials (PMMs). Pavement marking retroreflectivity data collected on the GDOT Test Deck and the National Transportation Product Evaluation Program (NTPEP) test decks were analyzed and combined with rich information from the literature for a comprehensive life-cycle cost analysis (LCCA) of PMMs, and a material selection matrix for GDOT was proposed. Key components of this study are summarized below.

1) GDOT Test Deck Data Analysis

A 4-step method (see Figure 0-1) was proposed to address variability in retroreflectivity measurements, which is commonly seen in this type of data. Inconsistent spatial and temporal retroreflectivity readings were excluded and, therefore, a more reliable pavement marking service life prediction could be achieved. Results in Table 0-1 suggest that the proposed methodology can effectively improve the reliability of service life prediction for PMMs after applying the proposed methodology (i.e., the "processed" columns in the table), which was more consistent with those in the literature.

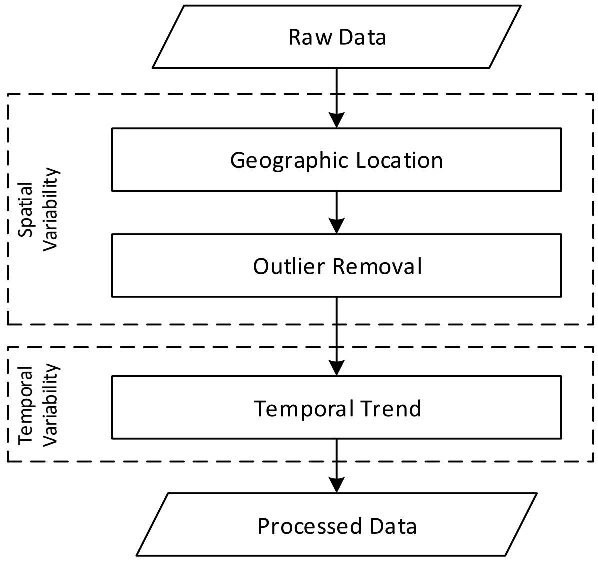


Figure 0-1 Proposed 4-step method to address data variability.

Table 0-1 GDOT Test Deck PMM Service Life Summary

Material	Line Type	Raw		Processed	
		Linear	Exponential	Linear	Exponential
Paint	White Edge	71.7	100.4	44.6	64.0
	White Skip	28.2	32.0	24.4	28.2
	Yellow Edge	281.8	335.0	29.4	35.4
Thermoplastic	White Edge	76.4	127.7	76.4	127.7
	White Skip	87.9	137.1	52.8	83.6
	Yellow Edge[1]	--	--	--	--
Preformed Tape	White Edge	27.2	42.0	27.2	42.0
	White Skip	25.5	34.1	25.5	34.1
	Yellow Edge	30.7	44.9	30.7	44.9
Epoxy	White Edge	22.7	25.3	22.7	25.3
	White Skip	30.2	44.0	30.2	44.0
	Yellow Edge	35.1	52.4	35.1	52.4
Methyl Methacrylate	White Edge	36.2	61.5	36.2	61.5
	White Skip	46.2	86.2	46.2	86.2
	Yellow Edge	62.3	117.3	62.3	117.3

(in months)

[1] Datasets with estimated service lives unreasonably larger (10 times) than the typical service life ranges, therefore not included in this summary.

2) NTPEP Data Analysis

Pavement marking test data in the NTPEP database, DataMine 2.0, which consists of 7 test sites in 3 states (Florida, Pennsylvania, and Minnesota) were used in this study to predict pavement marking service lives. Multiple linear models (MLMs) were developed to predict the service life of various types of PMMs (see Table 0-2).

Table 0-2 PMM Types used in this Study

Type	Description
1C	Waterborne paint
3A	Thermoplastic
3B	Preformed thermoplastic
4A	Preformed tape
5C	Polyurea
5D	Methyl methacrylate

The expected service lives of PMMs, derived from the developed MLMs, are summarized in Table 0-3 and Table 0-4. Note that for each type of material, analysis was conducted separately for different line colors and different pavement surface types. For example, for waterborne paint, four separate analyses were conducted for white paint on asphalt pavements (1CWA), yellow paint on asphalt (1CYA), white paint on concrete (1CWC), and yellow paint on concrete (1CYC).

Table 0-3 Expected Service Life of Pavement Markings (to 100 mcd/m²/lux)

ADT[2] (veh/day/ln)	1CWA	1CYA	1CWC	1CYC	3AWA	3AYA	3AWC	3AYC
2,000	6.5	5.3	15.6	12.2	11.9	13.8	9.0	9.4
3,750	6.5	5.4	15.0	11.7	11.9	13.7	8.7	9.1
4,000	6.5	5.4	14.9	11.7	11.8	13.7	8.7	9.0
7,500	6.6	5.5	13.8	10.8	11.7	13.6	8.2	8.4
10,000	6.6	5.6	13.0	10.2	11.6	13.5	7.8	8.0
20,000	6.7	6.0	9.9	7.6	11.2	13.1	6.3	6.2
ADT (veh/day/ln)	**3BWA**	**3BYA**	**3BWC**	**3BYC**	**4AWA**	**4AYA**	**4AWC**	**4AYC**
2,000	6.6	4.6	8.6	5.0	3.9	3.8	4.7	5.4
3,750	6.5	4.5	8.4	4.8	3.8	3.7	4.6	5.3
4,000	6.5	4.5	8.4	4.8	3.8	3.7	4.6	5.3
7,500	6.4	4.3	8.0	4.5	3.6	3.7	4.5	5.3
10,000	6.3	4.2	7.7	4.2	3.5	3.6	4.4	5.2
20,000	6.1	3.7	6.4	3.2	3.1	3.4	4.1	4.9
ADT (veh/day/ln)	**5CWA**	**5CYA**	**5CWC**	**5CYC**	**5DWA**	**5DYA**	**5DWC**	**5DYC**
2,000	2.6	2.3	2.6	3.0	3.6	8.0	4.1	8.6
3,750	2.5	2.3	2.5	3.0	3.6	7.8	4.0	8.4
4,000	2.5	2.3	2.5	2.9	3.6	7.8	4.0	8.4
7,500	2.5	2.2	2.4	2.8	3.5	7.6	3.9	7.9
10,000	2.4	2.1	2.4	2.7	3.4	7.4	3.8	7.6
20,000	2.2	1.9	2.1	2.3	3.2	6.7	3.5	6.4

(in years)

3) Life-Cycle Cost Analysis

Service life prediction results from the analyses of GDOT data and the NTPEP data were then combined with the rich information acquired from the literature in the recent decade. Moreover, unit costs of PMMs were comprehensively summarized from the unit price reports of seven state DOTs, including Georgia, Texas, Florida, North Carolina, Pennsylvania, Oregon, and Minnesota. Table 0 5 summarizes these results. The “unit

[2] Average Daily Traffic.

cost" refers to material cost and the "other cost" refers to the cost of material removal and surface preparation.

Table 0-4 Expected Service Life of Pavement Markings (to 250 mcd/m2/lux)

ADT (veh/day/ln)	1CWA	1CYA	1CWC	1CYC	3AWA	3AYA	3AWC	3AYC
2,000	3.0	-1.5	9.6	1.6	7.8	5.5	6.7	4.6
3,750	3.1	-1.4	9.0	1.2	7.8	5.5	6.4	4.2
4,000	3.1	-1.4	8.9	1.1	7.8	5.4	6.4	4.2
7,500	3.1	-1.2	7.8	0.2	7.6	5.3	5.8	3.6
10,000	3.1	-1.1	7.0	-0.4	7.5	5.2	5.5	3.2
20,000	3.2	-0.7	3.9	-2.9	7.2	4.8	3.9	1.4
ADT (veh/day/ln)	**3BWA**	**3BYA**	**3BWC**	**3BYC**	**4AWA**	**4AYA**	**4AWC**	**4AYC**
2,000	4.5	1.5	6.4	2.4	3.3	2.7	4.0	4.1
3,750	4.4	1.4	6.2	2.2	3.2	2.6	4.0	4.1
4,000	4.4	1.4	6.1	2.2	3.2	2.6	3.9	4.0
7,500	4.3	1.2	5.7	1.8	3.0	2.6	3.8	4.0
10,000	4.3	1.1	5.4	1.6	2.9	2.5	3.8	3.9
20,000	4.0	0.6	4.2	0.5	2.5	2.3	3.5	3.7
ADT (veh/day/ln)	**5CWA**	**5CYA**	**5CWC**	**5CYC**	**5DWA**	**5DYA**	**5DWC**	**5DYC**
2,000	1.9	1.4	2.1	2.1	2.8	4.6	3.2	5.6
3,750	1.9	1.3	2.1	2.0	2.7	4.5	3.1	5.4
4,000	1.9	1.3	2.1	2.0	2.7	4.5	3.1	5.4
7,500	1.8	1.2	2.0	1.9	2.6	4.3	3.0	5.0
10,000	1.8	1.2	1.9	1.8	2.6	4.1	2.9	4.6
20,000	1.6	0.9	1.6	1.4	2.3	3.4	2.6	3.4

(in years)

A life-cycle cost analysis (LCCA) was then conducted using the information in Table 0-5 under basic engineering economic assumptions (e.g., 10-year analysis period, and 4% discount rate). Results of the LCCA are shown in Table 0-6. While four materials, including paint, thermoplastic, epoxy, and polyurea have comparable life-cycle cost ranges; methyl methacrylate (MMA) and tape have higher life-cycle costs. Note that the potential safety benefits of PMMs, such as crash reduction due to better wet retroreflectivity, were not considered in the LCCA in this study. A benefit-cost analysis, considering potential safety benefits, is recommended to be conducted in the future.

Table 0-5 Expected Service Life and Unit Costs of Marking Materials

Material	Service Life Low (months)	Service Life High (months)	Unit Cost Low (per lf)	Unit Cost High (per lf)	Other Cost Low (per lf)	Other Cost High (per lf)
Paint	12	51	\$0.08	\$0.48	\$0.00	\$0.05
Thermoplastic	26	103	\$0.41	\$0.97	\$0.00	\$0.05
MMA	38	62	\$1.83	\$1.83	\$0.00	\$0.05
Tape	27	65	\$1.82	\$3.18	\$0.46	\$0.76
Epoxy	24	60	\$0.28	\$0.72	\$0.00	\$0.05
Polyurea	36	60	\$0.44	\$1.15	\$0.00	\$0.05

Table 0-6 Life-Cycle Costs for Marking Materials

Material	Low Life-Cycle Costs (per lf/yr)	High Life-Cycle Cost (per lf/yr)
Paint	\$0.03	\$0.55
Thermoplastic	\$0.09	\$0.53
MMA	\$0.41	\$0.78
Tape	\$0.51	\$2.05
Epoxy	\$0.06	\$0.41
Polyurea	\$0.10	\$0.50

4) Material Selection Matrix

From the LCCA results, with synthesized material use practices, a pavement marking selection matrix was proposed (see Table 0-7) for GDOT to use under various traffic (i.e., annual average daily traffic, AADT) and pavement types (asphalt and concrete).

Table 0-7 A Proposed PMM Selection Matrix for GDOT

Total AADT	Asphalt			Concrete*		
	2 Lanes	4 Lanes	Interstate /Freeway	2 Lanes	4 Lanes	Interstate /Freeway
n < 8,000	T/H/E/P	T/H/E/P		E/P	E/P	
8,000 ≤ n <15,000	T/E/P	T/H/E/P	T/E/P/M	E/P	E/P	E/P/M
15,000 ≤ n <40,000	T/E/P/M	T/E/P/M	T/E/P/M/F	E/P/M	E/P/M	E/P/M/F
n ≥ 40,000		T/E/P/M/F	T/E/P/M/F		E/P/M/F	E/P/M/F

H – Highbuild Paint and Wet Weather Paint Traffic Stripe
T – Standard and Wet Weather Thermoplastic Traffic Stripe
F – Preformed Plastic Pavement Markings
P – Standard and Wet Weather Polyurea Traffic Strip
E – Standard and Wet Weather Epoxy Traffic Strip
M – Methyl Methacrylate

*Contrast markings shall be used for all lane lines on PCC surfaces

1. INTRODUCTION

1.1 Research Background and Need

Pavement markings are important traffic control devices that provide navigation and roadway information to road users for safe travel, especially during nighttime and wet-weather conditions. It is estimated that, in 2007, approximately $2 billion was spent on pavement markings in the United States (Carlson et al., 2009). Moreover, approximately $3 million were spent by the Georgia Department of Transportation (GDOT) on pavement marking installation and replacement (Georgia Department of Transportation, 2012). Because of current stringent budgets for highway projects, it is critical for state DOTs to select and use cost-effective pavement marking materials (PMMs) that provide good visibility during nighttime and wet-weather conditions.

GDOT has a history of using a wide range of PMMs and have since developed standard specifications for various PMMs, such as paint, thermoplastic, polyurea, and preformed tape. However, with the rapid changing and improving PMM industry, many cost-effective and durable materials have been produced and used in many states. Consequently, in 2010, GDOT’s Testing Bureau of the Office of Materials and Research (OMR) (now the Office of Materials and Testing (OMAT)) established the GDOT Test Deck on I-16 and US-301/SR-73 near Statesboro, Georgia. Around 13 types of pavement markings were installed, and retroreflectivity measurements were taken 30 days after the installation and every 6 months thereafter. Retroreflectivity data collected from the GDOT Test Deck can be used to evaluate the performance of PMMs and set as a foundation for PMM selection practice in Georgia.

There is a need to (1) conduct a comprehensive study to evaluate the performance of commonly used PMMs; (2) summarize the state-of-the-practice of PMM; and, ultimately, (3) develop a pavement marking handbook that synthesizes the aforementioned information and serves as a knowledge base for GDOT's PMM selection and inspection practice.

1.2 Research Objectives and Scope

The objective of this research is to develop a pavement marking handbook by conducting field test deck evaluations on various PMMs to standardize the PMM selection and inspection. The handbook will assist both engineering and field personnel in selecting PMMs and inspecting pavement marking in the field. The following lists the major tasks.

1) Work Task 1: Literature Review
2) Work Task 2: Development of GDOT Pavement Marking Handbook
3) Work Task 3: Analysis of GDOT Test Deck Data
4) Work Task 4: Cost-Effectiveness Analysis of Selected PMMs
5) Work Task 5: Summarize Research Findings and Develop a Final Report

1.3 Organization of This Report

This report is organized as follows:

1) Chapter 1 introduces the background, research need, objectives, and work tasks of this research project.
2) Chapter 2 presents a review of up-to-date GDOT and other state DOTs' PMM selection criteria, as well as installation/inspection practices.

3) Chapter 3 presents the analysis of GDOT Test Deck data.
4) Chapter 4 presents the analysis of NTPEP test decks data
5) Chapter 5 presents a LCCA of selected PMMs.
6) Chapter 6 present the design and development of the handbook and the interactive tutorial.
7) Chapter 7 concludes the research and provides recommendations for further research.

2. LITERATURE REVIEW OF CURRENT PRACTICES

In this chapter, a comprehensive literature review is conducted to summarize the current practices that researchers and transportation agencies have used to inspect the performance of pavement markings, predict service lives of different PMMs, and select cost-effective materials under different traffic and roadway characteristics. The first section summarizes the standard measurement and practices for pavement marking condition inspection with a focus on pavement marking retroreflectivity. The second section summarizes pavement marking retroreflectivity degradation models that have been established in the literature to predict service lives of different PMMs. The third section summarizes current transportation agencies' PMM selection practices, which have been developed on the basis of the LCCA results, as well as the engineering experiences and decisions. Finally, the fourth section summarizes the review and identifies research needs.

2.1 Pavement Marking Condition Inspection Practices

Transportation agencies have developed various standard specifications for PMMs. These specifications require products to have specific composition (including binder and beads), color, physical properties (e.g., skid resistance), and chemical properties (e.g., drying time and installation temperature) for installation. After installation, the conditions of pavement markings need to be evaluated to ensure they serve their purpose, which is to provide delineation to road users. If markings fail to serve the purpose due to the lack of visibility or if markings are excessively worn out, they should be removed and/or replaced. Retroreflectivity and durability are two commonly used measures for quantitatively and qualitatively evaluating pavement marking conditions. In this section, we focus on the review of methods and standard practices for measuring retroreflectivity of pavement markings after installation, which is the most used quantitative measure for pavement marking performance.

2.1.1 What is Retroreflectivity?

Retroreflectivity is the ability of light to be reflected back in the direction from where it came (see Figure 2-1.) A pavement marking's retroreflectivity allows it to become visible to drivers during nighttime when the headlights of the vehicle reflect off the pavement marking. The retroreflectivity of pavement markings can be measured by a special apparatus called a retroreflectometer, which can be either handheld for manual data collection or mounted on a vehicle for mobile data collection. Retroreflectivity, or the coefficient of retroreflected luminance (R_L), is measured in millicandela (mcd) per square meter per luminous flux (lux), or mcd/m^2/lux.

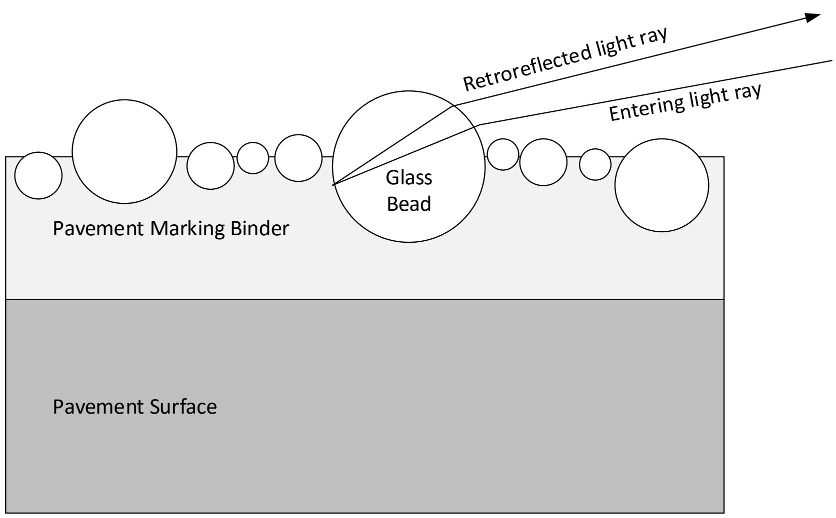


Figure 2-1 Light Retro-reflected by a Glass Bead

2.1.2 Measuring Retroreflectivity

Commonly used test methods for pavement marking retroreflectivity include dry and wet testing methods. Dry retroreflectivity readings are collected according to the ASTM Standard E 1710 –

standard test method for measurement of retroreflective PMMs (ASTM International 2008), which specifies the requirements for conducting dry retroreflectivity test. Wet retroreflectivity readings are commonly collected according to the ASTM Standard E 2177, the standard test method for measuring the coefficient of retroreflected luminance of pavement markings in a standard condition of wetness. To measure retroreflectivity according to the ASTM standard, it needs to slowly and evenly pour a bucket of 2 to 5 liters of water to the test area, and then, measure the retroreflectivity 45 seconds after the completion of pouring the water (ASTM International, 2011). Both ASTM standards require the measurement geometry of the measuring instrument to be at a viewing distance of 30 meters, a headlight mounting height of 0.65 meter and an eye height of 1.2 meter, which is equivalent to an observation angle of $1.05 \pm 0.02°$ between the light source and receiver of the instrument.

Another method that has been used to test pavement marking retroreflectivity under wet condition is the continuous wet method. ASTM Standard E 2832 (ASTM International, 2012a) depicts the standard test method for measuring the coefficient of retroreflected luminance of pavement markings in a standard condition of continuous wet (RL-2). As shown in Figure 2-2, the continuous wet test is carried out by covering the test area with a box that sprays water to simulate a raining condition. Although this method may be very close to real raining conditions, it is tedious and time-consuming, and its use has been limited.

Figure 2-2 Continuous Wet Retroreflectivity Test Method

2.1.3 Use of Retroreflectivity

Retroreflectivity has been extensively used to quantify the performance of a pavement marking and to determine the timing for restriping. It has also been used as threshold requirements for qualifying pavement marking products. For example, GDOT developed the following requirements for both dry (ASTM E 1710) and wet (ASTM E 2177) retroreflectivity levels for various materials used in Georgia.

Table 2-1 Dry Retroreflectivity Requirements According to ASTM E 1710 Test

	White		Yellow	
	30 Days	**180 Days**	**30 Days**	**180 Days**
Thermoplastic	400	400	300	300
Polyurea	600	600	400	400
Paint/High Build Paint	300	300	250	250
Preformed Plastic Tape	600	600	400	400
Epoxy	400	400	300	300

Table 2-2 Dry Retroreflectivity Requirements for Intersection Markings and Symbols

	30 Days	180 Days
Thermoplastic	275	275
Polyurea	275	275
Paint/High Build Paint	275	275
Preformed Plastic Tape	600	600
Epoxy	275	275

Table 2-3 Wet Retroreflectivity Requirements According to ASTM E 2177 Test

	White		Yellow	
	30 Days	180 Days	30 Days	180 Days
Thermoplastic	150	150	125	125
Polyurea	250	250	200	200
Paint/High Build Paint	150	150	100	100
Preformed Plastic Tape	250	250	200	200
Epoxy	150	150	125	125

In terms of the minimum retroreflectivity level that is deemed unacceptable and requires restriping, different practices and studies have been conducted. At the state level, states define the minimum acceptable retroreflectivity level as a universal threshold value or a range of values. For example, GDOT conventionally uses 100 mcd/m^2/lux as the minimum acceptable retroreflectivity level for longitudinal striping. One-hundred mcd/m^2/lux is also the most-used threshold retroreflectivity value in the literature (Abboud & Bowman, 2002; Hummer et al., 2011; Ozelim & Turochy, 2014; Thamizharasan et al., 2003; Zhang & Wu 2006). In addition, IDOT uses a Pavement Marking Index (PMI), which is a 0 to 100 scale. PMI is determined by both the retroreflectivity and the presence (durability). The minimum acceptable retroreflectivity is 100 mcd/m^2/lux for striping that still has 100% of the material at presence. The Texas Department of Transportation (TxDOT) suggests that pavement markings with an average retroreflectivity value of 80 to 100 mcd/m^2/lux should be considered for replacement. Minnesota DOT (MnDOT) conducted a study on public perception of marking brightness and suggested the threshold value of acceptable retroreflectivity fall in between 80 and 120 mcd/m^2/lux (Loetterle et al. 2000). MnDOT uses 120 mcd/m^2/lux as the threshold retroreflectivity value for marking replacement.

Note that many states' minimum requirements for acceptable retroreflectivity are determined by a universal value or a range of values. However, many studies in the literature have also considered other factors, such as road types, driver's age, posted speed limits, the presence of reflective raised pavement marker (RRPM), and line colors, to help determine different minimum retroreflectivity levels that are accustomed to different situations. For example, Parker conducted a study and suggested different minimum retroreflectivity levels based on different age groups (Parker, 2002). He suggested that the threshold retroreflectivity level appeared to be between 80 and 130 mcd/m^2/lux for drivers under 55 years and between 120 and 165 mcd/m^2/lux for drivers older than 55. He also suggested that the New Jersey DOT (NJDOT) use 130 mcd/m^2/lux as the threshold value for pavement marking replacement (Parker, 2002).

In addition, Zwahlen and Schnell conducted a study and developed the minimum required retroreflectivity recommendations for fully marked roadways in Table 2-4, for which they developed different minimum retroreflectivity levels based on different speed ranges and the presence of RRPMs. Similarly, as shown in Table 2-5, Debaillon et al. consider minimum retroreflectivity levels based on the posted speed, presence of RRPMs, and roadway marking configuration (Debaillon et al., 2007, 2008). The Federal Highway Administration (FHWA) considered similar factors and made recommendations for the minimum retroreflectivity levels to be incorporated into the MUTCD, as shown in Table 2-6 (Federal Highway Administration, 2013).

Table 2-4 Recommended Minimum Retroreflectivity Levels (Zwahlen and Schnell 2000)

		Minimum Required R_L [mcd/m^2/lx] for Fully Marked Roads Consisting of Two White Edgelines and a Dashed Yellow/White Center/Lane Line	
Vehicle Speed [mph]	Vehicle Speed [km/h]	Without RPMs, Preview Time=3.65 s	With RPMs, Preview Time=2.0 s
0-25	0-40	30	30
26-35	41-56	50	30
36-45	57-72	85	30
46-55	73-88	170	35
56-65	89-104	340	50
66-75	105-120	620	70

Table 2-5 Recommended Minimum Retroreflectivity Levels (Debaillon et al. 2007)

	Without RRPMs			With RRPMs
	Posted Speed Limit (MPH)			
	≤ 50	55 – 65	≥ 75	
Fully marked roadways (with center line, lane lines, and/or edge line, as needed)	40	60	90	40
Roadways with center lines only	90	250	575	50

Table 2-6 Proposed MUTCD Minimum Pavement Marking Retroreflectivity Levels (Federal Highway Administration 2013)

	Posted Speed Limit (MPH)		
	≤ 30	35 – 50	≥ 55
Two-Lane Roads with Centerline Markings Only	N/A	100	250
All Other Roads	N/A	50	100

2.2 Pavement Marking Degradation Modeling

Since the late 1990s, researchers have developed several statistical models to predict the degradation of PMMs. The majority of these models use retroreflectivity as the dependent variable and use elapsed time, traffic volume, initial retroreflectivity, and other roadway and pavement marking line properties as independent variables. These independent variables, as well as other factors that affect the performance of pavement markings, are summarized below:

1) **Elapsed time**: Elapsed time after marking installation, usually measured in days or months, is one of the most critical variables in the literature. Various models have verified the significance of time's effect on the degradation of pavement marking retroreflectivity (Abboud & Bowman, 2002; Andrady, 1997; Hummer et al., 2011; J.-T. Lee et al., 1999; Migletz et al., 2001; Mull & Sitzabee, 2012; Ozelim & Turochy, 2014; Robertson et al., 2012; Sitzabee et al., 2009, 2012; Thamizharasan et al., 2003; Zhang & Wu 2006).
2) **Traffic**: in the literature, the effect of traffic on the degradation of pavement markings has also been verified to be significant. Specifically, traffic has been considered in the following formats:
    a. Average daily traffic (ADT) or annual average daily traffic (AADT) (Abboud & Bowman, 2002; J.-T. Lee et al., 1999; Mull & Sitzabee 2012; Ozelim & Turochy, 2014; Robertson et al., 2012; Sitzabee et al., 2009, 2012)
    b. Cumulative traffic passages (CTP) (Migletz et al., 2001; Robertson et al., 2012; Thamizharasan et al., 2003)
    c. Commercial/truck traffic (J.-T. Lee et al., 1999)

3) **Initial retroreflectivity**: Initial retroreflectivity is the initial value measured shortly after the installation, usually within 30 days of installation. Initial retroreflectivity stands for the initial performance of the marking, and, for the same material type, initial retroreflectivity can also be used to compare the installation quality of different products, which is a good indicator of how well the product is expected to perform throughout its lifetime. Studies have considered initial retroreflectivity in degradation models, and it has been verified to be a significant variable (Mull and Sitzabee, 2012; Ozelim & Turochy, 2014; Sitzabee et al., 2009, 2012).
4) **Line properties**: Different line properties, including color, lateral location, and installation direction, have different effects on the pavement marking retroreflectivity (Sitzabee et al., 2009, 2012). For example, lane lines usually deteriorate faster than edge lines because the former are usually more exposed to traffic.
5) **Winter events**: Winter weather events, especially pavement surface treatments for snowfalls and snow plow activities, also have significant effects on the degradation of pavement markings in northern states (Mull & Sitzabee, 2012). Pavement markings deteriorate much faster in winter weather.
6) **Weather conditions**: In addition to winter weather, other weather conditions, such as temperature and humidity, also have certain effects on the performance of pavement markings (Robertson et al., 2012).
7) **Bead type and properties**: The quality of PMMs has improved over the past decade. New materials and beads have been used to increase nighttime and wet-weather visibility. Studies have looked into the effect of using conventional beads versus high reflective (ceramic) elements (Sitzabee et al., 2012). Bead embedment and bead dispersion rate

also play an important role on the retroreflectivity of markings (Stoudt and Vedam, 1973; Texas Department of Transportation, 2004).

8) **Other critical factors** (that have been identified as important by GDOT engineers but have not been considered as variables in past degradation models):

   a. Thickness: The thickness of pavement markings also has certain impact on how long and how well the striping can last. The literature has shown that high-build paint performs much better than conventional waterborne paint (Robertson et al., 2012).

   b. Roadway characteristics: Roadway characteristics can be the functional class of the road and the geometry of the road. For example, in some studies, analysis has been conducted separately for pavement markings on interstate highways and on other routes (Thamizharasan et al., 2003). This is because interstate highways have limited access and usually do not have intersections that require vehicles to decelerate/accelerate or turn frequently. In addition, pavement markings installed along a vertical and/or horizontal curve may perform differently than those installed along a longitudinal road segment. Different lane and/or shoulder widths may also affect the performance of the marking (Robertson et al., 2012).

Table 2-7 summarizes the degradation models of various PMMs in the literature. Simple linear and non-linear regression models that predict retroreflectivity based on a single variable, such as elapsed time or traffic volume, were used among the first several studies in the late 1990s and early 2000s (Abboud and Bowman, 2002; Andrady, 1997; J.-T. Lee et al., 1999; Migletz et al., 2001). For example, Lee et al. developed several simple linear regression models that predict retroreflectivity based on time, ADT, speed limit, or commercial traffic (J.-T. Lee et al., 1999). Abboud and Bowman predicted retroreflectivity for paint and thermoplastic materials using a logarithmic model that is based on single variables, such as time and ADT (Abboud and Bowman, 2002). While the goodness-of-fit of these first models were not impressive, these studies helped identify critical variables that affect pavement marking performance and built a solid foundation for the later research.

Table 2-7 Summary of Pavement Marking Degradation Models in the Literature

Study	Model(s)	Variable(s)	Material(s)	R^2	Location
(Andrady 1997)	Logarithmic	Time, Initial Retroreflectivity	Multiple	0.85+	Across the US
(J. T. Lee et al. 1999)	Simple Linear Regression	Time	Multiple	0.14	MI
(Migletz et al. 2001)	Simple Linear Regression, Quadratic, and Exponential Models	CTP[3]	Multiple	N/A	19 States in the US
(Abboud and Bowman 2002)	Logarithmic	Time, ADT[4]	Paint and Thermoplastic	0.32, 0.58	AB
(Thamizharasan et al. 2003)	Multiple Linear Regression[5]	Time, CTP	Thermoplastic and Epoxy	0.21 to 0.78	SC[6]
(Bahar et al. 2006)	Inverse Polynomial Model	Time	Multiple	N/A	AB, CA, MN, MS, PA, TX, UT, WI
(Zhang and Wu 2006)	Smoothing Spline and Time Series ARIMA Model	Time	Multiple	N/A	MI[7]
(Fitch 2007)	Logarithmic	Time	Thermoplastic, Epoxy, and Polyurea	0.53 to 0.87	VT

[3] Cumulative traffic passages
[4] Average daily traffic
[5] Dependent variables: percent retroreflectivity difference and absolute retroreflectivity difference
[6] All data were interstate highway data
[7] The data were collected on a NTPEP site in Mississippi.

Study	Model(s)	Variable(s)	Material(s)	R^2	Location
(Sasidharan et al. 2009)	Multiple Linear Regression	Time, Directional ADT, Line Type, Pavement Type	Epoxy and Waterborne Paint	N/A	PA
(Sitzabee et al. 2009)	Multiple Linear Regression	Time, Initial Retroreflectivity, AADT, Line Lateral Location, Line Color	Thermoplastic and Paint	0.60	NC
(Hummer et al. 2011)	Linear Mixed-Effects Model	Time	Paint	0.68	NC
(Sitzabee et al. 2012)	Multiple Linear Regression	Time, AADT[8], Bead Type, Initial Retroreflectivity, Line Lateral Location	Polyurea	0.64	NC
(Mull and Sitzabee 2012)	Multiple Linear Regression	Time, Initial Retroreflectivity, AADT, and Plow Events	Paint	0.76	NC
(Robertson et al. 2012)	Multiple Linear Regression[3]	Time, AADT, CTP, Temperature, Humidity, Lane Width, and Shoulder Width	Conventional Waterborne Paint and High-Build Paint	0.24 to 0.34	SC
(Fu and Wilmot 2012)	Multiple Linear Regression	Time, AADT, CTP	Thermoplastic, Tape, and Inverted Profile Thermoplastic	0.18 to 0.89	LA
(Ozelim and Turochy 2014)	Multiple Linear Regression	Time, AADT, Initial Retroreflectivity	Thermoplastic	Up to 0.49	AB

In the past decade, with more installation and roadway information being available, multiple linear regression models were established to consider the joint effects of multiple variables in the degradation models. Higher goodness-of-fit (R-squared values) values were achieved. For example, Thamizharasan et al. developed a multiple linear regression model based on time and CTP to predict retroreflectivity degradation of thermoplastic and epoxy materials on interstate

[8] Annual average daily traffic

highways in South Carolina. Their final models were able to achieve a 0.78 R-squared value (Thamizharasan et al., 2003). Other researchers also attempted to include more independent variables, such as winter events (e.g., number of snow plows and number of snows (Mull and Sitzabee, 2012)), bead type (e.g., standard beads and high reflective elements (Sitzabee et al., 2012)), line type (e.g., center line or skipped line (Sitzabee et al., 2009, 2012)), and land and shoulder widths (Robertson et al., 2012).

The statistical assumptions, such as "normality, constant variance, uncorrelated errors, linearity, and lack of multicollinearity," of multiple linear regression models were also justified by researchers (Mull and Sitzabee, 2012; Ozelim and Turochy, 2014; Sitzabee et al., 2009, 2012). These studies verified that the datasets used to develop the models were suitable for multiple linear regressions.

As for materials that have been studied, most studies developed degradation models for paint and thermoplastic materials because they account for the majority materials that have been used throughout the United States (Abboud and Bowman, 2002; Andrady, 1997; Hummer et al., 2011; J.-T. Lee et al., 1999; Migletz et al., 2001; Mull and Sitzabee, 2012; Robertson et al., 2012; Sitzabee et al., 2009; Thamizharasan et al., 2003; Zhang and Wu 2006). With the rising interests of other durable marking materials, such as epoxy and polyurea, researchers have also developed models to predict performance of these materials (Sitzabee et al., 2012; Thamizharasan et al., 2003). Degradation models of other commonly used PMMs, such as preformed tape and methyl methacrylate (MMA), however, have not yet been extensively studied.

From the literature summary, extensive studies have been conducted in the southeastern states, including North Carolina, South Carolina, Alabama, and Mississippi. While these models could be good references for Georgia because of the proximity of these states and the similarity in weather conditions, there is still a need to develop a robust model for Georgia, especially for the unique traffic characteristics in Metro Atlanta that do not exist in other states.

2.3 Pavement Marking Material Selection Practices

To select the most cost-effective PMMs, various factors that affect the performance of PMMs should be considered. These factors include the type of pavement surface, traffic characteristics, remaining service life of the pavement, climate conditions, presence of reflective raised pavement markers (RRPMs), and line color and usage. While it is unlikely for a state DOT to consider all the possible factors listed above, it is important that a state DOT identify the critical factors and select materials based on the consideration of these factors. In this section, we summarize the factors considered by state DOTs and the criteria the used for PMM selection.

2.3.1 Georgia's Practice

GDOT has internally used the matrix shown in Table 2-8 to select PMMs (Georgia Department of Transportation, 2013). The selection of PMM is determined by various criteria, including pavement surface type, traffic condition, and functional classification of road segment. For example, polyurea would be selected for an interstate highway with asphalt concrete surface and 30,000 AADT.

As shown in Table 2-8, four common materials, including paint, thermoplastic, preformed tape, and polyurea, are currently used by GDOT. Detailed specifications of these four materials have been developed and used to qualify manufacturers' products. In addition to these four materials, GDOT has recently developed specifications for epoxy and is in the process of developing specifications for MMA.

Table 2-8 GDOT Pavement Marking Selection Matrix

AADT	Asphalt			Concrete*		
	2 Lanes	**>2 Lanes**	**Interstate/ Freeway**	**2 Lanes**	**>2 Lanes**	**Interstate/ Freeway**
AADT < 8,000	H	H		F or P	P	
8,000 ≤ AADT < 15,000	H	T	T	F or P	P	F
15,000 ≤ AADT < 40,000	T	T or P	P	F or P	P	F
AADT ≥ 40,000		P	P		P	F

* Contrast markings shall be used for all lane lines on PCC surfaces
H – Highbuild Paint and Wet Weather Paint Traffic Stripe (Standard Specifications 652)
T – Standard and Wet Weather Thermoplastic Traffic Stripe (Standard Specifications 653)
F – Preformed Plastic Pavement Markings (Standard Specifications 657)
P – Standard and Wet Weather Polyurea Traffic Strip (Standard Specifications 658)

From this matrix, some rules of thumb for selecting PMMs in Georgia can be summarized. First, no paint or thermoplastic materials are to be used on concrete pavements. Secondly, no preformed tapes are to be used on asphalt concrete pavements. Thirdly, paint is generally used on asphalt pavements with lower traffic volume and fewer lanes. Fourthly, thermoplastic is used on asphalt pavements with medium to high traffic volume. Finally, polyurea is generally used under all traffic conditions, but it is typically used for high volume roads. These rules were put into practice based on the considerations of the cost, service life, and physical and chemical properties of different materials, as well as engineers' experience. For example, GDOT does not recommend the use of thermoplastics on concrete surfaces because the poor performance of thermoplastics on concrete surfaces, as shown in Figure 2-3, that have been observed over the years.

Figure 2-3 Poor Performance of Thermoplastic on Portland Cement Concrete Surface

2.3.2 Texas' Practice

TxDOT has published a pavement marking handbook that covers the guidelines for PMM selection, installation, and inspection (Texas Department of Transportation, 2004). A marking material is deemed appropriate when it is the most cost-effective material for the given circumstances. In its handbook, TxDOT summarized the use of each type of material based on the pavement surface type and traffic condition. Table 2-9 to Table 2-11 summarize the recommendations of the use of seven different PMMs, including thermoplastic, paint, preformed tape, epoxy, polyurea, modified urethane, and methyl methacrylate, based on selection criteria such as pavement's remaining service life, traffic characteristic, and pavement surface type (Texas Department of Transportation, 2004).

Similar to GDOT, TxDOT limits the use of thermoplastic and paint markings on concrete pavements. Note that if thermoplastic is to be applied to concrete pavements, additional primer material that increases overall material cost is required. Because of the increase in material cost, and the debonding of thermoplastic on concrete pavement, thermoplastic use is limited. Paint is suggested to be primarily used on low traffic volume roads, and preformed tapes are primarily used on high traffic volume roads. Both epoxy and polyurea markings are suitable for all types of pavement surface and all traffic conditions. Other materials, such as modified urethane and MMA markings, have had limited use in Texas.

Table 2-9 TxDOT Marking Material Selection Guide for Asphalt Concrete Pavements

	Pavement Remaining Service Life		
Traffic Characteristic	**0-2 years**	**2-4 years**	**> 4 years**
AADT < 1,000	**Thermo**, water-based paint	**Thermo**, water-based paint	**Thermo**, water-based paint, epoxy, modified urethane, polyurea, MMA
1,000 < AADT < 10,000	**Thermo**, water-based paint	**Thermo**, epoxy, modified urethane, polyurea, MMA	**Thermo**, preformed tape, epoxy, polyurea, modified urethane, MMA
AADT > 10,000	**Thermo**, epoxy, modified urethane	**Thermo**, preformed tape, epoxy, polyurea, modified urethane, MMA	**Preformed tape**, **thermo**, epoxy, polyurea, modified urethane, MMA
Heavy weaving or turning	**Thermo**, epoxy, modified urethane	**Thermo**, epoxy, polyurea, modified urethane, MMA	**Thermo**, epoxy, polyurea, modified urethane, MMA

Table 2-10 TxDOT Marking Material Selection Guide for Cement Concrete Pavements

	Pavement Remaining Service Life		
Traffic Characteristic	**0-2 years**	**2-4 years**	**> 4 years**
AADT < 1,000	**Thermo**, epoxy, modified urethane, water-based paint	**Epoxy, thermo**, modified urethane, water-based paint, polyurea, MMA	Epoxy, thermo, modified urethane, polyurea, water-based paint, MMA
1,000 < AADT < 50,000	**Thermo**, epoxy, modified urethane, water-based paint, polyurea	**Epoxy, thermo**, modified urethane, polyurea, water-based paint, MMA	**Epoxy, thermo,** preformed tape, polyurea, modified urethane, MMA
AADT > 50,000	**Epoxy, thermo,** modified urethane	**Epoxy, thermo,** preformed tape, polyurea, modified urethane, MMA	**Preformed tape, thermo,** polyurea, modified urethane, epoxy, MMA
Heavy weaving or turning	**Epoxy, thermo,** polyurea, modified urethane	**Epoxy, thermo,** preformed tape, polyurea, modified urethane, MMA	**Epoxy, thermo,** preformed tape, polyurea, modified urethane, MMA

Table 2-11 TxDOT Guidelines on Use of Marking Materials by AADT and Surface Type

	Asphalt			Concrete		
	< 1k	**1k – 10k**	**> 10k**	**< 10k**	**10k – 50k**	**> 50k**
Thermoplastic	Y	Y	Y	L	L	N
Paint	Y	Y	L	Y	L	N
Preformed Tape	N	Y	Y	N	Y	Y
Epoxy	Y	Y	Y	Y	Y	Y
Polyurea	Y	Y	Y	Y	Y	Y
Modified Urethane	L	L	L	L	L	L
Methyl Methacrylate	L	L	L	L	L	L
Y = suitable for use; N = not recommended; L = limited use.						

2.3.3 California's Practice

The California Department of Transportation (CalTrans) published a guideline for selecting materials and standard special provisions for traffic striping and pavement marking (California Department of Transportation, 2011). As shown in Figure 2-4, CalTrans developed a pavement marking selection decision guide that provides suggestions for the use of materials based on criteria such as the intended duration of usage (e.g., permanent or temporary), climate condition and environments (e.g., snow-removal, wet-night, or fog areas), and surface type (e.g., open-graded friction course, bituminous seal surface, or Portland cement concrete).

It is noted that CalTrans primarily considers the use of thermoplastic or two-component traffic paint (e.g., epoxy and polyurea) in this selection guide. According to this figure, thermoplastic markings are the most commonly used material on Portland cement concrete, hot-mixed asphalt, and open-graded friction course (OGFC) pavements. Prior to the installation of thermoplastic on PCC pavements, CalTrans suggests surface preparation (primer application) to ensure the successful installation. Thicker thermoplastic is recommended for OGFC pavements to ensure the durability of thermoplastic on porous or rough textured surface. Thermoplastic is also recommended for use in wet-night or fog areas. For pavement segments with snow-plow concerns, recessed thermoplastics, and two-component traffic paints are recommended (California Department of Transportation, 2011).

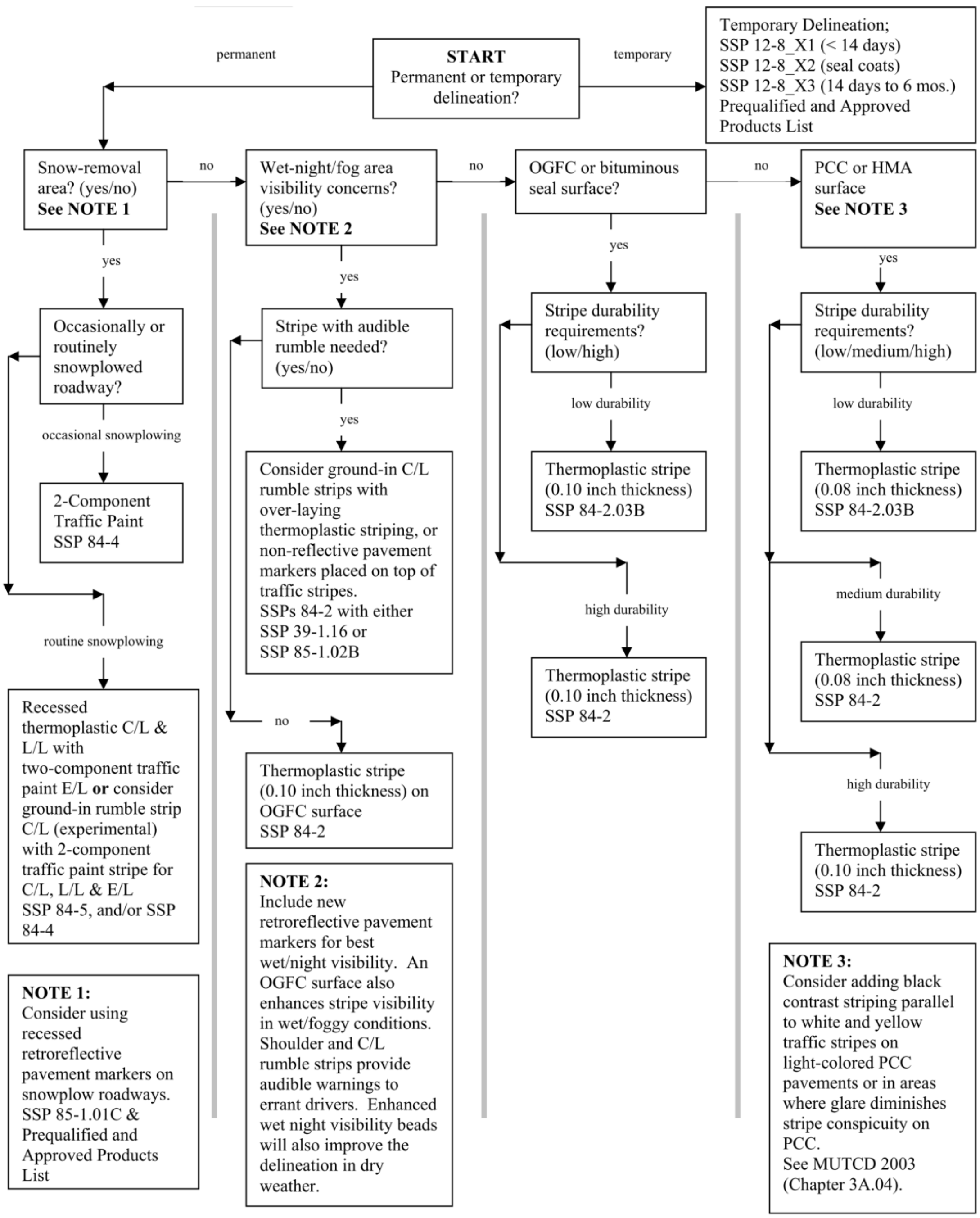


Figure 2-4 CalTrans' Pavement Marking Selection Guide

When compared to GDOT and TxDOT, CalTrans has a different strategy for the use of thermoplastic materials on PCC pavements, whereas the former states have no or limited use of thermoplastic on PCC surface. In addition, the use of preformed tapes is not warranted according to CalTrans' selection guide.

2.3.4 Kansas' Practice

The Kansas Department of Transportation (KDOT) published its pavement marking policy in 2002 (Kansas Department of Transportation, 2002). In this policy, KDOT developed a Brightness Benefit Factor (BBF) that is essentially a benefit-cost ratio for PMM selection as shown in the following equation. The benefit is the product of the average retroreflectivity and the service life of a material; and the cost is the average cost that includes material, road user, temporary tape, and existing marking removal costs (Kansas Department of Transportation, 2002).

$$BBF = (R_{L_{avg}} \times Life) \, / \, Cost \tag{2.1}$$

Using the BBF, KDOT selects cost-effective PMMs based on different traffic conditions and remaining service life of a pavement. As shown in Table 2-12, for each combination of traffic condition and remaining service life category, material with the highest BBF is selected (Kansas Department of Transportation, 2002). For example, if the remaining service life is 5 years, thermoplastic would be selected for a pavement segment with medium traffic condition (i.e., ADT 5,000 to 50,000 vehicle/day) because of its high brightness benefit factor (BBF = 593). From this table, it is noted that thermoplastics tend to have higher BBFs under most traffic conditions and service lives. Epoxy is more effective when used under lower traffic volumes. Paint has the highest BBF when the remaining service life is 1 year or less. Another unique finding from this table is that the combination of preformed tape (or PCP) center lines and epoxy edge lines also has fairly good BBF under low to medium traffic volumes. KDOT also stated that thermoplastics shall not be used on Portland cement concrete pavement surfaces, which is consistent with the practices of GDOT and TxDOT.

Table 2-12 Kansas Brightness Benefit Factors under Different ADTs and Remaining Lives

Service Life Remaining	Material Type	Brightness Benefit Factor for ADT of:		
		< 5,000	5,000 to 50,000	> 50,000
> 7 years	Patterned Cold Plastic	241	326	273
	Thermoplastic	780	593	587
	Spray Thermoplastic	357	0	0
	Epoxy	752	399	250
	Paint	369	343	310
	Modified Urethane	691	508	495
	Cementasious	154	149	131
	PCP CL & Epoxy EL	696	391	252
7 years	Patterned Cold Plastic	241	326	273
	Thermoplastic	780	593	587
	Spray Thermoplastic	357	0	0
	Epoxy	752	399	250
	Paint	369	343	310
	Modified Urethane	691	508	495
	Cementasious	140	136	120
	PCP CL & Epoxy EL	696	391	252
6 years	Patterned Cold Plastic	241	326	273
	Thermoplastic	780	593	587
	Spray Thermoplastic	357	0	0
	Epoxy	752	399	250
	Paint	369	343	310
	Modified Urethane	691	508	495
	Cementasious	129	125	111
	PCP CL & Epoxy EL	696	391	252
5 years	Patterned Cold Plastic	201	326	273
	Thermoplastic	717	593	587
	Spray Thermoplastic	357	0	0
	Epoxy	752	399	250
	Paint	369	343	310
	Modified Urethane	787	508	495
	Cementasious	115	112	99
	PCP CL & Epoxy EL	691	391	252

Service Life Remaining	Material Type	Brightness Benefit Factor for ADT of:		
		< 5,000	5,000 to 50,000	> 50,000
4 years	Patterned Cold Plastic	161	261	218
	Thermoplastic	607	576	570
	Spray Thermoplastic	357	0	0
	Epoxy	781	399	250
	Paint	369	343	310
	Modified Urethane	737	579	562
	Cementasious	98	95	84
	PCP CL & Epoxy EL	712	383	246
3 years	Patterned Cold Plastic	121	196	164
	Thermoplastic	482	500	495
	Spray Thermoplastic	357	0	0
	Epoxy	675	372	187
	Paint	369	343	310
	Modified Urethane	608	514	499
	Cementasious	78	76	67
	PCP CL & Epoxy EL	613	353	185
2 years	Patterned Cold Plastic	80	131	109
	Thermoplastic	351	363	359
	Spray Thermoplastic	357	0	0
	Epoxy	470	297	164
	Paint	369	343	310
	Modified Urethane	433	389	378
	Cementasious	52	51	45
	PCP CL & Epoxy EL	427	278	158
≤ 1 year	Patterned Cold Plastic	40	65	55
	Thermoplastic	183	187	185
	Spray Thermoplastic	179	0	0
	Epoxy	243	172	102
	Paint	369	343	310
	Modified Urethane	226	217	211
	Cementasious	26	25	22
	PCP CL & Epoxy EL	220	160	97

2.3.5 North Dakota's Practice

The North Dakota Department of Transportation (NDDOT) developed the following pavement marking selection matrix (North Dakota Department of Transportation, 2014). Different than other states, North Dakota does not include thermoplastics in its selection matrix because of the frequent winter plow events that can significantly damage thermoplastic pavement markings.

The three commonly used materials in North Dakota, as shown in Table 2-13, are paint, epoxy, and tape. For roads with lower traffic volumes and/or shorter anticipated surface lives, paint is the primary material used. For roads with more traffic and/or longer anticipated lives, epoxy and tape are generally used. It is noted that because of the weather conditions in North Dakota, grooving techniques have been used to ensure the durability of PMMs, such as tapes, on higher traffic roads and to minimize snow plow effects.

Table 2-13 PMM Selection Matrix of North Dakota

Anticipated Surface Life (years)		ADT					
Two Lane Highways							
		< 1,500		**1,500 – 4,000**		**> 4,000**	
		Edgeline	**Centerline**	**Edgeline**	**Centerline**	**Edgeline**	**Centerline**
0 – 2		Paint	Paint	Paint	Paint	Paint	Paint
2 – 4		Paint	Paint	Paint	Epoxy	Epoxy	Epoxy
4 – 6	**Asphalt**	Paint	Paint	Epoxy	Epoxy	Epoxy	Epoxy
	Concrete	Paint	Paint	Epoxy	Epoxy	Epoxy	Grooved Tape
6 +	**Asphalt**	Paint	Paint	Epoxy	Epoxy	Epoxy	Epoxy
	Concrete	Paint	Paint	Epoxy	Grooved Tape	Grooved Tape	Grooved Tape
Multilane Divided and Undivided Highways							
		< 1,500		**1,500 – 4,000**		**> 4,000**	
		Edgeline	**Centerline**	**Edgeline**	**Centerline**	**Edgeline**	**Centerline**
0 – 2		Paint	Paint	Paint	Paint	Paint	Paint
2 – 4		Paint	Paint	Paint	Epoxy	Epoxy	Epoxy
4 – 6	**Asphalt**	Epoxy	Epoxy	Epoxy	Epoxy	Epoxy	Epoxy
	Concrete	Epoxy	Grooved Tape	Epoxy	Grooved Tape	Epoxy	Grooved Tape
6 +	**Asphalt**	Epoxy	Epoxy	Epoxy	Epoxy	Epoxy	Epoxy
	Concrete	Epoxy	Grooved Tape	Epoxy	Grooved Tape	Grooved Tape	Grooved Tape

2.3.6 *Illinois' Practice*

Applied Research Associates, Inc. conducted a study in which it evaluated the performance of PMMs on both asphalt and concrete pavements over a 4-year period for the Illinois Department of Transportation (IDOT) (Dwyer et al., 2013). In this report, Applied Research Associates, Inc. recommended the use of materials, as shown in the following tables, according to different selection criteria, including surface type, remaining service life, new/existing pavement, geographical region, and AADT.

According to these tables, the recommendations can be summarized as follows. First, on PCC surfaces, IDOT does not recommend the use of thermoplastic, which is similar to most other states' policies; moreover, IDOT does not recommend the use of paint on PCC surfaces. Second, for hot-mixed asphalt (HMA) pavements, while most materials are recommended to be used on high traffic volume (AADT > 7,000) roads, only thermoplastics and paint (or thermoplastics and epoxy for recessed application) are recommended for low-traffic volume (AADT ≤ 7,000) roads. Third, IDOT recommend the use of preformed tapes on newly constructed pavements instead of on existing pavements as maintenance striping.

Table 2-14 Recommendations for Striping on HMA in Illinois

Maintenance Striping on HMA						
Zone	AADT	Pavement Service Life ≤ 5 Years		Pavement Service Life > 5 Years		
		Surface	Recessed	Surface	Recessed
Northern IL	Low (≤ 7000)	Thermoplastic, Paint	Thermoplastic, Epoxy	Thermoplastic, Paint	Thermoplastic, Epoxy
	High (> 7000)	Thermoplastic, Paint, Epoxy, Polyurea, Urethane	Thermoplastic, Epoxy, Urethane, Polyurea	Thermoplastic, Paint, Epoxy, Polyurea, Urethane	Thermoplastic, Epoxy, Urethane, Polyurea
Central IL	Low (≤ 7000)	Thermoplastic, Paint	Thermoplastic, Epoxy	Thermoplastic, Paint	Thermoplastic, Epoxy
	High (> 7000)	Thermoplastic, Epoxy, Paint, Urethane, Polyurea	Thermoplastic, Epoxy, Urethane, Polyurea	Thermoplastic, Epoxy, Urethane, Paint, Polyurea	Thermoplastic, Epoxy, Polyurea, Urethane
Southern IL	Low (≤ 7000)	Thermoplastic, Paint	Thermoplastic, Epoxy	Thermoplastic, Paint	Thermoplastic, Epoxy
	High (> 7000)	Thermoplastic, Paint, Epoxy, Urethane, Polyurea	Thermoplastic, Epoxy, Urethane, Polyurea	Thermoplastic, Paint, Epoxy, Urethane, Polyurea	Thermoplastic, Epoxy, Polyurea, Urethane

Table 2-15 Recommendations for Striping on PCC in Illinois

Maintenance Striping on PCC					
Zone	AADT	Pavement Service Life ≤ 5 Years		Pavement Service Life > 5 Years	
		Surface	Recessed	Surface	Recessed
Northern IL	Low (≤ 7000)	Epoxy Polyurea	Epoxy Polyurea	Epoxy Polyurea	Epoxy Polyurea
	High (> 7000)	Epoxy Polyurea Urethane	Epoxy Polyurea Urethane	Epoxy Polyurea Urethane	Epoxy Polyurea Urethane
Central IL	Low (≤ 7000)	Epoxy Urethane	Epoxy Polyurea	Epoxy Urethane	Epoxy Polyurea
	High (> 7000)	Epoxy Urethane Polyurea	Epoxy Polyurea Urethane	Epoxy Urethane Polyurea	Epoxy Polyurea Urethane
Southern IL	Low (≤ 7000)	Epoxy Urethane	Epoxy Polyurea	Epoxy Urethane	Epoxy Polyurea
	High (> 7000)	Epoxy Urethane Polyurea	Epoxy Polyurea Urethane	Epoxy Urethane Polyurea	Epoxy Polyurea Urethane

Table 2-16 Recommendations for Striping on New HMA in Illinois

Striping on New HMA			
Zone	**AADT**	**Surface**	**Recessed**
Northern IL	Low (≤ 7000)	Thermoplastic, Paint	Thermoplastic, Epoxy
	High (> 7000)	Thermoplastic, Epoxy, Polyurea, Preformed Plastic, Urethane	Thermoplastic, Epoxy, Polyurea, Preformed Plastic, Urethane
Central IL	Low (≤ 7000)	Thermoplastic, Paint	Thermoplastic, Epoxy
	High (> 7000)	Thermoplastic, Epoxy, Preformed Plastic, Polyurea, Urethane	Thermoplastic, Epoxy, Polyurea, Preformed Plastic, Urethane
Southern IL	Low (≤ 7000)	Thermoplastic, Paint	Thermoplastic, Epoxy
	High (> 7000)	Thermoplastic, Epoxy, Polyurea, Paint, Preformed Plastic, Urethane	Thermoplastic, Epoxy, Polyurea, Preformed Plastic, Urethane

Table 2-17 Recommendations for Striping on New PCC in Illinois

Striping on New PCC			
Zone	**AADT**	**Surface**	**Recessed**
Northern IL	Low (≤ 7000)	Epoxy, Polyurea, Preformed Plastic, Urethane	Epoxy, Polyurea
	High (> 7000)	N/A	Epoxy, Polyurea, Preformed Plastic, Urethane
Central IL	Low (≤ 7000)	Epoxy, Preformed Plastic, Polyurea, Urethane	Epoxy, Polyurea
	High (> 7000)	N/A	Epoxy, Polyurea, Preformed Plastic, Urethane
Southern IL	Low (≤ 7000)	Epoxy, Polyurea	Epoxy, Polyurea
	High (> 7000)	Epoxy, Polyurea, Preformed Plastic, Urethane	Epoxy, Polyurea, Preformed Plastic, Urethane

2.4 Summary

In this chapter, a literature review of PMM performance evaluation and selection practices has been performed. From the review, the following key findings are summarized:

1) The performance of PMMs can be influenced by many factors, such as weather conditions, traffic conditions, and roadway characteristics. Different states may have

vastly different weather and traffic conditions and, therefore, the same type of PMM may also behave very differently.

2) Degradation modeling, especially multiple linear regression models, has been verified as being adequate and useful for predicting the service lives of different PMMs. Important variables of these models include time, traffic, initial retroreflectivity, weather conditions, and installation information.

3) From the review of state DOTs' practices, many state DOTs have developed their own rules to select PMMs. Many different types of material have been used in states such as Texas, Illinois, and Georgia. These states shared interest in many key factors, including traffic characteristics or ADT, surface type (asphalt or concrete), line type (edge or center, white or yellow), remaining service life of pavement, and weather conditions (e.g., snow, wet, and fog). In addition, from the selection guidelines and practices of these states, some engineering experiences (i.e., rules of thumb) are summarized as follows:

    a. Paint is usually used on low-traffic volume roads because it can only last for approximately a year;

    b. Thermoplastic is typically not recommended to be used on PCC pavements because of the poor bonding and different surface behavior that hinder good performance of thermoplastics on concrete pavements. In addition, to use thermoplastic on concrete pavements, additional adhesives are needed and thus additional cost may apply;

    c. Epoxy and polyurea are durable marking materials with relatively low costs; in addition, they can be applied to both asphalt and cement concrete surfaces;

d. Methyl methacrylate has very limited use in the reviewed states probably because of its relatively higher cost than other durable materials;
e. In northern states, the use of grooved/recessed pavement marking installation technique is common, and fewer types of material can be applied because of the effects of snow plow events.

From the review, it is also identified that there has not yet a degradation model that is based on Georgia's data. Moreover, several other factors, such as marking thickness and roadway characteristics, have not yet been considered as independent variables in previous degradation models. GDOT Test Deck provides valuable information and can serve as a starting point to achieve this goal. In the near future, with continued collaboration with GDOT, it is our intent to develop a Georgia-specific marking material model that comprehensively considers all factors and variables that may have effect on the performance of PMMs and refines the PMM selection matrix for Georgia.

3. ANALYSIS OF GDOT TEST DECK DATA

In this chapter, the performance of PMMs installed on GDOT Test Deck is analyzed. To improve the reliability of performance evaluation results a methodology is first proposed in this chapter to systematically identify and remove irregular data prior to modeling pavement marking retroreflectivity performance.

This chapter is organized as follows. This first section gives a brief background of the GDOT Test Deck and the data currently available. The second section summarizes some observed data variability in GDOT Test Deck data. The third section describes the proposed methodology, which first discusses the concerns of data quality and then depicts the proposed method to assess and improve data quality. The fourth section shows the pavement marking performance evaluation results, including the estimated lives of PMMs before and after the application of the proposed methodology. The fifth section further discusses the implications of the results, as well as a preliminary comparison between the overall performance of different materials and GDOT's minimum retroreflectivity requirements. The last section summarizes the findings from this chapter.

3.1 Test Deck Description

To evaluate the performance of different PMMs, the Testing Bureau of GDOT established the GDOT Test Deck on I-16 from mile marker 116 to 122, and on US 301/SR 74 from I-16 to SR46. Each type of PMM was generally applied on a 2500-ft section. Table 3-1 lists all the testing materials and installation dates. Each product was given a product id for the research team's references.

For each product, three *line types*, including white edge, white skip, and yellow edge lines, were installed. Dry and wet weather retroreflectivity test readings of these lines have been collected periodically (i.e., initial, 30 days, 6 months, 12 months, 18 months, and 24 months) at every 100 ft and/or 250 ft along the segments. These data were collected in order to evaluate the performance of different PMMs for identifying cost-effective products to be used in Georgia in the future.

Table 3-1 GDOT Test Deck Products

Test Roadway (Pavement Type)	Material		Installation Date
	ID	Product	
I-16 EB MP 117-120 (Concrete)	C1	Preformed Tape	10/18/2010
	C2	Wet Weather Preformed Tape	10/18/2010
	C3	Epoxy	10/18/2010
	C4	Epoxy with Cluster Beads	10/18/2010
	C5	Thermoplastic	10/18/2010
	C6	Thermoplastic with Cluster Beads	10/18/2010
	C7	MMA	10/18/2010
	C8	MMA	10/18/2010
US 301/SR 73 NB and SB (Asphalt)	A1	Preformed Tape	7/11/2011
	A2	Wet Weather Preformed Tape	7/11/2011
	A3	Wet Reflective Thermoplastic	7/27/2011
	A4	High Build Waterborne Paint	7/12/2011
	A5	Inverted Profile Thermoplastic	7/13/2011
	A6	Preformed Tape	7/12/2011
	A7	Audible Thermoplastic (Cookies)	7/12/2011
	A8	Thermoplastic	7/12/2011
	A9	Wet Weather Thermoplastic	7/12/2011
	A10	Waterborne Paint	7/11/2011
	A11	Waterborne Paint	7/11/2011

For consistency and readability of the document, in this study, a *dataset* is defined as a set of data points collected at the same period of time (age) on the same line type of a specific material using the same test method. For example, the dry retroreflectivity readings of the yellow edge line of all thermoplastic materials (Products C5, C6, A3, A5, A7, A8, and A9) collected at the age of 12 months are considered one dataset. Other material groups include paint (Products A4, A10, and A11), epoxy (Products C3 and C4), MMA (Products C7 and C8), and preformed tape (Products C1, C2, A1, A2, and A6).

3.2 Variability in Retroreflectivity Data

In the literature, variability in retroreflectivity data has often not been considered, and, often, only the averages of different sets of measurements were used in the performance evaluation. In this section, we pointed out some observed factors that led to large data variability, which could affect the results of performance evaluation. Note that for better demonstration of the variability, instead of using all measurements of a material, the examples shown in this particular section focus on retroreflectivity measurements of a single product to show possible variability.

3.2.1 Variability from Roadway Characteristics

The GDOT Test Deck was selected to evaluate the performance of different PMMs along longitudinal sections with similar traffic conditions and roadway characteristics. While most lines were installed along continuous longitudinal sections, some were installed at sections with different roadway characteristics, such as turn lanes and intersections. Pavement markings installed at turn lanes or intersections may deteriorate faster than those installed on a typical continuous longitudinal section because of excessive vehicle acceleration/deceleration and turning movements at these locations. Aggregating measurements collected from sections with different characteristics could result in inconsistent performance evaluation.

Figure 3-1 shows the map of a 2500-ft test deck section with multiple turn lanes and intersections that are circled in red. As shown in this map, the intersecting roads are mostly unpaved roads, and the soil and sands from these unpaved roads were carried onto the test section. Figure 3-2 shows the retroreflectivity readings of the white edge line of the product (A6) collected along this section at different timestamps. As shown in Figure 3-2, at the two intersections (approximately 100 ft. and 900 ft. from the starting point), noticeably lower readings were observed.

Figure 3-1 Pavement Segment where Product A6 was installed U.S. highway 301

(Source: Google Earth)

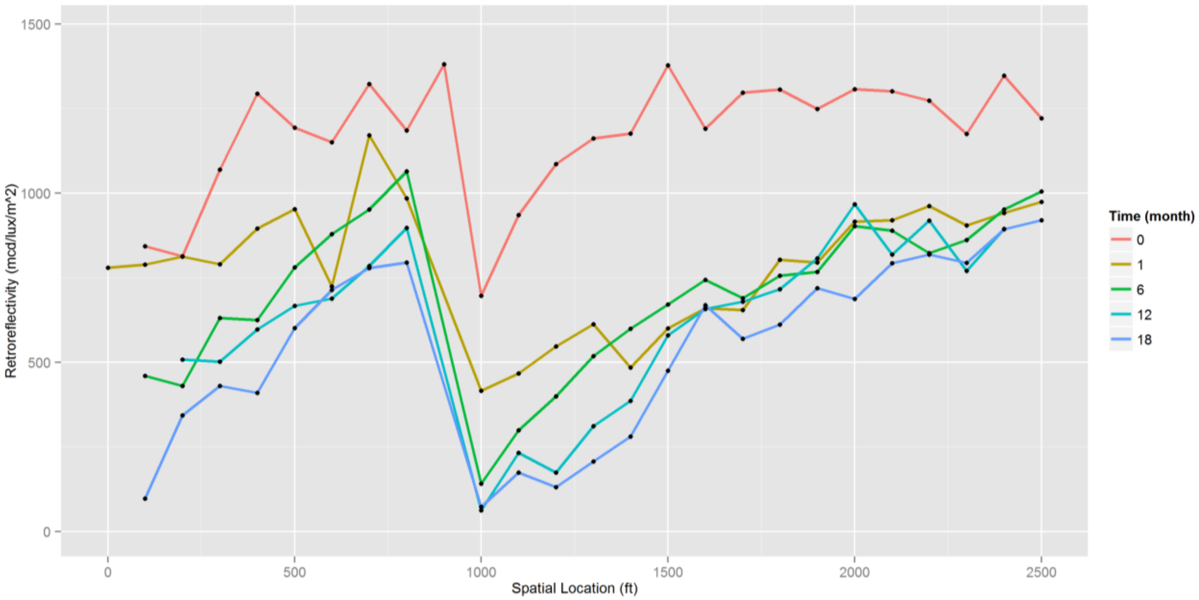


Figure 3-2 Retroreflectivity readings of product A6's white edge line along the test section.

3.2.2 Variability from Installation and Data Collection Processes

Data variability may also be caused by the process of installation and/or data collection. For example, materials that are installed manually can have larger data variability because of the inconsistent installation pace of binder and/or beads. Data variability resulting from data collection, on the other hand, may be caused by the use of different retroreflectometers, retroreflectometer issues, moisture or foreign objects on the pavement surface, and/or human error during data documentation. These factors can lead to inconsistent measurements, irregular spatial patterns, and/or irregular temporal trends.

The figures below show some examples of the observed data variability in this category. Figure 3-3 shows an irregular spatial pattern observed from the 1-month data of product C7’s white skip line. During the 1-month data collection process of this product, GDOT engineers observed inconsistent retroreflectivity measurements from one of the retroreflectometers, and they sent the device back to the manufacturer for recalibration. As shown in Figure 3-3, the first-month's dataset had a noticeably different spatial pattern than the other datasets. Figure 3-4 gives an example of localized, inconsistent measurements. As shown in this figure, the 1800-ft reading was significantly lower than all other measurements in the initial (0-month) dataset. Moreover, none of the other datasets had a pattern similar to the initial dataset at the 1800-ft location mark. This specific data point is more likely an outlier and should be excluded from the performance analysis. Figure 3-5 shows an example of an inconsistent temporal trend observed from product B08’s white edge line collected at different timestamps. According to the data, this line’s retroreflectivity increased long after 6 months. This trend is counter to the general knowledge that retroreflectivity should decrease over time.

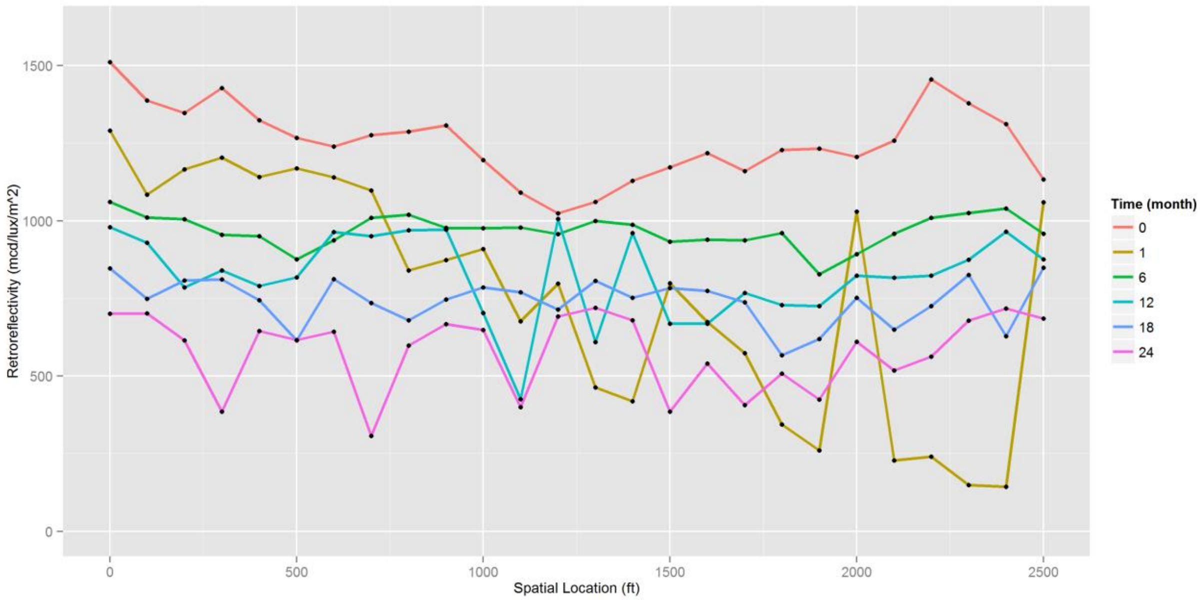


Figure 3-3 Retroreflectivity readings of product C7's white skip line along the test section.

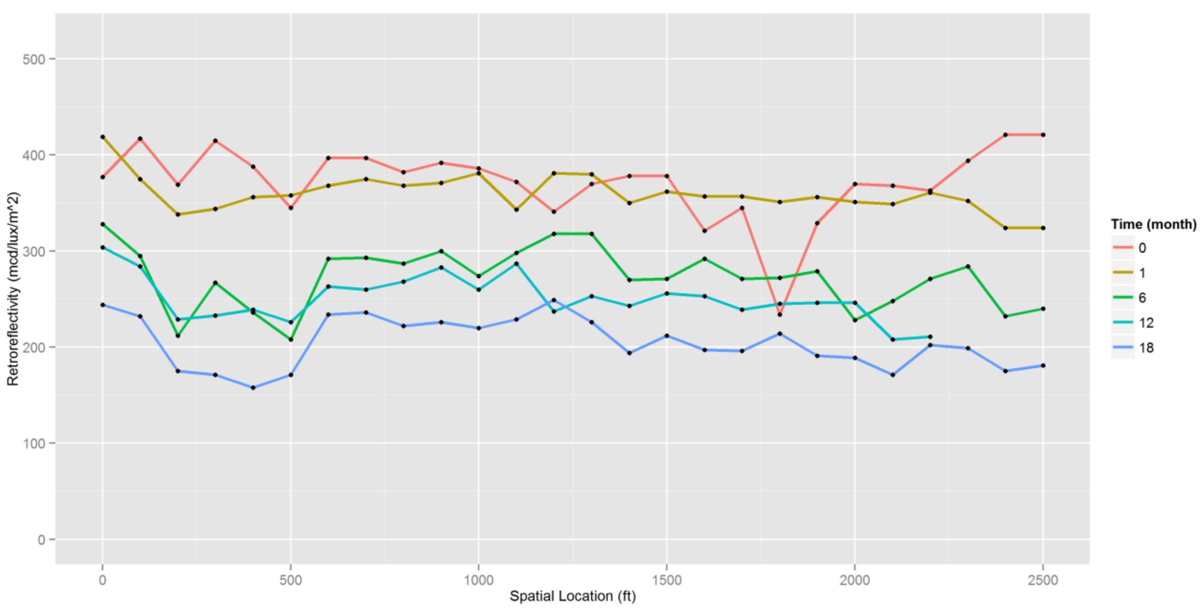


Figure 3-4 Retroreflectivity readings of product A11's white edge line along the test section.

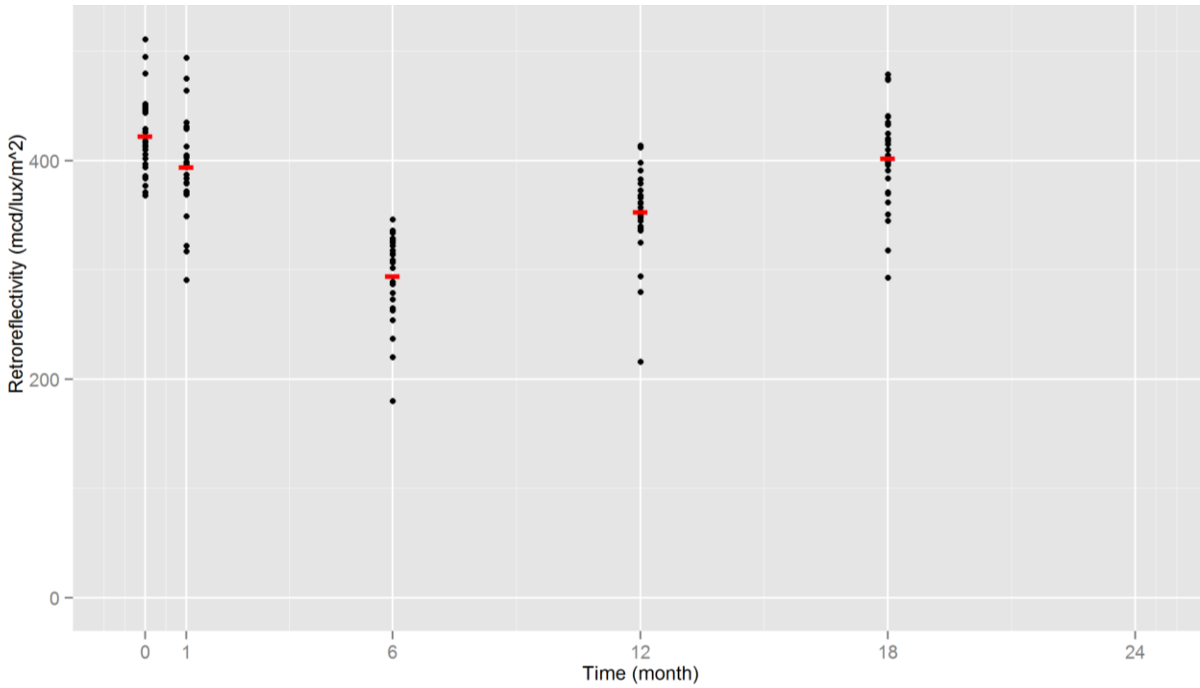


Figure 3-5 Retroreflectivity readings of product A8's white edge line along time.

The above examples show some known irregular variability in pavement marking retroreflectivity measurements that has not been addressed previously in literature. In the following sections, a new methodology is proposed to identify and remove these unrepresentative data, and a case study is conducted to better understand the effect of data variability in retroreflectivity measurements.

3.3 Methodology

To study the effect of data variability on pavement marking performance evaluation, the data variability (as described in the previous section) is categorized into two types: *spatial variability* and *temporal variability*. Spatial variability is the variability among measurements of a single dataset and is caused by factors such as different roadway characteristics and equipment error. Temporal variability, on the other hand, accounts for irregular temporal trends across multiple datasets and comes from inconsistent data collection at different timestamps. Figure 3-6 shows the proposed method for identifying and removing measurements/datasets with irregular spatial or temporal patterns pointed out in this paper.

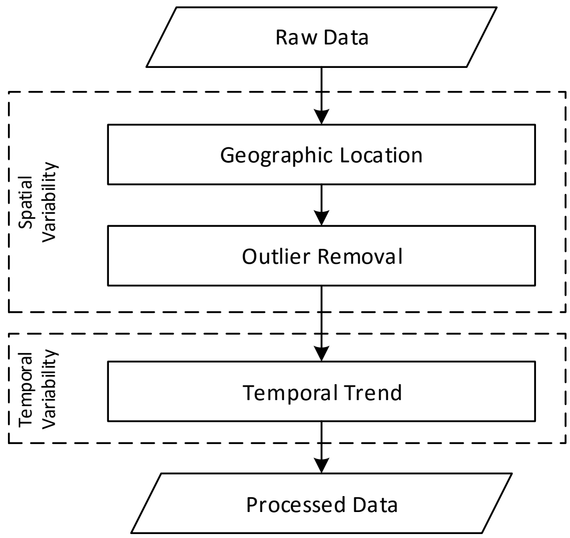


Figure 3-6 Proposed 4-step method to address data variability.

3.3.1 Processing Variability within a Single Dataset (Spatial Variability)

<u>Geographic Location (GL)</u>

At the end of test deck installation, GDOT engineers labeled data collection locations with 100-ft and 250-ft intervals using paints. These labeled locations were georeferenced to a map on which intersections and turn lanes were identified. To assess the effect of different roadway characteristics on performance evaluation, tests conducted at locations close (±100 ft.) to intersections and turn lanes were removed. This method is important, especially when dealing with small datasets, since small fluctuations in the measurements may lead to larger impact.

Outlier Removal (OR)

As mentioned previously, inconsistent measurements, such as local extremes or outliers within a dataset, could be caused by inconsistent installation and/or incorrect data collection procedures. To ensure the consistency of each dataset for reliable performance evaluation and to analyze the effect of inconsistent installation or incorrect data collection procedure, outliers in each dataset were identified and removed using the Box and Whisker Plot, which is also known as a boxplot.

A boxplot is a visualization tool that shows the quartiles and outliers of a dataset. As shown in Figure 3-7, the "box" shows the first quartile (Q1), the median (Q2), and the third quartile (Q3) of the dataset. In addition to the quartiles, outliers of the dataset are identified and illustrated as dots because they exceed the Whisker's extents, which are the upper and lower bars in the figure. The upper bar represents the largest data point that is smaller or equal to the value of Q3 plus 1.5 times the inter-quartile range (IQR), where IQR = Q3-Q1. Similarly, the lower bar represents the smallest data point that is larger or equal to the value of Q1 minus 1.5 times IQR. In this method, all outliers identified in the boxplot are excluded from the performance evaluation. Note that this method should only be applied when enough products and measurements are included in the datasets. For datasets with only a few products, removing outliers outside of the inter-quartile range may remove valid data points that are identified as outliers simply because there were not enough in the sample size. For this reason, in the following analysis, a boxplot is not applied to process GDOT Test Deck data.

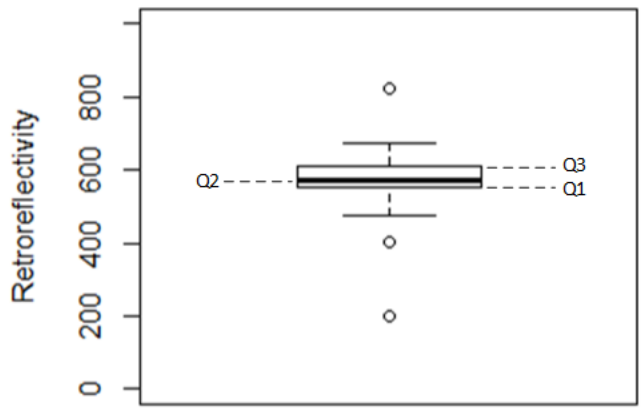


Figure 3-7 A typical boxplot.

3.3.2 Processing Variability among Multiple Datasets (Temporal Variability)

In the realm of transportation asset management, it is generally accepted that the performance of a transportation asset deteriorates over time. Therefore, datasets with irregular temporal trends, such as retroreflectivity increasing over time, may affect the results of performance evaluation. These "temporal jumps" may be caused by factors such as the use of different retroreflectometers during different test periods and the change of pavement surface condition (e.g., being washed or vacuumed). To identify and assess the effect of these temporal jumps, any dataset that has a mean that is statistically larger than its previous dataset(s) is identified using Student's T-test and excluded from the performance evaluation. Note that because the majority of PMMs have lower initial retroreflectivity than 1-month retroreflectivity due to the "polishing effect" after markings are opened to traffic, all initial datasets were not considered in the temporal variability analysis.

3.3.3 Statistical Assumptions

Note that the proposed method is to be used with caution. The specific method proposed to remove outliers (i.e., the boxplot) is used on the basis of certain statistical assumptions; to confidently apply this method, a large number of data points in a dataset is recommended. For

GDOT Test Deck, since most materials only had fewer than 5 products, using the outlier removal approach may have, in fact, accidentally removed valid measurements. Therefore, in this chapter, we only apply the Student's t-test to eliminate temporal variability and to demonstrate the proposed methodology. In future research, it is our intent to incorporate more pavement marking retroreflectivity measurements collected in Georgia to apply the full methodology.

3.3.4 Performance Evaluation

The performance of a PMM is usually presented by its service life. To evaluate the service life, various studies were conducted using statistical regression analysis, artificial neural networks, and other means. One popular method for performance evaluation uses the best-fitted curve to estimate the service life against the elapsed time or cumulative traffic (Kopf, 2004; Migletz et al., 2001). However, as discussed above, most previous studies used the average readings for performance evaluation. In this chapter, instead of using the average reading of a material, we fitted all retroreflectivity measurements of all products in the material (except for the initial readings because pavement marking's retroreflectivity usually picks up after it is opened to traffic) to the following commonly used models:

1. Linear model: $R_L = a + b \cdot Month$ (1)
2. Exponential decay model: $R_L = a \cdot \mathrm{e}^{b \cdot Month}$ (2)

where

Month = Elapsed time, measured in month

R_L = Retroreflectivity, measured in mcd/m^2/lux

a, b = Model coefficients

3.4 Results

GDOT Test Deck data analysis results are shown in Table 3-2. The raw column represents the estimated service lives using all retroreflectivity measurements collected in a two-year period; the processed column shows the estimated lives using measurements after the removal of datasets with irregular temporal variability.

Table 3-2 GDOT Test Deck PMM Service Life Summary

Material	Line Type	Raw		Processed[9]	
		Linear	Exponential	Linear	Exponential
Paint	White Edge	71.7	100.4	44.6	64.0
	White Skip	28.2	32.0	24.4	28.2
	Yellow Edge	281.8	335.0	29.4	35.4
Thermoplastic	White Edge	76.4	127.7	76.4	127.7
	White Skip	87.9	137.1	52.8	83.6
	Yellow Edge[10]	--	--	--	--
Preformed Tape	White Edge	27.2	42.0	27.2	42.0
	White Skip	25.5	34.1	25.5	34.1
	Yellow Edge	30.7	44.9	30.7	44.9
Epoxy	White Edge	22.7	25.3	22.7	25.3
	White Skip	30.2	44.0	30.2	44.0
	Yellow Edge	35.1	52.4	35.1	52.4
Methyl Methacrylate	White Edge	36.2	61.5	36.2	61.5
	White Skip	46.2	86.2	46.2	86.2
	Yellow Edge	62.3	117.3	62.3	117.3

(in months)

For example, Figure 3-8 and Figure 3-9 demonstrate the performance evaluation results before and after addressing temporal variability in the white edge line dataset of paint. Note that the 24-month data were removed from the modeling because it failed the Student's t-test, i.e., the 24-

[9] Datasets with irregular temporal jumps are removed from the modeling process.

[10] Datasets with estimated service lives unreasonably larger (10 times) than the typical service life ranges, therefore not included in this summary.

month retroreflectivity measurements were statistically higher than those measured in 18 months. Before applying the proposed method, the estimated service life, 71.7 months, was beyond the typical service lives summarized in the literature (i.e., 12 to 45 months, as shown in Table 5-7). After the proposed method was applied, the estimated service life became 44.6 months, a more reasonable service life for a typical paint marking. This result indicates that the proposed methodology can effectively address data variability issues and improve the quality of performance evaluation. Similar improvements can be found in Table 3-2.

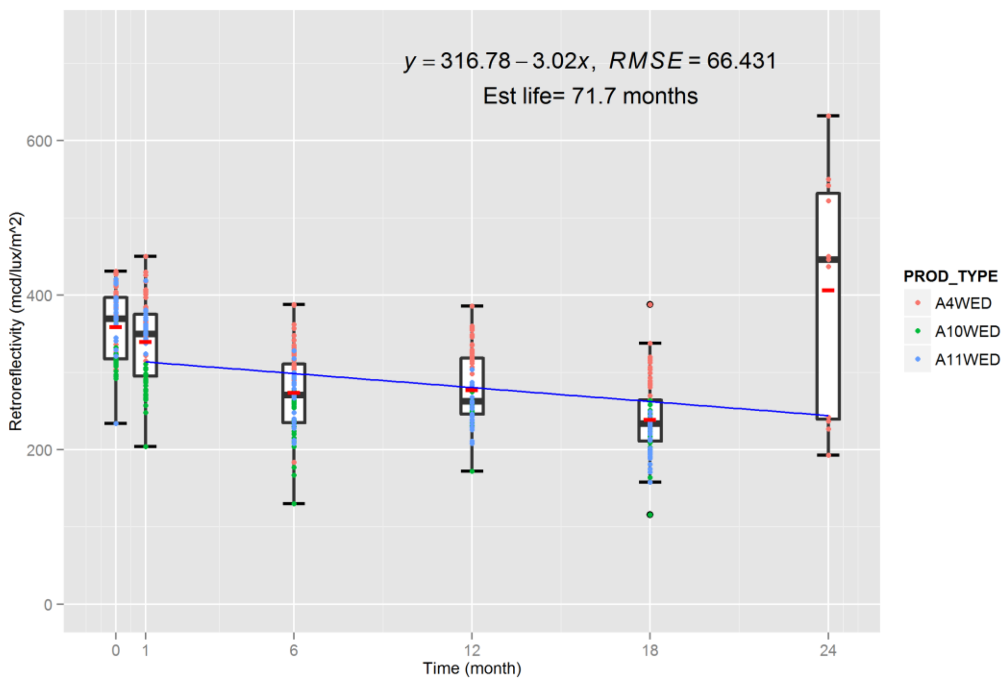


Figure 3-8 Linear Modeling for Paint before Addressing Temporal Variability

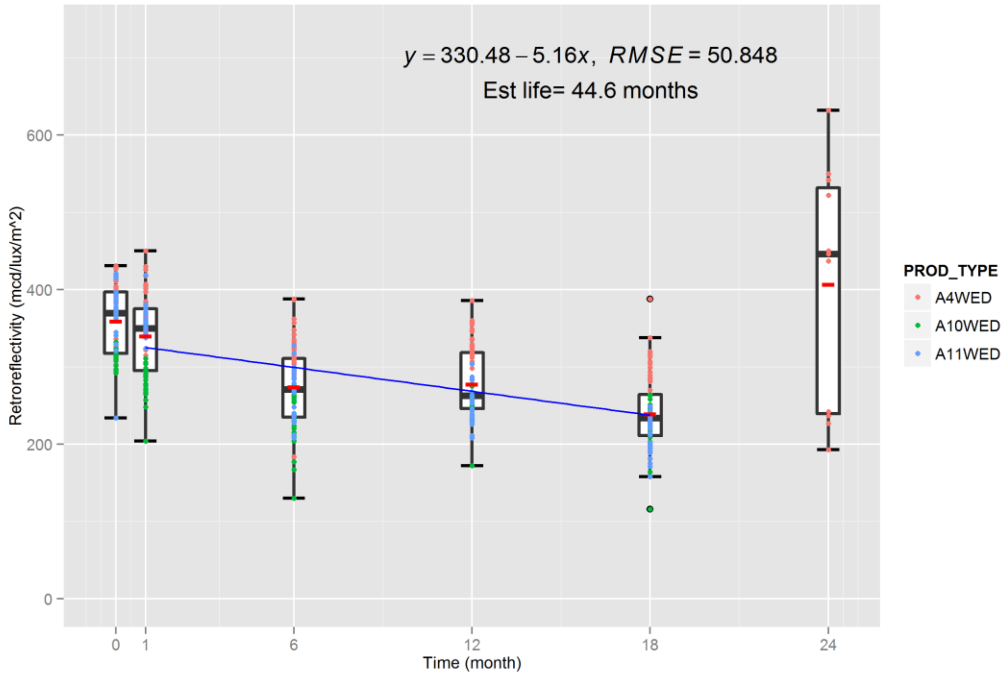


Figure 3-9 Linear Modeling for Paint after Addressing Temporal Variability

3.5 Discussions

One of the objectives of test deck data analysis is to examine the products based on GDOT's standard specifications on different PMMs. According to the minimum dry and wet weather retroreflectivity requirements shown in Table 3-3 and Table 3-4, products on GDOT Test Deck were examined. To provide a general idea about how the performance of marking products compared to the criteria set by GDOT, these products are evaluated based on material types. In other words, this analysis provides information about how well the overall available products can meet GDOT's requirements. Results are shown in Table 3-5 and Table 3-6. The results show that although most materials meet the requirements for dry retroreflectivity, none of them meet the requirements for wet retroreflectivity. In addition, the tapes installed on GDOT Test Deck failed both the dry and the wet requirements. The results indicate that higher performance is expected from products to be able to meet GDOT's requirements; meanwhile, the results also provide a useful insight to GDOT experts if they desire to adjust their requirements.

Table 3-3 Required Dry Retroreflectivity Readings in Accordance with ASTM E 1710

Required values in mcd/m²/lux X days after initial installation.	White 30 Days	White 180 Days	Yellow 30 Days	Yellow 180 Days
Thermoplastic	400	400	300	300
Polyurea	600	600	400	400
Paint/Highbuild Paint	300	300	250	250
Preformed Plastic Tape	600	600	400	400
Epoxy	400	400	300	300

Table 3-4 Required Wet Retroreflectivity Readings in Accordance with ASTM E 2177

Required values in mcd/m²/lux X days after initial installation.	White 30 Days	White 180 Days	Yellow 30 Days	Yellow 180 Days
Thermoplastic	150	150	125	125
Polyurea	250	250	200	200
Paint/Highbuild Paint	150	150	100	100
Preformed Plastic Tape	250	250	200	200
Epoxy	150	150	125	125

Table 3-5 White PMM Qualification Analysis Results

Material	Product ID	Dry Test PASS?	Wet Test PASS?
Paint	A4, A10, A11	Y	N
Thermoplastic	A3, A5, A7, A8, A9, C5, C6	Y	N
MMA	C7, C8	N/A	N/A
Tape	A1, A2, A6, C1, C2	N	N
Epoxy	C3, C4	Y	N

Table 3-6 Yellow PMM Qualification Analysis Results

Material	Product ID	Dry Test PASS?	Wet Test PASS?
Paint	A4, A10, A11	Y	N
Thermoplastic	A3, A5, A7, A8, A9, C5, C6	Y	N
MMA	C7, C8	N/A	N/A
Tape	A1, A2, A6, C1, C2	N	N
Epoxy	C3, C4	Y	N

3.6 Summary

In this chapter, a method was proposed to improve the reliability of PMM performance evaluation based on GDOT Test Deck data, using a series of data preprocessing and cleansing steps based on descriptive statistics. By applying the proposed method, retroreflectivity readings of each dataset were critically evaluated and their reliabilities could be improved by removing data with irregular spatial and temporal variability. The findings of this chapter are summarized as follows:

1) Characteristics and factors that cause spatial and temporal variability in field-collected retroreflectivity measurements were identified in this study. Irregular spatial and temporal variability can be shown in the form of irregular spatial patterns, local extremes, and increasing temporal trends. The proposed method used the geographic locations and descriptive statistics of measurements (i.e., a boxplot) to identify and remove irregular spatial variability; it also addressed irregular temporal variability by identifying datasets with increasing trends using statistical tests;
2) Results indicate that before and after applying the proposed method, significant differences can be observed in the estimated lives of these test deck products. Moreover, the R-squared values, which represent the goodness-of-fit of performance evaluation models, were improved after applying the proposed method, indicating that the evaluation results were more reliable when irregular variability was addressed;
3) The study suggests that current practices, which use mostly the average retroreflectivity and ignore possible spatial and temporal variability, can lead to inconsistent service life estimation results; and
4) The study also demonstrates that the proposed method can improve data quality for reliably evaluating PMM performance in compared with an average method.

From this study, the following recommendations are summarized:

1) A larger data set, including the data collected in other state DOTs, can be further tested by using the proposed method and further developing more comprehensive pavement marking performance models that are more specific to Georgia;
2) The proposed method can be modified and expanded for the quality assurance/quality control (QA/QC) of the routine pavement marking installation and data collection;
3) The results of the evaluation of the retroreflectivity requirements can be taken into considerations for future adjustments of retroreflectivity requirements, or for acquiring pavement marking products with better quality.

4. ANALYSIS OF NATIONAL TRANSPORTATION PRODUCT EVALUATION PROGRAM DATA

Since 1994, the American Association of State Highway and Transportation Officials' (AASHTO) NTPEP has tested numerous transportation products and provided results to the participating state DOTs and manufacturers. The most recent test results are stored in the DataMine 2.0 database (DataMine hereafter), which is a publicly accessible online database (National Transportation Product Evaluation Program, 2015a).

In this chapter, the effect of winter effects on retroreflectivity using all available data in DataMine was observed. Since severe winter weather events (e.g., snowplows) are not a primary concern in Georgia, NTPEP data affected by winter weather events were excluded from the analysis. Then, retroreflectivity degradation models were developed to predict pavement marking retroreflectivity using NTPEP data, excluding those that had been affected by winter weather events (such as snowplows). Finally, expected service lives of marking materials were derived from the models developed.

4.1 NTPEP Data Description

Available field test data in DataMine include (1) installation data, such as installation date, air, road, and material temperatures, applied thickness, material composition, and bead properties; and (2) inspection data, such as inspection date and interval, retroreflectivity, durability, and color measurements. Table 4-1 and Table 4-2 show the detailed data available.

Table 4-1 NTPEP Field Installation Data Description

Data Item	Description
NTPEP ID	A unique ID for a product installed in a certain year
Type	Type of PMM
Color	Color of material (e.g., yellow and white)
Deck	Pavement surface type (e.g., asphalt and concrete)
Installation Date	The date of installation
Thickness	Range of applied thickness during installation
Air Temperatures	Range of air temperatures at the time of installation
Road Temperatures	Range of road surface temperatures at the time of installation
Material Temperatures	Range of material temperatures at the time of installation
Humidity	Range of humidity at the time of installation
Bead Types	Types of beads applied
Bead Rates	Rates of beads application
Bead Coatings	Types of coatings used on beads

Table 4-2 NTPEP Field Inspection Data Description

Data Item	Description
NTPEP ID	A unique ID for a product installed in a certain year
Line	A unique ID for the specific line
Inspection Date	The data of inspection
Skip retroreflectivity	Retroreflectivity measured at the skip area of the line
Skip durability	Durability measured at the skip area of the line
Wheel retroreflectivity	Retroreflectivity measured in the wheelpath area of the line
Wheel durability	Durability measured in the wheelpath area of the line
Daytime Color	Daytime color measurements
Nighttime Color	Nighttime color measurements
Dry retroreflectivity	Retroreflectivity measured using ASTM Standard E 1710
Wet retroreflectivity	Retroreflectivity measured using ASTM Standard E 2177

Table 4-3 PMM Types used in this Study

Type	Description
1C	Waterborne paint
3A	Thermoplastic
3B	Preformed thermoplastic
4A	Preformed tape
5C	Polyurea
5D	Methyl methacrylate

Data used in this study include the available field test data of several materials in DataMine, which consists of data from 7 test decks in 3 states (Pennsylvania, Florida, and Minnesota) between 2008 and 2015. On each test deck, yellow and white pavement marking products were installed on asphalt and concrete sub-decks, and tests were conducted periodically (every month in the first year and every three months thereafter) throughout a three-year analysis period. For the six subject materials (see Table 4-3), there were 3,720 lines installed on the 7 test decks and a total of 26,166 inspection data entries used in this study (after excluding data affected by winter weather events, as discussed in Section 4.2).

Note that all pavement marking lines were installed in the transverse direction based on NTPEP's test deck standard design, and accelerated degradation in retroreflectivity may be expected (Hummer et al., 2011; Zhang & Wu, 2006). With that in mind, all retroreflectivity data used in this study were measurements collected in "skip areas" (i.e., within 9 in. to the long skip line in the corresponding lane), which are "considered to represent long line retroreflectivity performance" (National Transportation Product Evaluation Program, 2015b). Interested readers can find more details on the relationships between the performance of transverse and long lines in the study published by Pike and Songchitruksa (2015). In addition to NTPEP data, other data including ADT and average truck traffic (ADTT) were retrieved from the respective state DOTs' traffic data websites (Florida Department of Transportation, 2014; Minnesota Department of Transportation, 2015; Pennsylvania Department of Transportation, 2015) or provided by the corresponding DOTs.

4.2 Preliminary Observation of the Effect of Winter Weather Events

In order to better understand the effect of winter weather events and incorporate it into retroreflectivity modeling, the change of retroreflectivity must be examined. Figure 4-1 shows the degradation of MMA in Florida and Pennsylvania over time. Each dot in the figure represents one retroreflectivity measurement, and each line in the figure connects all measurements made on an actual pavement marking line at different times. For each inspection interval, a boxplot is drawn to see the distribution of retroreflectivity measurements in this interval. The bounding box in each boxplot shows the range of the middle 50 percentile of the points. Three horizontal lines of a bounding box denote the 25th, 50th, and 75th percentiles of the measurements in one interval. For instance, the three percentiles of interval 0 in Florida are approximately 360, 640, and 800 mcd/m^2/lux, respectively. Note that these graphs were summarized from multiple test decks within each state (2 decks in Florida and 3 decks in Pennsylvania), and some intervals were either not collected due to weather conditions or have not yet been collected/reported. For example, measurements between intervals 6 and 8 in all three Pennsylvania test decks were not collected due to severe winter weather conditions.

By comparing the changes in retroreflectivity in the two plots in Figure 4-1, interesting findings can be observed. In the first six intervals, the two states shared some similar degradation patterns. Retroreflectivity measurements in both states ranged from approximately 200 to 1,700 mcd/m^2/lux at interval 0, and these ranges gradually decreased in the first 6 intervals. Moreover, most median readings of these intervals were around 500 mcd/m^2/lux. Nevertheless, these similar patterns disappeared thereafter. While retroreflectivity measurements continued to gradually deteriorate in Florida, a dramatic decrease in retroreflectivity was observed between intervals 5 and 9, i.e., the first winter, in Pennsylvania. The median measurements dropped from approximately 500 to 300 mcd/m^2/lux after the first winter, and the distribution of measurements became slightly more skewed to the right (i.e., more low-retroreflectivity measurements). Using interval 10, for example, the range of measurements was approximately 150 to 950 mcd/m^2/lux in Florida and 100 to 700 mcd/m^2/lux in Pennsylvania, and the median readings were approximately 375 and 275 mcd/m^2/lux, respectively. Similar but less dramatic patterns can also be observed in the second winter (between intervals 15 and 21) and in the third winter (between intervals 27 and 33).

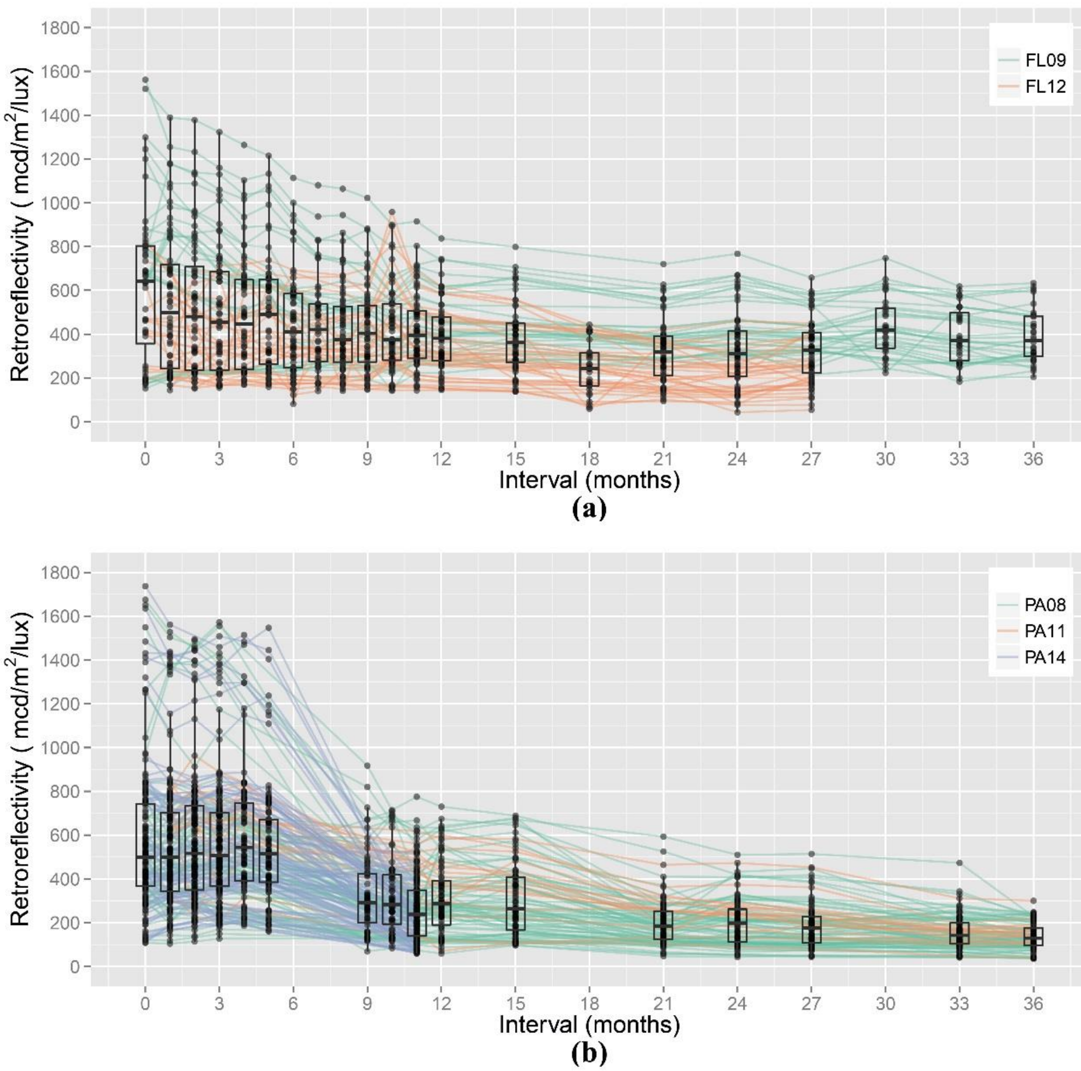


Figure 4-1 MMA Retroreflectivity Readings along Time

(Inspection Intervals) in Two States (a) Florida (test decks FL09 and FL12); and (b) Pennsylvania (test decks PA08, PA11, and PA14) as an Example

From these observations, it is noted that winter weather events, especially those in the first winter, can have significant, non-gradual impact on the performance of pavement markings. This type of physical damage should be explicitly considered in degradation models. As stated previously, the dataset contains data collected in Florida, Pennsylvania, and Minnesota. Florida shares similar weather with Georgia and, also, does not have severe winter weather conditions; therefore, all data from Florida were used. The latter two states, on the other hand, have snow events constantly, so only data prior to the first winter were used from these two states.

4.3 Pavement Marking Material Performance Modeling

Multiple linear models, as stated in previous sessions, are robust means for predicting pavement marking retroreflectivity and deriving expected service lives. Therefore, in this section, we developed MLMs to predict pavement marking retroreflectivity of multiple PMMs. The expected service life of each material under different traffic conditions was also derived. These information was then used in Chapter 5 for calculating the life-cycle costs of materials.

4.3.1 Variable Selection

To predict retroreflectivity, a list of potential variables is summarized below based on literature review and the availability of data in this study. Note that the maximum retroreflectivity was added for each line (*MaxRetro*) as a potential independent variable. The assumption was that, when compared with the *InitialRetro*, this variable can better improve the accuracy of the model by accounting for the “polish effect,” which the retroreflectivity "picks up" in the first couple of months then starts to deteriorate afterwards. Among these variables, ADT was pre-selected (starred) as a final variable for implementation purposes so that the proposed model can easily be implemented by state DOTs. Potential variables considered in this study are as follows:

1) *ADT**: average daily traffic per lane (veh/day/ln)
2) *Days*: elapsed days from installation
3) *MaxRetro*: maximum retroreflectivity from installation
4) *InitialRetro*: initial retroreflectivity from installation
5) *Thickness*: the average applied thickness
6) *MultipleBeads*: a binary variable, 1 if multiple types of beads were applied, 0 otherwise
7) *ADTT*: average daily truck traffic per lane
8) *RoadTemp*: the average road of temperatures during installation

Analysis of variance (ANOVA) and t-test were conducted to test the prediction power of these potential variables. In Table 4-4, the larger the absolute t-value is, the higher prediction power the corresponding variable has. Statistically significant t-values at the 95% level were highlighted in gray and bolded in this table. Note that the 4-digit column names of Table 4-4 denote the PMM type (first two digits, see Table 4-3), surface type (third digit, where A stands for asphalt and C stands for concrete), and line color (fourth digit, where W stands for white, and Y stands for yellow). From the results, *Days* and *MaxRetro* were the two variables with t-values that are constantly high and significant across all materials. *MaxRetro* turned out to be a better predictor than *InitialRetro* for all materials, for it is more often a significant predictor with higher prediction power, which verifies our previous assumption.

Consequently, the final selected independent variables were *ADT*, *Days*, and *MaxRetro*. Ten-fold cross-validation analyses were conducted to ensure the proposed models were not over-fitting.

Table 4-4 Prediction Power (Absolute *t* Value) of Potential Independent Variables

Variables	1CAW	1CAY	1CCW	1CCY	3AAW	3AAY	3ACW	3ACY	3BAW
*Days**	**-14.8**	**-14.1**	**-4.3**	**-8.7**	**-9.7**	**-5.3**	**-11.2**	**-9.6**	**-13.0**
InitialSkipRR	**10.6**	-0.2	**17.8**	**16.6**	**9.7**	-0.4	**8.4**	**9.0**	**6.9**
*MaxSkipRR**	**13.1**	**26.1**	**10.7**	**16.7**	**15.3**	**33.9**	**12.2**	**27.4**	**16.2**
AvgThickness	**-2.4**	**-2.7**	**8.1**	**5.5**	**3.3**	**7.4**	**4.3**	**3.4**	**-7.1**
SkipDura	**22.9**	**6.3**	**37.3**	**6.8**	**2.0**	**2.6**	0.1	1.2	-1.4
*ADT**	1.4	**5.8**	0.7	**-2.1**	**2.8**	**4.5**	**3.9**	1.2	-0.8
MultiBeads	0.4	-1.3	**-2.2**	-1.9	-1.7	**3.8**	**-2.3**	-0.6	1.9
ADTT	-1.7	**2.0**	-0.2	-1.6	-0.1	0.8	**3.7**	-1.4	0.6
AvgRoadTemp	0.0	1.0	**-4.2**	**-3.3**	-0.7	**3.7**	**-3.1**	1.6	-1.1

Variables	3BAW	3BAY	3BCW	3BCY	4AAW	4AAY	4ACW	4ACY	3BAW
*Days**	**-13.0**	**-14.7**	**-9.1**	**-13.1**	**-35.8**	**-31.6**	**-20.2**	**-17.9**	**-13.0**
InitialSkipRR	**6.9**	**6.7**	**4.9**	**5.0**	**-2.0**	-1.6	**7.3**	**6.6**	**6.9**
*MaxSkipRR**	**16.2**	**7.7**	**17.3**	**13.7**	**14.0**	**10.0**	**14.2**	**8.3**	**16.2**
AvgThickness	**-7.1**	**-4.5**	**-4.0**	-0.8	**6.4**	1.4	**5.1**	-1.3	**-7.1**
SkipDura	-1.4	-0.1	**2.7**	-0.1	0.9	0.2	**5.2**	**3.3**	-1.4
*ADT**	-0.8	**5.0**	-0.4	1.8	0.8	**-3.1**	1.9	1.7	-0.8
MultiBeads	1.9	-0.9	**-5.3**	**-4.1**	**-2.3**	1.0	0.8	0.1	1.9
ADTT	0.6	**2.5**	-0.8	1.8	1.7	**4.5**	1.3	-1.5	0.6
AvgRoadTemp	-1.1	0.0	-1.9	-0.5	**4.9**	**2.1**	**4.6**	**4.1**	-1.1

Variables	5CAW	5CAY	5CCW	5CCY	5DAW	5DAY	5DCW	5DCY	5CAW
*Days**	**-15.5**	**-19.0**	**-17.7**	**-14.0**	**-20.1**	**-7.4**	**-15.9**	**-5.1**	**-15.5**
InitialSkipRR	**-4.0**	1.8	0.9	**3.0**	-0.3	**-9.5**	**4.2**	0.1	**-4.0**
*MaxSkipRR**	**5.0**	**4.8**	1.5	**4.2**	**15.5**	**27.6**	**13.2**	**20.7**	**5.0**
AvgThickness	-1.3	**-2.9**	-1.2	-0.1	**7.8**	**4.4**	0.6	-0.3	-1.3
SkipDura	-0.9	-1.0	-0.8	0.5	**6.2**	**4.8**	**2.2**	**2.0**	-0.9
*ADT**	-1.1	-0.2	1.3	-0.5	**-2.2**	**4.0**	**2.1**	**-2.5**	-1.1
MultiBeads	**2.2**	-1.1	0.6	0.5	**12.3**	**10.6**	**3.3**	**4.4**	**2.2**
ADTT	-1.5	1.4	0.5	-0.1	-0.4	-1.4	**2.1**	-1.5	-1.5
AvgRoadTemp	**-2.7**	1.9	-1.3	0.9	**4.5**	-1.1	-1.5	-1.1	**-2.7**

* Final selected independent variables

4.3.2 Model Development

The final models were formulated as in Equation 4.1. This formulation is used to develop a retroreflectivity prediction model for each type of material under different pavement surface types and line colors. The results of modeling are shown in Table 4-5.

$$R_{L_i} = \alpha + \beta_1 ADT_i + \beta_2 Days_i + \beta_3 MaxRetro_i \tag{4.1}$$

where

R_{L_i} = retroreflectivity (mcd/m^2/lux);

ADT = average daily traffic per lane (veh/day/ln);

$Days$ = elapsed days from installation;

$MaxRetro$ = maximum retroreflectivity of the line (mcd/m^2/lux);

$\alpha, \beta_1, \beta_2, \beta_3$ = model coefficients; and

i = the *i*th measurement data entry.

Table 4-5 Final Model Coefficients and R-Squared Values

	1CWA	**1CYA**	**1CWC**	**1CYC**	**3AWA**	**3AYA**	**3AWC**	**3AYC**
α	-17.994	-19.549	125.059	70.325	57.503	34.541	194.739	120.323
β_1	0.000	0.001	-0.008	-0.004	-0.001	-0.001	-0.010	-0.005
β_2	-0.118	-0.061	-0.069	-0.039	-0.101	-0.050	-0.176	-0.085
β_3	0.965	0.955	0.790	0.787	0.815	0.807	0.699	0.672
R-squared	0.892	0.938	0.820	0.906	0.575	0.714	0.489	0.731
	3BWA	**3BYA**	**3BWC**	**3BYC**	**4AWA**	**4AYA**	**4AWC**	**4AYC**
α	-13.759	-1.145	126.678	110.632	96.720	77.289	171.705	86.402
β_1	-0.002	-0.002	-0.008	-0.006	-0.010	-0.003	-0.007	-0.003
β_2	-0.197	-0.134	-0.182	-0.156	-0.656	-0.374	-0.618	-0.319
β_3	0.959	0.998	0.838	0.775	0.917	0.828	0.821	0.824
R-squared	0.740	0.843	0.644	0.756	0.878	0.868	0.752	0.793
	5CWA	**5CYA**	**5CWC**	**5CYC**	**5DWA**	**5DYA**	**5DWC**	**5DYC**
α	175.508	78.059	190.893	151.899	137.060	39.100	126.905	74.688
β_1	-0.005	-0.004	-0.008	-0.006	-0.004	-0.003	-0.005	-0.006
β_2	-0.644	-0.429	-0.866	-0.447	-0.470	-0.124	-0.449	-0.138
β_3	0.776	0.866	0.839	0.773	0.771	0.883	0.796	0.887
R-squared	0.632	0.907	0.887	0.945	0.804	0.941	0.784	0.919

4.4 Expected Service Life

The developed models in Section 4.3.2 can be used to further derive the service lives of pavement markings under different traffic conditions and surface types. By plugging the minimum acceptable retroreflectivity, *MinRetro*, into Equation 4.1, the expected service life (L_c) for each category (i.e., material type, line color, and surface type) can be derived using Equation 4.2. For example, assuming the minimum acceptable retroreflectivity is 100 mcd/m^2/lux (the current practice of GDOT), with a maximum retroreflectivity of 773 mcd/m^2/lux and an ADT of 10,000 veh/day/ln, the expected life of white MMA on asphalt pavement with no winter weather events is $(100 - 137.060 + 0.004 \times 10000 - 0.771 \times 773)/(-0.470) = 1{,}261$ days, or approximately 3.4 years.

$$L_c = \frac{MinRetro - \alpha - \beta_1 ADT_i - \beta_3 MaxRetro_i}{365 \times \beta_2} \tag{4.2}$$

where

L_c	=	expected service life (in years) for category c;
c	=	pavement marking products that share the same material type, line color, and surface type; and
$MinRetro$	=	minimum acceptable retroreflectivity (in mcd/m^2/lux).

Note that in Equation 4.2, for each category (i.e., material type, color, and surface type), the mean maximum retroreflectivity (shown in Table 4-6) was used to derive service life.

Table 4-6 Mean Maximum Retroreflectivity

	1CWA	1CYA	1CWC	1CYC	3AWA	3AYA	3AWC	3AYC
Mean *MaxRetro*	413	246	481	267	594	392	718	419
	3BWA	**3BYA**	**3BWC**	**3BYC**	**4AWA**	**4AYA**	**4AWC**	**4AYC**
Mean *MaxRetro*	614	330	675	371	1039	655	1212	784
	5CWA	**5CYA**	**5CWC**	**5CYC**	**5DWA**	**5DYA**	**5DWC**	**5DYC**
Mean *MaxRetro*	695	453	884	586	773	483	823	532

(in mcd/m^2/lux)

Table 4-7 and Table 4-8 show the expected service life of pavement markings. In Table 4-7, a minimum retroreflectivity of 100 mcd/m^2/lux was used; in Table 4-8, a minimum retroreflectivity of 250 mcd/m^2/lux was used.

Table 4-7 Expected Service Life of Pavement Markings (to 100 mcd/m^2/lux)

ADT (veh/day/ln)	1CWA	1CYA	1CWC	1CYC	3AWA	3AYA	3AWC	3AYC
2,000	6.5	5.3	15.6	12.2	11.9	13.8	9.0	9.4
3,750	6.5	5.4	15.0	11.7	11.9	13.7	8.7	9.1
4,000	6.5	5.4	14.9	11.7	11.8	13.7	8.7	9.0
7,500	6.6	5.5	13.8	10.8	11.7	13.6	8.2	8.4
10,000	6.6	5.6	13.0	10.2	11.6	13.5	7.8	8.0
20,000	6.7	6.0	9.9	7.6	11.2	13.1	6.3	6.2
ADT (veh/day/ln)	**3BWA**	**3BYA**	**3BWC**	**3BYC**	**4AWA**	**4AYA**	**4AWC**	**4AYC**
2,000	6.6	4.6	8.6	5.0	3.9	3.8	4.7	5.4
3,750	6.5	4.5	8.4	4.8	3.8	3.7	4.6	5.3
4,000	6.5	4.5	8.4	4.8	3.8	3.7	4.6	5.3
7,500	6.4	4.3	8.0	4.5	3.6	3.7	4.5	5.3
10,000	6.3	4.2	7.7	4.2	3.5	3.6	4.4	5.2
20,000	6.1	3.7	6.4	3.2	3.1	3.4	4.1	4.9
ADT (veh/day/ln)	**5CWA**	**5CYA**	**5CWC**	**5CYC**	**5DWA**	**5DYA**	**5DWC**	**5DYC**
2,000	2.6	2.3	2.6	3.0	3.6	8.0	4.1	8.6
3,750	2.5	2.3	2.5	3.0	3.6	7.8	4.0	8.4
4,000	2.5	2.3	2.5	2.9	3.6	7.8	4.0	8.4
7,500	2.5	2.2	2.4	2.8	3.5	7.6	3.9	7.9
10,000	2.4	2.1	2.4	2.7	3.4	7.4	3.8	7.6
20,000	2.2	1.9	2.1	2.3	3.2	6.7	3.5	6.4

(in years)

Table 4-8 Expected Service Life of Pavement Markings (to 250 mcd/m^2/lux)

ADT (veh/day/ln)	1CWA	1CYA	1CWC	1CYC	3AWA	3AYA	3AWC	3AYC
2,000	3.0	-1.5	9.6	1.6	7.8	5.5	6.7	4.6
3,750	3.1	-1.4	9.0	1.2	7.8	5.5	6.4	4.2
4,000	3.1	-1.4	8.9	1.1	7.8	5.4	6.4	4.2
7,500	3.1	-1.2	7.8	0.2	7.6	5.3	5.8	3.6
10,000	3.1	-1.1	7.0	-0.4	7.5	5.2	5.5	3.2
20,000	3.2	-0.7	3.9	-2.9	7.2	4.8	3.9	1.4
ADT (veh/day/ln)	**3BWA**	**3BYA**	**3BWC**	**3BYC**	**4AWA**	**4AYA**	**4AWC**	**4AYC**
2,000	4.5	1.5	6.4	2.4	3.3	2.7	4.0	4.1
3,750	4.4	1.4	6.2	2.2	3.2	2.6	4.0	4.1
4,000	4.4	1.4	6.1	2.2	3.2	2.6	3.9	4.0
7,500	4.3	1.2	5.7	1.8	3.0	2.6	3.8	4.0
10,000	4.3	1.1	5.4	1.6	2.9	2.5	3.8	3.9
20,000	4.0	0.6	4.2	0.5	2.5	2.3	3.5	3.7
ADT (veh/day/ln)	**5CWA**	**5CYA**	**5CWC**	**5CYC**	**5DWA**	**5DYA**	**5DWC**	**5DYC**
2,000	1.9	1.4	2.1	2.1	2.8	4.6	3.2	5.6
3,750	1.9	1.3	2.1	2.0	2.7	4.5	3.1	5.4
4,000	1.9	1.3	2.1	2.0	2.7	4.5	3.1	5.4
7,500	1.8	1.2	2.0	1.9	2.6	4.3	3.0	5.0
10,000	1.8	1.2	1.9	1.8	2.6	4.1	2.9	4.6
20,000	1.6	0.9	1.6	1.4	2.3	3.4	2.6	3.4

(in years)

4.5 Discussions

Results in Table 4-5 show that the R-squared values of developed MLMs range from 0.489 to 0.945, with the majority of them higher than 0.700. This result indicates that MLMs can generally fit the data fairly well and can provide accurate prediction of pavement marking retroreflectivity with limited errors. The results are also comparable, if not better, than those in the literature, which further implies that these models can be applied to predict pavement marking retroreflectivity under different traffic, color, and surface conditions. These models can be improved by including different variables to predict the retroreflectivity of different PMMs, especially those with significant prediction power, as shown in Table 4-4.

From Table 4-7 and Table 4-8, several findings are summarized. First, both yellow and white paint pavement markings (Type 1C) performed well on both asphalt and concrete pavements, with the expected service life ranges from 5.3 to 15.6 years when the minimum retroreflectivity is 100 mcd/m^2/lux; however, their performance dropped dramatically when the minimum retroreflectivity was 250 mcd/m^2/lux. This indicates that although paints may have long lives, their retroreflectivity usually starts low and remains low. Therefore, for roads with higher traffic volumes, such as interstate highways that require better visibility (e.g., the suggested minimum retroreflectivity in Table 2-6), paints may not perform as well as if they were applied to general roads that require lower visibility.

Second, preformed tape, on the other hand, performed consistently throughout different surface types and roadway conditions under different minimum retroreflectivity requirements. This indicates that tape markings usually start at a very high retroreflectivity, gradually deteriorates in the first half of its life, and then deteriorates faster when it is approaching its service life. In other words, given the consistency and good, long, expected life, tape markings could be a good candidate material to be comprehensively applied to both general roads and interstate highways.

Third, thermoplastic markings (Type 3A) generally performed better and more consistently when compared with preformed thermoplastics (Type 3B). This result indicates that truck-mounted pavement marking applications generally work better than manual installation for thermoplastic markings. In addition, thermoplastic usually deteriorates much faster on concrete pavements, especially on higher traffic volume roads, which confirms the general practice of not using thermoplastic on concrete surfaces. Moreover, if we compare the average service life of different materials in Table 4-7, thermoplastic markings are expected to have the longest life, followed by paint, preformed thermoplastic, MMA, tape, and polyurea. Similar comparison can be made in Table 4-8, and the order of material's service life (from long to short) becomes thermoplastic, MMA, tape, preformed thermoplastic, paint, and polyurea. This result confirms the finding in the previous point: thermoplastic can perform consistently well under various traffic, line color, and pavement surface types. Note that although thermoplastic performs worse on concrete than on asphalt, it still outperforms other materials. Polyurea, on the other hand, are expected to have the shortest average life among these materials, according to these results. The results also show that, in addition to thermoplastic, MMA and preformed tape can also be good candidates for roads with higher visibility needs, e.g., interstate highways.

Finally, regarding the effect of line colors, although most white markings performed better than yellow markings for all materials, yellow MMA lines (Type 5D), in fact, performed better than white MMA lines. This indicates that MMA can potentially be a good candidate for center lines and/or edge lines.

4.6 Summary

In this chapter, NTPEP data were used to develop statistical models to predict the retroreflectivity of various PMMs. The developed models were then used to derive the service lives of PMMs. From the results of the NTPEP data analysis presented in this chapter, the following findings can be summarized:

1) Multiple linear models with independent variables, such as the elapsed days, average daily traffic, and maximum retroreflectivity, provide robust results for predicting pavement marking retroreflectivity. These models can be improved by including different, additional independent variables according to their prediction power for different PMMs, as shown in Table 4-4.

2) The derived service lives of different PMMs using minimum retroreflectivity measurements of 100 mcd/m^2/lux and 250 mcd/m^2/lux show that thermoplastic generally outperformed other materials under various traffic conditions, line colors, and pavement surface types. Results also showed that polyurea performed not as well as other materials and generally has the shortest expected service life.
3) Expected service life analysis results also indicate that for standard roads, thermoplastic and paint are two types of materials that are expected to perform well, whereas for higher traffic volume roads (e.g., interstate highways) that require higher retroreflectivity, thermoplastic, MMA, and tape are expected to perform well.
4) Specific materials may also have unique performance. For example, similar to the current practice and literature findings, thermoplastic performs worse on concrete pavements, especially when the traffic volume is high. In addition, yellow MMA performs better than white MMA, which implies that MMA may be a good candidate material for center lines.

5. COST-EFFECTIVE PAVEMENT MARKING MATERIAL SELECTION

In this chapter, general performance and costs of PMMs are summarized and a LCCA is conducted to evaluate the life-cycle costs of PMMs throughout a 10-year analysis period. Then, a cost-effective PMM selection matrix is developed on the basis of the analysis results, as well as engineering experience.

This chapter is organized as follows: the first section summarizes performance of different PMMs from various sources including the literature, state DOT handbooks, as well as GDOT Test Deck analysis results from Chapter 3; the second section summarizes the costs of PMMs from the most recent bid item prices of seven different state DOTs, including Georgia, Florida, North Carolina, Texas, Pennsylvania, Minnesota, and Oregon; the third section presents LCCA along a 10-year analysis period, and the annual costs of various PMMs are summarized; the fourth section presents a preliminary PMM selection matrix for GDOT based on the LCCA results as well as engineers' experience.

5.1 Pavement Marking Material Performance

Tables 5.1 to 5.6 summarize expected service lives of six different PMMs from the literature and from the analysis results of GDOT Test Deck data. In each table, expected service lives are summarized using the following two approaches: (1) for literature that developed degradation models, if the variables considered in the models are only AADT and the minimum retroreflectivity, a minimum retroreflectivity of 100 mcd/m^2/lux and GDOT's AADT category thresholds (i.e., 8,000, 15,000, and 40,000 vehicles/day) are plugged into these models to obtain the respective service lives; and (2) for literature that either has more complex factors/models or is based on engineering experiences, the reported service lives in these sources are directly used.

For example, Table 5-1 summarizes the expected service lives for paint from 10 different references. The model presented in the study by Abboud and Bowman (2002), was used to calculate the service lives of paint, and the expected service life of paint is 8.9, 23.7, and 44.5 months under an AADT of 8,000, 15,000, and 40,000 vehicles/day, respectively. Another example is the linear model presented by Sitzabee et al. (2009); because their model required the initial retroreflectivity of pavement markings, it falls into the second category of literature, and its reported service life for paint (i.e., 26 to 31 months) were directly summarized in Table 5-1 (Sitzabee et al., 2009). Note that since compositions of materials advances over time, performance of materials also improves over time. Therefore, for consistency and up-to-date information, data prior to 2001 were not included in the summaries in this section.

Table 5-1 Expected Service Life for Paint

Study	Marking Material	Degradation Formula Model	AADT/Functional Classification	Service Life (Months)
Abboud and Bowman (2002)	Paint	Service life[11] = (exp((267.27- R_{min})/(19.457))*(1000/(AADT*30.4))	n < 8,000	> 44.5
			8,000 ≤ n <15,000	23.7 – 44.5
			15,000 ≤ n < 40,000	8.9 – 23.7
			n ≥ 40,000	< 8.9
TxDOT (2004)	Paint	N/A	N/A	< 12
Zhang and Wu (2006)	Paint	N/A	N/A	21.4 – 32.7
Sitzabee et al (2009)	Paint	R_L = 55.2 + 0.77* $R_{initial}$ – 4.17*time	N/A	26 – 31
Hummer et al. (2011)	Paint	Multiple Linear Mixed-Effects Models	N/A	37.5 – 38.9
Mull and Sitzabee (2012)	Paint	[12]R_L = 65.5 + 0.72* $R_{initial}$ – 2.55*time – 3.22*s – 0.0005*AADT	N/A	21 – 51

[11] Assuming a 2-lane highway in the calculation.
[12] Number of snow plow events

Study	Marking Material	Degradation Formula Model	AADT/Functional Classification	Service Life (Months)
Robertson et al. (2012)	Paint	ΔR_L = -0.1447 (days) [waterborne] [13]ΔR_L = -51.2835 (CTP) [high-build]	N/A	40.0
Dwyer (2013)	Paint	N/A	N/A	12 – 36
GDOT Test Deck Analysis (this study)	Paint	N/A	N/A	24.4 – 44.5
NTPEP Data Analysis (this study)	Paint	N/A	N/A	63.6 – 187.2

Table 5-2 Expected Service Life for Thermoplastic

Study	Marking Material	Degradation Formula Model	AADT/Functional Classification	Service Life (Months)
Abboud and Bowman (2002)	Thermo	Service life = (exp((639.66-R_{min})/(70.806))*(1000/(AADT*30.4))	$n < 8{,}000$	> 16.8
			$8{,}000 \leq n < 15{,}000$	9.0 – 16.8
			$15{,}000 \leq n < 40{,}000$	3.4 – 9.0
			$n \geq 40{,}000$	< 3.4
Thamizharasan et al. (2003)	Thermo	ΔR_L = -0.06 (days) – 6.80 [white] ΔR_L = -0.03 (days) – 3.63 [yellow]	N/A	65 – 103
TxDOT (2004)	Thermo	N/A	N/A	36 – 48
Zhang and Wu (2006)	Thermo	N/A	N/A	26.0 – 37.2
Sitzabee et al (2009)	Thermo	[14]$R_L = 190 + 0.39 R_{initial} – 2.09 \cdot time – 0.0011 \cdot AADT + 20.7 X_1 – 20.7 X_2 + 19 X_3 – 19 X_4$	N/A	85 – 102
Dwyer (2013)	Thermo	N/A	N/A	36 – 72
Ozelim and Turochy (2014)	Thermo	R_L = 619.4 – 5.13*time – 0.00699* AADT [white]	$n < 8{,}000$	> 90.3
			$8{,}000 \leq n < 15{,}000$	80.8 – 90.3
			$15{,}000 \leq n < 40{,}000$	46.7 – 80.8
			$n \geq 40{,}000$	< 46.7
		R_L = 407.3 – 4.969*time – 0.00217* AADT [yellow]	$n < 8{,}000$	> 58.3
			$8{,}000 \leq n < 15{,}000$	55.3 – 58.3
			$15{,}000 \leq n < 40{,}000$	44.4 – 55.3
			$n \geq 40{,}000$	< 44.4
GDOT Test Deck Analysis (this study)	Thermo	N/A	N/A	52.8 – 76.4
NTPEP Data Analysis (this study)	Thermo	N/A	N/A	38.4 – 165.6

[13] CTP = cumulative traffic passage

[14] X_1=1 if edge line, 0 otherwise; X_2=1 if middle line, 0 otherwise; X_3=1 if white line, 0 otherwise; and X_4=1 if yellow line, 0 otherwise

Table 5-3 Expected Service Life for Tape

Study	Marking Material	Degradation Formula Model	AADT/Functional Classification	Service Life (Months)
TxDOT (2004)	Tape	N/A	N/A	< 48
Zhang and Wu (2006)	Tape	N/A	N/A	17.9 – 27.9
Dwyer (2013)	Tape	N/A	N/A	36 – 72
GDOT Test Deck Analysis (this study)	Tape	N/A	N/A	27.2 – 30.7
NTPEP Data Analysis (this study)	Tape	N/A	N/A	37.2 – 64.8

Table 5-4 Expected Service Life for MMA

Study	Marking Material	Degradation Formula Model	AADT/Functional Classification	Service Life (Months)
TxDOT (2004)	MMA	N/A	N/A	< 60
GDOT Test Deck Analysis (this study)	MMA	N/A	N/A	36.2 – 62.3
NTPEP Data Analysis (this study)	MMA	N/A	N/A	38.4 – 103.2

Table 5-5 Expected Service Life for Epoxy

Study	Marking Material	Degradation Formula Model	AADT/Functional Classification	Service Life (Months)
Thamizharasan et al. (2003)	Epoxy	ΔR_L = -0.16 (days) + 1.22 [white] ΔR_L = -0.05 (days) – 4.29 [yellow]	N/A	48 – 75
TxDOT (2004)	Epoxy	N/A	N/A	36 – 48
Dwyer (2013)	Epoxy	N/A	N/A	24 – 60
GDOT Test Deck Analysis (this study)	Epoxy	N/A	N/A	22.7 – 35.1

Table 5-6 Expected Service Life for Polyurea

Study	Marking Material	Degradation Formula Model	AADT/Functional Classification	Service Life (Months)
TxDOT (2004)	Polyurea	N/A	N/A	36 – 48
Sitzabee et al. (2012)	Polyurea	R_L = 486.3 – 139.9*(time^0.2)	N/A	80.3
Dwyer (2013)	Polyurea	N/A	N/A	36 – 60
NTPEP Data Analysis (this study)	Polyurea	N/A	N/A	22.8 – 36

To summarize the generally expected service life ranges of different PMMs and eliminate any potential extreme cases caused by model differences or other special traffic or weather conditions, the second highest/lowest service life was used as the upper/lower boundaries of the expected service life ranges for the respective materials.

Table 5-7 summarizes the high and low expected service lives for the six selected PMMs. These service life ranges are mostly consistent with those presented in the literature, for example, the NCHRP Synthesis 306 report (Migletz & Graham, 2002).

Table 5-7 Summary of Service Lives for Marking Materials

Material	Service Life Low (months)	Service Life High (months)
Paint	12	51
Thermoplastic	26	103
MMA	38	62
Tape	27	65
Epoxy	24	60
Polyurea	36	60

5.2 Pavement Marking Material Costs

In this section, the expected PMM costs, in terms of the agency cost, are summarized from the most recent item average bid prices of seven different state DOTs. These states were considered because of their proximity to Georgia, as well as data availability and whether or not it hosted a NTPEP test deck in recent years. Table 5-8 summarizes the report period for each average price summary from these state DOTs.

Each state DOT has slightly different ways to summarize their unit prices. For instance, while some states specifically separate different line types (solid, broken, and dotted lines), colors (white, yellow, and others), widths, and thicknesses of pavement markings, others only summarize unit prices based on material types. The following subsections describe the specific items we found in different state DOTs' item unit price summaries.

Table 5-8 Summary of the Average Bid Price Reports used in this Chapter

State	Report Period
Georgia	3/1/2014 – 2/28/2015
Texas	3/1/2014 – 2/28/2015
North Carolina	1/1/2014 – 12/31/2014
Florida	2/1/2014 – 1/31/2015
Pennsylvania	10/4/2012 - 10/9/2014
Minnesota	1/1/2014 – 7/31/2014
Oregon	1/1/2014 – 12/31/2014

5.2.1 Georgia DOT

GDOT publishes all its average bid prices (known as the item mean summary) on its website[15]. An interactive database query system is available online for users to customize a specific time period for the item mean summary. In this study, the item mean summary was searched from March 1, 2014 to February 28, 2015, and Table 5-9 shows the detailed descriptions of the items we obtained from GDOT's IMS. Note that the majority of pavement markings installed in Georgia is with a width of 5 in, which is different from the commonly used 4-in and 6-in markings in other states.

[15] gobi4rp.dot.ga.gov/ISA/ItemMeanSummary.jsp

Table 5-9 Items in GDOT's Item Mean Summary

Item Code	Material Description	Color	Line Type	Width	Thickness
652-2501	Traffic Stripe (Paint)	White	Solid	5 in.	N/A
652-2502	Traffic Stripe (Paint)	Yellow	Solid	5 in.	N/A
652-3501	Traffic Stripe (Paint)	White	Skip	5 in.	N/A
652-3502	Traffic Stripe (Paint)	Yellow	Skip	5 in.	N/A
652-5301	Traffic Stripe (Paint)	White	Solid	6 in.	N/A
652-5303	Traffic Stripe (Paint)	White	Solid	6 in.	N/A
652-5451	Traffic Stripe (Paint)	White	Solid	5 in.	N/A
652-5452	Traffic Stripe (Paint)	Yellow	Solid	5 in.	N/A
652-6301	Traffic Stripe (Paint)	White	Skip	6 in.	N/A
652-6501	Traffic Stripe (Paint)	White	Skip	5 in.	N/A
652-6502	Traffic Stripe (Paint)	Yellow	Skip	5 in.	N/A
653-1501	Thermoplastic	White	Solid	5 in.	N/A
653-1502	Thermoplastic	Yellow	Solid	5 in.	N/A
653-2501	Thermoplastic	White	Solid	5 in.	N/A
653-2502	Thermoplastic	Yellow	Solid	5 in.	N/A
653-3501	Thermoplastic	White	Skip	5 in.	N/A
653-3502	Thermoplastic	Yellow	Skip	5 in.	N/A
653-4501	Thermoplastic	White	Skip	5 in.	N/A
653-4502	Thermoplastic	Yellow	Skip	5 in.	N/A
656-0050	Thermoplastic Removal	N/A	N/A	5 in.	N/A
657-1054	Preformed Plastic (Tape)	White	Solid	5 in.	N/A
657-3054	Preformed Plastic (Tape)	White	Skip	5 in.	N/A
657-6054	Preformed Plastic (Tape)	Yellow	Solid	5 in.	N/A
657-8054	Preformed Plastic (Tape)	Yellow	Skip	5 in.	N/A
657-9110	Wet Reflective Preformed Plastic	White	Solid	5 in.	N/A
657-9111	Wet Reflective Preformed Plastic	Yellow	Solid	5 in.	N/A
657-9210	Wet Reflective Preformed Plastic	White	Solid	5 in.	N/A
657-9211	Wet Reflective Preformed Plastic	Yellow	Solid	5 in.	N/A
658-1200	Polyurea	White	Solid	5 in.	N/A
658-1201	Polyurea	Yellow	Solid	5 in.	N/A
658-1300	Polyurea	White	Skip	5 in.	N/A

5.2.2 Texas DOT

TxDOT publishes all its average low bid unit prices on its website. The data used were published on February 28, 2015, summarized on a twelve-month moving average[16], and the items are shown in Table 5-10.

[16] http://ftp.dot.state.tx.us/pub/txdot-info/cmd/cserve/bidprice/as1458.txt

Table 5-10 Items in TxDOT's Average Low Bid Unit Prices

Item Code	Material Description	Color	Line Type	Width	Thickness
677 2002	Eliminate existing marking	N/A	N/A	6 in.	N/A
677 6002	Eliminate existing marking	N/A	N/A	6 in.	N/A
678 2002	Pavement surface preparation	N/A	N/A	6 in.	N/A
666 2023	Reflective pavement marking Type I[17]	White	Solid	6 in.	90 mils
666 2024	Reflective pavement marking Type I	White	Solid	6 in.	100 mils
666 6024	Reflective pavement marking Type I	White	Solid	6 in.	100 mils
666 2119	Reflective pavement marking Type I	Yellow	Solid	6 in.	90 mils
666 2120	Reflective pavement marking Type I	Yellow	Solid	6 in.	100 mils
666 6135	Reflective pavement marking Type I	Yellow	Solid	6 in.	100 mils
666 2014	Reflective pavement marking Type I	White	Broken	6 in.	90 mils
666 2015	Reflective pavement marking Type I	White	Broken	6 in.	100 mils
666 2114	Reflective pavement marking Type I	Yellow	Broken	6 in.	100 mils
666 6014	Reflective pavement marking Type I	White	Broken	6 in.	90 mils
666 6015	Reflective pavement marking Type I	White	Broken	6 in.	100 mils
666 6129	Reflective pavement marking Type I	Yellow	Broken	6 in.	100 mils
8908 2004	Reflective pavement marking all weather[18]	White	Solid	6 in.	100 mils
2240 2004	Reflective pavement marking all weather	White	Solid	6 in.	100 mils
8994 2001	Reflective pavement marking all weather	White	Solid	6 in.	125 mils
8994 2006	Reflective pavement marking all weather	Yellow	Solid	6 in.	125 mils
2240 2002	Reflective pavement marking all weather	Yellow	Solid	6 in.	100 mils
2240 2001	Reflective pavement marking all weather	Yellow	Broken	6 in.	100 mils
2240 2003	Reflective pavement marking all weather	White	Broken	6 in.	100 mils
8908 2003	Reflective pavement marking all weather	White	Broken	6 in.	100 mils
8909 2005	Reflective pavement marking all weather	Yellow	Broken	6 in.	N/A
8994 2004	Reflective pavement marking all weather	Yellow	Broken	6 in.	125 mils
8994 2007	Reflective pavement marking all weather	White	Broken	6 in.	125 mils
8020 2005	Preformed pavement marking Type I[19]	White	Solid	6 in.	100 mils
8020 2009	Preformed pavement marking Type I	Yellow	Solid	6 in.	100 mils
8020 2011	Preformed pavement marking Type I	Yellow	Broken	6 in.	100 mils
8744 2003	Inverted profile pavement marking[20]	Yellow	Solid	6 in.	N/A
8744 2006	Inverted profile pavement marking	White	Solid	6 in.	N/A
8744 2007	Inverted profile pavement marking	White	Broken	6 in.	N/A
666 2149	Reflective pavement marking Type II[21]	White	Solid	6 in.	N/A
666 2181	Reflective pavement marking Type II	Yellow	Solid	6 in.	N/A
666 2146	Reflective pavement marking Type II	White	Broken	6 in.	N/A
8909 2006	Reflective pavement marking wet (paint)	Yellow	Solid	6 in.	N/A
8909 2008	Reflective pavement marking wet (paint)	White	Solid	6 in.	N/A
6473 2004	Multipolymer (polyurea, epoxy etc.)	White	Solid	6 in.	N/A
6473 2014	Multipolymer (polyurea, epoxy etc.)	Yellow	Solid	6 in.	N/A
6473 2005	Multipolymer (polyurea, epoxy etc.)	White	Broken	6 in.	N/A
6473 2015	Multipolymer (polyurea, epoxy etc.)	Yellow	Broken	6 in.	N/A

[17] Hot-applied thermoplastic
[18] All-weather thermoplastic
[19] Preformed thermoplastic
[20] Audible thermoplastic
[21] Paint

5.2.3 *Florida DOT*

Florida is one of the states with NTPEP test decks in recent years; in addition, its climate conditions are similar to Georgia. Florida DOT summarizes its item average unit costs using a 12-month moving average and publishes it online[22]. Items found in the most recent average unit cost are shown in Table 5-11.

Table 5-11 Items in FDOT's Item Average Unit Cost

Item Code	Material Description	Color	Line Type	Width	Thickness
0710 11111	Painted pavement marking	White	Solid	6 in.	N/A
0710 11131	Painted pavement marking	White	Skip	6 in.	N/A
0710 11211	Painted pavement marking	Yellow	Solid	6 in.	N/A
0710 11231	Painted pavement marking	Yellow	Skip	6 in.	N/A
0711 15111	Standard thermoplastic	White	Solid	6 in.	N/A
0711 15131	Standard thermoplastic	White	Skip	6 in.	N/A
0711 15211	Standard thermoplastic	Yellow	Solid	6 in.	N/A
0711 15231	Standard thermoplastic	Yellow	Skip	6 in.	N/A
0711 16111	Standard thermoplastic	White	Solid	6 in.	N/A
0711 16131	Standard thermoplastic	White	Skip	6 in.	N/A
0711 16211	Standard thermoplastic	Yellow	Solid	6 in.	N/A
0711 16231	Standard thermoplastic	Yellow	Skip	6 in.	N/A
0713 102131	Preformed tape	White	Skip	6 in.	N/A

5.2.4 *North Carolina DOT*

North Carolina DOT summarizes bid average history and makes it available online[23]. Items found in the most recent bid average history are summarized in Table 5-12.

[22] ftp://ftp.dot.state.fl.us/LTS/CO/Estimates/12MonthsMoving.pdf
[23] https://connect.ncdot.gov/letting/pages/central-letting-resources.aspx

Table 5-12 Items in NCDOT's Statewide Bid Averages

Item Code	Material Description	Color	Line Type	Width	Thickness
4685000000-E	Thermoplastic	N/A	N/A	4 in.	90 mils
4686000000-E	Thermoplastic	N/A	N/A	4 in.	120 mils
4688000000-E	Thermoplastic	N/A	N/A	6 in.	90 mils
4690000000-E	Thermoplastic	N/A	N/A	6 in.	120 mils
4770000000-E	Cold applied plastic (Tape)	N/A	N/A	4 in.	N/A
4775000000-E	Cold applied plastic (Tape)	N/A	N/A	6 in.	N/A
4810000000-E	Paint	N/A	N/A	4 in.	N/A
4815000000-E	Paint	N/A	N/A	6 in.	N/A
4847000000-E	Polyurea (with elements)	N/A	N/A	4 in.	N/A
4847100000-E	Polyurea (with elements)	N/A	N/A	6 in.	N/A
4850000000-E	Line removal	N/A	N/A	4 in.	N/A
4855000000-E	Line removal	N/A	N/A	6 in.	N/A

5.2.5 Pennsylvania DOT

Pennsylvania is one of the states with NTPEP test decks in recent years. Table 5-13 summarizes PMMs in Pennsylvania DOT's *Publication #287 – Item Price History for Projects Let from 10/4/2012 to 10/9/2014*[24].

Table 5-13 Items in PennDOT's Item Price History for Projects Let

Item Code	Material Description	Color	Line Type	Width	Thickness
0960-0001	Thermoplastic	White	N/A	4 in.	N/A
0960-0002	Thermoplastic	Yellow	N/A	4 in.	N/A
0960-0005	Thermoplastic	White	N/A	6 in.	N/A
0960-0006	Thermoplastic	Yellow	N/A	6 in.	N/A
0962-1000	Waterborne paint	White	N/A	4 in.	N/A
0962-1001	Waterborne paint	White	N/A	6 in.	N/A
0962-1005	Waterborne paint	Yellow	N/A	4 in.	N/A
0962-1006	Waterborne paint	Yellow	N/A	6 in.	N/A
0963-0004	Marking removal	N/A	N/A	4 in.	N/A
0963-0006	Marking removal	N/A	N/A	6 in.	N/A
0964-0001	Epoxy	White	N/A	4 in.	N/A
0964-0002	Epoxy	Yellow	N/A	4 in.	N/A
0964-0005	Epoxy	White	N/A	6 in.	N/A
0964-0006	Epoxy	Yellow	N/A	6 in.	N/A
0965-0001	Preformed Thermoplastic	White	N/A	4 in.	N/A
0965-0002	Preformed Thermoplastic	Yellow	N/A	4 in.	N/A
0965-0005	Preformed Thermoplastic	White	N/A	6 in.	N/A

[24] ftp://ftp.dot.state.pa.us/public/Bureaus/design/Pub287/Pub%20287.pdf

5.2.6 *Minnesota DOT*

Minnesota is also one of the states with NTPEP test decks in recent years. Table 5-14 summarizes PMMs included in MnDOT's average bid prices for awarded projects from 1/1/2014 to 7/31/2014, which is published on MnDOT's website[25].

Table 5-14 Items in MnDOT's Average Bid Prices for Awarded Projects

Item Code	Material Description	Color	Line Type	Width	Thickness
2102.502/00010	Pavement marking removal	N/A	N/A	4 in.	N/A
2582.502/11104	Paint	White	Solid	4 in.	N/A
2582.502/11106	Paint	White	Solid	6 in.	N/A
2582.502/11204	Paint	White	Broken	4 in.	N/A
2582.502/12104	Paint	Yellow	Solid	4 in.	N/A
2582.502/12106	Paint	Yellow	Solid	6 in.	N/A
2582.502/12204	Paint	Yellow	Broken	4 in.	N/A
2582.502/21104	Preformed poly (Tape)	White	Solid	4 in.	N/A
2582.502/21204	Preformed poly (Tape)	White	Broken	6 in.	N/A
2582.502/41104	Epoxy	White	Solid	4 in.	N/A
2582.502/41106	Epoxy	White	Solid	6 in.	N/A
2582.502/41204	Epoxy	White	Broken	4 in.	N/A
2582.502/42104	Epoxy	Yellow	Solid	4 in.	N/A
2582.502/42204	Epoxy	Yellow	Broken	4 in.	N/A
2582.603/11105	Paint (wet reflective)	White	Solid	4 in.	N/A
2582.603/11106	Paint (wet reflective)	White	Solid	6 in.	N/A
2582.603/11204	Paint (wet reflective)	White	Broken	4 in.	N/A
2582.603/12104	Paint (wet reflective)	Yellow	Solid	4 in.	N/A
2582.603/12204	Paint (wet reflective)	Yellow	Broken	4 in.	N/A
2582.603/61104	Epoxy (wet reflective)	White	Solid	4 in.	N/A
2582.603/61106	Epoxy (wet reflective)	White	Solid	6 in.	N/A
2582.603/61204	Epoxy (wet reflective)	White	Broken	4 in.	N/A
2582.603/62104	Epoxy (wet reflective)	Yellow	Solid	4 in.	N/A
2582.603/62204	Epoxy (wet reflective)	Yellow	Broken	4 in.	N/A

[25] http://www.dot.state.mn.us/bidlet/avgPrice.html

5.2.7 *Oregon DOT*

Unlike other state DOTs, Oregon DOT was selected in this analysis because it is one of the few state DOTs that commonly use MMA. PMMs included in Oregon DOT's weighted average item prices report[26] are summarized in Table 5-15.

Table 5-15 Items in Oregon DOT's Weighted Average Item Prices

Item Code	Material Description	Color	Line Type	Width	Thickness
0860-0200000F	Paint	N/A	N/A	4 in.	15 mils
0865-0116500F	Methyl Methacrylate (profiled)	N/A	N/A	4 in.	N/A
0865-0116530F	Methyl Methacrylate (non-profiled)	N/A	N/A	4 in.	N/A
0865-0116600F	Thermoplastic (profiled)	N/A	N/A	4 in.	N/A
0865-0116610F	Thermoplastic (non-profiled)	N/A	N/A	4 in.	N/A
0865-0119600F	Thermoplastic (sprayed)	N/A	N/A	4 in.	N/A
0865-0127000F	Tape	N/A	N/A	4 in.	N/A
0865-0140000F	Thermoplastic (non-profiled)	N/A	N/A	4 in.	120 mils
0865-0150000F	Methyl Methacrylate (non-profiled)	N/A	N/A	4 in.	N/A
0865-0160000F	Thermoplastic (non-profiled)	N/A	N/A	4 in.	N/A
0866-0103000F	High-build paint	N/A	N/A	4 in.	25 mils

5.2.8 *Summary of Pavement Marking Costs*

Most items in these seven state DOTs' item unit cost summaries provide specific information about the line type (solid or skip/broken) and color information; therefore, in this study, the general price ranges of different PMMs in a similar fashion are summarized. Items without specified color and line type information are also summarized to provide general information about the cost ranges. Similar items in different state DOTs' summaries are combined into different material categories. For example, TxDOT's reflective pavement marking wet (paint)

[26] http://www.dot.state.mn.us/bidlet/avgPrice.html

and MnDOT's paint (wet reflective) are categorized into all-weather paint in Table 5-16. All information summarized in Table 5-16 is based on materials that have been commonly used in the seven DOTs. To develop a cost range table that provides general cost information and avoid fluctuated prices due to small quantities or other special situations, in this table, only the costs of materials used on projects longer than 2 miles are summarized. In other words, if a PMM was, on average, used for projects shorter than 2 miles, its associate costs were not considered in Table 5-16.

Table 5-16 into Table 5-17 list a general PMM cost ranges according to the six material types summarized in Section 4.1. Note that for consistency, only the costs of non-skip lines are used to generate Table 5-17. The cost ranges summarized in this table are also consistent with previous studies and literature, such as the *NCHRP Synthesis 306* report (Migletz & Graham, 2002), *Pavement Marking Handbook* (Texas Department of Transportation, 2004), and *Evaluating Pavement Markings on Portland Cement Concrete (PCC) and Various Asphalt Surfaces* (Dwyer et al., 2013).

Table 5-16 Average PMM Unit Price Summary[27]

<table>
<tr><th>Material</th><th>Color</th><th>Type</th><th>Minimum ($/lf)</th><th>Maximum ($/lf)</th></tr>
<tr><td rowspan="5">Standard Paint</td><td rowspan="2">White</td><td>Solid</td><td>0.08</td><td>0.20</td></tr>
<tr><td>Skip</td><td>0.07</td><td>0.17</td></tr>
<tr><td rowspan="2">Yellow</td><td>Solid</td><td>0.10</td><td>0.21</td></tr>
<tr><td>Skip</td><td>0.08</td><td>0.09</td></tr>
<tr><td>N/A</td><td>N/A</td><td>0.13</td><td>0.24</td></tr>
<tr><td rowspan="4">All Weather Paint</td><td rowspan="2">White</td><td>Solid</td><td>0.36</td><td>0.48</td></tr>
<tr><td>Skip</td><td>0.38*</td><td>0.38*</td></tr>
<tr><td rowspan="2">Yellow</td><td>Solid</td><td>0.33</td><td>0.36</td></tr>
<tr><td>Skip</td><td>0.36</td><td>0.36</td></tr>
</table>

[27] Price ranges summarized from state DOTs' items with an average of 2 miles or more per usage

Material	Color	Type	Minimum ($/lf)	Maximum ($/lf)
Standard Thermoplastic	White	Solid	0.41	0.82
		Skip	0.27	0.52
	Yellow	Solid	0.41	0.81
		Skip	0.22	0.26
	N/A	N/A	0.48	0.97
All Weather Thermoplastic	White	Solid	0.66	0.69
		Skip	0.74	0.78
	Yellow	Solid	0.52	0.69
		Skip	0.65	0.74
Preformed Thermoplastic	White	Solid	0.83	0.83
		Skip	N/A	N/A
	Yellow	Solid	0.95	0.95
		Skip	0.89*	0.89*
Preformed Tape	White	Solid	3.18	3.18
		Skip	1.71*	2.74*
	Yellow	Solid	3.18	3.18
		Skip	2.85*	2.85*
	N/A	N/A	1.82	3.08
Epoxy	White	Solid	0.28	0.44
		Skip	0.52	0.52
		N/A	0.37	0.37
	Yellow	Solid	0.32	0.48
		Skip	0.48*	0.48*
		N/A	0.39	0.63
All Weather Epoxy	White	Solid	0.56	0.72
		Skip	0.72*	0.72*
	Yellow	Solid	0.62	0.62
		Skip	0.55	0.55
Polyurea	White	Solid	0.44	0.44
		Skip	0.52	0.52
	Yellow	Solid	0.48	0.48
		Skip	0.48*	0.48*
All Weather Polyurea	N/A	N/A	0.84	1.15
Methyl Methacrylate	N/A	N/A	1.83	1.83
Marking Removal	N/A	N/A	0.46	0.71
Surface Preparation	N/A	N/A	0.05	0.05

* Unit price averaged from less than 2 mile per usage

Table 5-17 Summary of PMM Costs

Material	Unit Cost Low (per lf)	Unit Cost High (per lf)
Paint	$0.08	$0.48
Thermoplastic	$0.41	$0.97
MMA	$1.83	$1.83
Tape	$1.82	$3.18
Epoxy	$0.28	$0.72
Polyurea	$0.44	$1.15
Marking Removal	$0.46	$0.71
Surface Prep	$0.00	$0.05

5.3 Life-Cycle Cost Analysis

To evaluate the cost-effectiveness of different PMMs on the same basis, a 10-year LCCA is conducted in this section. Table 5-18 recalls the expected high and low service lives, as well as unit costs of six different marking materials summarized in previous sections. Some basic assumptions made of the LCCA are as follows:

1. Since all service lives are presented in months, a 0.3274% monthly compound discount rate is assumed (which is equivalent to a 4% annual discount rate, a typical discount rate used by GDOT);
2. For every installation, existing pavement marking removal as well as surface preparation expenses apply;
3. A high life-cycle cost is calculated using the low costs and the high-service life;
4. A low life-cycle cost is calculated using the high costs and the low-service life; and
5. No salvage value is expected.

Table 5-18 Expected Service Life and Unit Costs of Marking Materials

Material	Service Life Low (months)	Service Life High (months)	Unit Cost Low (per lf)	Unit Cost High (per lf)	Other Cost Low (per lf)	Other Cost High (per lf)
Paint	12	51	$0.08	$0.48	$0.00	$0.05
Thermoplastic	26	103	$0.41	$0.97	$0.00	$0.05
MMA	38	62	$1.83	$1.83	$0.00	$0.05
Tape	27	65	$1.82	$3.18	$0.46	$0.76
Epoxy	24	60	$0.28	$0.72	$0.00	$0.05
Polyurea	36	60	$0.44	$1.15	$0.00	$0.05

Note that other cost of marking materials in Table 5-18 include both the removal and surface preparation costs. It is assumed that there is no removal cost if the PMM is compatible to be reapplied to the same material type (see Table 5-20). For example, since paint can be directly applied on top of existing paint, the other cost of paint ranges from $0 (no removal nor surface preparation needed) to $0.05 (surface preparation needed). For tape, since the general practice of tape is to not restripe it on existing tape, a removal cost is needed. The other cost range for tape is, therefore, from $0.46 (low cost removal only) to $0.76 (high-cost removal plus surface preparation).

Table 5-19 PMM Compatibility Matrix (Adopted from TxDOT)

Original Material	New Material					
	Paint	Thermo-plastic	Preformed Tape	Epoxy	Polyurea	MMA
Paint	Y	Y	N	N	N	N
Thermoplastic	Y	Y	N	N	N	N
Preformed Tape	N	N	N	N	N	N
Epoxy	Y	Y	N	Y	N	--
Polyurea	Y	Y	N	N	Y	--
MMA	Y	Y	N	N	--	Y

Using preformed tape as an example, the detailed steps for calculating the high life-cycle cost of tape is demonstrated below:

1) Cash flow diagram:

   Figure 5-1 shows a cash flow diagram of tape throughout the 10-year analysis period. Since we are calculating the high life-cycle cost, we use the short service life (i.e., 27 months), the high unit cost ($3.18/lf), and the high removal cost ($0.71/lf) for the following calculation:

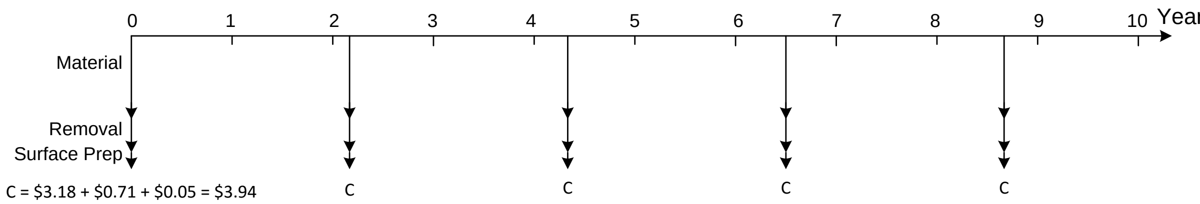


Figure 5-1 Cash Flow Diagram for Thermoplastic

2) Net present value:

To calculate the total net present value (NPV) of this cash flow diagram, we first calculate the effective discount rate for each payment period (i.e., 27 months) using the following equation:

$$i_{payment} = (1 + i_{month})^{27} - 1 \tag{5.1}$$

where

$i_{payment}$ = effective discount rate per payment period (i.e., 27 months); and

i_{month} = monthly discount rate, 0.3274%.

From Equation 5.1, we get the effective discount rate of 9.226%. Therefore, the NPV of this diagram can be calculated using the following equation:

$$NPV = C + C \times \frac{(1+i_{payment})^n - 1}{i_{payment}(1+i_{payment})^n} \tag{5.2}$$

$$= \$3.94 + \$3.94 \times \frac{(1+9.226\%)^4 - 1}{9.226\%(1+9.226\%)^4}$$

$$= \$16.64$$

where

NPV = net present value;

C = uniform cost per payment period, which includes PMM cost, marking removal cost, and surface preparation cost; and

n = number of payment periods, not counting the first payment that is made in year 0.

3) Equivalent annual uniform cost:

The high life-cycle cost of tape can then be calculated by converting the NPV to an equivalent annual cost using the following equation:

$$LCC = NPV \times \frac{i_{annual}(1+i_{annual})^m}{(1+i_{annual})^m - 1} \quad (5.3)$$

$$= \$16.64 \times \frac{4\%(1+4\%)^{10}}{(1+4\%)^{10} - 1}$$

$$= \$2.05/lf/yr$$

where

LCC = life-cycle cost per linear foot per year;

i_{annual} = effective discount rate per year, $(1 + i_{month})^{12} - 1 = 4\%$; and

m = number of years = 10.

Following the above three steps, the high life-cycle cost of tape is \$2.05 per linear foot per year, as shown in the last column in Table 5-20. Using the same steps, all low and high life-cycle costs for all PMMs can be computed, and they are shown in Table 5-20. In addition, Figure 5-2 illustrates the ranges of life-cycle cost of different PMMs; in this figure, it is clearly seen that there is not a single material that is completely cheaper or more expensive than another material. In addition to life-cycle costs, the selection of PMM will, also, be dependent on other factors, such as material properties, traffic conditions, amount of material used, and weather conditions, which we discuss more in the next section.

Table 5-20 Life-Cycle Costs for Marking Materials

Material	Low Life-Cycle Costs (per lf/yr)	High Life-Cycle Cost (per lf/yr)
Paint	$0.03	$0.55
Thermoplastic	$0.09	$0.53
MMA	$0.41	$0.78
Tape	$0.51	$2.05
Epoxy	$0.06	$0.41
Polyurea	$0.10	$0.50

From the results of LCCA, four materials, including paint, thermoplastic, epoxy, and polyurea show comparable life-cycle cost ranges, indicating that under the assumptions in the analysis, these four material are expected to have similar costs throughout the same analysis period. MMA and tape, on the other hand, are expected to cost more than the aforementioned four materials under the same assumptions.

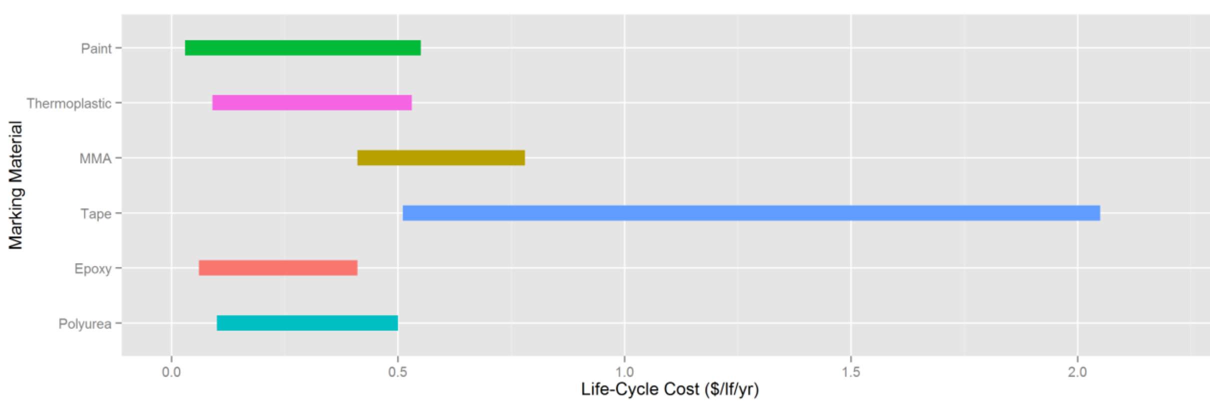


Figure 5-2 Life-Cycle Cost Ranges of Different PMMs

Note that some advantages of PMMs, such as high wet retroreflectivity and short/no drying time, were not reflected in the LCCA in this study, and this is part of the reason that MMA and tape seemed to be much more expensive than other materials. These advantages can have benefits, such as shortened traffic control time (user cost saving) and increased safety. In future research, a benefit-cost analysis may be conducted to consider and compare possible benefits of PMMs.

5.4 Proposed Pavement Marking Material Selection Matrix

Based on the LCCA results, as well as engineering experiences summarized from state DOTs' practices, a pavement marking selection matrix for GDOT is proposed in Table 5-21.

Table 5-21 A Proposed PMM Selection Matrix for GDOT

Total AADT	Asphalt			Concrete*		
	2 Lanes	4 Lanes	Interstate /Freeway	2 Lanes	4 Lanes	Interstate /Freeway
n < 8,000	T/H/E/P	T/H/E/P		E/P	E/P	
8,000 ≤ n <15,000	T/E/P	T/H/E/P	T/E/P/M	E/P	E/P	E/P/M
15,000 ≤ n <40,000	T/E/P/M	T/E/P/M	T/E/P/M/F	E/P/M	E/P/M	E/P/M/F
n ≥ 40,000		T/E/P/M/F	T/E/P/M/F		E/P/M/F	E/P/M/F

H – Highbuild Paint and Wet Weather Paint Traffic Stripe
T – Standard and Wet Weather Thermoplastic Traffic Stripe
F – Preformed Plastic Pavement Markings
P – Standard and Wet Weather Polyurea Traffic Strip
E – Standard and Wet Weather Epoxy Traffic Strip
M – Methyl Methacrylate

*Contrast markings shall be used for all lane lines on PCC surfaces

As shown in this table, the recommended use of the materials summarized below:

1) **Paint**: paint material is used only on asphalt concrete pavements with low AADT, such as 2-lane highways with total AADT < 8,000 vehicles/day, or 4-lane highways with total AADT < 15,000. GDOT does not recommend use of paint on concrete pavements.
2) **Thermoplastic**: thermoplastic has exceptionally good life-cycle cost range and can be used on all asphalt pavements. It could possibly be used on concrete pavements, but caution needs to be taken to ensure the quality of thermoplastic on concrete pavements. GDOT does not recommend use of thermoplastic on concrete pavements.
3) **Epoxy and polyurea**: these two materials are low-cost, durable materials that can be used on all types of surfaces under all traffic conditions.

4) **MMA**: MMA performs like other durable materials, such as thermoplastic and tape; its unique patterned texture can provide good wet retroreflectivity; moreover, it can be used on all surface types; however, due to its higher unit cost, this type of material is only recommended to be used for high traffic volume roads.
5) **Tape**: similarly, tape performs like other durable materials. One great advantage of tape is that no drying time is required for its installation; in addition, patterned tapes can provide high wet retroreflectivity. Tape can also perform consistently under various weather and traffic conditions; it can also perform consistently in different line colors and on different pavement surface types. Due to its high life-cycle cost, nevertheless, tape is only considered/recommended for use on roads with a high volume of traffic.

6. DEVELOPMENT OF GDOT PAVEMENT MARKING HANDBOOK AND INTERACTIVE TUTORIAL

This chapter summarizes the development of the GDOT Pavement Marking Handbook and the interactive tutorial. The first section presents the objectives and organization of the handbook. The second section presents the objectives and design of tutorial.

6.1 Objectives and Organization of Handbook

The objective of this handbook is fourfold. First, this handbook gives a summary of standard test methods, practices, and specifications used in Georgia. Second, it provides a list of commonly used PMMs and their properties and notes for installation. Third, it provides general pre-installation and post-installation preparation and inspection procedures. Fourth, it provides PMM selection suggestions based on the cost-effectiveness of different materials under the considerations of different traffic conditions, surface types, and functionalities of roads.

The handbook consists of three major topics: PMMs, pavement marking installation inspection, and PMM selection. The first topic, PMMs, comprehensively covers commonly used PMMs in terms of the history, physical properties, application procedures, and advantage and disadvantages. The second topic, pavement marking installation inspection, describes the general required procedures to prepare pavement surface for installation and the methods for inspecting and assessing pavement marking performance. The third topic, PMM selection, summarizes material costs and expected performance in terms of service life and provides suggestions for cost-effective PMMs according to the road's traffic condition, surface type, and functionalities. For details, the full version of the handbook is shown in Appendix I.

6.2 Objectives and Design of the Interactive Tutorial

The objective of the interactive tutorial is to convert texts into interactive messages that combine texts, images, videos, and interactive functions to help users navigate through the tutorial and find the information they need.

The design of this interactive tutorial is to provide intuitive navigation for users to quickly absorb information. Instead of putting everything in texts and tables, we use icons, figures, videos, and interactive functions to help achieve this goal. Below are some examples of the simple and easy design of this tool. Figure 6-1 shows the home page of this tool. With four images clearly show the functions provided, users can easily select the function/topic they would like to use or learn. Figure 6-2 shows the material selection page. This page is designed for decision-makers to quickly identify cost-effective materials by entering the traffic condition, pavement surface type, and roadway functionality. Figure 6-3 shows the installation inspection page, which consists of two main modules: inspection before installation and inspection after installation. Again, simple image and text combination on this page helps the target users easily navigate to the information they would like to learn.

Figure 6-4 shows the material description page, which conveys fundamental knowledge, such as material properties, costs, usage, advantages and disadvantages, and some requirements of different PMMs, which allows newly hired engineers to quickly navigate and absorb the information. Similarly, Figure 6-5 provides detailed information of reflective beads, which is also essential to pavement markings, allowing users to quickly learn and navigate the handbook to learn the fundamental knowledge, such as types, properties, and usage, of reflective beads.

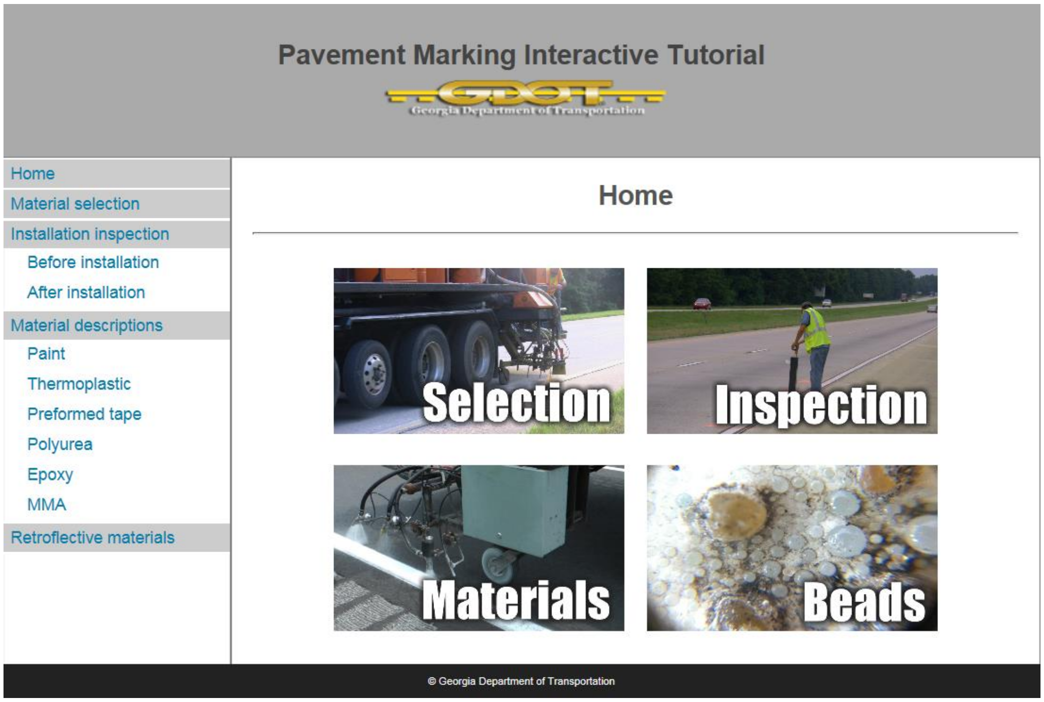


Figure 6-1 Home Page of the Interactive Tutorial

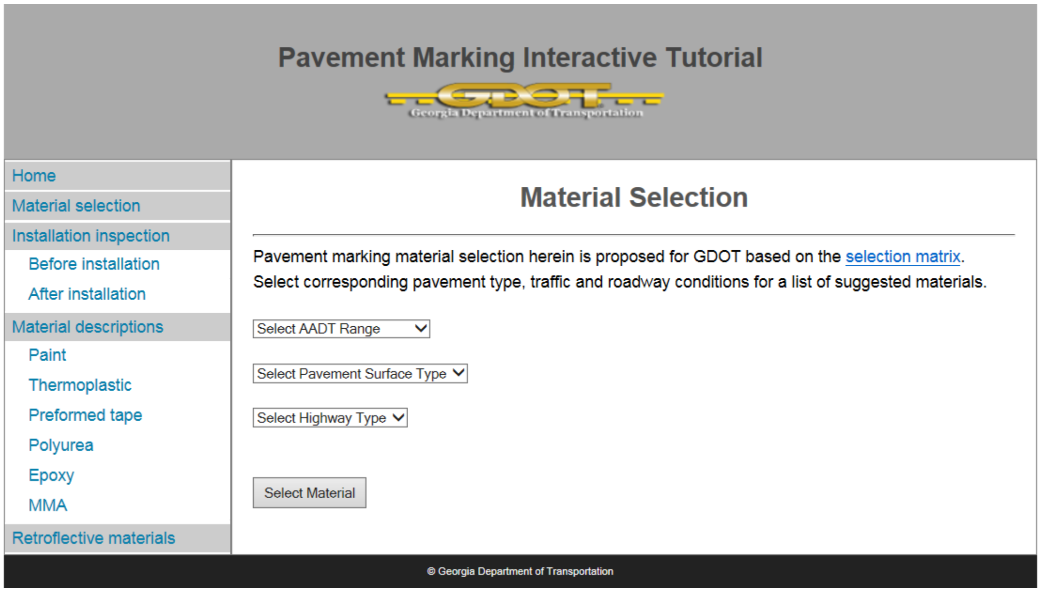


Figure 6-2 Interactive Material Selection Functions on the Material Selection Page

Figure 6-3 Installation Inspection Page

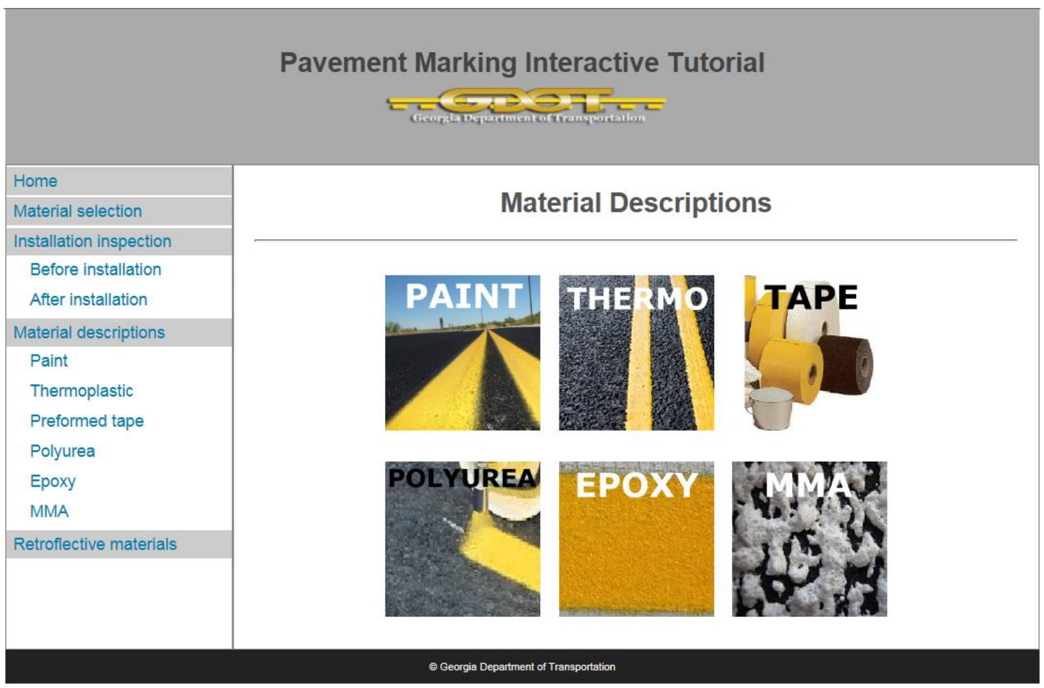


Figure 6-4 Common Materials on the Material Description Page

Pavement Marking Interactive Tutorial

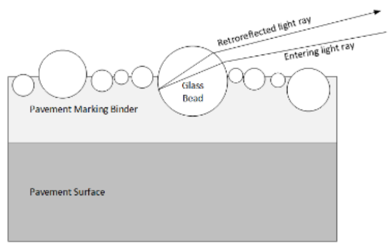
Georgia Department of Transportation

- Home
- Material selection
- Installation inspection
  - Before installation
  - After installation
- Material descriptions
  - Paint
  - Thermoplastic
  - Preformed tape
  - Polyurea
  - Epoxy
  - MMA
- Retroflective materials

Retroflective Materials

Retroreflectivity is one of the most critical factors that provide nighttime and wet visibility of traffic control devices, including traffic signs, pavement markings, and other safety and delineation means. The Federal Highway Administration (FHWA) has required minimum retroreflectivity levels on traffic signs with different colors and sheeting types, and is working on determining similar requirements for pavement markings.

Retroreflectivity of pavement markings is achieved by affixing retroreflective materials to the surface of markings (see the figure below). There are a variety of type of glass spheres and other retroreflective optics available in the market and their properties and applications play a crucial role in the performance of the finished markings. This section depicts the types of glass sheres and reflective composite optics available, the properties of bead application, and the factors that affect these properties that contribute to the short-term and long-term performance of pavement markings.



A Light Retroreflected by a Reflective Bead

Bead Types | Physical Properties | Application Properties | Influencing Factors

Glass Spheres

The American Association of State Highway and Transportation Officials (AASHTO) have developed a Standard Specification for Glass Beads Used in Pavement Markings [1] that specified the types and requirements of standard glass spheres used in pavement markings.

Currently, there are five different types of glass spheres, differentiated by their difference in the size and gradation of beads as shown in the table below. Typically, the size of the beads increases (small to large) as the type number increases from 0 to 5. Moreover, larger beads are more likely to have better retroreflectivity especially in wet conditions because the impact of the refraction of the water film would be smaller.

Figure 6-5 Reflective Beads Page

7. CONCLUSIONS AND RECOMMENDATIONS

In this study, a pavement marking handbook was developed for GDOT in support of the standard procedures for PMM selection, installation, and inspection. In addition, an interactive tutorial tool was also developed to facilitate the learning of the handbook. Key contributions and findings of this study are summarized below:

1) A 4-step method was proposed to cleanse pavement marking retroreflectivity data for better service life prediction using statistical analysis. This method can effectively identify and remove irregular retroreflectivity measurements that are inconsistent spatially (e.g., readings collected at intersections) and temporally (e.g., retroreflectivity jump). Using this proposed method, simple linear regression models were developed to predict retroreflectivity on GDOT Test Deck.
2) Multiple linear regression models were developed to predict pavement marking retroreflectivity using NTPEP data. In order to develop these models with important variables and prevent overfitting, statistical test methods were applied to identify significant independent variables with higher prediction power; the final variables for the MLMs include ADT, maximum retroreflectivity, and elapsed days. Results of this analysis indicate that the MLMs developed were robust (had high R-squared values).
3) Expected service lives of PMMs were derived from the simple linear models for the GDOT test deck data and from MLMs for the NTPEP data. Results of these expected life were combined with recent literature to develop a comprehensive range of expected life for each type of material. Similarly, unit costs of PMMs were summarized from seven state DOTs to synthesize a range of potential unit cost for each type of material.

4) LCCA was conducted using the service life and cost ranges synthesized in this study, and life-cycle cost ranges of six different materials, including paint, thermoplastic, tape, epoxy, polyurea, and methyl methacrylate, were calculated. These results provide rich, general information for each type of material, which can be used by other agencies. In addition, providing a range of costs instead of a specific value can better reflect the real world contract situation, which can, therefore, better support decision-making and material selection.
5) A handbook and an interactive tutorial were developed for GDOT. The handbook is a useful resource for GDOT's day-to-day practices, training, and decision-making regarding PMMs; they serves as a good foundation for future studies. Development of the interactive tutorial can allow target users, such as decision- makers and newly hired employees/trainees to navigate and obtain information needed efficiently and effectively.

Recommendations for future research are as follows:

1) It is recommended to develop training material on a) PMM selection and field inspection, b) test deck data filtering and data processing, and c) use of the developed interactive tutorial tool for implementation of this research outcomes. The training material is valuable to GDOT and to local transportation agencies for a standardized operation, and for knowledge transfer.
2) It is recommended to update and refine the life/performance matrix for Georgia's specific data for the refined decision matrix. One possible approach is to use the existing required retroreflectivity data reported during the initial and 6-month inspections of all newly installed pavement markings.

3) A pool fund study for collecting and sharing the pavement marking performance data in the southeast states with similar weather condition, is also recommended.
4) For pavement marking asset management, more routine and accurate methods, e.g., mobile retroreflectivity measurements using mobile retroreflectometer or Light Detection and Ranging (LiDAR) sensing technology, need to be explored.
5) A benefit-cost analysis can be conducted to take into consideration the potential benefits of PMMs. Examples of potential benefits include user cost saving as a result of shorter traffic control, as well as reduced crash rate as a result of more visible pavement markings, especially under dark and wet conditions.
6) Bead embedment and bead dispersion (e.g. density) will also impact the performance of pavement marking retro-reflectivity and a routine field inspection method need to be developed.

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APPENDIX I GEORGIA DOT PAVEMENT MARKING HANDBOOK

Georgia Department of Transportation

Pavement Marking Handbook

Prepared by:
Georgia Institute of Technology

Prepared for:
Georgia Department of Transportation

December 2015

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I. INTRODUCTION

Pavement markings, including striping, texts, and symbols, on both state-maintained and local roads provide important guidance and information for road users. Several specifications and other sources of pavement marking installation and inspection information have been developed by Federal transportation agencies, such as the Federal Highway Administration (FHWA), the American Association of State Highway and Transportation Officials (AASHTO), and the American Society for Testing and Materials (ASTM), and state DOTs, such as the Georgia Department of Transportation (GDOT) and the Texas DOT. In addition, various studies have been performed to evaluate the performance of different pavement marking materials and their cost-effectiveness. This handbook is intended to gather and synthesize comprehensive information about pavement marking materials, including material properties, installation, inspection, costs, and expected performance, with a special focus on the applications in Georgia.

This document includes results from the GDOT Research Project No. 12-31, *Developing a GDOT Pavement Marking Handbook using Field Test Deck Evaluation and Long-term Performance Analysis*, including the comprehensive literature review, the analysis of GDOT and National Transportation Product Evaluation Program (NTPEP) test decks, and the life-cycle cost analysis of selected pavement marking materials (PMMs); it also presents a PMM selection matrix that synthesizes the aforementioned components into recommended usage of PMMs under different traffic conditions and pavement surface types.

This handbook is organized as follows: Chapter 2 introduces commonly used pavement marking materials, their characteristics, and application procedures. Chapter 3 summarizes the general process and preparation of pavement marking installation and inspection. Chapter 4 presents the proposed PMM selection matrix for GDOT.

II. PAVEMENT MARKING MATERIALS

2.1 Overview
In this chapter, a variety of commonly used pavement marking materials is reviewed. The use of these materials in Georgia, their characteristics, and application procedures are summarized. In addition to the materials (binders), retroreflective bead properties and performance are discussed.

2.2 Pavement Marking Materials
2.2.1 Introduction
Many pavement marking materials have been used by different state DOTs. However, the performance, costs, and service lives vary significantly from product to product. How to cost-effectively select pavement marking materials in different regions of the state remains challenging. In this section, the characteristics and application procedures of a variety of commonly used pavement marking materials are summarized.

2.2.2 Summary of Georgia's Specifications
The most common pavement marking materials in Georgia and their specifications[1] are as follows:
- Standard Specification Section 652 – Painting Traffic Stripe
- Standard Specification Section 653 – Thermoplastic Traffic Stripe
- Standard Specification Section 657 – Preformed Plastic Pavement Markings
- Standard Specification Section 658 – Polyurea Traffic Stripe
- Standard Specification Section 659 – Hot Applied Preformed Plastic Pavement Markings
- Special Provision Section 661– Standard and Wet Weather Epoxy Traffic Stripe
- Standard Specification Section 870 – Paint

Qualified Product Lists of pavement marking materials are as follows:
- QPL 46 – Traffic Markings
- QPL 71 – Glass Bead Manufacturers
- QPL 74 – Preformed Plastic Markings
- QPL 76 – Raised Pavement Markers and Channel Markers

2.2.3 Paint
<u>Introduction</u>
Paint was the first ever pavement marking material and has been used widely on all roads in the United States. It is, also, primarily, the least expensive pavement marking material available. Because paint is typically less durable than other pavement marking materials, it is mostly used on roads with low traffic volumes (e.g., total AADT < 8,000 veh/day). In Georgia, paint is used only on asphalt pavements. GDOT's specifications for the paint material can be referred to *Standard Specification Section 652 – Painting Traffic Stripe*, and *Section 870 – Paint*.

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[1] Revised on August 24, 2012 and first use on October 19, 2012.

Characteristics and General Requirements

Material Composition

Traffic stripe paint material consists of two major components: the pigment and the vehicle. The pigment component is the colorant by which the color of the paint is determined. The vehicle component serves as the binder and diluent that provides adherence and spreadability to paint. GDOT's requirements for the composition of traffic stripe paint are shown in Table 1.

Table 1 Waterborne Traffic Line Paint Composition Requirements

Requirement		Maximum	Minimum
Paint composition (percent by weight)	Pigment	63.0	60.0
	Vehicle	40.0	37.0
Non-volatile vehicle (percent by weight of vehicle)		50.0	42.0

Retroreflective Beads

In addition to the paint material, retroreflective beads (e.g., glass spheres/reflective composite optics) are required for use in luminous traffic lines. GDOT specifies the use of AASHTO M 247 beads and/or reflective composite optics to ensure the high-build paint pavement markings meet the reflectance performance requirements. Do not use glass spheres and/or reflective composite optics containing greater than 200 ppm total arsenic, 200 ppm total antimony, or 200 ppm total lead when they have been tested according to US EPA Methods 3052 and 6010C or other approved methods. See Section 2.3 for detailed descriptions of glass spheres and reflective composite optics.

Advantages and Disadvantages

Table 2 summarizes some of the major advantages and disadvantages of paint markings.

Table 2 Pros and Cons of Paint

Advantages	Disadvantages
• Fast curing time • Low unit cost • Cost-effective on lower volume roads	• Not suitable for high traffic volume roads • Adhesive is weaker on concrete

Application

Equipment

Unless areas or markings are not adaptable to machine application, use a traffic stripe painter (Figure 1) that can travel at a predetermined speed both uphill and downhill, applying paint uniformly. The paint machine should be equipped with the following:

1. Three adjacent spray nozzles capable of simultaneously applying separate stripes, either solid or skipped, in any pattern
2. Nozzles equipped with the following:
    - Cutoff valves for automatically applying skip lines
    - A mechanical bead dispenser that operates simultaneously with the spray nozzle to uniformly distribute beads at a specified rate

    - Line-guides consisting of metallic shrouds or air blasts
3. Tanks with mechanical agitators
4. Small, portable applicators or other special equipment as needed

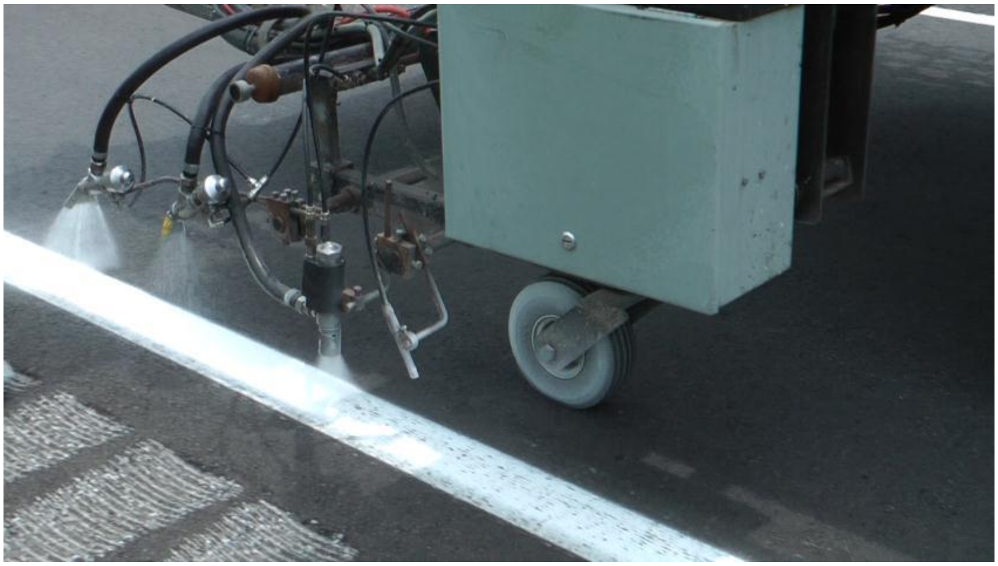

Figure 1 Application of High Build Waterborne Paint

Application Settings

1. Application rates:
    - Apply 5-in-wide (125 mm) traffic stripe at the following minimum rates:
        - Solid traffic stripe paint: at least 34 gal/mile (80 L/km)
        - Skip traffic stripe paint: at least 10 gal/mile (24 L/km)
    - Apply a layer of glass spheres and/or reflective composite optics at a rate to meet the reflectance performance requirements specified in Section 3.3.6 immediately after laying the paint.
2. Thickness:
   Apply the paint material at a rate to maintain a 25 mils (0.58mm) minimum wet average thickness above the surface of the pavement.

Application Conditions

Do not apply paint to areas of pavement when:

- The surface is moist or covered with foreign matter
- Air temperature in the shade is below 50°F (10 °C)
- Wind causes dust to land on prepared areas or blows paint and retroreflective beads around during application

2.2.4 Thermoplastic

Introduction

Thermoplastic is one of the most commonly used and durable pavement marking materials in the United States[2]. In Georgia, thermoplastic has been widely used on asphalt pavements, primarily on medium-level traffic (approximately $8,000 \leq$ AADT $< 15,000$), interstate highways, and non-interstate roads, as well as on high-traffic volume (approximately AADT $\geq 15,000$) non-interstate roads. Detailed thermoplastic material specifications can be found in GDOT's *Standard Specification Section 653 – Thermoplastic Traffic Stripe*, as well as *AASHTO Designation M 249 – Standard Specification for White and Yellow Reflective Thermoplastic Striping Material* (Solid Form).

Characteristics and General Requirements

Thermoplastic material is composed of resin (binder), pigment, and retroreflective beads; the composition and characteristics of this material are as follows:

Resin and Pigment

- Alkyd binder consists of a mixture of synthetic resins with at least one resin that is solid at room temperature, and high boiling point plasticizers
- A total binder content of 18% or more by weight
- A pigmented binder that is well-dispersed and free of dirt, foreign objects, or ingredients that cause bleeding, staining, or discoloration
- At least 50% of the binder composition or at least 8% by weight of the entire material formulation is 100% maleic-modified glycerol ester resin

Retroreflective Beads

- Glass spheres and/or reflective composite optics of thermoplastic markings must be intermixed and dropped on
- Use glass spheres and/or reflective composite optics that meet the requirements of GDOT's specifications (see Section 3.3.6 for details)
- Do not use glass spheres and/or reflective composite optics containing greater than 200 ppm total arsenic, 200 ppm total antimony, or 200 ppm total lead when tested according to US EPA Methods 3052 and 6010C or other approved methods

Advantages and Disadvantages

Table 3 summarizes the major advantages and disadvantages of thermoplastic markings.

Table 3 Pros and Cons of Thermoplastic

Advantages	Disadvantages
• Improved nighttime visibility • Low unit cost • Excellent durability on asphalt • Fast curing time	• Less durable on concrete • Preformed thermoplastic performs less consistently • Can be damaged by snow plows

[2] Source: NCHRP Synthesis 306, Table 31.

Application

Equipment

Hand equipment and truck-mounted application units are used for installation of thermoplastic material based on the marking required.

1. Application machine:
    - Primary equipped features:
        - Parts continuously mix and agitate the material
        - Truck-mounted units for uniform application of striping material; the unit is mobile and maneuverable enough to follow straight lines and make normal curves in a true arc
        - Mixing and conveying parts, including the shaping die or gun, maintain the material at the plastic temperature with heat transfer oil or electrical element controlled heat. Do not use an external source of direct heat
        - Conveying parts between the main material reservoir and the shaping die or gun to prevent accumulation and clogging
        - Applicator cleanly and squarely cuts off stripe ends and applies skip lines
        - Parts produce varying widths of markings
    - Automatic bead dispenser:
        - Apply reflective beads to the surface of the stripe using a dispenser attached to the application machine to automatically dispense the beads instantaneously upon the installed line
        - Synchronize the bead dispenser cutoff with the automatic cutoff of the thermoplastic material
    - Special kettle:
      Use a kettle equipped with automatic thermoplastic control devices that provide positive temperature control and prevent overheating
2. Hand equipment:
    - Use hand equipment for projects with small quantities of lane lines, edge lines, and center lines or for conditions requiring the equipment
    - Hand equipment should hold 150 lbs of molten material and be maneuverable to install required lines

Application Settings

1. Application methods:
   The thermoplastic material can be applied using one of the following methods:
    - Spray techniques
    - Extrusion methods wherein one side of the shaping die is the pavement, and the other three sides are contained by or are part of the suitable equipment to heat and control the flow of materials
    - Extrusion methods using a pressurized ribbon gun to control the application of the material
2. Application rates and thickness:
    - Apply the thermoplastic material at a rate to maintain the following minimum average dry thicknesses above the surface on all types of pavement:
        - 90 mils (2.3 mm) for lane lines;
        - 60 mils (1.5 mm) for edge lines;

    - 120 mils (3.0 mm) for gore area lines;
    - 3/32 in (2.4 mm) for the edges and 3/16 in (4.8 mm) for the center of crosswalks, stop bars, and symbols.
  - Apply the beads above the minimum rate recommended by the manufacturer to produce the required retroreflectivity value in accordance to the requirements specified in Section 3.3.6. For messages, symbols, and transverse lines, the minimum reflectance value is 275 mcd/lux/m^2 within 30 days of installation.
3. Bead embedment:
   Apply glass spheres and/or reflective composite optics top-coating with a pressure-type gun to embed at least 50% of the bead's diameter into the thermoplastic immediately after the application of the material

Figure 2 Extruded Thermoplastic with Double Drop Beads

Application Conditions

1. Surface condition:
   - Use brushes, brooms, scrapers, grinders, high-pressure water jets, or air blasters to remove dirt, dust, grease, oil, and other foreign matter from paining surfaces without damaging the underlying pavement
   - Remove vegetation and road film from the striping area
   - Remove all the laitance and curing compound of new Portland Cement Concrete pavement surface before striping
   - Remove the existing traffic stripe completely when
     - On Portland cement concrete pavement where the new stripe will be placed at the same location as the existing marking;
     - On pavement where the new stripe will be placed at a different location from the existing marking.
2. Moisture:
   - Do not apply thermoplastic striping if the surface is moist or covered with foreign matter.
3. Temperature:
   - Do not apply thermoplastic striping if the air temperature in the shade is below 40 °F (4 °C) during application

- Install thermoplastic material in a melted state at the manufacturer's recommended temperature but not at less than 375 °F (190 °C)

4. Bonding to existing surface/old stripe
    - Apply a binder-sealer material when installing the thermoplastic in each of the following cases:
        - Where directed by the Engineer for sprayed thermoplastic;
        - Old asphalt concrete pavements with exposed aggregates;
        - Portland cement concrete pavements.
    - If the old stripe is to be renewed by overlaying the new material, ensure the new material bonds to the old line without splitting or cracking

Other Forms of Thermoplastic Markings

Hot-Applied Preformed Plastic Pavement Markings

Hot-applied preformed plastic markings are cut into the shapes needed, positioned onto pavement surface, and affixed to asphalt or Portland cement concrete pavements by the use of heating equipment, such as a torch. Hot-applied preformed plastic pavement markings have been commonly used for small scale applications, such as legends, arrows, stop lines, crosswalks, and symbols.

Detailed characteristics and requirements for preformed plastic pavement markings can be referred to GDOT's *Standard Specification Section 659 – Hot Applied Preformed Plastic Pavement Markings*. Refer to GDOT's Qualified Products List QPL-74 for qualified products.

Hot-applied preformed plastic material consists of resin (hydrocarbon, alkyd, or modified ester rosin), pigments, binders, and beads. The material should conform to AASHTO M 249 standard specifications except for relevant differences due to the material being supplied in a preformed state. Other major characteristics are summarized as follows:

1. Beads: the markings should contain at least 30% AASHTO M 247 Type 1 glass spheres and at least 80% of the beads should be true spheres.
2. Thickness: the thickness of hot-applied preformed plastic markings should be at least 125 mils (3.175 mm).
3. Resealability: the hot-applied preformed markings should have resealing characteristics so that it will fuse with itself and with previously applied marking material of the same composition under normal conditions of use.

Key notes for applying hot-applied preformed pavement markings are as follows:

1. Apply markings only when the temperature is 35 °F (2 °C) or above.
2. Apply markings when the pavement is clean, dry, and free of debris.
3. Apply drop-on glass spheres to the entire surface of the preformed markings that do not have factory pre-applied surface beads.
4. Apply drop-on glass spheres to the material while still in a liquid state.

Types of preformed thermoplastic markings include word, symbol, arrow, stop bar, crosswalk, and lane line. For example, preformed thermoplastics have been used for words, symbols, and arrows of different traffic and bicycle lanes (see Figure 4).

Figure 3 Word and Arrow Hot-Applied Preformed Thermoplastic Markings

Figure 4 Symbol for Bicycle Lanes[3]

Audible Thermoplastic Markings

In addition to the typical flat-surfaced thermoplastic striping, alternations have been made for safety considerations. Audible thermoplastic markings, shown in Figure 5, are applied with special surface profiles/features, similar to rumble strips or raised pavement markers, which create noise and/or vibrations to warn drivers.

[3] Source: http://www.bikocity.com/atlantas-1st-colored-bike-lane/green-bike-lane/

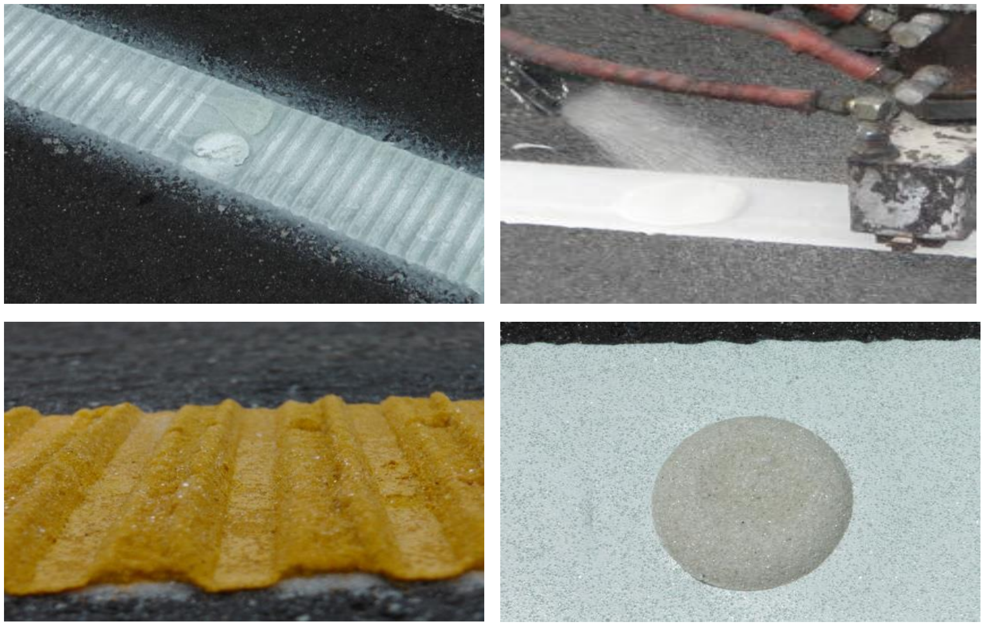

Figure 5 Audible Thermoplastic Markings
(Left: Inverted Profile Markings; Right: Cookies)

2.2.5 Cold-Applied Preformed Plastic Pavement Markings

<u>Introduction</u>

Preformed plastic pavement markings are premade/cut into the shapes needed and affixed to asphalt or Portland cement concrete pavements by pressure-sensitive precoated adhesive or liquid contact cement. Although preformed plastic markings usually cost significantly more than paint or thermoplastic materials, they provide more consistent (less variability) performance and longer service lives than other materials. In addition, the application procedure is much easier and does not require expensive application equipment or equipment calibrations.

This material has also been widely used in the United States[4], slightly less commonly than paint and thermoplastic. Among the different types of preformed plastic pavement markings depicted in the following, the permanent types have been widely used on Georgia's roads, especially on interstate highways and Portland cement concrete pavements.

According to GDOT's Standard Specification Section 657, preformed plastic pavement markings can be categorized into the following five types:

1. Type TR – Temporary Removable Plastic Marking;
2. Type TN – Temporary Non-removable Plastic Marking;
3. Type PA – Permanent Plastic Marking;
4. Type PB – Permanent Patterned Plastic Marking;
5. Type PB-WR – Permanent Patterned Wet Reflective Plastic Markings.

[4] Source: NCHRP Synthesis 306, Table 31.

Detailed characteristics and requirements for preformed plastic pavement markings can be referred to GDOT's *Standard Specification Section 657 – Preformed Plastic Pavement Markings*. Refer to GDOT's Qualified Products List QPL-74 for qualified products.

Characteristics and General Requirements

Preformed plastic pavement markings are made of resins and plasticizers (20% minimum by weight), pigments (30% minimum by weight), and glass spheres (33% minimum by weight). The composition may vary from product to product; however, they should conform the requirements (including conformability, elongation and tensile strength, skid resistance, abrasion resistance, and glass bead retention) specified in GDOT's Standard Specification Section 657. Similarly, pigments should also comply with the State and Federal requirements. Other characteristics are summarized below:

Adhesion

Use markings that can be affixed to bituminous or Portland cement concrete pavements by pressure-sensitive precoated adhesive or a liquid contact cement. Preformed plastic markings are typically supplied with the following:

- A precoated adhesive;
- An easily removable backing to protect the adhesive;
- An adhesive backing that allows repositioning of marking on the surface before permanently sticking with greater pressure;
- A precoated adhesive but without protective backing material for rolls (see Figure 6) of preformed plastic lane lines.

Retroreflective Beads

Use markings with a layer of glass spheres and/or reflective composite optics bonded to the surface according to the marking type.

- Type PB and PB-WR contain glass spheres and/or reflective composite optics.
- Types TR, TN, and PA contain only glass spheres.
- Do not use glass spheres and /or reflective composite optics containing greater than 200 ppm total arsenic, 200 ppm total antimony, or 200 ppm total lead when tested according to US EPA Methods 3052 and 6010C or other approved methods.
- Use glass spheres and/or reflective composite optics that meet the requirements of GDOT's specifications (see Section 3.3.6 for details).

Elongation and Tensile Strength

- Type TR:
  Provide temporal preformed plastic markings with 50% maximum elongation and 40 lbs/in^2 (275 kPa) minimum tensile strength.
- Types PA, PB, and PB-WR:
  Provide permanent preformed plastic markings with 50% maximum elongation and 150 lbs/in^2 (1035 kPa) minimum tensile strength.

Thickness

- Types TR and TN:

Ensure that the removable marking material is at least 20 mils (0.50 mm) thick, not including the backing adhesive.

- Type PA:
  Ensure the permanent material is at least 60 mils (1.52 mm) thick, without the pre-coated adhesive.
- Types PB and PB-WR:
  Ensure the permanent material is at least 60 mils (1.52 mm) thick at the thickest portion of the patterned cross-section, and at least 20 mils (0.508 mm) at the thinnest portion of the cross-section.

Conformability
Use markings that will mold to pavement contours, breaks, faults, and the like, by normal action of traffic at normal pavement temperatures.

Removability (Type TR)
Ensure the marking material can be removed from asphalt and Portland cement concrete pavements as follows:

- Lifted intact or in large pieces;
- Lifted either manually or with a roll-up device;
- Lifted at temperatures above 40 °F (5 °C) without using heat, solvents, sand blasting, or grinding;
- Pavement shows no objectionable staining or damage after removing the marking.

Advantages and Disadvantages
Table 4 summarizes the major advantages and disadvantages of preformed plastic pavement markings.

Table 4 Pros and Cons of Preformed Tape

Advantages	**Disadvantages**
• Easily applied • No curing time required • Excellent durability performance on high and low volume roads • No need for drop-on retroreflective beads	• High life-cycle cost • Requires special equipment to remove from concrete – higher restriping cost • Cannot be fully removed from asphalt if not temporary tapes

Application

Equipment
Truck-mounted automatic machine and mobile hand equipment are used to install preformed plastic markings (see Figure 6 and Figure 7). Use equipment according to the manufacturer's recommendations and ensure the installed markings meet GDOT's requirements.

Figure 6 Preformed Plastic Pavement Marking Application Machine

Figure 7 Preformed Plastic Pavement Marking Hand Equipment

Application Conditions

1. Surface condition:
    - Clean with compressed air, hand brooms, rotary brooms, scrapers, or other approved methods that leave the pavement thoroughly clean and undamaged.
    - Remove all vegetation and road film from the area to be striped.
    - Mechanically wire brush or abrasive blast clean all new Portland cement concrete pavement surfaces to remove all laitance and curing compound from the area to be striped.
    - Remove at least 90% of existing traffic stripe under either of the following conditions:
        - On Portland cement concrete pavement where the new stripe is to be placed at the same location as the existing marking;
        - On all pavements where the new stripe is to be placed at a location different from the existing marking.
2. Temperature:
    - Ambient temperature:
        - Types PB and PB-WR: 40 °F (4 °C) and rising;
        - Types TR, TN, and PA: 60 °F (15 °C) and rising.
    - Pavement temperature:

- Types PB and PB-WR: 40 °F (4 °C) and rising;
    - Types TR, TN, and PA: 70 °F (21 °C) and rising;
    - At least 120 °F (49 °C) if applying any type on new asphalt pavement.
  - Previous night temperature:
    Did not fall below 40 °F (4 °C).
3. Moisture:
   No significant rainfall occurred 24 hours prior to the plastic's application.
4. Drying Time:
   There is typically no drying time for preformed plastic pavement markings because they are usually cold-applied and can be opened to traffic immediately after the application.

2.2.6 Polyurea

Introduction

Polyurea is a two-component, 100% solid material, which is "*a type of elastomer that is derived from the reaction product of an isocyanate component and a synthetic resin blend component through step-growth polymerization*[5]." The development of this type of material took place in the 1990's and has been a relatively new material for pavement markings. It has not been as widely used in the United States as other traditional materials[6]. In Georgia, polyurea markings are used on both asphalt and Portland cement concrete (PCC) pavements and can be applied to roads with the majority of traffic conditions (high, mid, and low AADTs). Detailed characteristics and requirements can be referred to GDOT's *Standard Specification Section 658 – Polyurea Traffic Stripe*.

Characteristics and General Requirements

Polyurea material consists of a mixture of high-quality resins and curing agent, pigments, and a reflective layer bonded to the top surface consisting of glass spheres and/or reflective composite optics. The polyurea material consists of two primary components, Part A and Part B. Part A is the isocyanate component and Part B is the amine-terminated polymer resin. Polyurea material is marketed as durable pavement markings with slightly more expensive costs than traditional paint and thermoplastic materials. Its service life has been reported to be up to 5 years. In addition, some polyurea products can be applied with ceramic elements in the markings to enhance pavement marking retroreflectivity, especially under wet conditions[7]. Some general requirements are as follows:

Composition

- Ensure that the retroreflective pavement markings consist of a mixture of high-quality resins, curing agents and pigments, with a reflective layer bonded to the top surface consisting of glass spheres and/or reflective composite optics.

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[5] Source: Polyurea, Wikipedia, http://en.wikipedia.org/wiki/Polyurea
[6] Source: NCHRP Synthesis 306, Table 31.
[7] Gates, Hawkins, and Rose (2003), Effective Pavement Marking Materials and Applications for Portland Cement Concrete Roadways, Texas Transportation Institute

- Ensure the liquid markings consist of a two-component (Part A and Part B), 100% solid polyurea film formulated and designed to provide a simple volumetric mixing ratio as recommended by the manufacturer.
- Ensure that these films are manufactured without the use of lead chromate pigments or other similar lead-containing chemicals.
- Ensure that the white polyurea contains not less than 13% by weight rutile titanium dioxide pigment to ensure adequate opacity, hiding power, and reflective properties.

Retroreflective Beads

- Use glass spheres and/or reflective composite optics that meet the requirements of GDOT's specifications (see Section 3.3.6 for details).
- Do not use glass spheres and/or reflective composite optics containing greater than 200 ppm total arsenic, 200 ppm total antimony, or 200 ppm total lead when tested according to US EPA Methods 3052 and 6010C or other approved methods.

Advantages and Disadvantages

Table 5 summarizes the major advantages and disadvantages of polyurea markings.

Table 5 Pros and Cons of Polyurea

Advantages	Disadvantages
• Can be applied on all pavement surface types • Great initial retroreflectivity • Fast curing time • Effective on high volume roads • Can be applied at lower temperatures	• Color deterioration

Application

Equipment

Use a mobile, truck-mounted and self-contained pavement marking machine, specifically designed to apply two-component liquid materials and glass spheres in a continuous and skip-line pattern. Select the necessary accessories, such as spray tip, mix chamber or static tube, and rod diameter, to ensure proper mixing. Ensure the machine meets the following requirements:

- Capable of applying three separate stripes, either solid or skip, in any pattern by utilizing three adjacent spray nozzles at the same time;
- Each nozzle is equipped with satisfactory cutoff valves that will apply skip lines automatically;
- The application equipment is maneuverable to the extent that straight lines can be followed and normal curves can be made in a true arc;
- The truck-mounted unit is provided with accessories to allow for the marking of symbols and legends.

Application Settings and Conditions

1. Surface condition:

Use brushes, brooms, scrapers, grinders, high-pressure water jets, or air blasters to remove dirt, dust, grease, oil, and other foreign matter from the painting surfaces without damaging the underlying pavement.

2. Temperature:
   Both the surface and the ambient temperature should be above 40 °F (4 °C) at the time of installation.
3. Moisture:
   - Only apply polyurea markings during dry weather and subsequently dry pavement surfaces.
   - Ensure relative humidity is not greater than 85% at the time of installation.
4. Thickness:
   The minimum average uniform dry thicknesses on
   - Open graded asphalt concrete friction courses: 25 mils ± 2 mils (0.635 mm ± 0.051 mm);
   - All other pavements: 20 mils ± 2 mils (0.508 mm ± 0.051 mm).
5. Drying time:
   The typical drying time is 3 to 8 minutes; ensure that the polyurea markings reach a no-track condition in less than 10 minutes.

2.2.7 Epoxy

Introduction

Epoxy is also a two-component pavement marking material that has been widely used nationwide on roadways under the majority of traffic conditions. It was originally developed by the Minnesota Department of Transportation and H. B. Fuller and Company in the early 1970's[8]. Detailed characteristics and requirements can be referred to in GDOT's *Special Provision Section 661 – Standard and Wet Weather Epoxy Traffic Stripe*.

Characteristics and General Requirements

Composition

The two components are the resins and the curing agent. The curing agent is the catalyst that accelerates the curing process. Other materials in the composition include filler, pigment, and retroreflective beads. The use of pigments and beads should conform to Federal requirements to obtain stripes that meet the expectancy of road users. Other requirements are as follows:

- Ensure that the retroreflective pavement markings consist of a mixture of high-quality resins, curing agent and pigments, with a reflective layer bonded to the top surface consisting of glass spheres and/or reflective composite optics.
- Ensure the liquid markings consist of a two-component (Part A and Part B), 100% solids epoxy film formulated and designed to provide a simple volumetric mixing ratio as recommended by the manufacturer.

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[8] Gates, Hawkins, and Rose (2003), Effective Pavement Marking Materials and Applications for Portland Cement Concrete Roadways, Texas Transportation Institute

- Ensure that these films are manufactured without the use of lead chromate pigments or other similar, lead-containing chemicals.
- Ensure that the white epoxy contains not less than 13% by weight rutile titanium dioxide pigment to insure adequate opacity, hiding power, and reflective properties.

Retroreflective Beads

- Use glass spheres and/or reflective composite optics that meet the requirements of GDOT's specifications (see Section 3.3.6 for details).
- Do not use glass spheres and/or reflective composite optics containing greater than 200 ppm total arsenic, 200 ppm total antimony, or 200 ppm total lead when tested according to US EPA Methods 3052 and 6010C or other approved methods.

Advantages and Disadvantages

Although quicker (e.g., 2-minute) drying epoxies are available, the typical curing/drying time of epoxy has been reported to be between 30 to 40 minutes, which is significantly higher than other materials described in this manual. Another commonly reported disadvantage of epoxy is the color instability under intense ultraviolet exposure. Epoxy's advantages, on the other hand, include its lower insensitivity to application factors than other materials and its durable service life that has shown to exceed 5 years on low to mid traffic volumes[9]. Table 6 summarizes the advantages and disadvantages of epoxy markings.

Table 6 Pros and Cons of Epoxy

Advantages	Disadvantages
• Can be applied on all surface types • High durability on low volume roads • Able to be applied at low temperatures	• Slower curing time • Color deterioration

Application

Equipment

1. Traveling Traffic Striping Machine:
   Use a mobile, truck-mounted and self-contained pavement marking machine specifically designed to apply two-component liquid materials and glass spheres in a continuous and skip-line pattern. Select the necessary accessories, such as spray tip, mix chamber, or static tube, and rod diameter to ensure proper mixing. Ensure the machine meets the following requirements:
   - Capable of applying three separate stripes, either solid or skip, in any specified pattern by utilizing three adjacent spray nozzles at the same time;
   - Each nozzle is equipped with satisfactory cutoff valves that will apply skip lines automatically;
   - The application equipment is maneuverable to the extent that straight lines can be followed and normal curves can be made in a true arc.

[9] Gates, Hawkins, and Rose (2003), Effective Pavement Marking Materials and Applications for Portland Cement Concrete Roadways, Texas Transportation Institute

- The truck-mounted unit is provided with accessories to allow for the marking of symbols and legends.

2. Hand Equipment (Figure 8):
   Use hand equipment for projects with small quantities of bike lanes, lane lines, edge lines, and center lines, or for conditions that require the equipment.

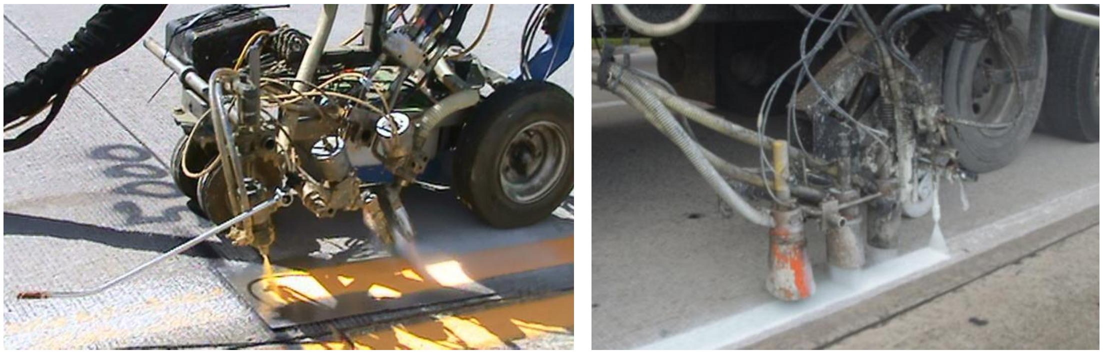

Figure 8 Applications of Epoxy Pavement Marking
(Left: Hand Equipment; Right: Traveling Traffic Striping Machine)

Application Settings and Conditions

1. Surface condition:
   Use brushes, brooms, scrapers, grinders, high-pressure water jets, or air blasters to remove dirt, dust, grease, oil, and other foreign matter from painting surfaces without damaging the underlying pavement.
2. Temperature:
   Although epoxies can be applied at surface temperatures as low as 35ºF (2°C), GDOT's current requirement is that both the surface and the ambient temperature should be above 40°F (4°C) at the time of installation.
3. Moisture:
   Although epoxies can be applied when pavement surfaces are slightly wet, the current GDOT requirements are as follows:
   - Do not apply when the surface is moist.
   - Ensure relative humidity is not greater than 85% at the time of installation.
4. Thickness:
   The minimum average uniform dry thicknesses on
   - Open graded asphalt concrete friction courses: 25 mils ± 2 mils (0.635 mm ± 0.051 mm).
   - All other pavements: 20 mils ± 2 mils (0.508 mm ± 0.051 mm).
5. Drying time:
   Ensure that the epoxy markings reach a no-track condition in less than 30 minutes.

2.2.8 Methyl Methacrylate (MMA)

Introduction

Methyl methacrylate is another two-component pavement marking material. It has been used in the United States but is relatively limited. This type of pavement markings has been reported to have more than three years of life, and some even reported a six- to eight-year service life[10].

Characteristics and Application

This material is cold applied, i.e., no heating equipment is required for the installation. The two components, methyl methacrylate and the catalyst (e.g., benzoyl peroxide powder[11]), are mixed immediately before the application. The mixed methyl methacrylate material can be sprayed or extruded onto pavements. Figure 9 and Figure 10 show two different types of MMA extrusion techniques. Figure 9 shows a unique texture of MMA; Figure 10 shows another installation technique by which the appearance of installed MMA is similar to thermoplastics. The typical thickness is about 35 to 40 mils for sprayed MMA and 90 to 120 mils for extruded MMA[12].

Figure 9 Extruded Patterned MMA Pavement Markings

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[10] Gates, Hawkins, and Rose (2003), Effective Pavement Marking Materials and Applications for Portland Cement Concrete Roadways, Texas Transportation Institute

[11] WSDOT (2013), Standard Specifications for Road, Bridge, and Municipal Construction, Washington State Department of Transportation

[12] WSDOT (2013), Standard Specifications for Road, Bridge, and Municipal Construction, Washington State Department of Transportation

Figure 10 Extruded Solid MMA Pavement Markings

Advantages and Disadvantages
Its greatest reported advantages are the ability to be applied at a low temperature and durability. Its disadvantages, on the other hand, are the expensive cost and slow curing time (20 minutes). Table 7 summarizes the major advantages and disadvantages of MMA markings.

Table 7 Pros and Cons of MMA

Advantages	Disadvantages
• Can be applied on all pavement types • Great wet retroreflectivity • High durability • Chemically resistant • Low volatile organic compound emissions • No need for heat to cure • Best performance at lower temperature	• Higher initial material cost • Requires special application equipment • Lower installation temperature requirement (problem in summer months) • Flammable at high temperature

2.3 Retroreflective Beads

2.3.1 Introduction

Retroreflectivity is one of the most critical factors that provide nighttime and wet visibility of traffic control devices, including traffic signs, pavement markings, and other safety and delineation means. The FHWA has required minimum retroreflectivity levels on traffic signs with different colors and sheeting types and is working on determining similar requirements for pavement markings.

Retroreflectivity of pavement markings is achieved by affixing retroreflective beads to the surface of markings (see Figure 11). There are a variety of type of glass spheres and other retroreflective optics available in the market, and their properties and applications play a crucial role in the performance of the finished markings. This section depicts the types of glass spheres and reflective composite optics available, the properties of bead application, and the factors that affect these properties that contribute to the short-term and long-term performance of pavement markings.

Table 8 Gradations of AASHTO M 247 Standard Glass Spheres

Sieve Designation		Mass Percent Passing					
Standard, mm	Alternate No.	Type 0	Type 1	Type 2	Type 3	Type 4	Type 5
2.35	8						100
2.00	10					100	95 – 100
1.70	12				100	95 – 100	80 – 95
1.40	14				95 – 100	80 – 95	10 – 40
1.18	16		100	100	80 – 95	10 – 40	0 – 5
1.00	18				10 – 40	0 – 5	0 – 2
0.850	20		95 – 100	90 – 100	0 – 5	0 – 2	
0.710	25				0 – 2		
0.600	30	100	75 – 95	50 – 75			
0.425	40	90 – 100		15 – 45			
0.300	50	50 – 75	15 – 35	0 – 15			
0.180	80	0 – 5		0 – 5			
0.150	100		0 – 5				

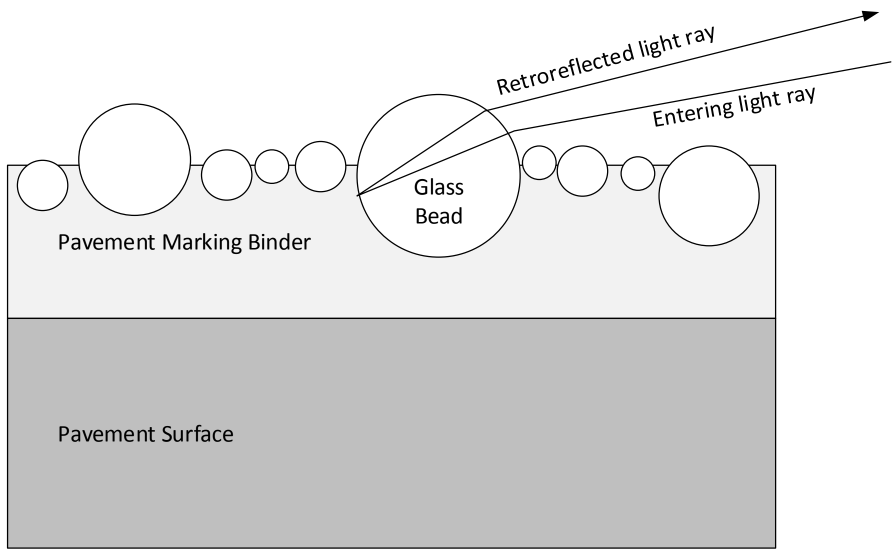


Figure 11 A Light Retroreflected by a Glass Bead in the Pavement Marking

2.3.2 Bead Types

Glass Spheres

AASHTO has developed a Standard Specification for Glass Beads Used in Pavement Markings[13] that specify the types and requirements of standard glass spheres used in pavement markings.

Currently, there are five different types of glass spheres, differentiated by their differences in size and gradation of beads (shown in Table 8). Typically, the size of beads increases (small to large) as the type number increases from 0 to 5. Moreover, larger beads are more likely to have better

[13] AASHTO (2012), Standard Specification for Glass Beads Used in Pavement Markings, AASHTO Designation: M 247, *Standard Specifications for Transportation Materials and Methods of Sampling and Testing*, 32nd Edition and AASHTO Provisional Standards, 2012 Edition.

retroreflectivity, especially in wet conditions, because the impact of the refraction of the water film would be smaller. Other important properties of glass spheres include the clarity, roundness, and the refractive index.

Reflective Composite Optics

In recent years, besides glass spheres, other types of retroreflective beads, such as reflective composite optics, have also been used. This type of bead, by definition, is made of composite materials. Figure 12 shows a standard glass bead and a reflective composite optic placed side by side.

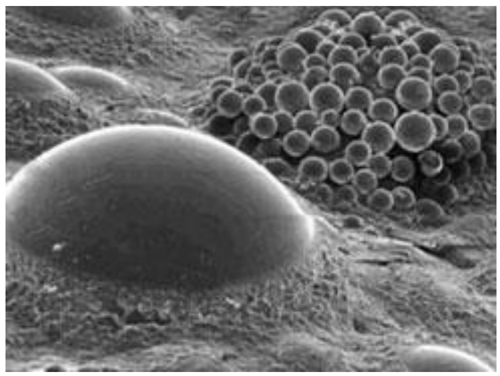


Figure 12 Standard Glass Bead (left) and Reflective Composite Optics (right)[14]

2.3.3 Bead Physical Properties

Clarity

The clarity of beads indicates the degree of transparency, cleanliness, and colorlessness, as well as how free from the bead is milkiness, pits, and/or excessive air bubbles.

Roundness

The roundness of a bead is a measurement used to assess how the shape of the bead is close to a true sphere. AASHTO M 247 specifies that standard glass spheres should have a minimum of 70 percent of true spheres; other stricter requirements may apply, depending on different state DOTs' specifications. The test method for roundness can be found in*ASTM Test Method for Roundness of Glass Spheres* (ASTM D 1155).

Refractive Index

The refractive index (RI) is an important physical parameter used to determine the chemical makeup of the beads. A typical RI of glass beads used in pavement markings is 1.5. The higher the RI of the bead, the better, purer, and more expensive the bead is. Glass beads used for airport markings are usually high, e.g., 1.9 RI. Some manufacturers now use reflective optics with beads with 1.95 RI to increase the visibility of markings. Refer to *ASTM Standard Test Method for the Automated Determination of Refractive Index of Glass Samples Using the Oil Immersion Method and a Phase Contrast Microscope* (ASTM E 1967) for testing details. For

[14] Source: FHWA (2012), INNOVATOR - Accelerating Innovation for the American Driving Experience, Vol. 5, Issue 30

manufacturers and products that meet the standard, please refer to GDOT's Qualified Product List *QPL-71 – Glass Bead Manufacturers* for details.

2.3.4 Bead Application Properties

In addition to the physical properties described in the previous section, several application properties, including the amount, dispersion, and embedment of beads, may significantly affect the performance of the final product. These properties are further discussed below.

Amount

In general, the higher amount of glass spheres on the surface of pavement markings provides better retroreflectivity, although too many beads may affect the proper dispersion and embedment of beads, and, therefore reduce the retroreflectivity.

Dispersion

The dispersion of glass spheres also impacts the retroreflectivity of markings. In general, glass spheres should be evenly distributed on the surface area of pavement markings without any clusters or biases.

Embedment

The embedment of glass spheres has a significant impact on the retroreflectivity of pavement marking. As shown in Figure 13, the actual image (color) retroreflected is the pavement marking material itself. If a glass bead is not embedded deeply enough, the light will likely be refracted in other direction, and, therefore, limited light will be retroreflected to the driver. If a bead is embedded too deeply, on the other hand, limited light will be retroreflected, especially during wet conditions. In general, an embedment at 50 to 60 percent of the bead diameter is recommended (see Figure 13).

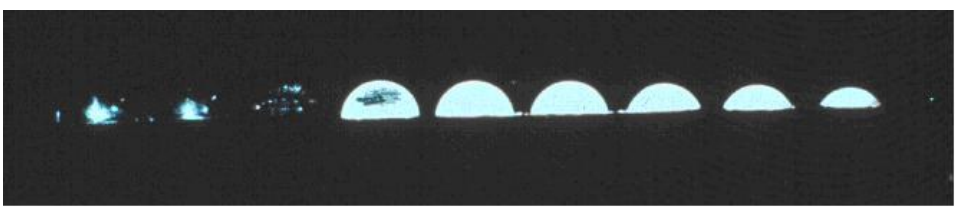


Figure 13 Effect of Bead Embedment on Retroreflectivity[15]

2.3.5 Factors that Influence Bead Application Properties

Several factors may greatly impact the aforementioned application properties. In the following paragraphs, these factors are discussed.

[15] Source: TxDOT (2012), *Pavement Marking Handbook*, Texas Department of Transportation http://onlinemanuals.txdot.gov/txdotmanuals/pmh/images/Fig_3_04.jpg

Equipment

1. Bead dispenser and dropping rate: the functionality and setup of the bead dispenser used to dispense beads will also affect the amount, dispersion, and embedment of beads. The bead dropping rate may directly influence the total amount of beads being applied.
2. Speed of truck or equipment: the speed of the truck may affect the dispersion and amount of beads. As the truck travels faster, fewer beads will be distributed, and the distribution will be sparser.
3. Equipment coordination: Poor coordination between the setup of the bead dispenser and the truck speed may cause the misalignment of the marking binder and beads at curves; i.e., beads will be dispersed in the tangent direction while marking binders are applied along the curve, leading to nonuniform dispersion of the beads.

Environment and Material

Environmental factors, as well as properties of the material, may also affect the application of beads:

1. Ambient temperature: the ambient temperature may affect the drying time of the marking and can likely affect the embedment of beads.
2. Wind speed: wind may significantly affect bead dispersion, causing a reduced number of and dispersion of beads. Strong winds may also impact the application of pavement marking binders, causing problems to the alignment and width of markings.
3. Material temperature: the temperature of material may excessively affect the viscosity of the material and, therefore, influence the depth at which glass spheres can be embedded into the binder.

III. PAVEMENT MARKING INSTALLATION INSPECTION

3.1 Overview

In this chapter, critical pavement marking installation information, as well as the preparation and inspection before, during, and after the installation is discussed.

3.2 Pre-Installation Preparation and Inspection

3.2.1 Surface Preparation

Marking Removal

Because of the characteristics of different pavement marking materials, the removal of existing pavement markings may be required if the new material cannot be compatible with the existing one. Table 9 shows the compatibility matrix that depicts the condition when marking removal is necessary to ensure the performance of new pavement markings.

Table 9 Pavement Marking Material Compatibility Matrix (Adopted from TxDOT)

Original Material	New Material					
	Paint	Thermo	Preformed Tape	Epoxy	Polyurea	MMA
Paint	Y	Y	N	N	N	N
Thermoplastic	Y	Y	N	N	N	N
Preformed Tape	N	N	N	N	N	N
Epoxy	Y	Y	N	Y	N	N/A
Polyurea	Y	Y	N	N	Y	N/A
MMA	Y	Y	N	N	N/A	Y

When necessary, remove existing markings from the pavement before applying the new markings:

1. Removal: utilize blasting, such as sand blasting or water blasting (Figure 14), grinding (Figure 15), or other approved methods to completely remove pavement markings without materially damaging the pavement surface or texture. Repair (at the contractor's expense) damage to the pavement or other surfaces caused by removing the markings. Use repair methods acceptable to GDOT.
2. Blast cleaning:
    - Immediately remove residue and dust when the sand hits the pavement surface.
    - Use a vacuum attachment operating simultaneously with blast cleaning.

Figure 14 High-Pressure Water Jets

Figure 15 Grinding Truck

<u>Surface Cleaning</u>

The existence of dirt, dust, weeds, debris, or other foreign matter may significantly hinder the performance and reduce the life of pavement markings. Figure 16 shows an example of unclean pavement surface that may affect the installation of pavement marking: weeds and debris of old pavement marking materials significantly degrade the quality of new stripe installation.

Make sure the surface is clean before the application:

1. Use brushes, brooms, scrapers (Figure 17), air blasters (Figure 17), grinders, high-pressure water jets, and/or vacuums (Figure 18) to remove dirt, dust, grease, oil, and other foreign matter from the surfaces to be painted without damaging the underlying pavement.
2. Remove vegetation and road film from the striping area.
3. Remove all laitance and curing compound of new Portland Cement Concrete pavement surface before striping.

Figure 16 Effect of Unclean Pavement Surface on Pavement Marking Installation

Figure 17 Thoroughly Clean Pavement Surface using Scraper and Air Blaster

Figure 18 Vacuum Trucks

3.2.2 Inspection

<u>Surface Moisture</u>

Almost all pavement marking materials require a dry pavement surface for application; therefore, the inspection for surface moisture is very important. If directed, perform a moisture test on the Portland Cement Concrete surface as follows:

1. Place approximately 1 yd^2 (0.8 m^2) of roofing felt on the pavement surface.
2. Pour approximately 0.5 gallon (2 L) of molten thermoplastic onto the roofing felt.

3. After 2 minutes, lift the roofing felt and inspect it to see if moisture is present on the pavement surface or underside of the roofing felt.
4. If moisture is present, do not proceed with the striping operation until the surface has dried sufficiently to be moisture-free.

Ambient and Surface Temperature

Different materials have different requirements on the ambient and surface temperatures. Table 10 serves as a reference for minimum temperatures for materials application. Follow GDOT standard specifications and/or manufacturer's recommendations to ensure proper application.

Table 10 Minimum Ambient and Surface Temperatures

Material	Minimum Ambient and/or Surface Temperature
Paint	40 °F
Thermoplastic	40 °F
Preformed Plastic	60 °F / 70 °F and rising
Polyurea	40 °F
Epoxy	40 °F
MMA	35 °F

Material Temperature

Similarly, different pavement marking materials have different temperature requirements for the material itself; inspect material temperature and follow the specifications or manufacturer's recommendations.

3.2.3 Striping Equipment Inspection

Inspect the striping equipment, and make sure each aspect and requirement is met before the striping operation. Inspect the following items:

1. Spray nozzles capable of simultaneously applying separate stripes, either solid or skip, in any pattern.
2. Nozzles equipped with the following:
    - Cutoff valves for automatically applying skip lines;
    - A mechanical bead dispenser that operates simultaneously with the spray nozzle to uniformly distribute beads at the specified rate;
    - Line-guides consisting of metallic shrouds or air blasts.
3. Tanks with mechanical agitators;
4. Small, portable applicators or other special equipment as needed.

3.3 Inspection During and After Installation

As mentioned previously, construction quality is one of the most important factors that affects the performance of the completed pavement markings; therefore, inspection during installation (field evaluation) is very crucial to the longevity of pavement markings. In general, the inspection may include a test line evaluation immediately before the application procedure, evaluation during the application, and evaluation after the application. Note that it is recommended that before the application of any test lines, wet film thickness, line width, glass bead application rate, and glass bead distribution should meet the specification. The following sections discuss the items for inspection.

3.3.1 Thickness

There are two methods used by GDOT to measure pavement marking thickness: wet film thickness gauge and thickness gauge. Wet film thickness is measured by the metal wet film thickness gauge (see Figure 19) immediately after the application of pavement marking.

Figure 19 Wet Film Thickness Gauge

Thickness gauges, on the other hand, measure the dry pavement marking using an electronic thickness gauges in the field or laboratory to determine the thickness (see Figure 20).

Figure 20 Electronic Thickness Gauge

GDOT's current thickness requirements are summarized in Table 11.

Table 11 Thickness Requirements Measured from the Surface (1mil = 1/1000 in)

Striping Materials	Interstate OGFC	Interstate Concrete	Asphalt	Edge Line	Center Line	Intersection Markings, Symbols and Gore Areas
Thermoplastic				60	90	120
Polyurea	25	20	20	20	20	
Paint/High Build Paint (wet thickness)			25	25	25	
Epoxy	25	20	20	20	20	

3.3.2 Color

Currently GDOT engineers inspect pavement marking color visually without using any standard color spectrophotometer. Although GDOT currently does not use any specification for daytime or nighttime marking color, pavement marking materials can be tested using ASTM Standard Specification for Color of Pavement Marking Materials and the International Commission on Illumination (CIE) with chromaticity coordinates as shown in Table 12 and Table 13.

Table 12 Daytime Color Standards

NOTE 1—Daytime, Geometry – 45/0 (0/45), CIE illuminant D65 and the CIE 1931 (2°) standard observer.

Color	Daytime Chromaticity Coordinates (Corner Points)							
	1		2		3		4	
	x	y	x	y	x	y	x	y
White	0.355	0.355	0.305	0.305	0.285	0.325	0.335	0.375
Yellow	0.560	0.440	0.490	0.510	0.420	0.440	0.460	0.400
Red	0.480	0.300	0.690	0.315	0.620	0.380	0.480	0.360
Blue	0.105	0.100	0.220	0.180	0.200	0.260	0.060	0.220

Table 13 Nighttime Color Standards

NOTE 1—Nighttime, Geometry – observation angle of 1.05° and entrance angle of 88.76°. CIE illuminant A and the CIE 1931 (2°) standard observer.

Color	Nighttime Chromaticity Coordinates (Corner Points)							
	1		2		3		4	
	x	y	x	y	x	y	x	y
White	0.480	0.410	0.430	0.380	0.405	0.405	0.455	0.435
Yellow	0.575	0.425	0.508	0.415	0.473	0.453	0.510	0.490

3.3.3 Alignment

To ensure the alignment of pavement markings, temporary guide lines or other means may be used (see Figure 21). The alignment of the stripe shall not deviate from the intended alignment by more than 1 in (25 mm) on tangents and on curves up to and including 1 degree (radius of 1,745 m or greater). On curves exceeding 1 degree (radius less than 1,745 m), the alignment of the stripe shall not deviate from the intended alignment by more than 2 in (50 mm). Stop work when deviation exceeds the above dimensions (see Figure 22), and remove the nonconforming stipe.

Figure 21 Temporary Guide Lines for Alignment Assuring

Figure 22 Example of a Deviated Pavement Marking

3.3.4 Width and Length

No traffic stripe shall be less than the specified width and shall not exceed the specified width by more than 1/2 in (13 mm). The length of the 10 ft (3 m) segment for skip stripe and the 30 ft (9 m) gap between segments may vary plus or minus 1 ft (300 mm). Stop work when deviation exceeds the above dimensions (see Figure 23), and remove the nonconforming stripe.

Figure 23 Example of Pavement Marking with High Variation in Width

3.3.5   Glass Bead Application Properties

Visual inspection (see Figure 24) on bead application properties as mentioned in Section 2.3.4 is needed during the installation. Stop work when the dispersion, amount, and embedment of beads do not meet the expectancy, and remove the nonconforming stripe. Figure 25 shows examples of an even bead dispersion pavement marking (the left image) and an uneven dispersion pavement marking (the right image). Note that the glass spheres in the right image only appeared on the right half of the marking material, and none were affixed to the left half of the marking.

Figure 24 Inspection of Bead Application Properties

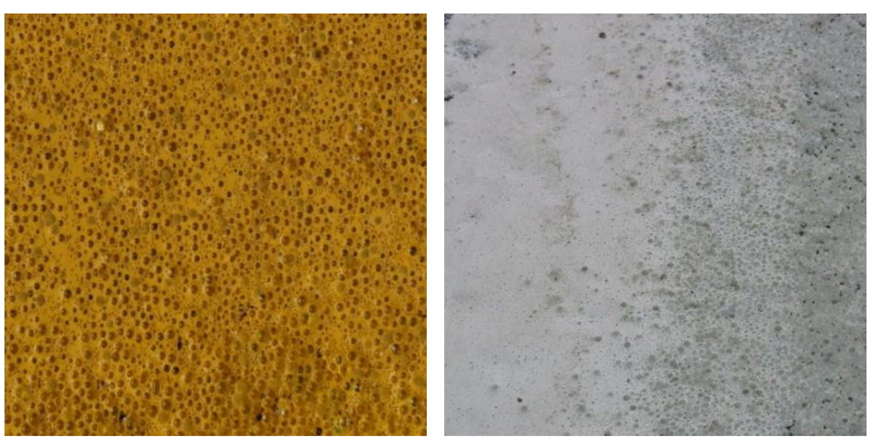


Figure 25 Even (Left) and Uneven (Right) Bead Dispersions in Epoxy Material

3.3.6 Retroreflectivity

Retroreflectivity of the pavement marking is measured in mcd/lux/m^2 and is required to be measured twice before the acceptance of work in GDOT. The first measurement is performed within 30 days since installation. The second measurement is performed 180 days after installation. The contractor, at its own expense, is responsible to restripe if the marking does not meet GDOT's requirements. The retroreflectivity requirements for initial and 180-day readings are shown in Table 14, Table 15, and Table 16:

Table 14 Dry Retroreflectivity Requirements in Accordance with ASTM E 1710

	White 30 Days	**White 180 Days**	**Yellow 30 Days**	**Yellow 180 Days**
Thermoplastic	400	400	300	300
Polyurea	600	600	400	400
Paint/High Build Paint	300	300	250	250
Preformed Plastic Tape	600	600	400	400
Epoxy	400	400	300	300

Table 15 Dry Retroreflectivity Requirements for Intersection Markings and Symbols

	30 Days	**180 Days**
Thermoplastic	275	275
Polyurea	275	275
Paint/High Build Paint	275	275
Preformed Plastic Tape	600	600
Epoxy	275	275

Table 16 Wet Retroreflectivity Requirements in Accordance with ASTM E 2177

	White 30 Days	**White 180 Days**	**Yellow 30 Days**	**Yellow 180 Days**
Thermoplastic	150	150	125	125
Polyurea	250	250	200	200
Paint/High Build Paint	150	150	100	100
Preformed Plastic Tape	250	250	200	200
Epoxy	150	150	125	125

IV. PAVEMENT MARKING MATERIAL SELECTION

Table 17 shows a pavement marking material selection matrix developed based on life-cycle costs of materials, as well as engineering experiences. For a specific pavement surface type, traffic condition, and roadway characteristic, this matrix provides a list of cost-effective materials recommended to be used.

Table 17 Pavement Marking Material Selection Matrix

Total AADT	Asphalt			Concrete*		
	2 Lanes	4 Lanes	Interstate /Freeway	2 Lanes	4 Lanes	Interstate/Freeway
n < 8,000	T/H/E/P	T/H/E/P		E/P	E/P	
8,000 ≤ n <15,000	T/E/P	T/H/E/P	T/E/P/M	E/P	E/P	E/P/M
15,000 ≤ n <40,000	T/E/P/M	T/E/P/M	T/E/P/M/F	E/P/M	E/P/M	E/P/M/F
n ≥ 40,000		T/E/P/M/F	T/E/P/M/F		E/P/M/F	E/P/M/F

H – Highbuild Paint and Wet Weather Paint
T – Standard and Wet Weather Thermoplastic
F – Preformed Plastic Pavement Markings
P – Standard and Wet Weather Polyurea
E – Standard and Wet Weather Epoxy
M – Methyl Methacrylate

*Contrast markings shall be used for all lane lines on PCC surfaces

As shown in this table, the recommended use of the materials are summarized below:

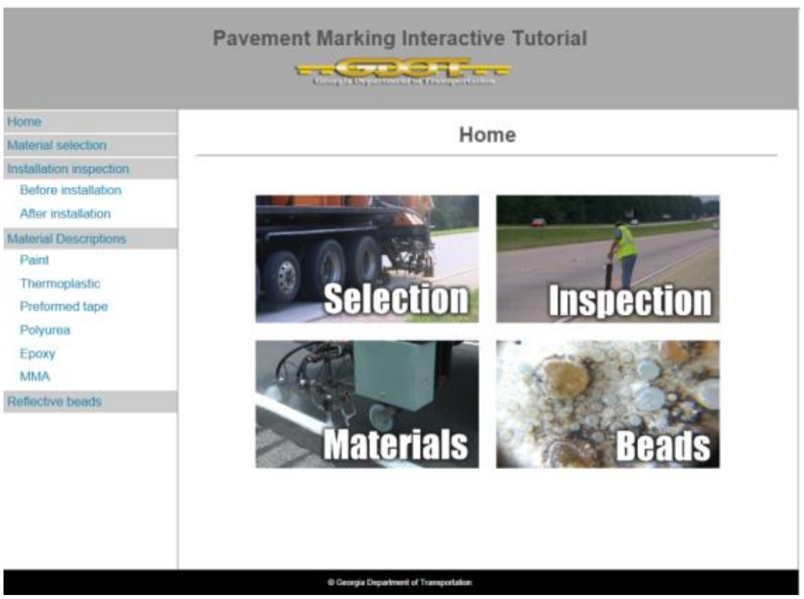
1. **Paint**: Paint material is used only on asphalt pavements with low AADT, such as 2-lane highways with the total AADT < 8,000 vehicles/day, or 4-lane highways with the total AADT < 15,000. GDOT does not recommend use of paint on concrete pavements.
2. **Thermoplastic**: Thermoplastic has exceptional good life-cycle cost range and can be used on all asphalt pavements. It could be possibly used on concrete pavements, but caution needs to be taken to ensure the quality of thermoplastic on concrete pavements. GDOT does not recommend use of thermoplastic on concrete pavements.
3. **Epoxy and polyurea**: These two materials are low-cost, durable materials that can be used on all types of surfaces under all traffic conditions.
4. **MMA**: MMA performs like other durable materials, such as thermoplastic and tape; its unique patterned texture can provide good wet retroreflectivity. Moreover, it can be used on all surface types; however, due to its higher unit cost, this type of material is only recommended to be used for high traffic volume roads.
5. **Tape**: Similarly, tape performs similar like durable materials. One great advantage of tape is that no drying time is required for its installation; in addition, patterned tapes can provide high wet retroreflectivity. Tape can also perform consistently under various weather and traffic conditions. It can also perform consistently in different line colors and on different pavement surface types. Due to its high life-cycle cost, nevertheless, tape is only considered/recommended for use on roads with a high traffic volume.

APPENDIX II PAVEMENT MARKING TUTORIAL USER MANUAL

Georgia Department of Transportation

Pavement Marking Interactive Tutorial

-- User Manual --



Prepared by:
Georgia Institute of Technology

Prepared for:
Georgia Department of Transportation

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I. GENERAL INTRODUCTION AND SYSTEM OVERVIEW

The content of this web-based interactive tutorial is essentially summarized from the Pavement Marking Handbook; it has additional interactive functions and videos that can be used as a means for pavement marking material selection and personnel training.

In this user guide, the basic functions and modules of the interactive tutorial are introduced. This web-based tutorial is designed to be used by desktop or laptop users; it can be opened by most modern web browsers, including Internet Explorer (IE), Chrome, and Firefox. Note that because Javascript was used to develop these interactive functions (mainly in the Material Selection Module), IE users need to allow the default restriction and enable the webpage to run scripts (see Figure 1). It is recommended that the most updated browser version be used.

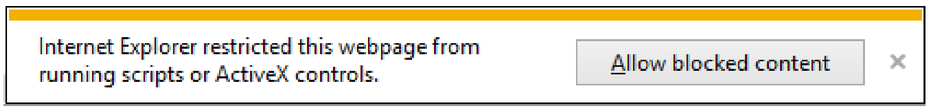


Figure 1 Internet Explorer Alert: Allow Blocked Content

II. REFERENCES

Most pavement marking material specifications in this tutorial, in terms of composition, binder, pigment, temperature, thickness, and more, were extracted from GDOT's standard specifications or provisional standards as follows:

- Standard Specification Section 652 – Painting Traffic Stripe
- Standard Specification Section 653 – Thermoplastic Traffic Stripe
- Standard Specification Section 657 – Preformed Plastic Pavement Markings
- Standard Specification Section 658 – Polyurea Traffic Stripe
- Standard Specification Section 659 – Hot Applied Preformed Plastic Pavement Markings
- Special Provision Section 661– Standard and Wet Weather Epoxy Traffic Stripe
- Standard Specification Section 870 – Paint

Besides the specifications and standards, a pavement marking material selection matrix proposed by the Georgia Research Team is used to recommend materials under various traffic and pavement conditions. Table 1 summarizes the recommended materials for different AADT, highway functions, and pavement surface types.

Table 1 A Proposed Pavement Marking Material Selection Matrix for GDOT

AADT	Asphalt			Concrete*		
	2 Lanes	4 Lanes	Interstate/Freeway	2 Lanes	4 Lanes	Interstate/Freeway
n < 8,000	T/H/E/P	T/H/E/P		E/P	E/P	
8,000 ≤ n <15,000	T/E/P	T/H/E/P	T/E/P/M	E/P	E/P	E/P/M
15,000 ≤ n <40,000	T/E/P/M	T/E/P/M	T/E/P/M/F	E/P/M	E/P/M	E/P/M/F
n ≥ 40,000		T/E/P/M/F	T/E/P/M/F		E/P/M/F	E/P/M/F

H – Highbuild Paint and Wet Weather Paint Traffic Stripe
T – Standard and Wet Weather Thermoplastic Traffic Stripe
F – Preformed Plastic Pavement Markings
P – Standard and Wet Weather Polyurea Traffic Strip
E – Standard and Wet Weather Epoxy Traffic Strip
M – Methyl Methacrylate

*Contrast markings shall be used for all lane lines on PCC surfaces

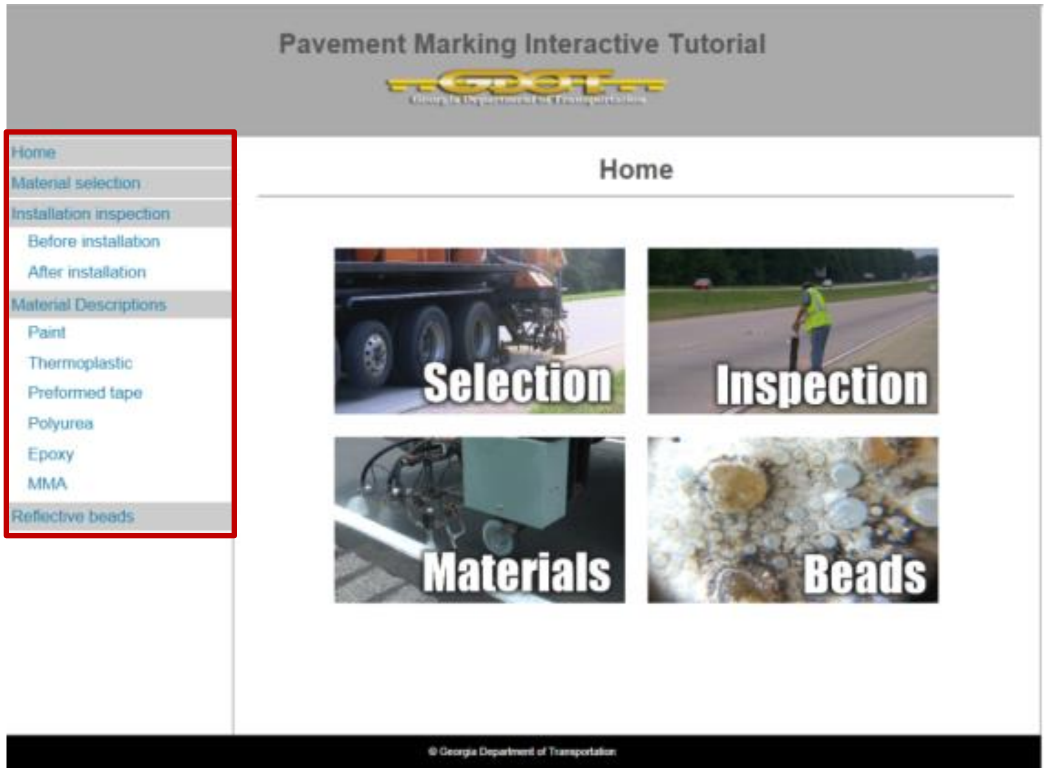


Figure 2 Primary Navigation Panel of the Interactive Tutorial

III. NAVIGATION

This tutorial provides two levels of navigation options. First, on the webpages, as shown in Figure 2, the left column presents the primary navigation for the primary modules and secondary-level pages. The primary modules consist of *Material Selection*, *Installation Inspection*, *Material Descriptions*, and *Reflective Materials*. Some modules, such as *Installation Inspection* and *Material Descriptions*, have sub-modules, which are categorized based on the timing of the inspection (before or after) and the types of materials (e.g., paint, thermoplastic, epoxy, polyurea, tape, or methyl methacrylate). This navigation panel is shown on every webpage of the tutorial, so users can navigate to any of the primary modules or individual categories easily. On the Home Page, links to the four modules are also provided as hyperlinked pictures, as shown in Figure 2.

Second, on some pages where more details are presented, subpage tabs will be available in the right column under a brief description of the page. Users can navigate among the tabs under the same module and category easily by clicking the desired tab. As shown in Figure 3, six different tabs, including *Thickness*, *Color*, *Alignment*, *Width and Length*, *Glass Beads Propeties*, and *Retroreflectivity* are available for *After Installation* page under the *Installation Inspection Module*.

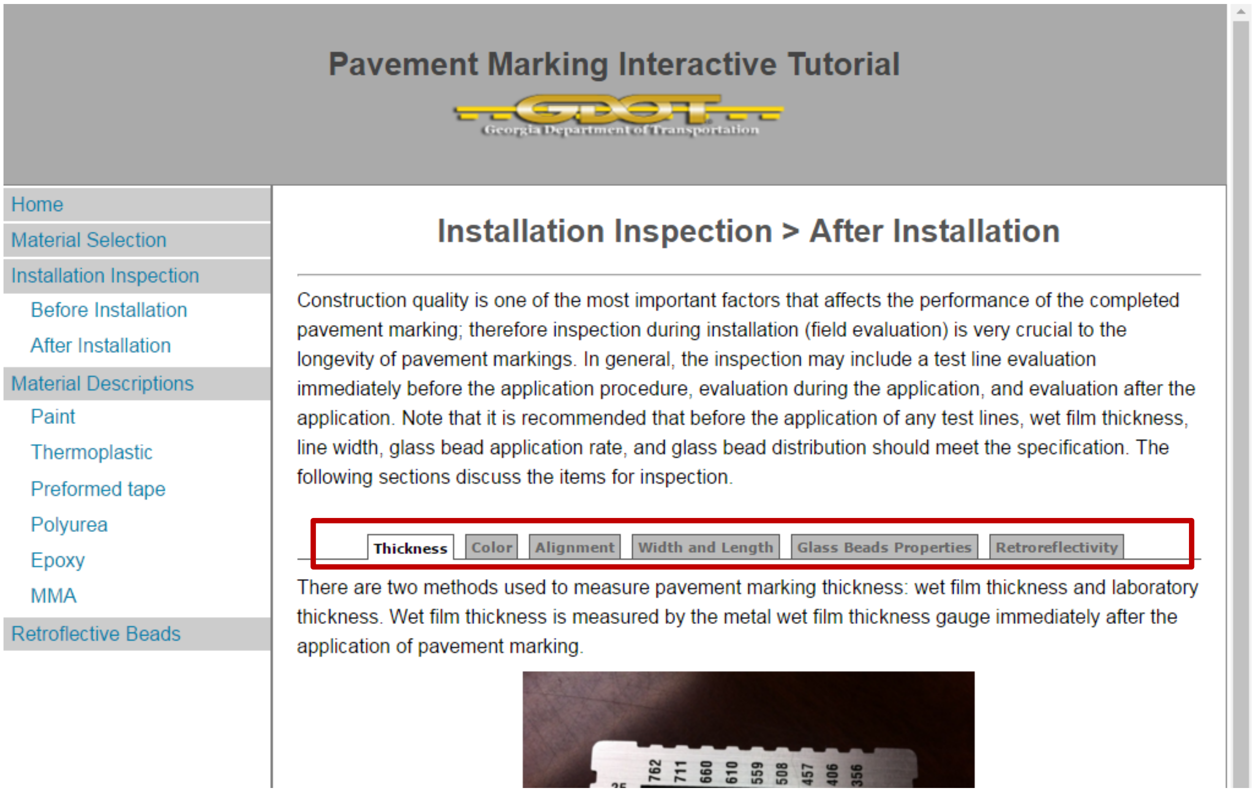


Figure 3 Secondary Navigation within an Individual Topic

IV. MODULES AND FUNCTIONS

In the tutorial, there are four primary modules; each provides useful information and a knowledge base of pavement markings. In this section, the details of each module are summarized.

4.1 Material Selection

This module is developed for engineers to quickly identify possible materials to be installed under various traffic and pavement characteristics. Criteria used include the annual average daily traffic (AADT), lane number and/or functional class (highway type), and pavement surface types. As shown in Figure 4, each dropdown menu provides options for each criterion. Figures 5-7 shows the options for each criterion.

Users are required to select all three of these criteria before the selection function can be carried out. If one or more criteria is not selected, an alert message will pop up to remind the user to select all three attributes before any possible materials are selected.

Figure 8 demonstrates the results of material selection based on user input (*8,000 ≤ AADT < 15,000*; *Portland Cement Concrete*; and *Interstate/Freeway*). From the results, pavement materials, such as epoxy, polyurea, and MMA, are recommended under these conditions, which is the same as those from the selection matrix in Table 1. Note that each of the icon pictures is a link to the specific material's description in the *Material Descriptions* module.

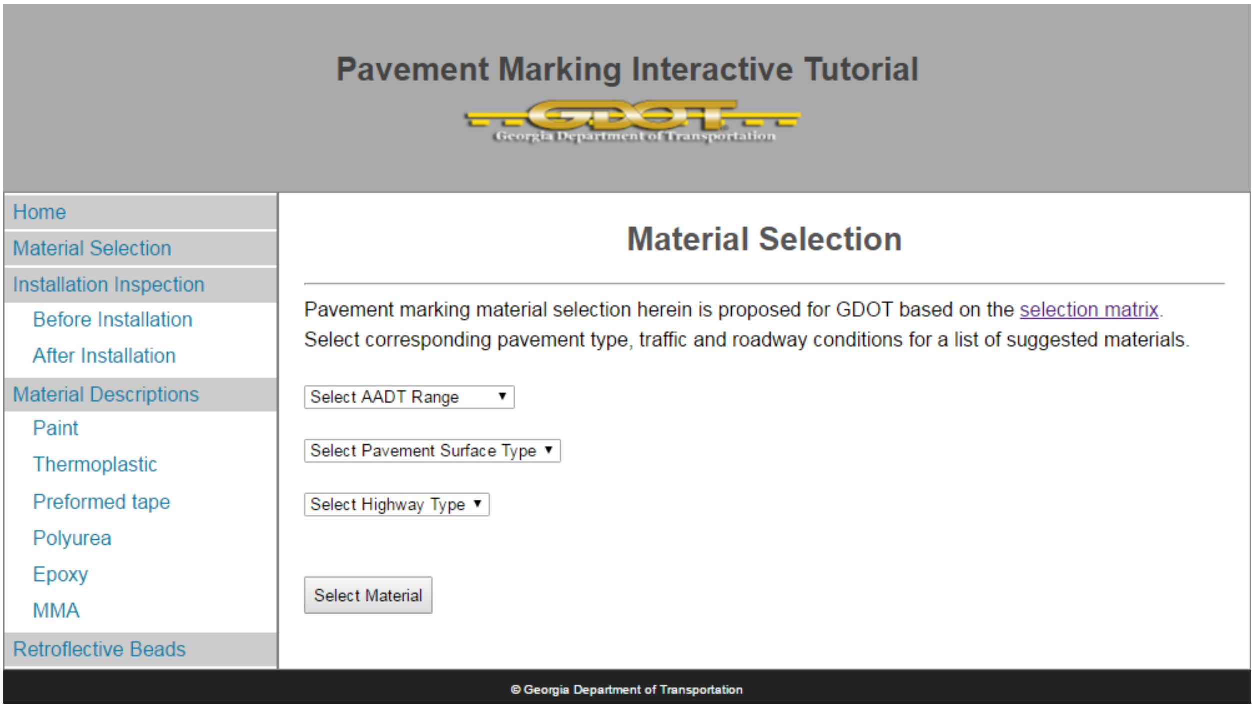


Figure 4 Material Selection Module

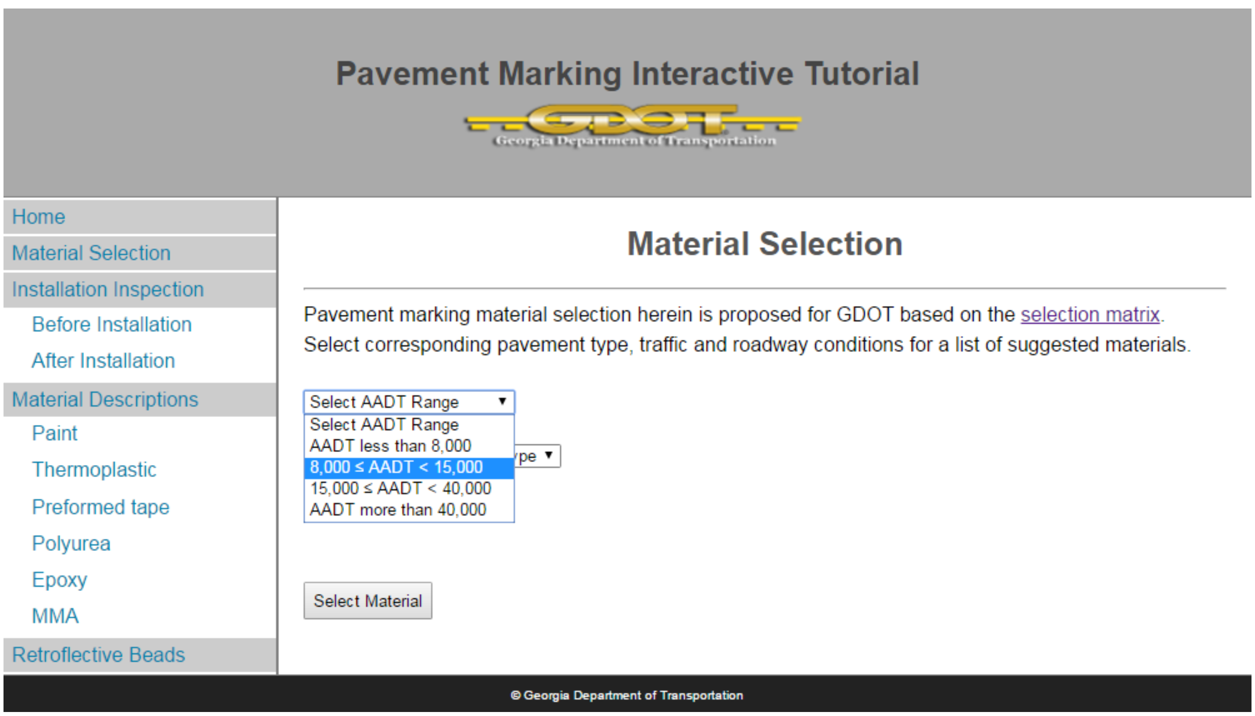


Figure 5 Material Selection Module – AADT Options

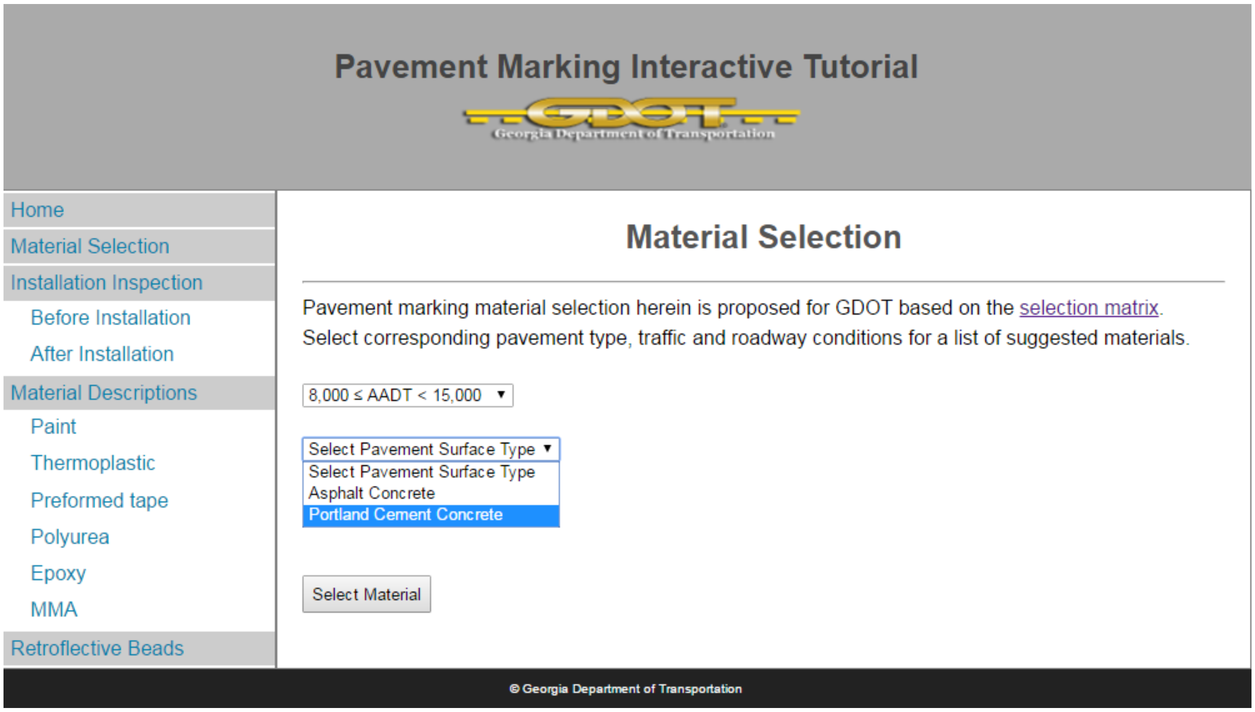


Figure 6 Material Selection Module – Pavement Surface Type Options

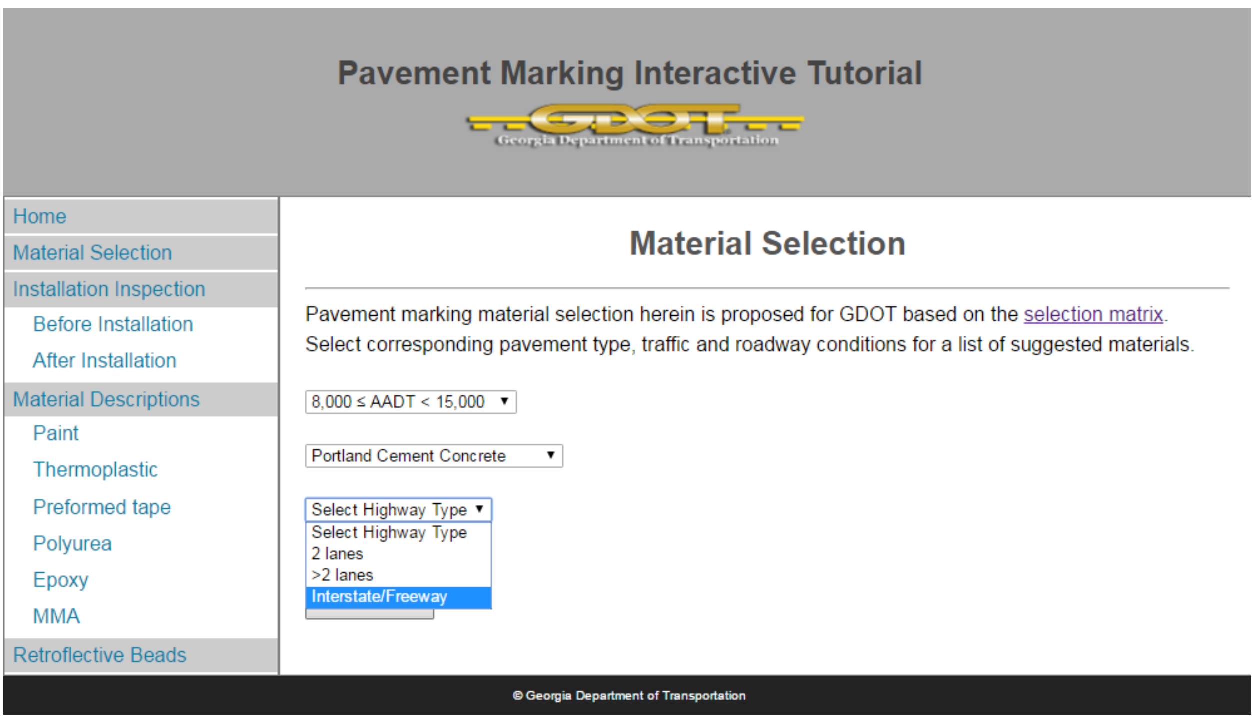


Figure 7 Material Selection Module – Highway Type Options

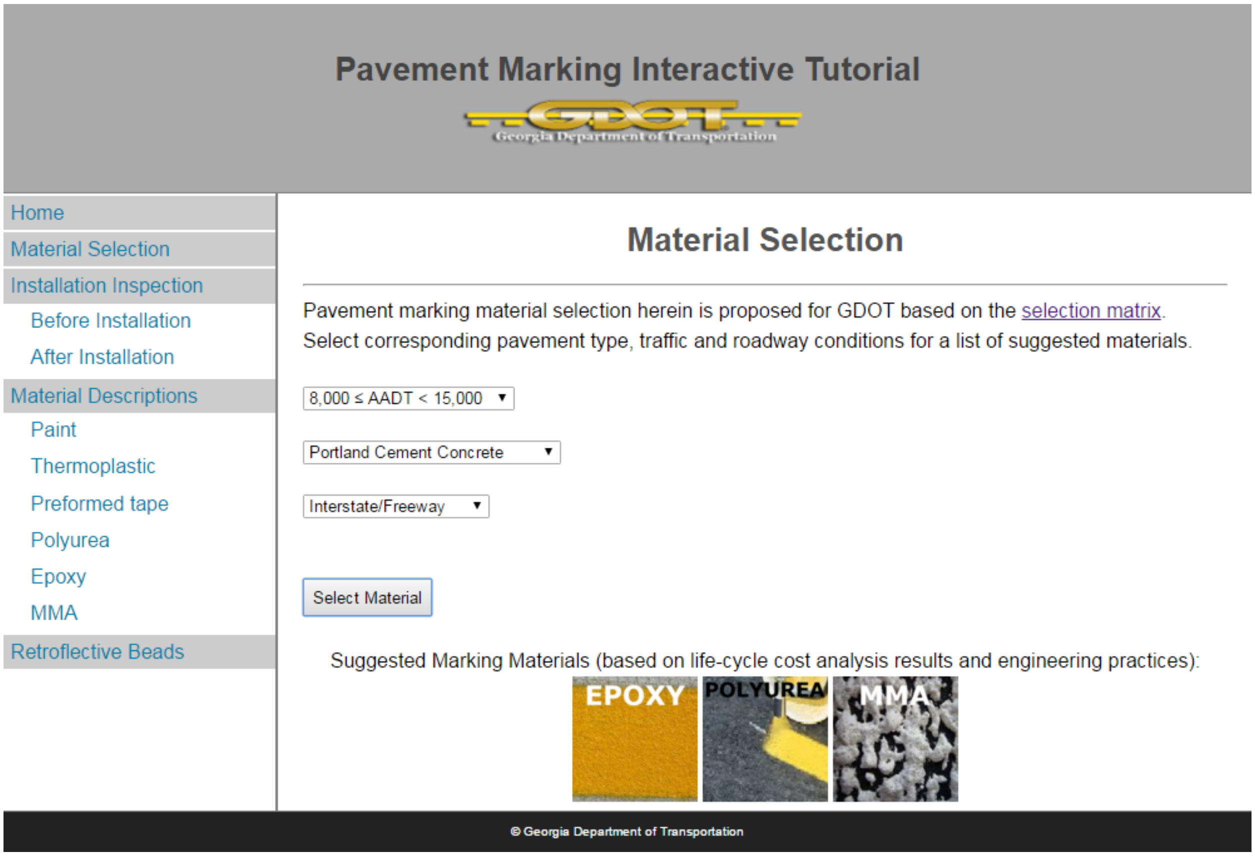


Figure 8 Suggested Materials Dynamically Generated Based on User Input

4.2 Installation & Inspection

This module describes the preparation, inspection, and installation of pavement marking materials. It is further divided into two sub-modules: *Before Installation* and *After Installation*. Both sub-modules can be accessed from the navigation panel on the left or from the hyperlinked pictures on the module front page (see Figure 9).

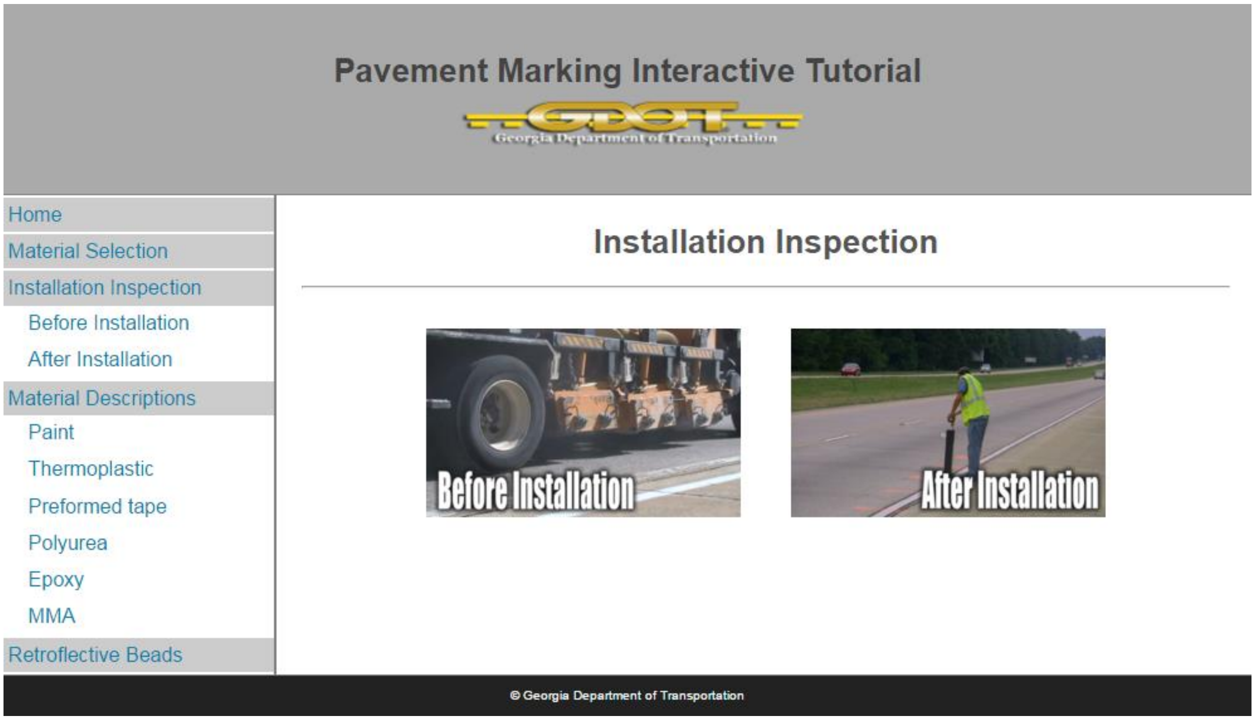


Figure 9 Installation Inspection Module Front Page

4.2.1 Inspection before Installation

The Before Installation sub-module, as shown in Figure 10, includes the following tabs and detailed information:

- Surface Preparation
  a. Marking Removal
  b. Surface Cleaning
- Inspection
  a. Surface Moisture
  b. Ambient and Surface Temperature
  c. Material Temperature
  d. Equipment

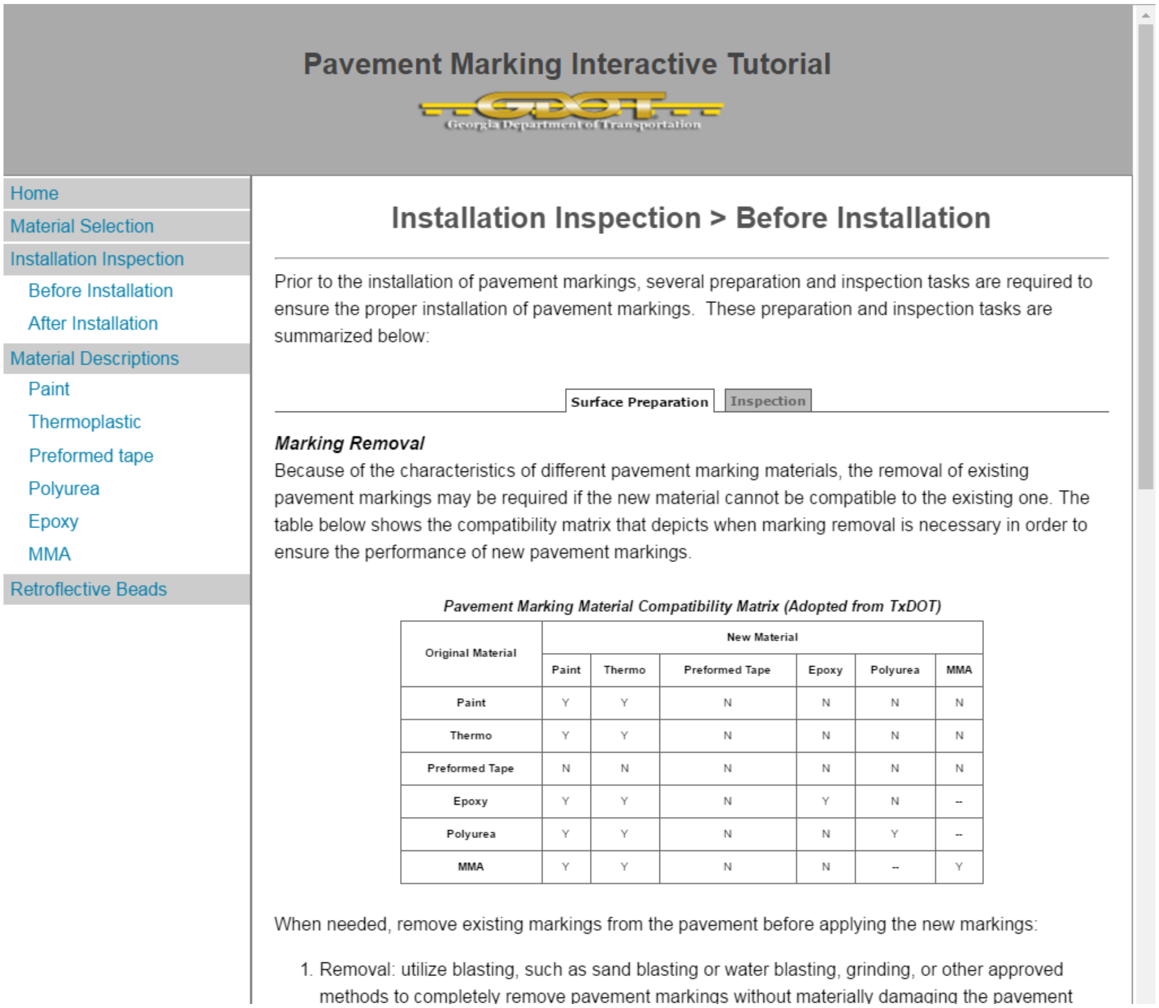


Figure 10 Before Installation Sub-module

4.2.2   Inspection after Installation

The After Installation sub-module contains the requirements of the following items:

- Thickness
- Color
- Alignment
- Width and Length
- Glass Beads Properties (e.g., dispersion, amount, embedment)
- Retroreflectivity

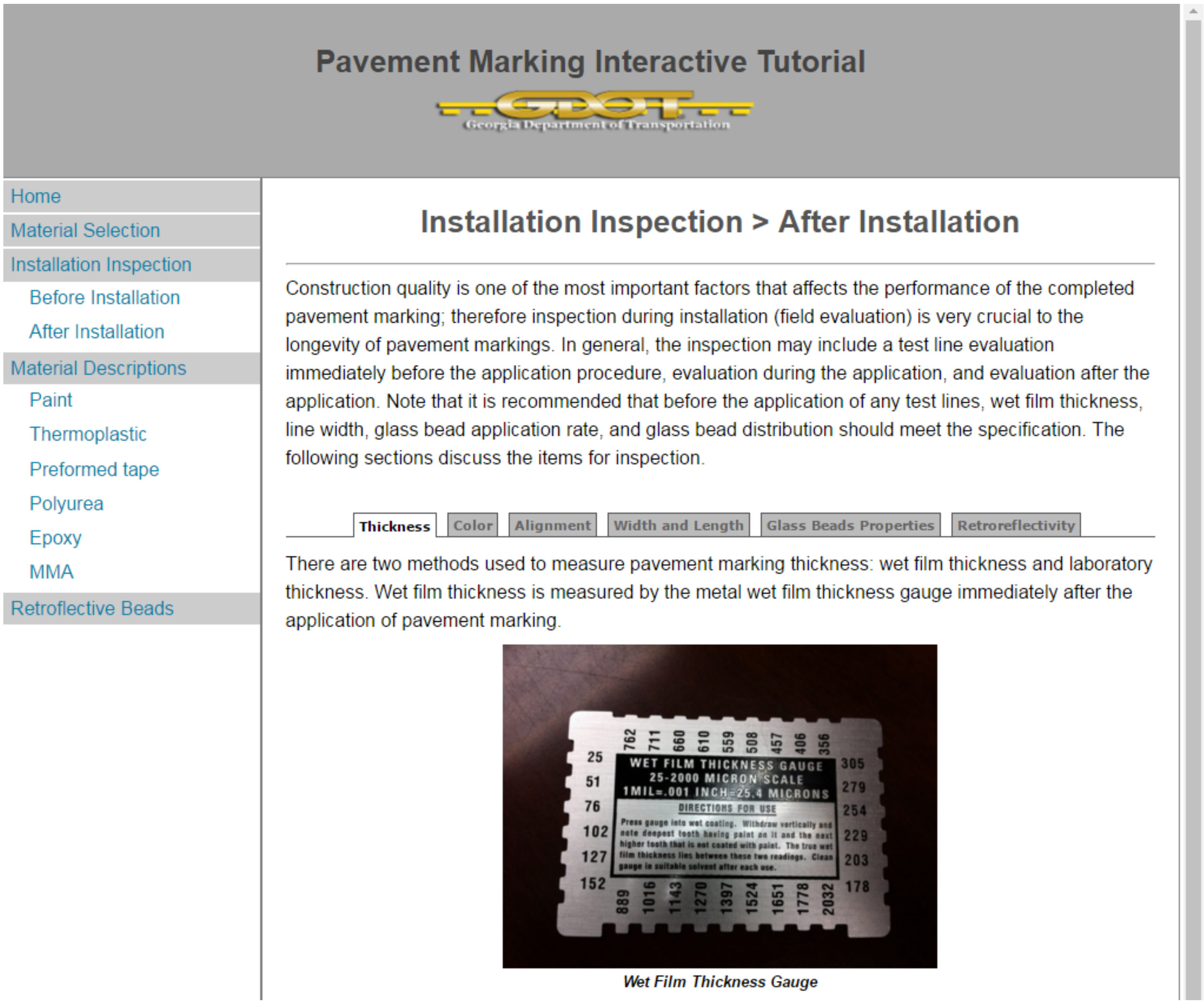


Figure 11 After Installation Sub-module

4.3 Material Descriptions

This module provides general descriptions of commonly used pavement marking materials and specifies lab and field requirements for the inclusion of products into the quality product list (QPL). For each material, information below (if available) are summarized in separate tabs:

- Material characteristics
- General requirements
- Application of materials

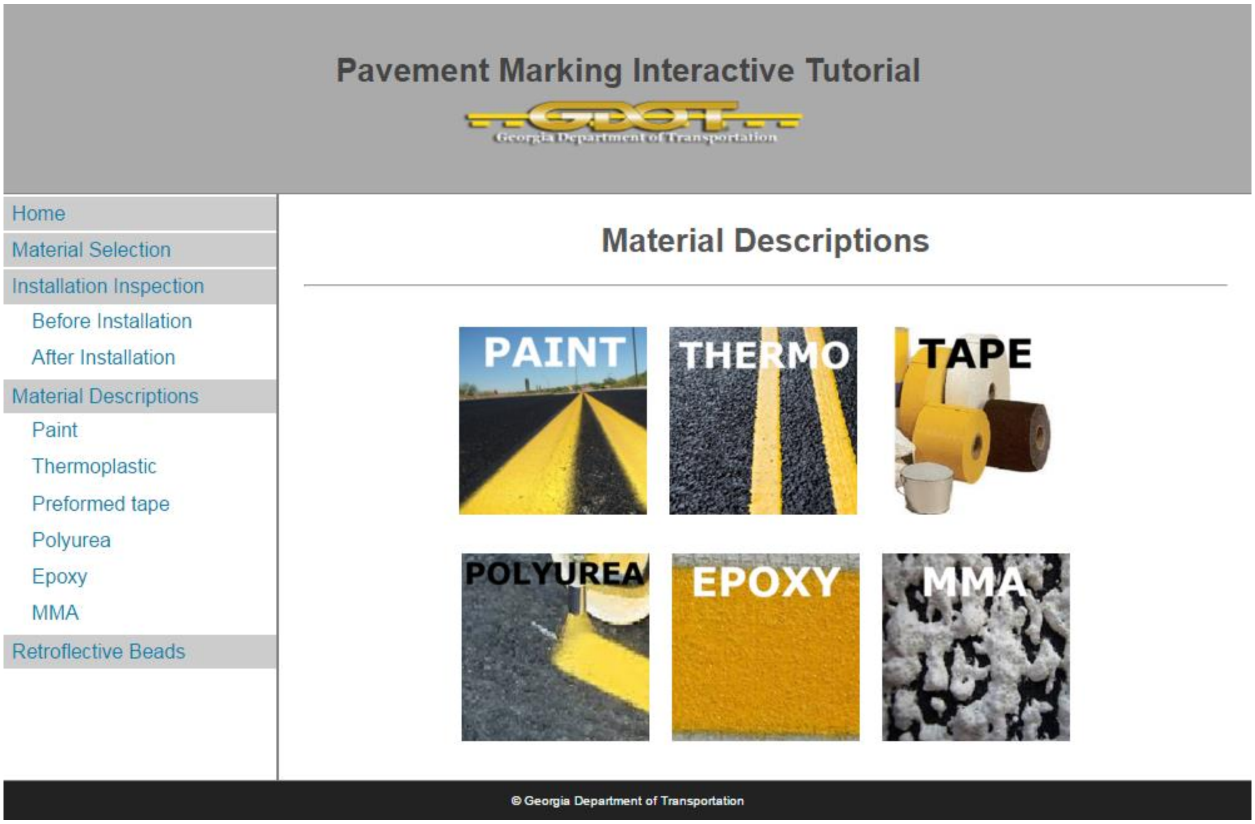


Figure 12 Material Descriptions Module Front Page

4.3.1 Paint

The front page of the paint materials is shown in Figure 13. Paint information provided in the tutorial includes:

- Characteristics and General Requirements
    a. Material Composition
    b. Retroreflective Beads
    c. Advantages and Disadvantages
- Application
    a. Equipment
    b. Application Settings
    c. Application Conditions

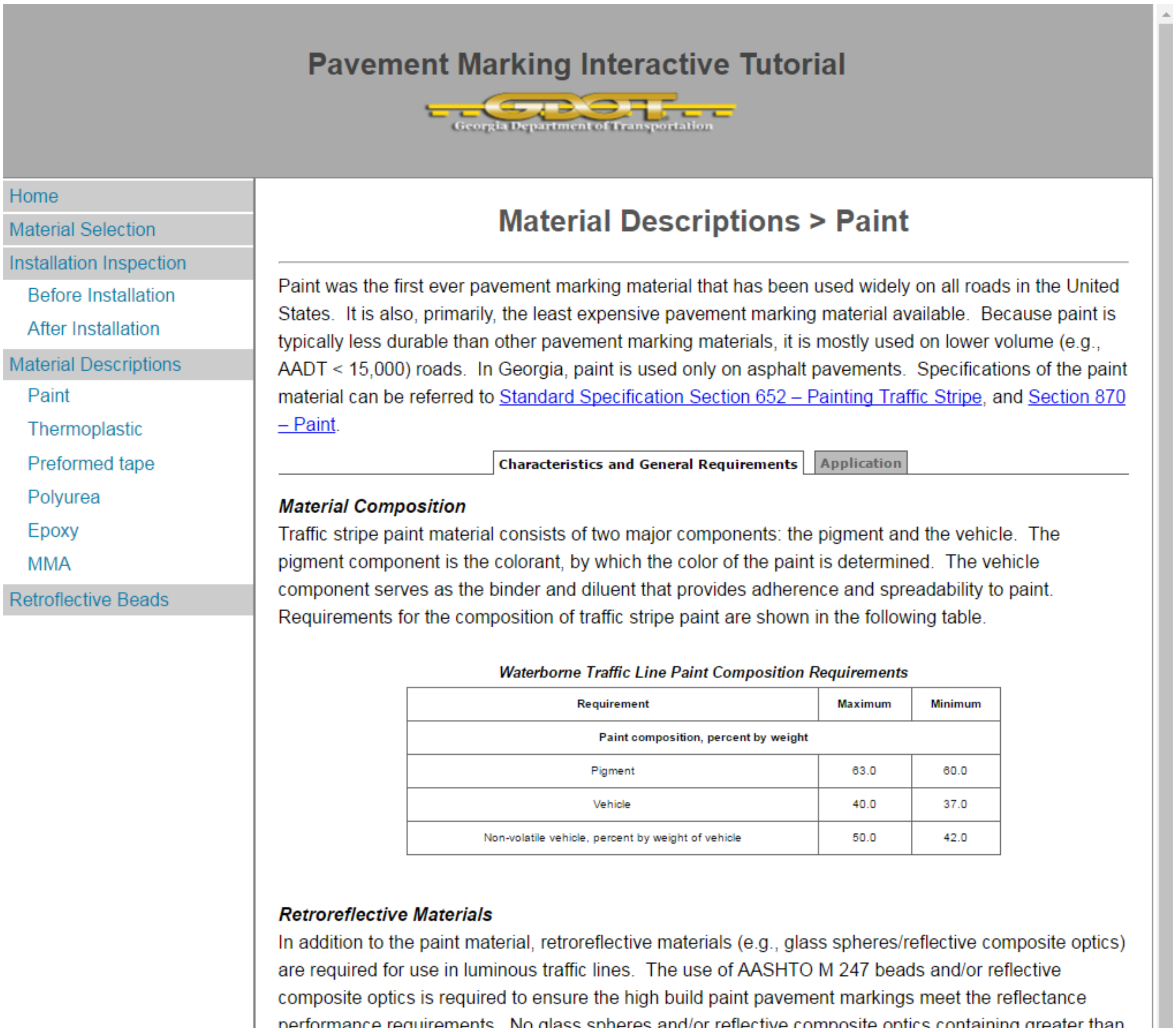
4.3.2 Thermoplastic

The front page of thermoplastic materials is shown in Figure 14. Information about thermoplastics includes the following:

- Characteristics and General Requirements
    a. Resin and Pigment
    b. Retroreflective Beads
    c. Advantages and Disadvantages
- Application

a. Equipment
b. Application Settings
c. Application Conditions

- Other Forms of Thermoplastic
  a. Hot-Applied Preformed Plastic Pavement Markings
  b. Audible Thermoplastic Markings



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Material Descriptions > Paint

Paint was the first ever pavement marking material that has been used widely on all roads in the United States. It is also, primarily, the least expensive pavement marking material available. Because paint is typically less durable than other pavement marking materials, it is mostly used on lower volume (e.g., AADT < 15,000) roads. In Georgia, paint is used only on asphalt pavements. Specifications of the paint material can be referred to Standard Specification Section 652 – Painting Traffic Stripe, and Section 870 – Paint.

Characteristics and General Requirements | Application

Material Composition
Traffic stripe paint material consists of two major components: the pigment and the vehicle. The pigment component is the colorant, by which the color of the paint is determined. The vehicle component serves as the binder and diluent that provides adherence and spreadability to paint. Requirements for the composition of traffic stripe paint are shown in the following table.

Waterborne Traffic Line Paint Composition Requirements

Requirement	Maximum	Minimum
Paint composition, percent by weight		
Pigment	63.0	60.0
Vehicle	40.0	37.0
Non-volatile vehicle, percent by weight of vehicle	50.0	42.0

Retroreflective Materials
In addition to the paint material, retroreflective materials (e.g., glass spheres/reflective composite optics) are required for use in luminous traffic lines. The use of AASHTO M 247 beads and/or reflective composite optics is required to ensure the high build paint pavement markings meet the reflectance performance requirements. No glass spheres and/or reflective composite optics containing greater than

Figure 13 Material Descriptions – Paint

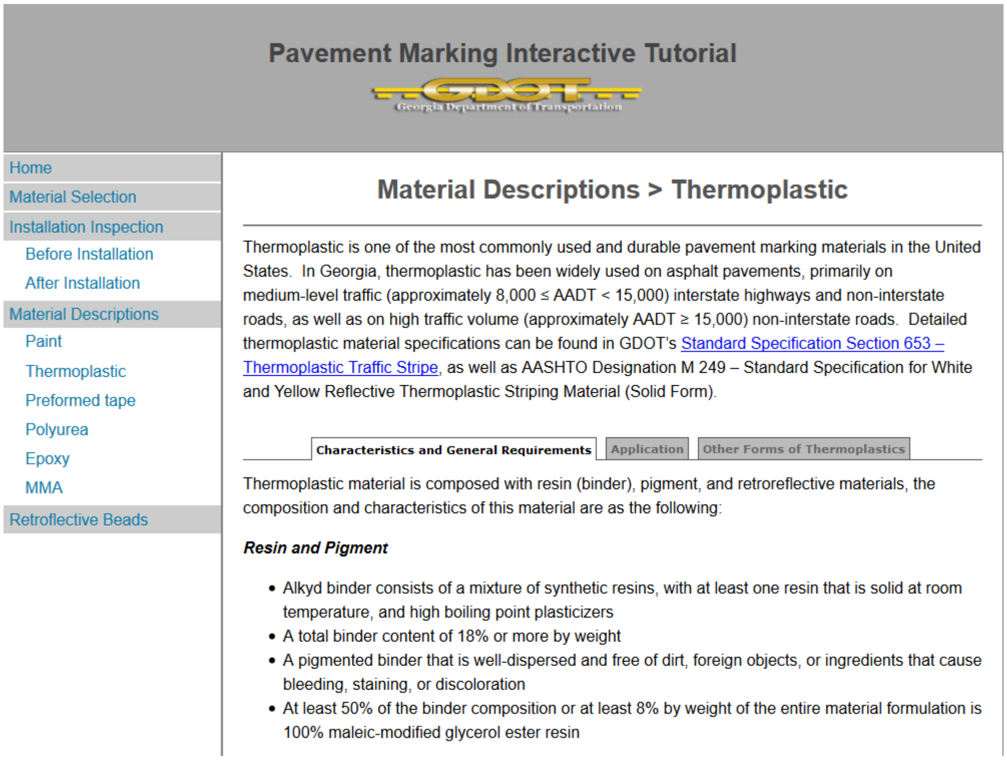


Figure 14 Material Descriptions – Thermoplastic

4.3.3 Preformed Tape

The front page of preformed tape materials is shown in Figure 15. Detailed information of preformed tape is summarized as follows:

- Characteristics and General Requirements
    a. Adhesion
    b. Retroreflective Beads
    c. Elongation and Tensile Strength
    d. Conformability
    e. Removability (Type TR)
    f. Advantages and Disadvantages
- Application
    a. Equipment
    b. Application Conditions

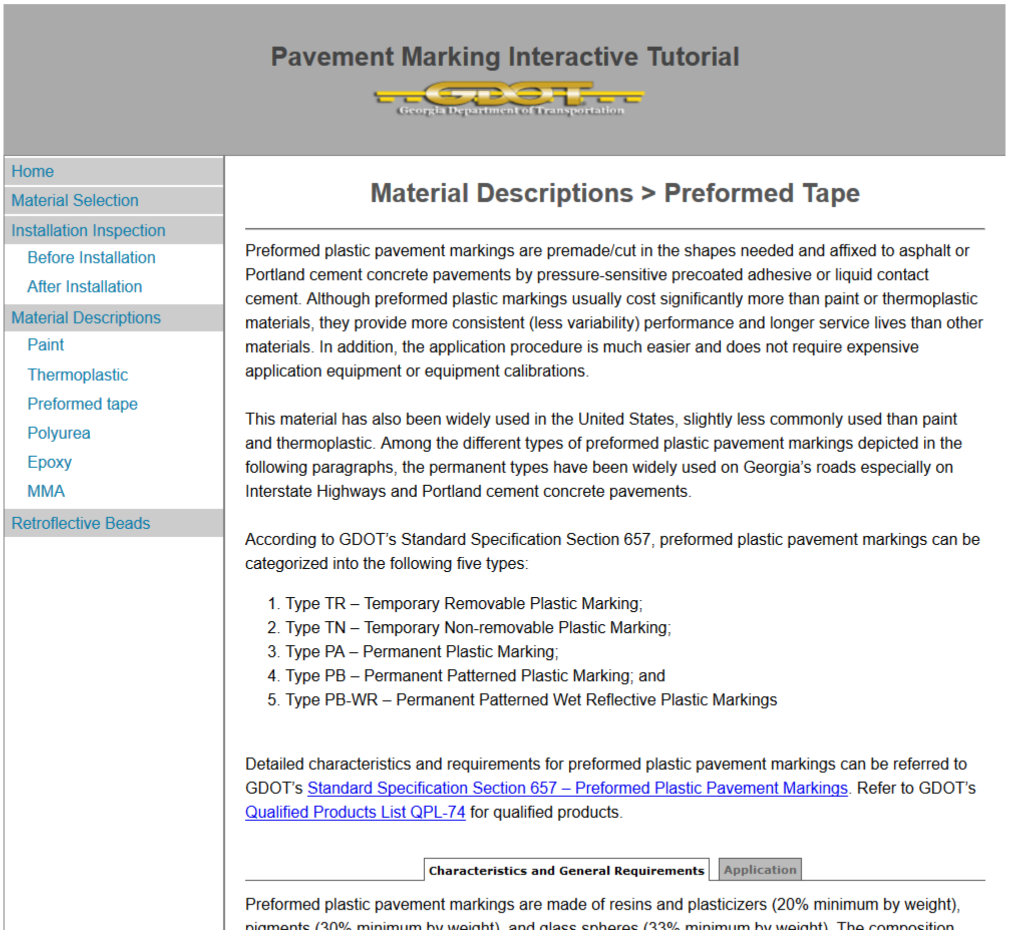


Figure 15 Material Descriptions – Preformed Tape

4.3.4 Polyurea

The front page of polyurea materials is shown in Figure 16. Detailed information of polyurea is summarized as follows:

- Characteristics and General Requirements
  a. Composition
  b. Retroreflective Beads
  c. Advantages and Disadvantages
- Application
  a. Equipment
  b. Application Settings

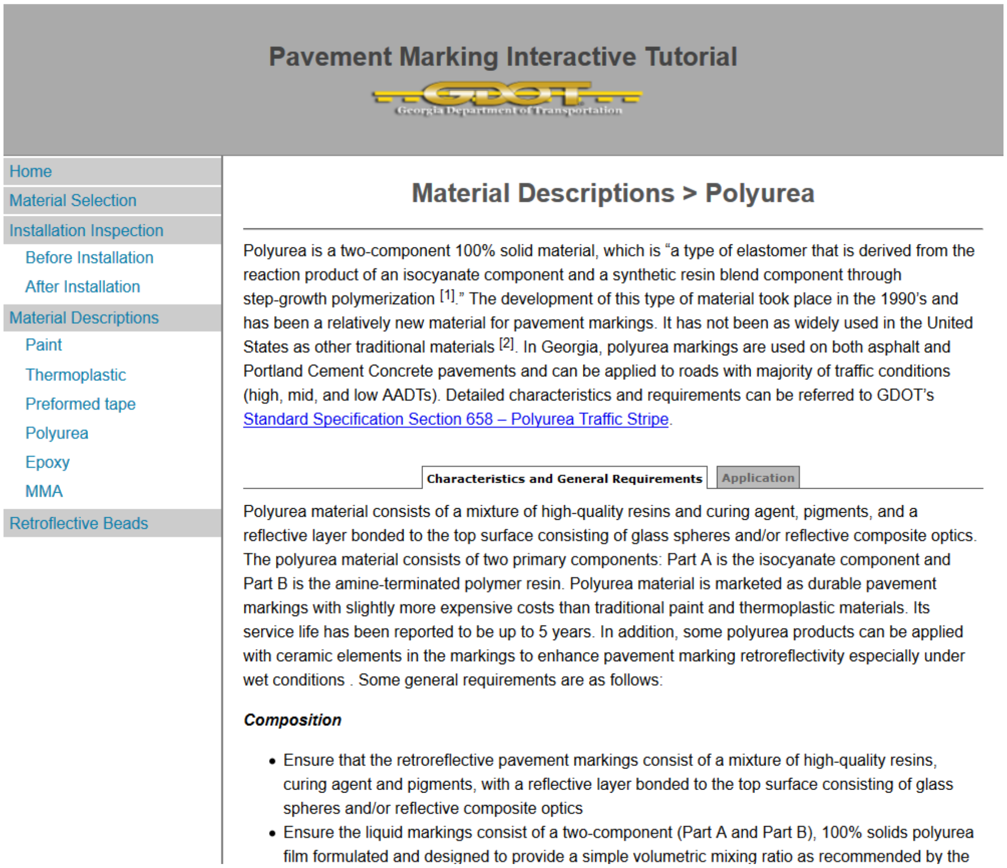


Figure 16 Material Descriptions – Polyurea

4.3.5 Epoxy

The front page of epoxy materials is shown in Figure 17. Detailed information about epoxy is summarized as follows:

- Characteristics and General Requirements
    - a. Composition
    - b. Retroreflective Beads
    - c. Advantages and Disadvantages
- Application
    - a. Equipment
    - b. Application Settings & Conditions

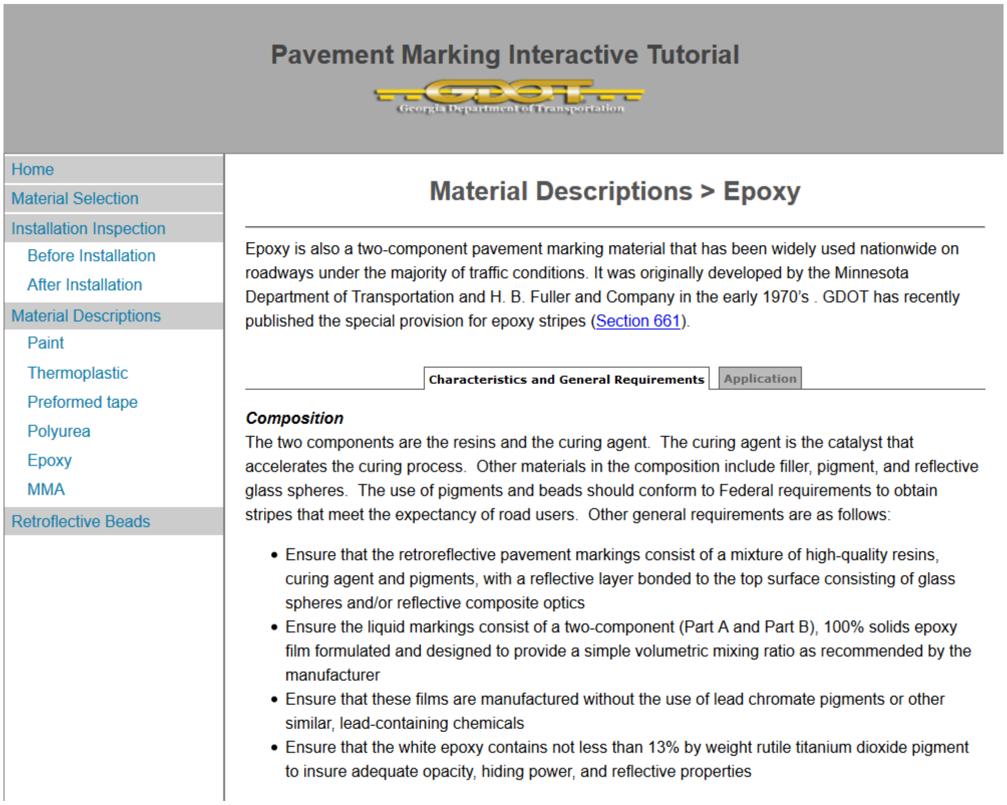


Figure 17 Material Descriptions – Epoxy

4.3.6 Methyl Methacrylate

The front page of MMA materials is shown in Figure 17. Detailed information about MMA is summarized as follows:

- Characteristics and Application
    a. Advantages and Disadvantages

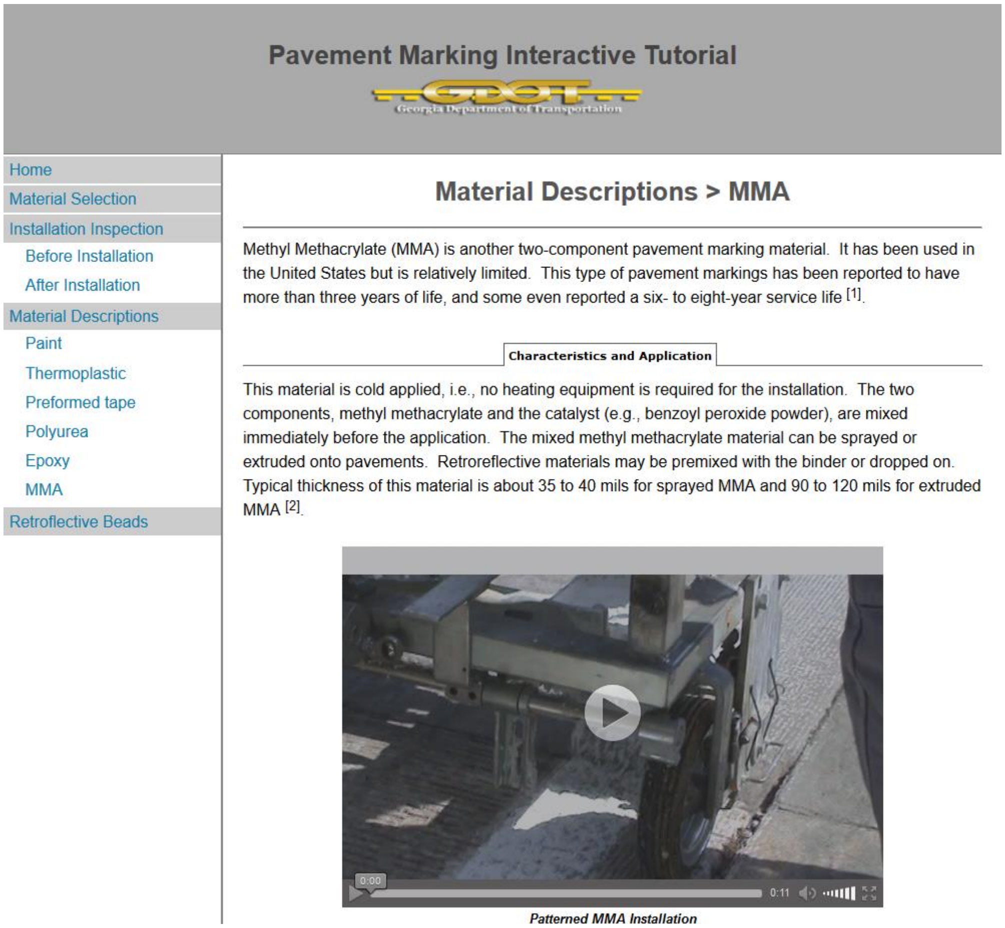
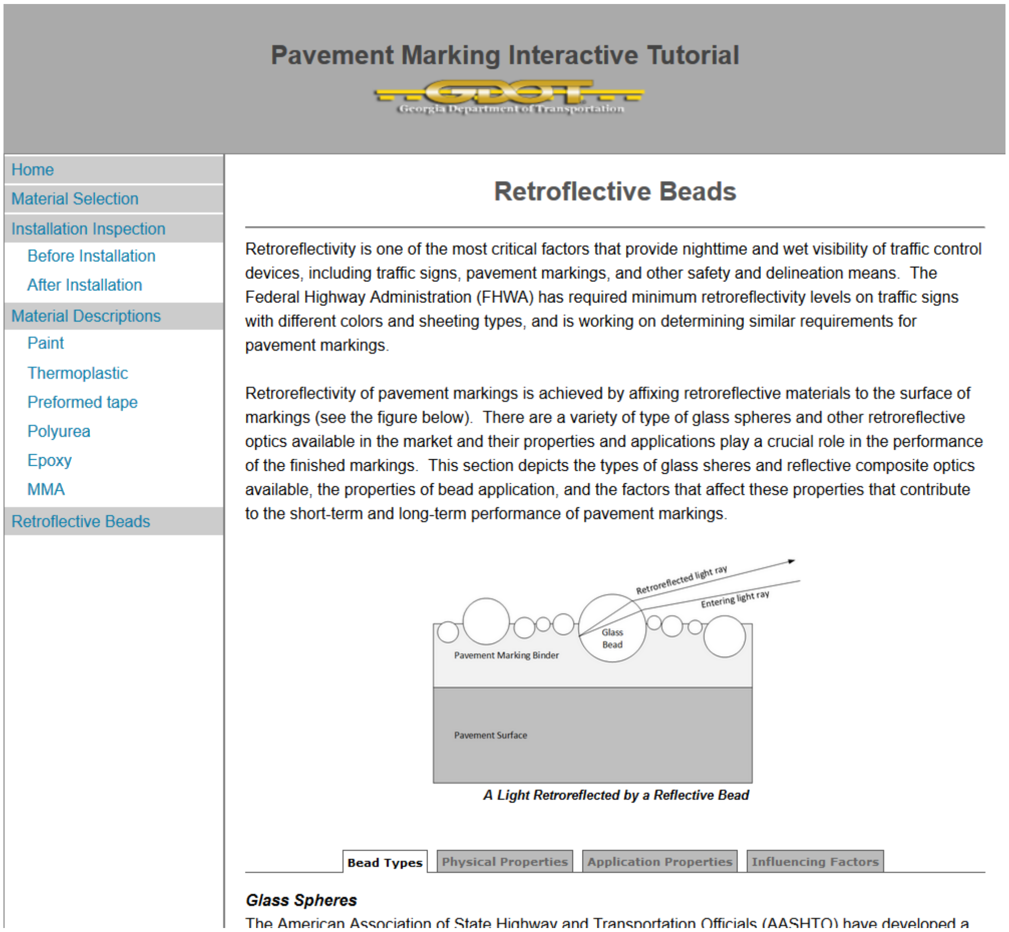


Figure 18 Material Descriptions – MMA

4.4 Retroreflective Beads

This module provides useful information with regard to retroreflective beads (e.g., glass beads and composite optics). As shown in Figure 19, detailed information is available about the following item:

- Bead types
    a. Glass Spheres
    b. Reflective Composite Optics
- Bead physical properties
    a. Clarity
    b. Roundness
    c. Refractive Index
- Bead application properties
    a. Amount
    b. Dispersion
    c. Embedment
- Influencing factors (Factors influencing bead application properties)
    a. Equipment
    b. Environment and Material



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Retroflective Beads

Retroreflectivity is one of the most critical factors that provide nighttime and wet visibility of traffic control devices, including traffic signs, pavement markings, and other safety and delineation means. The Federal Highway Administration (FHWA) has required minimum retroreflectivity levels on traffic signs with different colors and sheeting types, and is working on determining similar requirements for pavement markings.

Retroreflectivity of pavement markings is achieved by affixing retroreflective materials to the surface of markings (see the figure below). There are a variety of type of glass spheres and other retroreflective optics available in the market and their properties and applications play a crucial role in the performance of the finished markings. This section depicts the types of glass sheres and reflective composite optics available, the properties of bead application, and the factors that affect these properties that contribute to the short-term and long-term performance of pavement markings.

A Light Retroreflected by a Reflective Bead

Bead Types | Physical Properties | Application Properties | Influencing Factors

Glass Spheres

The American Association of State Highway and Transportation Officials (AASHTO) have developed a

Figure 19 Retroreflective Beads Module