Nighttime Visibility of 3M AWP and 3M 380WR ES Durable Tape under Dry, Wet, and Rainy Conditions

Ala R. Abbas, Ph.D.
Priyanka Sarker, B.S.
Department of Civil Engineering
The University of Akron
Akron, OH 44325-3905

for the
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16. Abstract

Snow plowable raised pavement markers (RPMs) have been used in Ohio for the last four decades to provide visual guidance to motorists under inclement weather conditions. In recent years, due to the extended pavement resurfacing cycle employed by the Ohio Department of Transportation (ODOT), rare incidents have occurred where the aged pavement surface failed to provide adequate support to the RPM castings. As a result, ODOT adopted a rigorous plan to identify and replace loose RPMs. In addition, ODOT initiated this study to evaluate the performance of other alternative materials and determine whether they can provide equivalent or better delineation than the existing system. These materials included 3M all weather paint (AWP) and 3M 380 wet retroreflective (WR) extended season (ES) durable tape, in addition to the standard extruded thermoplastic that is commonly being used by ODOT on new asphalt surfaces. All materials were installed on Interstate 70 following an asphalt resurfacing project. The 3M AWP was installed on rumble strips and on the surface, while the 3M 380WR ES durable tape and the extruded thermoplastic were installed in groove and on the surface. These materials were evaluated for dry and wet retroreflectivity, dry and wet night visibility, daytime color, and durability for a period of 1.5 years. As expected, the extruded thermoplastic had the lowest retroreflectivity values and night visibility distances under wet conditions. The 3M AWP and the 3M 380WR ES durable tape provided high initial dry and wet retroreflectivity and night visibility. However, their performance was significantly compromised during the first and second winter seasons due to traffic and snow plowing activities. Finally, the RPMs had consistently higher wet night visibility distances than all pavement markings. Therefore, it was concluded that given the harsh environmental conditions in Ohio, it will not be cost effective to use 3M AWP or 3M 380WR ES durable tape as a replacement for RPMs.

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Prepared by:

Ala R. Abbas, Ph.D.
Associate Professor
The University of Akron
Department of Civil Engineering
Akron, Ohio 44325-3905
Phone: (330) 972-8242
Fax: (330) 972-6020
Email: abbas@uakron.edu

&

Ms. Priyanka Sarker
Graduate Assistant
The University of Akron
Department of Civil Engineering
Akron, Ohio 44325-3905

Prepared in Cooperation with
The Ohio Department of Transportation
&
The U. S. Department of Transportation
Federal Highway Administration

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DISCLAIMER

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ABSTRACT

Snow plowable raised pavement markers (RPMs) have been used in Ohio for the last four decades to provide visual guidance to motorists under inclement weather conditions. In recent years, due to the extended pavement resurfacing cycle employed by the Ohio Department of Transportation (ODOT), rare incidents have occurred where the aged pavement surface failed to provide adequate support to the RPM castings. As a result, ODOT adopted a rigorous plan to identify and replace loose RPMs. In addition, ODOT initiated this study to evaluate the performance of other alternative materials and determine whether they can provide equivalent or better delineation than the existing system. These materials included 3M all weather paint (AWP) and 3M 380 wet retroreflective (WR) extended season (ES) durable tape, in addition to the standard extruded thermoplastic that is commonly being used by ODOT on new asphalt surfaces. All materials were installed on Interstate 70 following an asphalt resurfacing project. The 3M AWP was installed on rumble strips and on the surface, while the 3M 380WR ES durable tape and the extruded thermoplastic were installed in groove and on the surface. These materials were evaluated for dry and wet retroreflectivity, dry and wet night visibility, daytime color, and durability for a period of 1.5 years. As expected, the extruded thermoplastic had the lowest retroreflectivity values and night visibility distances under wet conditions. The 3M AWP and the 3M 380WR ES durable tape provided high initial dry and wet retroreflectivity and night visibility. However, their performance was significantly compromised during the first and second winter seasons due to traffic and snow plowing activities. Finally, the RPMs had consistently higher wet night visibility distances than all pavement markings. Therefore, it was concluded that given the harsh environmental conditions in Ohio, it will not be cost effective to use 3M AWP or 3M 380WR ES durable tape as a replacement for RPMs.

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CHAPTER I
INTRODUCTION

1.1 Problem Statement

Pavement markings play an important role in providing visual guidance to motorists. They are used to delineate the intended travel path and guide drivers regarding their location on the road (MUTCD 2009). In order to function properly, pavement markings must be visible under all weather conditions. In general, most pavement markings provide satisfactory performance under dry conditions. However, under wet night conditions, the visibility of these materials degrades significantly as the marking surface becomes flooded with water, leading to partial or complete disappearance of the marking. There are two primary reasons for this phenomenon (Carlson et al. 2007). First, the accumulated water over the pavement marking scatters the light away before it reaches the marking surface, resulting in a specular reflection rather than retroreflection. Second, the accumulated layer of water changes the efficiency of the reflective media in the pavement markings, resulting in a shorter detection distance for the drivers. Therefore, under wet night conditions, driving becomes more challenging because less guidance is provided to the drivers by the pavement markings.

Snow plowable raised pavement markers (RPMs) are typically used in Ohio to provide visual guidance to road users under inclement weather conditions. In recent years, due to the extended pavement resurfacing cycle employed by the Ohio Department of Transportation (ODOT), rare incidents have occurred where the aged pavement surface failed to provide adequate support to the RPM castings. As a result, ODOT has adopted a rigorous plan to identify and replace loose RPMs. In addition, ODOT initiated this study to evaluate the performance of other alternative materials and determine whether they can provide equivalent or better delineation than the existing system. Two materials especially designed to improve pavement marking visibility under wet weather conditions were included in this study. These materials included 3M all weather paint (AWP) and 3M 380 wet retroreflective (WR) extended season (ES) durable tape. This report provides a summary of the performance evaluation results along with conclusions regarding the performance of these materials.

1.2 Objectives of the Study

The primary objective of this study is to evaluate the wet night performance of 3M 380WR ES and 3M AWP and determine the feasibility of using them as a replacement for RPMs in Ohio. The specific objectives of this study include:

- Evaluate the wet night performance of the 3M materials based on dry and wet retroreflectivity, dry and wet night visibility, daytime color, and durability;
- Compare the wet night performance of these materials;
- Compare the evaluated materials based on their cost effectiveness; and
- Determine the feasibility of using them as a replacement for RPMs in Ohio.

1.3 Report Organization

This report is organized into eight chapters. A review of the literature is presented in Chapter 2. Chapter 3 provides a summary of the evaluated materials and their installation techniques. The performance evaluation plan implemented in this study is discussed in Chapter 4. A summary of the results obtained from the periodic evaluations is presented in Chapter 5. Chapter 6 presents an estimation of the predicted service life of the marking materials, while Chapter 7 deals with the calculation of the life cycle cost for the materials. Conclusions and recommendations drawn from the performance of the evaluated materials are included in Chapter 8.

CHAPTER II
LITERATURE REVIEW

2.1 Introduction

Pavement markings provide visual guidance to a motorist by delineating the intended travel path and informing the driver about the vehicle's location on the road. Pavement markings can be classified into three main categories: longitudinal markings, transverse markings; and special markings. When properly installed, pavement markings are able to control, guide, and warn traffic; supplement other traffic control devices; and separate opposing streams of traffic (MUTCD 2009, Migletz et al. 1994).

From a safety standpoint, it is essential that pavement markings be uniformly applied on roads and that intended traveled paths are clearly delineated for drivers. An American Association of State Highway and Transportation Officials (AASHTO) report published in 2008 indicates that at least one death occurs every 21 minutes on the nation's highways due to lane departure, and these departures account for about 60% of crashes. AASTHO has developed a list of 22 objectives to reduce these fatal crashes (AASTHO 2008), and the first of those objectives is to keep the drivers in their respective travel lanes on the roadway. Because pavement markings are essential for delineating lanes, a significant amount of funding (approximately $2 billion annually) is directed for providing pavement markings in the United States alone (Carlson et al. 2009).

In order to provide effective guidance to drivers, pavement markings need to be visible in daylight, at night, and under adverse weather conditions. While pavement markings are typically visible in sunlight, they are not equally effective in reflecting light from a vehicle's headlights back to its source (a process referred to as "retroflection") to reach the eyes of a driver under low light conditions. According to the statistics on fatal crashes in 1996, death rates are about four times higher while driving at night than driving during the day based on driven mileage (Schnell et al. 2004). Reduced retroreflectivity of pavement marking materials is a contributing factor in a number of these crashes.

Reduced retroreflectivity is also a concern under wet conditions, when the marking surface becomes flooded with water and pavement markings can become partially or completely invisible to a driver. There are two primary reasons for this (Higgins et al. 2009). First, the accumulated water over the markings creates a specular reflection of light from the water surface before it can reach the beads on the marking surface, resulting in light being scattered away rather than retroreflected toward the driver. Second, the accumulated layer of water will change the optical efficiency of the optics used in pavement markings; this significantly reduces the retroreflectivity of the markings, resulting in a much shorter visibility detection distance for the drivers.

The color of a pavement marking provides important information to drivers by indicating the direction of traffic in adjacent lanes. Color is expressed through the brightness of white and yellow markings when seen with ambient or retroreflected light. To have optimum visibility for drivers, the color values of white and yellow markings on Ohio roadways must fall within an acceptable range that meets ODOT requirements.

Durability is another important consideration for pavement markings. Roadways in Ohio are subjected to severe weather conditions and snow/ice removal practices, including snow plowing. Durability will affect the service life of the markings and will determine how frequently markings will need to be reapplied.

Pavement marking materials vary in cost, effectiveness in providing a contrast in color from that of the underlying surface, visibility under adverse weather conditions such as rain and fog, adherence to different pavement surfaces, and durability under different traffic and environmental conditions. As a result, each of the previous factors must be considered in determining which material to use for the striping project in question. The most common factors in the selection of the pavement marking material are the type of the line (longitudinal, transverse, or auxiliary), pavement surface (asphalt or concrete), highway classification (interstate highway, multilane highway, two-lane highway, and two-way highway), and average daily traffic (ADT); (Migletz and Graham 2002). Other factors include highway lighting, number of skilled workers, installation equipment, environmental effects, pavement maintenance schedule, and whether the marking material manufacturer offers any warranties on their products or not (Thomas and Schloz 2001). In order to be a good steward of taxpayer dollars, ODOT seeks to provide a cost-effective solution that will not compromise its high standards for safety on Ohio roadways.

2.2 Pavement Marking Performance Evaluation Criteria and Methods

Several factors are important in evaluating the performance of pavement markings including retroreflectivity, nighttime visibility, daytime color, and durability. The following subsections describe these criteria and the methods used for their evaluation.

2.2.1 Retroreflectivity

Retroreflectivity is the most important criteria in evaluating nighttime visibility of pavement markings. Retroreflectivity is typically expressed as the coefficient of retroreflected luminance, R_L, represented in millicandelas per square meter per lux (mcd/m^2/lux) measured by the amount of light retroreflected toward the driver after hitting the marking surface. Higher retroreflectivity generally implies a longer detection distance, which translates into a longer preview time for drivers. Several factors affect the retroreflectivity performance of pavement markings: age of the drivers, bead types, refractory index of the beads used, presence of RPMs, vehicle type, vehicle speed, and weather conditions.

Retroreflectivity of a material is measured using a retroreflectometer. Two types of retroreflectometers, mobile and handheld, can be used to measure the retroreflectivity. A hand held retroreflectometer is normally operated by a single person and is manually placed on pavement markings to collect measurements. A mobile retroreflectometer is attached to the side of a vehicle, and retroreflectivity values are taken as the vehicle drives down the road. Mobile retroreflectometers are more expensive than the handheld ones. Mobile retroreflectometers are less time consuming to use, as they will cover a greater distance in a given amount of time; however, they need to be operated by trained personnel because they are more sensitive to factors such as the calibration process, software operation, driving of the vehicle, and environmental conditions.

The American Society for Testing and Materials (ASTM) has three standards for measuring retroreflectivity of pavement markings under different conditions: ASTM E1710 for dry conditions, ASTM E2176 for continuous wetting conditions, and ASTM E2177 for wet recovery conditions.

ASTM E1710

The European Committee for Standardization (CEN) developed a test method to determine the coefficient of retroreflected luminance of horizontal pavement marking materials at 30-meter geometry under dry conditions; this test procedure was subsequently adopted by ASTM. For this method, retroreflectivity is measured using either a handheld or mobile retroreflectometer. The entrance and observation angles that represent the 30-meter geometry are 88.76º and 1.05º, respectively. Figure 2.1 shows the standard 30-meter geometry for measuring retroreflectivity as presented in ASTM E1710.

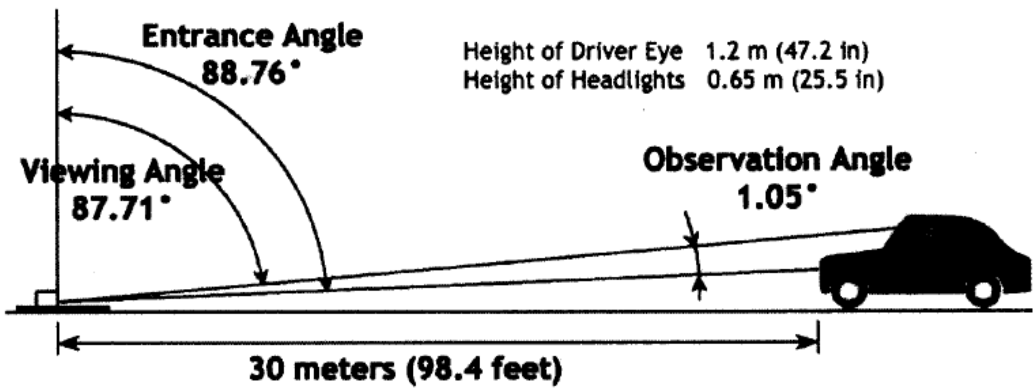


Figure (2.1): Standard 30-meter Geometry as Described in ASTM E1710 (After Migletz and Graham 2002)

ASTM E2176

ASTM E2176 is a standard test method to measure the retroreflectivity of pavement markings under a continuous wetting condition, and it is also known as the “continuous wetting” or “spray” method. It measures retroreflectivity under a condition that is found during a rain event. The procedure specifies a spray area of 20 ± 2 inches (0.51 ± 0.05 meters) in diameter, a spray head height of 18 ± 6 inches (0.45 ± 0.15 meters), and a spray rate of approximately 0.2 ± 0.05 gallons/min (0.8 ± 0.2 L/min). Measurements should be taken every 10 to 15 seconds after starting to spray the water till a steady state is reached. The Figure 2.2 shows the setup of ASTM E2176.

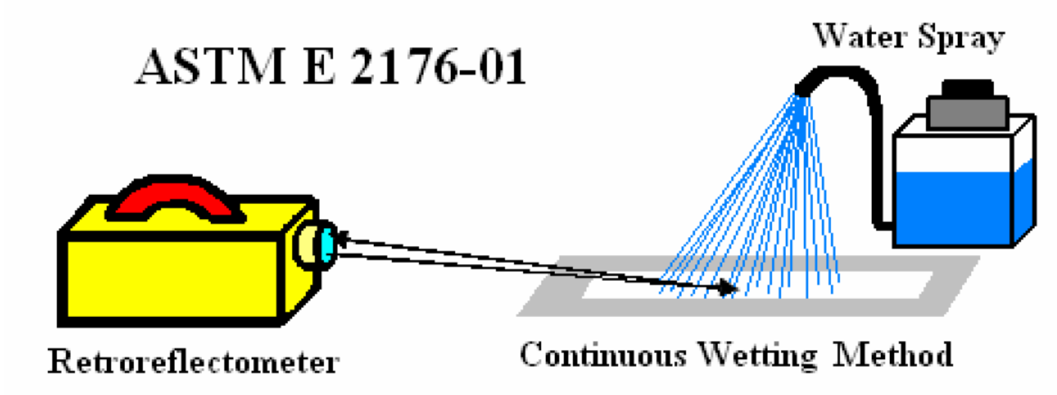


Figure (2.2): Continuous Wetting Setup (After Pike 2005)

ASTM E2177

ASTM E2177 describes a standard method to measure the retroreflectivity of the markings in a wet recovery state, and it is also known as the "recovery" or "bucket" method. This method produces a condition of wetness like that found just after rainfall. In this test procedure, 0.53 to 1.32 gallons (2 to 5 liters) of water is poured on the pavement marking using a bucket and allowed 45 ± 5 seconds to drain off before retroreflectivity is measured. This waiting period allows some water to drain, leaving a surface in a wet condition. Figure 2.3 shows the setup of ASTM E2177.

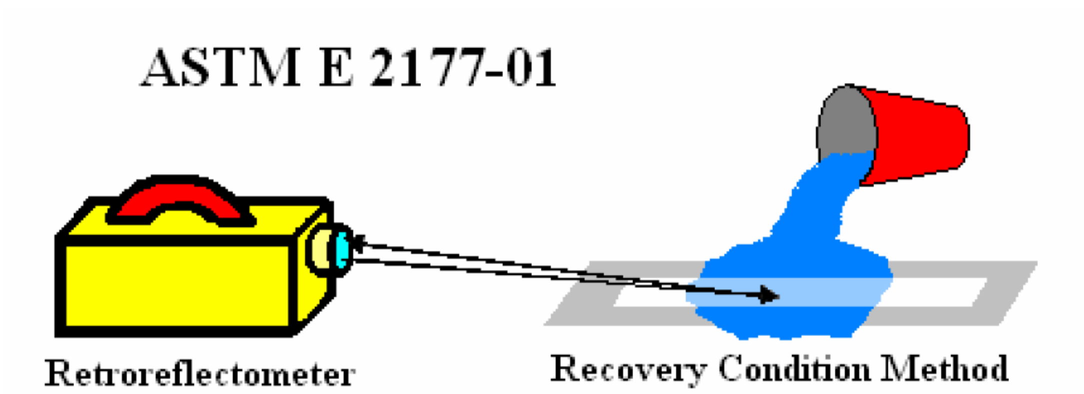


Figure (2.3): Wet Recovery Setup (After Pike 2005)

2.2.2 Visibility

Visibility is assessed by the available luminance contrast between the pavement markings and the underlying road surface. Visibility of pavement markings is generally assessed by measuring the visibility distance, which involves observing the pavement markings from a stationary or moving vehicle under low beam headlight illumination and determining the longest visible distance.

2.2.3 Color

Color is generally rated with the help of a colorimeter, which provides coordinates in Commission Internationale de l'Eclairage (CIE) color units. The coordinates obtained using a colorimeter can be plotted on a CIE chromaticity diagram to determine the color of the pavement marking, as shown in Figure 2.4. According to this diagram, an increase in x value will result in an increase in the red quality of the color, and the green quality of the color increases as y increases. The brightness or luminosity of the object is also described with a Y reading, which is measured using spectro-colorimeters but is not presented in Figure 2.4.

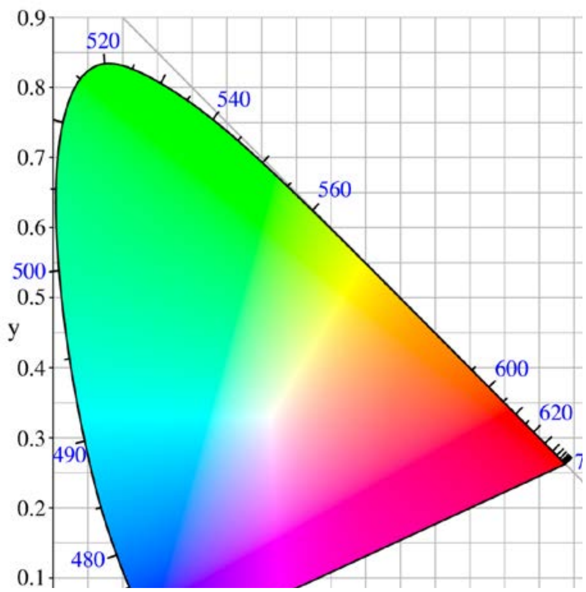


Figure (2.4): CIE Chromaticity Diagram

2.2.4 Durability

Pavement marking durability relates to the resistance of the marking material to abrasion from traffic and snow removal activities. Marking durability is affected by material composition, type and quality of binder used, and ability of the binder to adhere to the underlying pavement. Durability performance of the marking is also governed by factors such as surface preparation, installation quality, traffic volume, the number and severity of snowstorms, and snowplowing activity (Migletz et al. 1994).

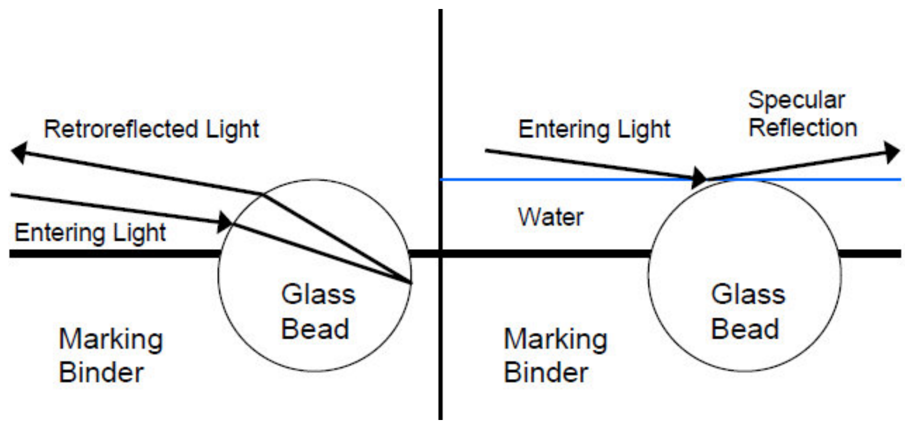
Durability is evaluated by determining the proportion of material remaining on the surface over a period of time. For the evaluation process, an experienced evaluator will rate the durability of the marking on a scale of 0 to 10 by visual inspection, where 0 indicates that the material has been completely lost to abrasion and 10 indicates that 100% of the marking material has been retained. Since durability is assessed through the use of subjective criteria, the rating will vary from person to person.

2.3 Recent Advances in Wet Pavement Markings

Several pavement marking materials are available including traffic paint, thermoplastic, epoxy, polyurea, methyl methacrylate, and durable tapes. While these materials have shown satisfactory performance under dry conditions, their performance can be significantly compromised under wet conditions. A number of techniques have been developed in recent years to improve the wet night performance of pavement markings. These techniques include the use of improved reflective media, profiled pavement markings, wider lines, and striping on rumble strips. The following subsections offer a more detailed discussion about some of these techniques.

2.3.1 Use of Improved Reflective Media

Pavement marking retroreflectivity is generally achieved using glass beads that are premixed and/or applied on the surface of the pavement marking during installation (Higgins et al. 2009). The retroreflectivity of the marking depends on several factors such as the size, shape, and refractive index of the reflective media. The refractive index (RI) is a measure of the change in direction of light when passing from one medium to another. Basically all markings use the same principle to retro-reflect the light back towards the driver. Light emitting from the vehicle enters the bead and hits the back of reflective medium, and a portion of light is reflected back in the direction of light source (Figure 2.5a). However, under wet night conditions when the pavement marking is covered with water, these materials can become completely invisible. The extra layer of water covering the marking does not permit the light from the vehicles to enter the reflective media of the markings (Figure 2.5b). As a result, no light is reflected back to the driver's eyes, and the driver is unable to see the marking.



(a) Dry Condition (b) Wet Condition

Figure (2.5): Glass Bead Retroreflection (After Carlson et al. 2009)

One of the most commonly used techniques to provide the markings with better wet retroreflectivity is using large beads. While standard glass beads get completely covered with water under wet weather conditions, the raised portion of the large beads may still protrude above that water layer and maintain retroreflectivity, as shown in Figure 2.6.

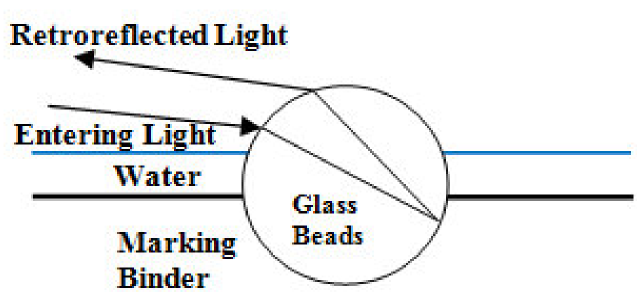


Figure (2.6): Pavement Marking with Large Beads

One of the latest developments to improve the refractive media in the marking is the introduction of dual optics double drop technology (Higgins 2009). Figure 2.7 presents a photo of the reflective media used in the dual optics double drop system. As can be seen from this figure, this technology consists of a double drop application of standard glass beads incorporating a 1.5 RI along with specially designed optical elements having ceramic cores surrounded by very small microcrystalline beads with 1.9 and 2.4 RI. The combined pavement marking optical system is visible both under wet and dry conditions. Under dry conditions, ordinary 1.5 RI index beads and the 1.9 RI beads on the element core provide the retroreflectivity, while the 2.4 RI beads perform under wet weather conditions. Conventional materials can lose their brightness very quickly and are not durable under heavy traffic loads, but the microcrystalline structure of the high index beads has been proven to be durable under laboratory simulated heavy traffic loading tests (sandblasting). This "all weather performance" technology can be used with high build waterborne paint, thermoplastic, epoxy, and polyurea.

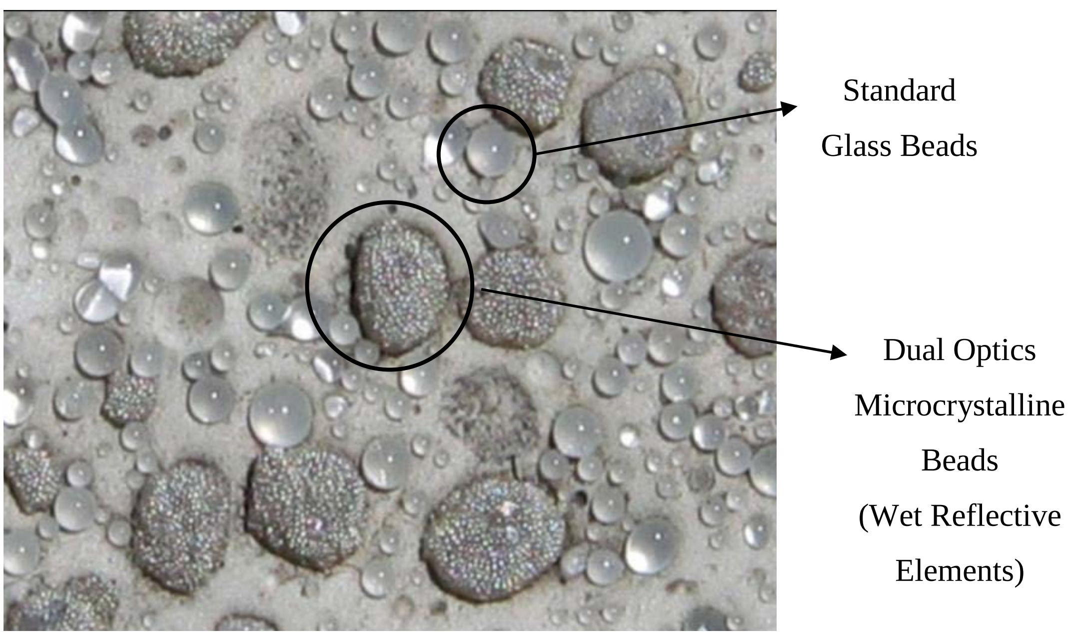


Figure (2.7): Dual Optics Double Drop System (After www.azite.org)

In addition to the previous materials, several tape products such as the 3M wet reflective durable tape also use these high index microcrystalline beads bonded in a highly durable polyurethane topcoat to provide high retroreflectivity under wet conditions. In these tapes, the reflective lenses are encapsulated and thus have a high level of continuous reflective performance, ensuring that the markings are as bright in rain conditions as they are when the surface is dry.

2.3.2 Profiled Pavement Markings

Profiled markings such as profiled thermoplastic are patterned marking products with profiled sections that drain water away from the surface of the material, keeping the retroreflective surface above the water (Figure 2.8). Thermoplastic materials are typically used on asphalt pavements. They are heated to a molten state (400 to 440ºF) and then applied to the pavement surface by extrusion or spraying. The main drawback of this material is that it becomes completely invisible when covered with water under wet weather conditions. Therefore, the wet performance of this material can be improved by introducing these profiled surfaces.

Figure (2.8): Profiled Thermoplastic (After www.azite.org)

The same concept is also used in structured pavement markings such as wet reflective tapes that feature a patterned surface with a near vertical profile to maintain retroreflectivity under wet conditions (Figure 2.9). As mentioned earlier, wet reflective durable tapes also contain specially designed high index optical beads to improve retroreflectivity under wet weather conditions.

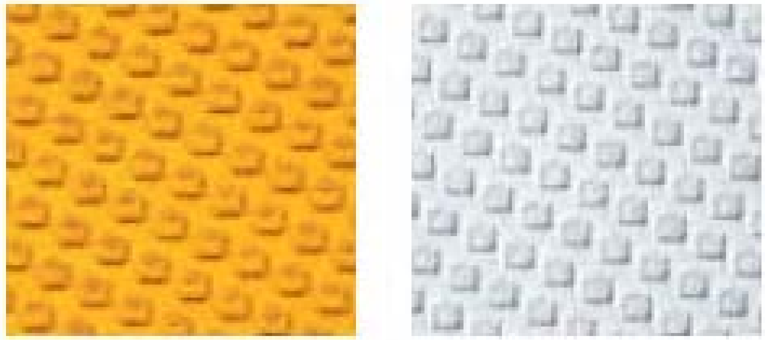


Figure (2.9): Wet Weather Tape (After www.tapconet.com)

2.3.3 Rumble Strip Marking

Rumble strips are grooved or raised patterns in the road surface that serve to warn an inattentive driver by producing a physical vibration and audible rumbling once the tires of the vehicle cross them. Applying a marking to the rumble strip can be an effective way to enhance the wet night visibility, as it is unlikely that the raised portion of these rumble strips will be completely filled with water. Figure 2.10 shows an example of rumble strip marking. While rumble strip markings are typically used along the edge lines, they have also been used along the centerlines.

Figure (2.10): Rumble Strip Marking (After Gibbons and Hankey 2007)

2.4 Previous Studies on the Wet Performance of Pavement Marking Materials

Over the last two decades, several research studies have been conducted to evaluate the performance of pavement markings. Most of these studies focused on the dry performance of the markings. However, in recent years, concern about the effectiveness of pavement markings under wet conditions has gained increased attention and has led to additional research on this topic. The following is a brief summary of some of these studies, with highlights of their findings.

Schnell et al. (2003) conducted an experimental study sponsored by the Federal Highway Administration (FHWA) to evaluate the performance of three types of preformed tape materials under different weather conditions. The materials evaluated in this study were preformed flat marking tape (1.5 index beads), preformed patterned (structured) tape (1.75 index ceramic beads), and wet-weather tape with enclosed lens design that had special optics to give a high level of dry and wet reflective performance. The testing conditions included both dry, wet (immediately after rainfall), and simulated rain conditions (rainfall rate of 1 inch per hour). The evaluation took place on a test track in Cottage Grove, Minnesota, that had a road section equipped with spray nozzles capable of simulating a 1-inch-per-hour rain event. The researchers evaluated the performance of these materials in terms of detection distances, eye-fixation distributions, and pavement-marking retro-reflectance. As part of the study, a total of 18 participants were asked to drive their vehicles along the pavement marking lines and to state the earliest point at which they could detect the end of the markings. Eye movement data of those participants were collected to analyze the eye-fixation distributions, eye-fixation durations, numbers of eye fixations, eye-fixation distances, and eye-fixation frequencies for each material under each condition. Retroreflectance of each material was measured using handheld retroreflectometers in accordance with ASTM E1710 (dry), ASTM E2177 (wet recovery), and ASTM E2176 (continuous wetting). This study showed that under dry conditions, all three pavement markings provided long detection distances. However, under wet conditions, the wet-weather tape performed the best, followed by the patterned tape and the flat tape. Under wet conditions, about 70%, 49% and 35% of the dry detection distance was lost for the flat tape, patterned tape and wet weather tape, respectively. However, under simulated rain conditions, the wet weather tape showed a loss of about 52% of its dry detection distance. As for the eye fixation distribution criterion, wet weather tape saw the most concentrated eye movements, followed by the patterned and flat tape. This concentrated eye fixation was interpreted as a gain in the visual search comfort for the participants. Retroreflectance of the flat, patterned and wet weather tapes were 69 mcd/m^2/lux, 179 mcd/m^2/lux and 739 mcd/m^2/lux, respectively, under wet conditions and 30 mcd/m^2/lux, 15 mcd/m^2/lux, 649 mcd/m^2/lux under simulated rain conditions. Flat tape and patterned tapes were completely invisible under simulated rain conditions. Good correlation was reported between the detection distances under continuous rain and retroreflectivity values measured using ASTM E2176 and between the detection distances under recovery conditions and retroreflectivity values measured using ASTM E2177. It was emphasized, however, that retroreflectivity measurements from ASTM E2176 and ASTM E2177 are not interchangeable. Hence, ASTM E2177 cannot be used to determine the effectiveness of pavement markings under continuous rain, and ASTM E2176 cannot be used to determine the effectiveness of pavement markings after rain cessation.

In a follow up study by Aktan and Schnell (2004), the nighttime visibility of a large beaded permanent pavement marking was compared to two patterned tapes (one with high-index beads and the other with mixed high-index beads) under dry, wet, and simulated rain conditions. The evaluation was conducted on the same test track mentioned earlier and using the same evaluation techniques. Most participants from the previous study also participated in the evaluations. It was found that the patterned tape with mixed high-index beads performed best under all three weather conditions. The permanent pavement marking with large beads was comparable to the tape with high-index beads under wet and rainy conditions. However, under dry conditions, the permanent pavement marking with large beads performed the worst.

In a study funded by the Texas Department of Transportation (TxDOT), Carlson et al. (2005, 2007) evaluated the performance of a wide range of pavement markings under dry and wet conditions. In addition to RPMs, these materials included waterborne traffic paint, thermoplastic, durable tapes, epoxy, polyurea, and methyl methacrylate. This study also looked into the effects of increasing the pavement marking width (from 4 inches to 6 inches) and rumble strip markings on the wet visibility performance. The evaluation was conducted on a 1600 ft long test track with rain tunnel located at the Texas A&M University's Riverside Campus. The pavement markings were placed along the rain tunnel in 8 ft strips. Three rainfall rates were utilized in the evaluation. These rates included 0.28, 0.52, and 0.87 inches per hour representing low, medium, and high rainfall rates, respectively. Thirty four participants drove through the rain tunnel and reported the beginning of the pavement markings, which was used to determine their detection distance. In addition, retroreflectivity was measured under dry, continuous rain, and wet recovery conditions using ASTM E1710, ASTM E2176, and ASTM E2177, respectively. This study found no correlation between dry and wet retroreflectivity measurements or between retroreflectivity measurements obtained using ASTM E2176 and ASTM E2177. However, a moderate correlation was reported between the visual observations for all rainfall levels and ASTM E2176 and ASTM E2177 retroreflectivity measurements with an r^2 value of 0.619 and 0.595, respectively. An average wet night detection distance of over 550 ft was reported for the RPMs, which was 200 ft greater than any of the other materials tested. The tapes were also found to perform better than the rest of the materials, with the exception of the RPMs. Additionally, the 6 inch wide lines were observed to have 30% longer detection distances than the corresponding 4 inch lines.

Gibbons et al. (2005) evaluated the performance of six pavement marking treatments under different weather conditions. These treatments included standard latex paint and glass beads with RPMs, standard latex paint and glass beads, standard latex paint with large glass beads (visibeads), profiled thermoplastic (drop-on line), wet retroreflective tape, and semi-wet retroreflective tape. The experiment was conducted at the Virginia Smart Road facility where participants were subjected to a simulated rain event of 0.8 inch of rain per hour and a simulated recovery (10 minutes after rain cessation). The participants rated the visibility of the pavement markings under dry, continuous rain, and recovery period by counting the number of skip lines visible from a stationary vehicle (*static experiment*). Figure 2.11 presents the mean visibility distances found in the study for both dry and wet conditions. The continuous rain evaluation indicated that all pavement markings performed better under dry conditions than under wet conditions, with the exception of the RPMs that performed the same under both conditions. The recovery evaluation showed that the time required for the visual performance of a pavement marking to recover from rain is significantly higher for paints and bead products than for profiled, wet, and semi-wet pavement markings. The visual observations from both continuous rain and wet recovery were also compared to retroreflectivity measurements obtained using ASTM E2176 and ASTM E2177. A high degree of correlation was reported. However, a definitive level of retroreflectivity required to meet drivers' needs in wet night conditions was not found.

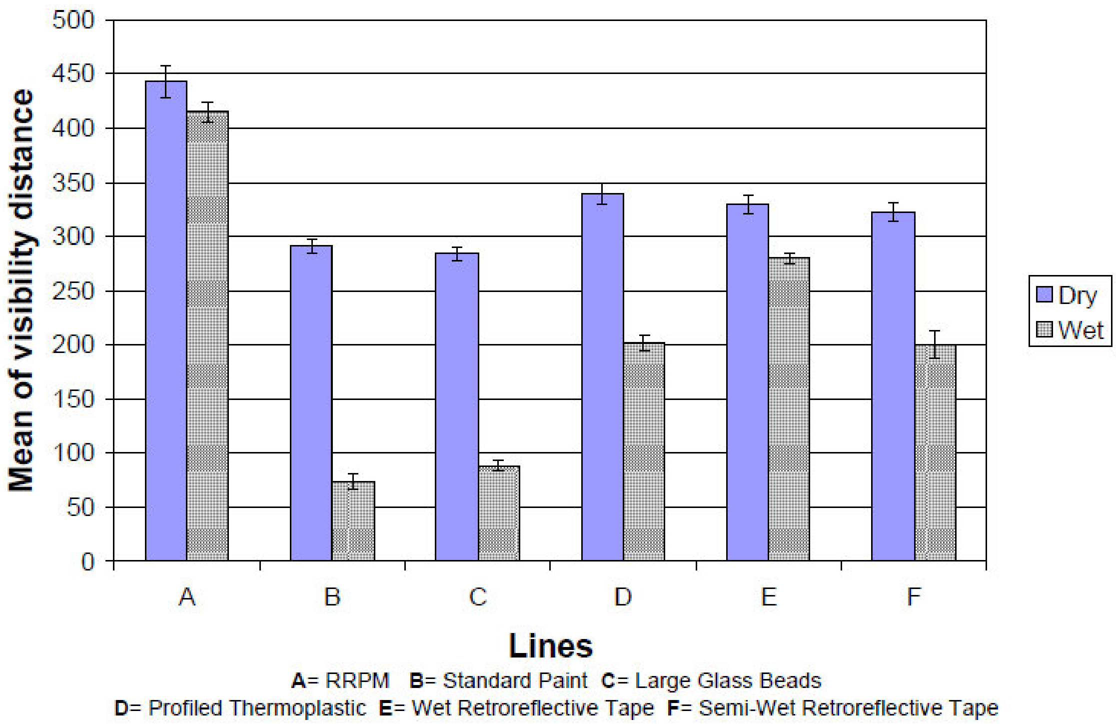


Figure (2.11): Comparison between Dry and Wet Visibility of Different Marking Materials (After Gibbons et al. 2005)

In a subsequent study by the same research group (Gibbons et al. 2007), the performance evaluation was conducted under continuous rain (0.8 inch/hr or 20.32 mm/hr) while driving a vehicle on a closed test track (*dynamic experiment*). Four pavement markings were evaluated. These materials included standard latex paint and glass beads, standard latex paint with large glass beads (visibeads), profiled thermoplastic (drop-on line), and wet retroreflective tape. The performance evaluation was conducted under variable lighting conditions in the presence and absence of glare. It consisted of determining the detection distance of the start or end point of a white 4-inch edge line. This study found that the wet retroreflective tape had the longest wet visibility distance, followed by the profiled thermoplastic and the standard latex paint with large glass beads, then the standard latex paint and glass beads. However, it was concluded that none of the materials tested provided adequate visibility distance at speeds greater than 45 mph.

In a more recent study, Gibbons et al. (2011) evaluated the wet night performance of four recently developed marking materials – white wet-reflective tape, yellow wet-reflective tape, fast dry waterborne paint (rumble striped), and polyurea liquid durable pavement marking – using the same test facilities as in their 2007 study. The purpose of this new study was to set a minimum retroreflectivity requirement for the four materials under wet night conditions. The test took place on a 2.2-mile-long controlled access smart road in Virginia, and the materials were evaluated under dry, continuous rain (with a rain rate of 0.8 inch/hr or 20.32 mm/hr), and recovery conditions. For the evaluation, 36 participants including both female and male drivers from two different age groups (a group aged 18–34 years and a group aged 65 years and above) were asked to identify the start or the end of a line in order to determine the detection distance of the pavement marking. The dry and wet retroreflectivity measurements were measured according to ASTM E1710 and ASTM E2177, respectively. The researchers concluded that a minimum retroreflectivity value of 150 mcd/m^2/lux for both white and yellow pavement markings was required to provide adequate visibility at 55 mph in dry conditions and 40 mph in wet conditions (at 1 inch/hr or 25.4 mm/hr rain). The study also found that amount of increase in detection distance reduces with the amount of increase in retroreflectivity value after a certain point; this tendency for diminishing returns become apparent as the retroreflectivity value goes above 200–250 mcd/m^2/lux in dry conditions and 150 mcd/m^2/lux for wet conditions. This study also found that recent materials perform better than previously tested materials (with the exception of old-style tapes) and that rumble stripes showed a good recovery performance in comparison to other materials evaluated.

In a study funded by the Federal Highway Administration (FHWA) Highways for LIFE Technology Partnerships Program, Higgins et al. (2009) evaluated the performance of several temporary pavement markings for work zone projects. Three experimental optics-on-paint marking systems incorporating high refractive index dual-optics drop-on elements, specially designed to provide good visibility in both dry and wet conditions, and two commercially available temporary markings (one glass beads-on-paint system and one wet-reflective removable tape) were evaluated under dry, wet-recovery (just after rainfall), and simulated rain conditions of 0.5 inch/hr (12.7 mm/hr). The reader is referred to Table 2.1 for a complete description of the materials evaluated in that study. Thirty participants drove through simulated work zones on a closed test track and viewed the pavement markings at night under all three weather conditions. Each driver was asked to identify the direction of work zone lane shift tapers delineated by the markings. Figure 2.12 presents the mean detection distances for each marking system under the various conditions. This study found that all three experimental marking

Table (2.1): Description of Prototype and Reference Pavement Marking Systems (After Higgins et al. 2009)

Marking	Binder	Optics
Prototype A	High-build waterborne paint	3M series 90S high refractive index dual optics drop on elements (4g/linear ft drop rate) with MODOT type P drop-on 1.5 index glass beads
Prototype B	High-build waterborne paint	3M series 90S high refractive index dual optics drop on elements (8g/linear ft drop rate) with MODOT type P drop-on 1.5 index glass beads
Prototype C	High-build waterborne paint	3M series 90S high refractive index dual optics drop on elements (8g/linear ft drop rate) in combination AASTHO M247 type 1 drop-on 1.5 index glass beads
Benchmark 1	High-build waterborne paint	AASTHO M247 type 1 drop-on 1.5 index glass beads
Benchmark 2	Removable preformed wet reflective structured tape	Specially designed optics to provide high retroreflectivity under dry and wet conditions.

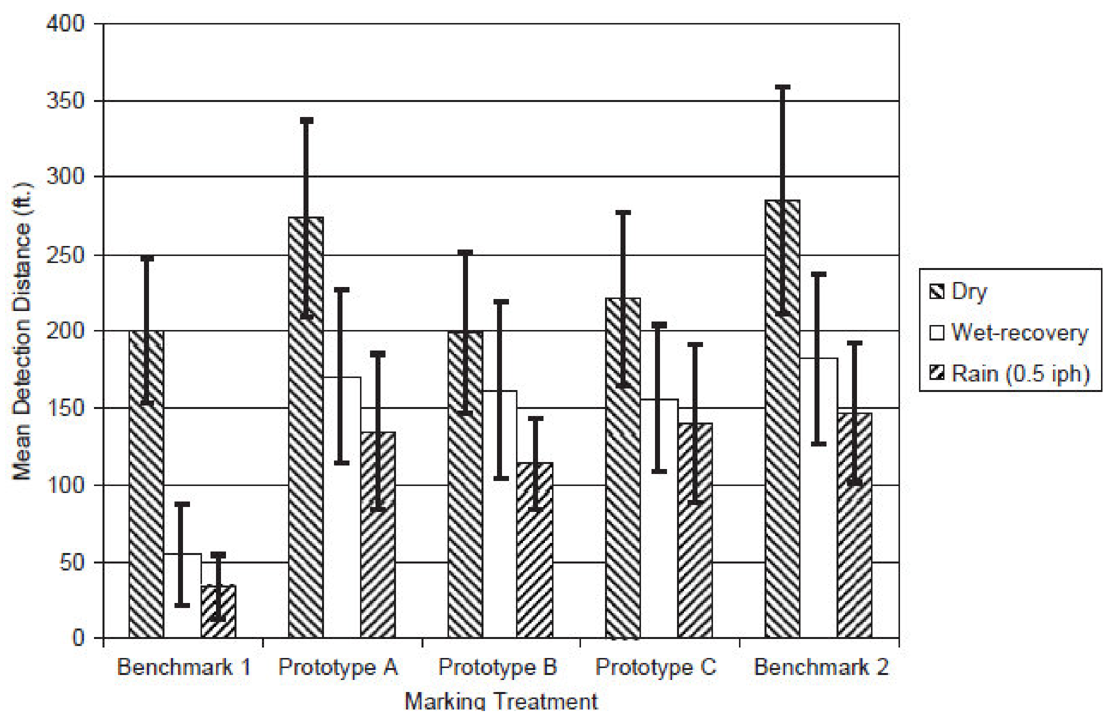


Figure (2.12): Mean Detection Distance as Function of Pavement Marking System and Environmental Condition (After Higgins et al. 2009)

systems and the wet-reflective tape retained 50% to 70% of their average dry detection distances under simulated rain and 60% to 80% of their average dry detection distances under wet recovery. Meanwhile, the average wet-recovery and rain detection distances for the conventional glass beads-on-paint system dropped to 28% and 17% of its dry detection distance, respectively. Furthermore, it was reported that participants failed to detect the conventional glass beads-on-paint system in nearly half of the observations in the rain condition.

Lindly and Narci (2009) conducted a study to evaluate the performance of double drop glass beads edge lines in Alabama and compare them to standard thermoplastic, rumble stripes, and profiled pavement marking, in terms of service life, life-cycle cost, and dry and wet retroreflectivity. The double drop glass beads edge lines were found to have the highest dry retroreflectivity followed by the rumble stripes, then the standard thermoplastic, and finally the profiled pavement marking. As for the wet retroreflectivity, the double drop glass beads edge lines had the highest retroreflectivity values, followed by the profiled pavement marking and the rumble stripes. The standard thermoplastic had the lowest wet retroreflectivity values. This study also indicated that the double drop glass beads edge lines are expected to have the longest service life, followed by the rumble stripes, the standard thermoplastic, and the profiled pavement marking.

The previous studies revealed valuable information about the wet night performance of pavement markings and the methods used to characterize their performance. However, most of these studies focused on the initial performance, which is not necessarily indicative of the long term performance of these materials. In addition, none of these studies accounted for the effect of snow plowing on the performance of the evaluated materials. Therefore, results from these studies are not applicable to the State of Ohio. Consequently, this research was conducted to identify more durable and cost-effective pavement marking materials and to improve the wet night visibility of pavement markings on roadways that are subjected to snow plowing.

CHAPTER III
PRODUCT INFORMATION AND INSTALLATION

3.1 Introduction

This study evaluated the performance of 3M all weather paint (3M AWP) and 3M 380 Wet Reflective Extended Season durable tape (3M 380 WR ES) along with a traditional extruded thermoplastic under dry and wet night conditions. All materials were installed on a stretch of Interstate 70 (I-70) in Licking County, Ohio. The pavement on I-70 was constructed during the 1970s, and the selected location for the evaluation was scheduled for resurfacing with an asphalt overlay in 2008. This presented a good opportunity to evaluate the performance of these materials on a new asphalt surface. All materials used in this study were installed in August 2008, and the evaluation took place over a period of 1.5 years following the installation.

The evaluation location on I-70, situated between mile markers 138 and 143, is a segment of highway with two 12-ft (3.7-m) lanes running in each direction. The average annual daily traffic at the test site is approximately 44,000 vehicles per day, equally divided between the eastbound and westbound directions, with approximately 30% truck traffic. The evaluation site receives an average annual snowfall of 20 to 30 inches (about 50 to 76 cm). Snow removal in this area is accomplished using trucks with front-mounted plow blades and rear-mounted deicing salt spreaders. ODOT employs a bare pavement surface policy in its snow removal activities, where the plow blade runs on the pavement surface, leaving behind little to no snow or ice. Because of the high levels of traffic and the moderately high snowfall, the stretch of roadway in the evaluation area was considered adequate for determining the effects of wear by traffic and damage from snow removal activities.

Installation of the test materials followed 2005 ODOT Construction and Material Specifications (C&MS). Long lines were applied using a standard line width of 4 inches (101 mm). Yellow lines were installed on the left edge of the roadway, and white lines were installed at the right. Broken lines were applied in 10 ft (3.0 m) long segments with 30 ft (9.1 m) gaps in between. The materials were applied in six different treatments (including the control treatment), as shown in Table 3.1.

Table (3.1): Pavement Marking Materials and Experimental Design

Treatment No.	Mile Marker	Line Type	Treatment Type
1[a]	138-139 (EB)	Yellow Edge Line	AWP on Rumble Strips
		White Lane Line	AWP on Surface
		White Edge Line	AWP on Rumble Strips
2[b]	139-140 (EB)	Yellow Edge Line	WR Durable Tape on Surface
		White Lane Line	WR Durable Tape on Surface
		White Edge Line	WR Durable Tape on Surface
3[b]	140-141 (EB)	Yellow Edge Line	WR Durable Tape in Groove
		White Lane Line	WR Durable Tape in Groove
		White Edge Line	WR Durable Tape in Groove
4[a]	141-142 (EB)	Yellow Edge Line	Thermoplastic in Groove
		White Lane Line	Thermoplastic in Groove
		White Edge Line	Thermoplastic in Groove
5[a]	142-143 (EB)	Yellow Edge Line	AWP on Surface
		White Lane Line	Thermoplastic on Surface
		White Edge Line	AWP on Surface
Control[a]	138-143 (WB)	Yellow Edge Line	Thermoplastic on Surface
		White Lane Line	Thermoplastic on Surface
		White Edge Line	Thermoplastic on Surface

[a] RPMs were installed at 120 ft along the lane line.
[b] No RPMs were used.

For this evaluation, the 3M AWP was installed on rumble strips and on the surface, while the 3M 380WR ES durable tape and the extruded thermoplastic were installed in grooves and on the surface. The 3M AWP was applied at a thickness of 20-mil (0.51 mm); the 3M 380WR ES durable tape was about 90-mil (2.3 mm) thick at the raised profile; and the extruded thermoplastic was applied at a thickness of 125-mil (3.2 mm). Where applicable, a groove depth of 90 ± 10 mil was used for the 3M 380WR ES durable tape, and a groove depth of 125 ± 10-mil was used for the extruded thermoplastic. These groove depths were equal to the pavement marking thickness so as to protect them from snow plowing activities during winter. RPMs were installed on the lane lines where 3M AWP and extruded thermoplastic were used, but not where the 3M 380WR ES durable tape was applied. It was hoped that 3M 380WR ES durable tape would provide adequate visibility under wet conditions without the need for RPMs. The following section provides a detailed summary for each of the materials installed during the evaluation.

3.2 Evaluated Marking Materials

3.2.1 *3M All Weather Paint*

3M all weather paint (3M AWP) consists of a traditional fast dry waterborne traffic paint mixed with standard glass beads and 3M elements specially designed to improve wet night visibility. Each element is comprised of a silicon core topped with a mixture of two types of microcrystalline ceramic beads: 80% are wet reflective beads with a refraction index of 2.4, and 20% are dry reflective beads with a refraction index of 1.9. Under dry conditions, retroreflectivity is provided by the standard glass beads and the 1.9 refraction index ceramic beads. The 2.4 refraction index ceramic beads are not effective under dry conditions. However, in the presence of water (which has a refraction index of 1.33), the overall refraction of the element-water system becomes ideal for wet pavement marking retroreflectivity.

3M AWP was installed with standard painting equipment, using conventional Type 1 glass beads and the 3M elements. As mentioned earlier, the 3M AWP was installed on rumble strips and on the surface. The target thickness was 20 mils (0.51 mm), with Type 1 glass beads applied at a rate of 12 lbs per gallon (1.44 kg per liter) and 3M elements applied at a rate of approximately 5 lbs per gallon (0.6 kg per liter).

3.2.2 *3M 380 Wet Reflective Extended Season Tape (3M 380WR ES Durable Tape)*

The 3M 380WR ES durable tape – which is manufactured by 3M Stamark™ and is available in 300 ft (91.4 m) rolls in both yellow and white colors – has a standard width of four inches (101.6 mm). The tape consists of a base bead-filled pliant polymer layer topped with a polyurethane coating intermixed with microcrystalline ceramic beads. It utilizes specially designed optics to improve wet night visibility. In addition, the tape has a patterned structure with raised, near vertical surfaces that improve retroreflectivity under wet weather conditions.

3M 380WR ES tape can typically be used without any surface adhesive preparation during the application season defined by the 3M climate guide. However, these tapes can be applied in early spring and late autumn at temperatures as low as 40º F (4.4º C) with the use of a special surface preparation adhesive (such as 3M P-50). The 3M 380WR ES durable tape was installed in August, and hence no special surface preparation was used. A manual highway tape applicator was used to roll the 3M 380WR ES tape onto the edge lines. On skip lane lines, the tape was placed manually. To ensure proper adhesion to the underlying pavement surface, tamper carts weighing more than 200 lbs (90.7 kg) were used to tamp the tapes.

3.2.3 *Thermoplastic*

Standard alkyd thermoplastics are commonly used by ODOT for pavement markings on new asphalt surfaces. These thermoplastics incorporate Type C glass beads and intermixed glass beads as reflective media. According to the 2005 ODOT C&MS, the ambient temperature must be above 50º F (10º C) and the thermoplastic needs to be heated to a range between 400º and 440º F (204º to 227º C) prior to installation on a new asphalt pavement. The C&MS also requires the thermoplastic to be installed at a thickness of 125 mils (3.2 mm), with Type C glass beads applied to the surface at a minimum rate of 12 lbs per 100 square feet (0.59 kg per m^2) of marking area.

Thermoplastic was selected as a control material in this evaluation. It was installed with standard equipment using the extrusion method. The thermoplastic was installed at the target thickness of 125 mils (3.2 mm), and Type C glass beads were applied at the rate specified in the C&MS.

CHAPTER IV
PERFORMANCE EVALUATION PLAN

4.1 Introduction

The performance of the pavement markings was evaluated under dry and wet conditions on a semi-annual basis for a period of 1.5 years, with evaluations conducted in September 2008, April 2009, September 2009, and April 2010. The first evaluation was carried out within one month from installation. Subsequent evaluations were conducted every approximately six months thereafter. This schedule allowed for evaluating the performance of the materials over two winter seasons.

4.2 Performance Evaluation Measures

The performance evaluation plan included monitoring dry and wet retroreflectivity, dry and wet nighttime visibility, daytime color, and durability. The following subsections describe these performance measures and the methods used for their evaluation.

4.2.1 Retroreflectivity

The dry retroreflectivity of the pavement marking materials was measured in accordance with ASTM E1710 using a Delta LTL-X handheld retroreflectometer. The same LTL-X retroreflectometer was used to measure the wet retroreflectivity of the materials according to ASTM 2177. However, the device was first calibrated and outfitted with a base plate and two wet night feet before being used to measure wet retroreflectivity. Wet retroreflectivity of the materials was measured in a wet recovery state. It involved wetting the marking surface using a bucket filled with 0.53 to 1.32 gallons (2 to 5 liters) of water. Retroreflectivity of the marking was measured 45 ± 5 seconds after wetting. This waiting period allowed some water to drain, simulating the surface condition of the pavement marking after rain cessation. For rumble stripes, the device was placed 13 inches (33.0 cm) away from the highest point on the rumble strip when readings were taken. At each location, an effort was made to collect ten dry and five wet retroreflectivity readings per line for evaluation.

4.2.2 Nighttime Visibility

Nighttime visibility was evaluated at night on both dry and wet pavements in accordance with ODOT Supplement 1047, which is presented in Appendix A. To evaluate the nighttime visibility performance, a group of experts from ODOT observed the pavement markings as well as the RPMs from a passenger vehicle under low beam headlight illumination in order to determine the longest visible distance. Dry nighttime visibility was evaluated from a stationary vehicle, whereas wet nighttime visibility was evaluated from a moving vehicle. The following scale factors were taken into consideration to evaluate the nighttime visibility performance of the pavement markings:

a. Dry nighttime visibility: a night visibility rating on dry pavement will be given in feet by looking to see how far the long line pavement markings are visible.
b. Wet nighttime visibility: a night visibility rating on wet pavement will be given in feet by looking to see how far the long line pavement markings are visible.

For the nighttime visibility ratings, the distances were estimated by counting the number of RPMs that were visible from the stationary vehicle and multiplying by 120 ft (36.58 m), which is the standard spacing used by ODOT for RPMs, or by counting the number of lane lines that were visible from the stationary vehicle and multiplying by 40 ft (12.19 m), which includes the 10 ft (3.05 m) lane line and the 30 ft (9.14 m) gap following the marking. When assessing edge line visibility, the lane lines were used as a gauge to estimate distance. These evaluations were done in a periodic manner over the course of the project. The variables in this procedure were the material types, ambient lighting, windshield wiper speed, and age of the evaluators. The constant factors were the location of the vehicles and the position of the pavement markings.

4.2.3 Daytime Color

Daytime color of the pavement markings was measured using a MiniScan XE Plus (Model 4500L) spectro-colorimeter. This model employs the 45°/0° geometry in measuring daytime color, where the system illuminates the sample at an angle of 45° and measures its color at an angle of 0° (perpendicular to the surface). This model has a relatively large view area over which color is measured, with a 1.25 inch (31.8 mm) measurement port. Color readings are provided in the Commission Internationale de l'Eclairage (CIE) color units. In this study, color was measured every six months. An effort was made to collect five color readings per line per evaluation.

4.2.4 Durability

Durability performance of the materials was evaluated according to ODOT Supplement 1047, which is available in Appendix A. In this evaluation, a group of experienced and trained evaluators visually judged the percentage of the pavement markings remaining on a line segment of ten feet in length. Evaluators then reported durability as an integer on a scale of 0 (the material is completely missing) to 10 (where 100% of the material remains). The minimum acceptable value of the durability rating in this evaluation was taken as nine; a material was assumed to have failed if the rating dropped down to eight or less.

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CHAPTER V
PERFORMANCE EVALUATION RESULTS

5.1 Introduction

As mentioned earlier, three materials were evaluated in this study for their performance under dry and wet conditions. These materials included 3M all weather paint (3M AWP), 3M 380 wet reflective extended season (3M 380 WR ES) durable tape, and extruded thermoplastic. The 3M AWP was installed on rumble strips and on the surface. The 3M 380 WR ES durable tape was installed in groove and on the surface. The extruded thermoplastic was installed in groove and on the surface. The performance of these materials was evaluated for 1.5 years. The periodic evaluations were conducted approximately every six months. In each evaluation, the performance of these materials was evaluated in terms of dry and wet retroreflectivity, dry and wet nighttime visibility, daytime color, and durability.

This chapter summarizes the performance evaluation results obtained during the performance evaluation period. It examines the variables affecting the performance of each material such as prevailing weather conditions (dry vs. wet), installation method (on surface, in groove, or on rumble strips), line type (edge line vs. lane line) and color (white vs. yellow). It also provides a comparison between the evaluated materials in terms of retroreflectivity, nighttime visibility, color, and durability.

5.2 Dry and Wet Retroreflectivity

Figures 5.1 and 5.2 present the average dry and wet retroreflectivity values obtained during the periodic evaluations for all six treatments. The following observations were made based on the analysis of retroreflectivity values that were obtained during the evaluation period:

- Initial and Retained Dry and Wet Retroreflectivity
  - The 3M 380WR ES durable tape (Treatments 2 and 3) had both the highest initial dry and wet retroreflectivity values. This was to be expected, since these tapes have specially designed optics to improve their performance under both dry and wet conditions.
  - The initial dry retroreflectivity of the 3M AWP was comparable to that of the extruded thermoplastic. However, the 3M AWP had significantly higher initial wet

retroreflectivity, which was anticipated since this material contains wet-reflective elements to improve wet visibility.

- The extruded thermoplastic had moderately high dry retroreflectivity, with the lowest retroreflectivity deterioration rate (i.e. year-to-year drop in retroreflectivity). This was especially true for lines that were installed in groove, which probably had a better glass bead retention. Thermoplastic, however, had the lowest wet retroreflectivity values of all materials. This was to be expected, since this material uses standard glass beads that are not designed for wet conditions. The extruded thermoplastic installed on the surface showed higher wet retroreflectivity values than that installed in groove. This was attributed to the ability of the surface installed extruded thermoplastic to better drain water off its surface.
- Even 1.5 years after installation, the 3M 380WR ES durable tape retained the highest dry and wet retroreflectivity values with only one exception, where the dry value of 3M tapes installed on white lane line (Treatment 3) dropped below the dry values of other products. However, the wet retroreflectivity of this material dropped significantly during the first and second winter seasons, especially on the right edge and lane lines that are typically subjected to higher traffic volumes.
- Similar to the durable tape, the wet retroreflectivity of the 3M AWP dropped significantly during the winter. This material lost most of its wet retroreflectivity during the first winter season, which was the case for 3M AWP installed on the surface and, to a lesser extent, 3M AWP installed on the rumble strips.
- In some cases, thermoplastics exhibited a higher one-year value than the corresponding six-month value. The increase in retroreflectivity is attributed to the fact that thermoplastic had intermixed glass beads that were exposed to the surface after the markings were subjected to traffic, because the glass beads that sank due to overheating during installation surfaced on the markings when the traffic markings wore out. However, after 1.5 years from the installation, the retroreflectivity value of thermoplastic materials dropped from its one-year-old values. The retroreflectivity values of 1.5-year-old markings were taken after a winter season; the decrease in value is probably due to harsh weather and snowplowing activities.

- White vs. Yellow
  - In general, white lines showed higher retroreflectivity values than yellow ones with only one exception: white lane lines installed with 380 380WR tapes (Treatment 3) had the lowest value. This decline in value is probably due to presence of a knob on the edge of one side of the raised profiles of 3M tapes. These knobs cause the tapes to have a preferred directionality with respect to retroreflectivity. When installed in the same direction as the traffic direction, these projections scatter light rays emitted from moving vehicles, which results in a decrease in the retroreflectivity. This is why it is recommended that these knobs be placed in the opposite direction of traffic to reach optimum performance.

- Edge vs. Lane Lines
  - Edge lines deteriorated at a higher rate than the lane lines. In particular, white edge lines deteriorated a higher rate than the other lines. This is due to the heavy truck concentration in the right lane.
  - 3M AWP (Treatment 1) saw the highest retroreflectivity deterioration rate among all the materials. It is likely that the glass beads had a poor adhesion to rumble strips, which is why the retroreflectivity value dropped rapidly.

- Groove vs. Surface
  - It was observed that materials installed in grooves typically exhibited a significantly lower deterioration rate (year-to-year drop in retroreflectivity) for the same materials installed on the surface. The drop in deterioration is most likely due to the fact that the surface material was worn by traffic and snow plows at a higher rate than the material installed in grooves.

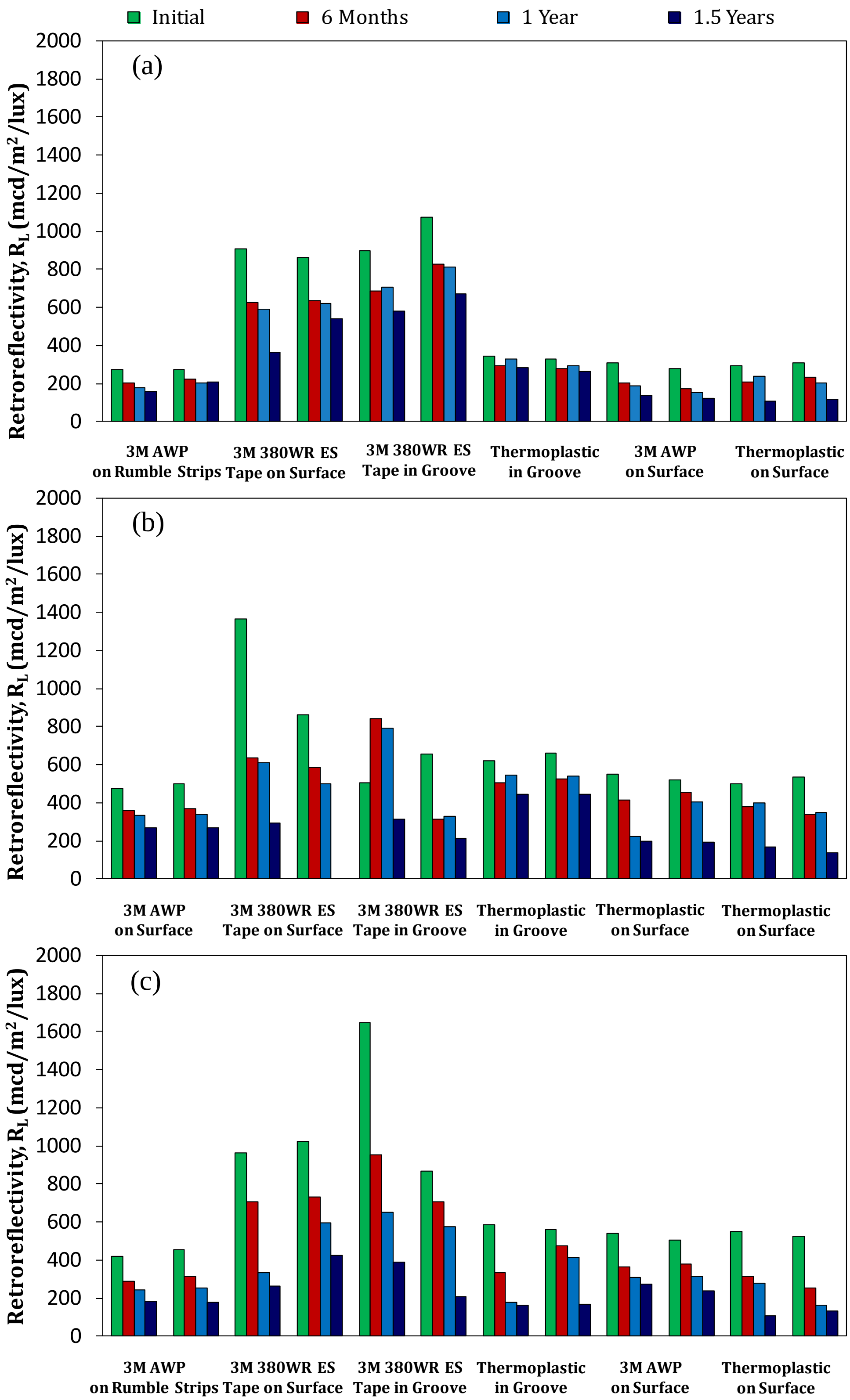


Figure (5.1): Dry Retroreflectivity: a) Yellow Edge Line, b) White Lane Line, and c) White Edge Line

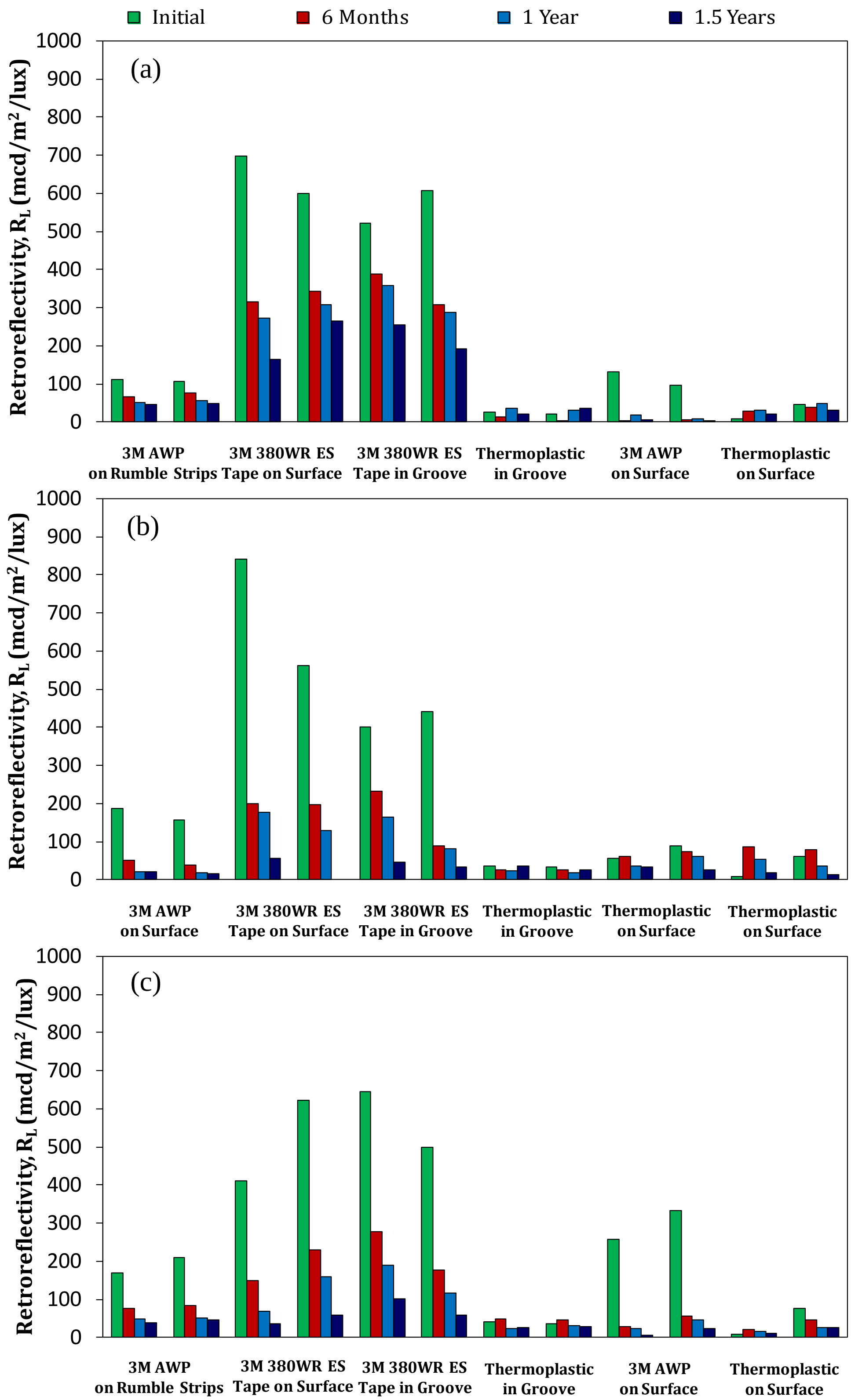


Figure (5.2): Wet Retroreflectivity: a) Yellow Edge Line, b) White Lane Line, and c) White Edge Line

5.3 Nighttime Visibility

This evaluation was conducted at night on both dry and wet pavements. It involved observing the pavement markings as well as the RPMs from a stationary vehicle under low beam headlight illumination to determine the longest visible distance. Distances were estimated by counting the number of RPMs that were visible and multiplying by 120 ft (36.58 m) or by counting the number of lane lines that were visible and multiplying by 40 ft (12.19 m).

Figures 5.3 and 5.4 present the dry and wet nighttime visibility distances obtained during the periodic evaluations for the pavement markings, respectively. Figures 5.5 and 5.6 show the dry and wet nighttime visibility distances obtained for the RPMs, respectively. As can be observed from these figures, The RPMs had an initial dry night visibility distance of 720 ft (219.5 m), which went down to 480 ft (146.3 m) after 1.5 years (Figure 5.5). The initial dry night visibility distances of 3M 380WR ES durable tape ranged from 400 to 420 ft (121.9 to 128.0 m) which dropped to 240 to 360 ft (73.1 to 109.7 m) after 1.5 years. The 3M AWP had an initial dry night visibility distance of 480 to 600 ft (146.3 to 182.9 m), which dropped to 240 ft (73.2 m) on the surface and 240 to 300 ft (73.1 to 91.4 m) on the rumble strips after 1.5 years. The extruded thermoplastic had an initial dry night visibility distance of 320 to 480 ft (97.5 to 146.3 m), which dropped to 240 ft (73.1 m) after 1.5 years.

As can be seen from these figures, the RPMs also exhibited longest initial wet night visibility distance among all materials (Figure 5.6). They had an initial wet night visibility distance of 600 ft (182.9 m), which dropped to 360 ft (109.7 m) after 1.5 years. The 3M 380WR ES durable tape had an initial wet night visibility distance of 240 to 420 ft (73.1 to 128.0 m), which dropped to 120 to 160 ft (36.6 to 48.8 m) after 1.5 years. The 3M AWP had an initial wet night visibility distance of 240 to 420 ft (73.1 to 128.0 m), which dropped to 40 to 80 ft (12.2 to 24.4 m) on the surface and 240 ft (73.1 m) on the rumble strips after 1.5 years. Meanwhile, the extruded thermoplastic had an initial wet night visibility distance of 50 to 240 ft (15.2 to 73.2 m), which dropped to 40 to 120 ft (12.2 to 36.6 m) after 1.5 years.

It is noted that in some instances the wet visibility distance of some of the pavement markings increased rather than decreased over time. These variations are expected since ratings are subjective and may vary from one person to another and due to variations in natural rainfall levels during the wet nighttime visibility evaluations.

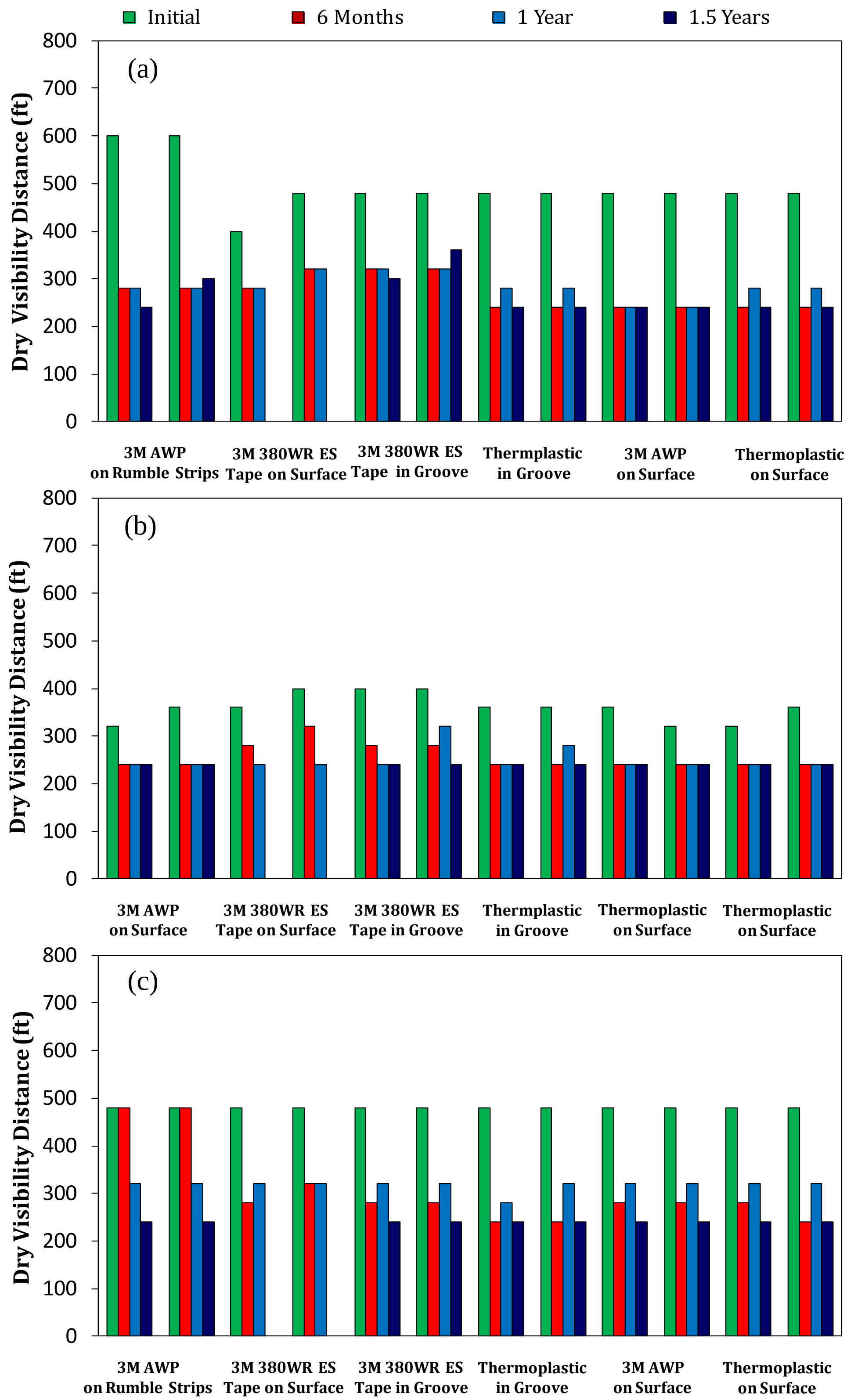
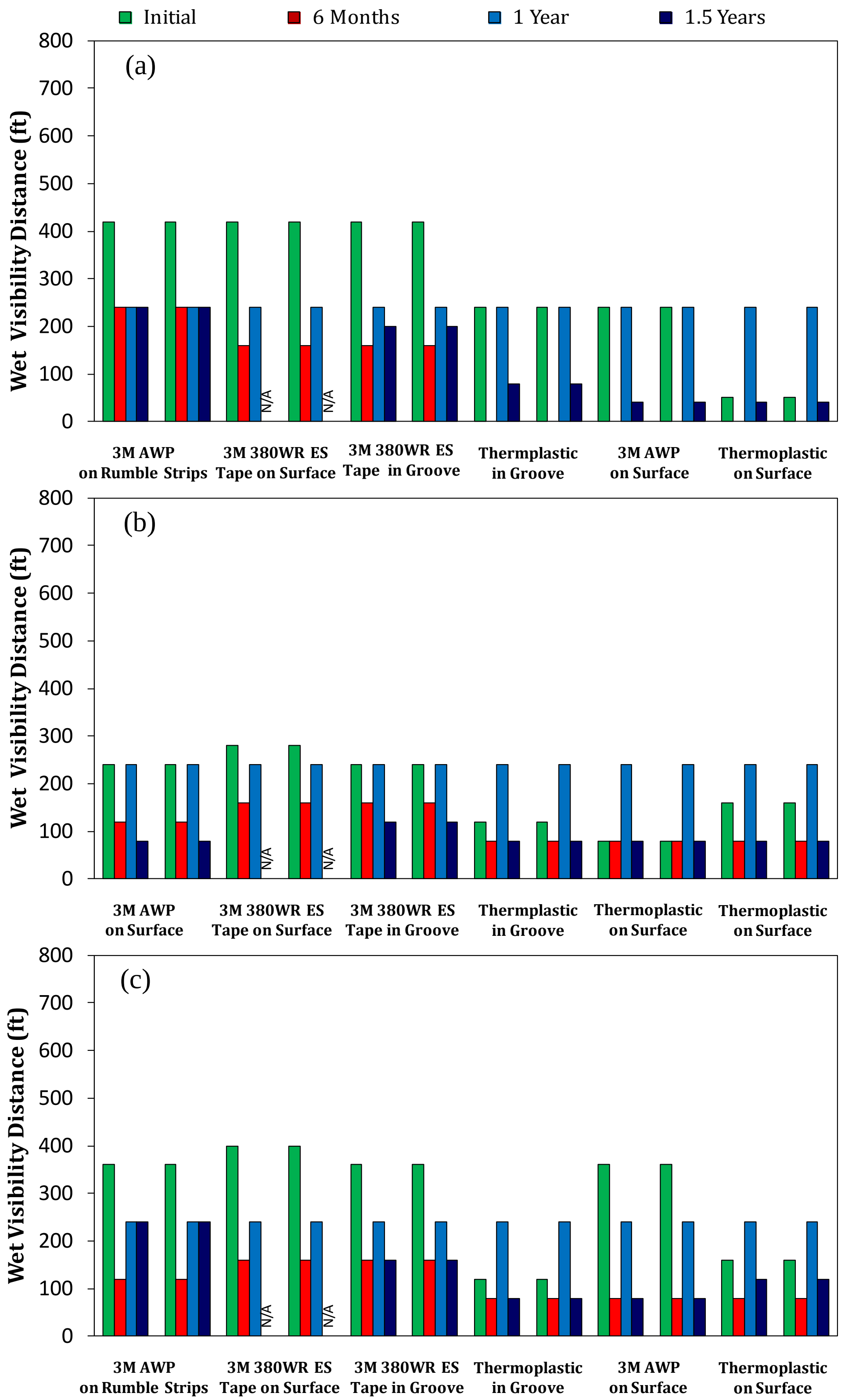


Figure 5.3: Dry Night Visibility Distance: a) Yellow Edge Line, b) White Lane Line, and c) White Edge Line



.Figure (5.4): Wet Night Visibility Distance: a) Yellow Edge Line, b) White Lane Line, and c) White Edge Line

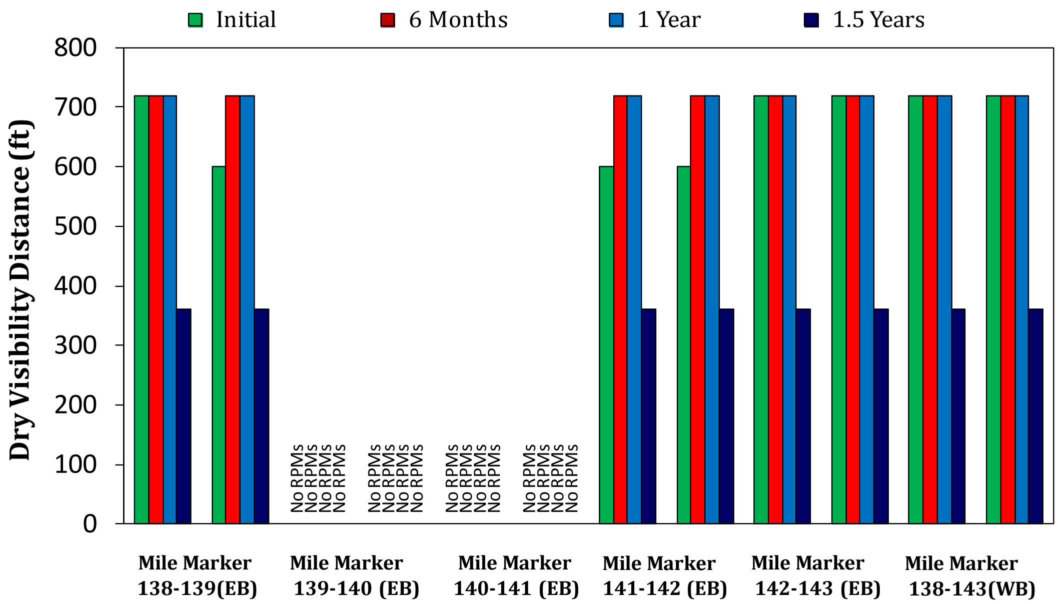


Figure (5.5): Dry Night Visibility Distance for RPMs along the White Lane Line

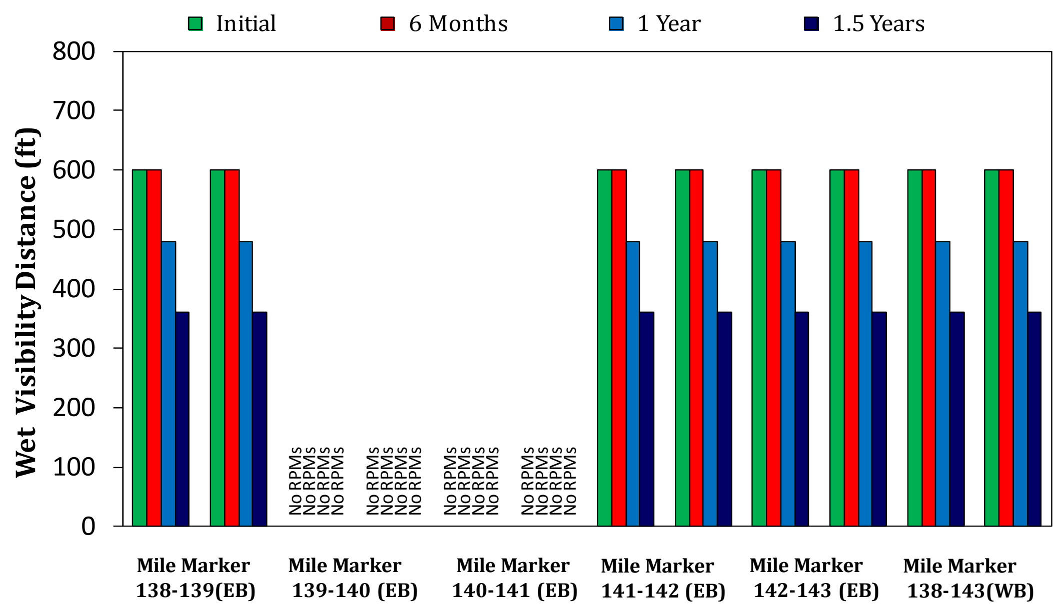


Figure (5.6): Wet Night Visibility Distance for RPMs along the White Lane Line

5.3 Color

The color readings obtained using the Miniscan XE Plus (Model 4500L) colorimeter were compared with ODOT color specification for yellow and white markings. Figure 5.7 shows ODOT color requirements for white and yellow markings plotted on a CIE chromaticity diagram. Color readings are considered to be satisfactory if they fall within the corresponding specification box. A set of formulas was developed using Excel to find out mathematically whether the color readings met ODOT specifications. The Excel results were verified by plotting the CIE color readings and ODOT color specifications on the same chromaticity diagram. An example of a color diagram for one of the materials is shown in Figure 5.8. Color diagrams obtained for the remaining materials are presented in Appendix B of this report. From Figure 5.8, it was observed that 3M AWP met ODOT color specifications for white markings at all times as well as yellow markings for both initial and 6-month evaluations. However, it did not meet ODOT color specifications for yellow markings after 1 and 1.5 years. The remaining materials met ODOT color specifications for both white and yellow markings at all times. The 3M AWP likely failed due to significant wearing of the material followed by subsequent loss of color. Dirt accumulation over the marking surface might also be responsible for the loss of color.

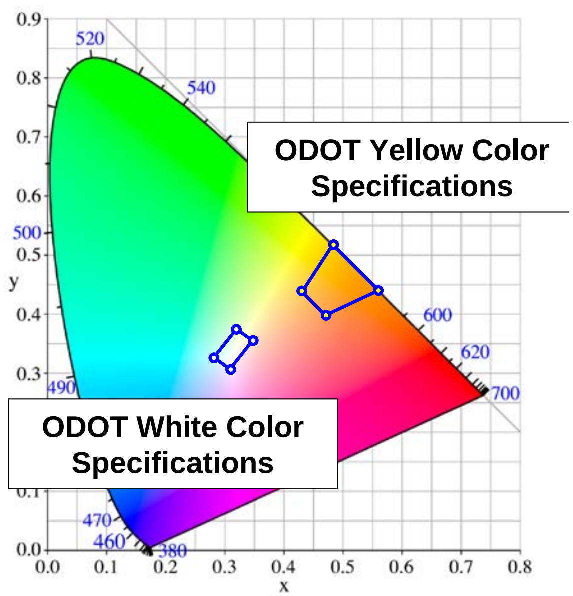


Figure (5.7): ODOT Color Requirements For White And Yellow Markings Plotted On A CIE Chromaticity Diagram

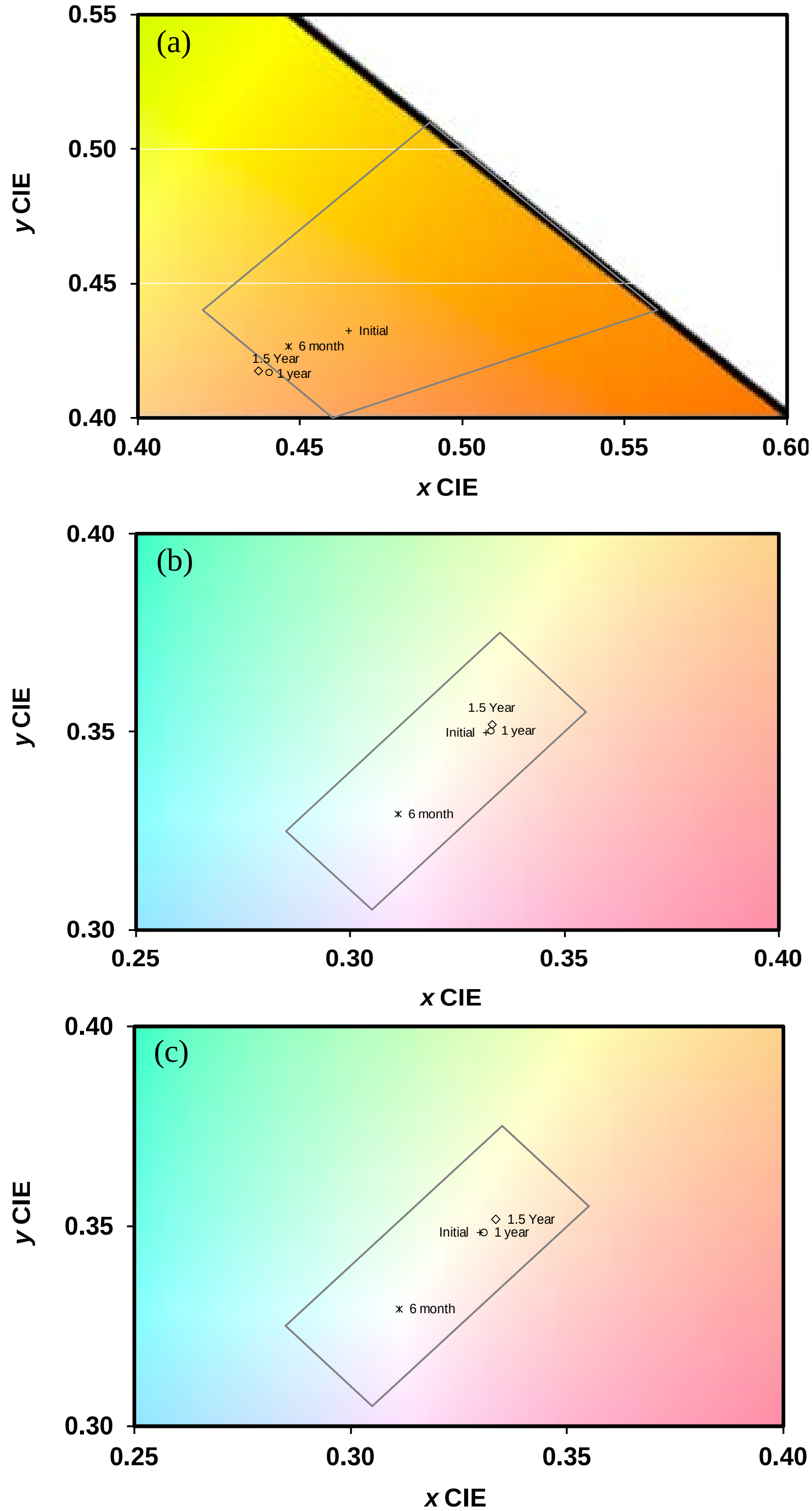


Figure (5.8): Comparison between 3M AWP Color Readings and ODOT Color Specifications: a) Yellow Edge Line (Installed on Rumble Strips), b) White Lane Line (Installed on Surface), and c) White Edge Line (Installed on Rumble Strips)

5.4 Durability

As mentioned earlier, durability of the pavement marking materials were judged visually by experienced evaluators from ODOT. The durability ratings of the materials were given on a scale of 0 to 10 and are presented in Appendix C. From these ratings, it was observed that almost all materials performed satisfactorily during the first year of evaluation. The only material that showed a drop in durability in that year was the 3M AWP. During the second winter season, the 3M 380WR ES durable tape installed on the surface was caught and removed by snow plows in many locations. As a result, this material was restriped using fast dry traffic paint in the following summer.

CHAPTER VI
ESTIMATION OF PAVEMENT MARKING SERVICE LIFE

6.1 Introduction

Observations made based on the actual field measurements and ratings obtained during the evaluation period, as discussed in the previous chapter, were useful in characterizing the short term performance of the evaluated pavement marking materials. This chapter discusses the estimation of service life of the marking materials, which is represented by the time required for the retroreflectivity of a marking to drop to certain point where the marking is no longer deemed effective for delineation. By fitting various mathematical models to both the dry and wet retroreflectivity data collected during the evaluation and solving for model parameters, service life for the evaluated pavement marking materials can be estimated.

6.2 Retroreflectivity Models

In this analysis, four mathematical models were used to predict the future trend of behavior for the retroreflectivity performance of the markings: linear model, exponential model, logarithmic model and power model. Table 6.1 presents the mathematical expressions for these models.

Table (6.1): Pavement Marking Retroreflectivity Models

Model Type	Mathematical Form	
Linear	$y = a + bx$	$R_L = a + b.Age$
Power	$y = ax^b$	$R_L = a.Age^b$
Exponential	$y = ae^{bx}$	$R_L = ae^{b.Age}$
Natural Logarithmic	$y = a + b.\ln(x)$	$R_L = a + b.\ln(Age)$

The abovementioned models were fitted to the retroreflectivity data ($R_{L,}$ expressed in mcd/m^2/lux) and age of the marking (Age, expressed in days) collected during the evaluation of the materials. The analysis was performed using Microsoft Excel and was repeated for each evaluated material.

6.2.1 Regression Model Parameters

As mentioned previously, an effort was made to collect ten dry and five wet retroreflectivity readings per line per evaluation at each location. In a very few instances, retroreflectivity readings were significantly higher or lower than the sample mean; however, removal of these values does not seem to have any major impact on the model parameters. Therefore, this analysis was performed using all the available data points.

Table 6.2 and 6.3 present the retroreflectivity model parameters obtained from fitting each of the four models discussed earlier to the retroreflectivity data for 3M 380WR ES durable tape installed on surface. These parameters, along with the corresponding retroreflectivity model, can be used to predict the retroreflectivity of the material at any point of time. For example, using the exponential model, the estimated dry retroreflectivity of 3M 380WR ES durable tape installed on surface along the white lane lines after one year (365 days) is $y = ae^{b.x} = 1080 \times e^{(-0.002 \times 365)}$ which is equal to 520.5 mcd/m^2/lux. The average one year retroreflectivity value for the material on this line based on field measurements was 554 mcd/m^2/lux.

Table (6.2): Dry Retroreflectivity Model Parameters
for 3M 380WR ES Tapes Installed on Surface

		Retroreflectivity Model Parameters		
Retroreflectivity Model	Model Parameter	Yellow Left Edge Line	White Lane Line	White Right Edge Line
Linear	A	853	1050	983
	B	-0.749	-1.47	-1.27
Exponential	A	878	1080	1050
	B	-0.001	-0.002	-0.002
Power	A	1890	3690	3780
	B	-0.217	-0.352	-0.367
Natural Logarithmic	A	1350	1960	1770
	B	-135	-252	-220

Table (6.3): Wet Retroreflectivity Model Parameters for 3M 380WR ES Tapes Installed on Surface

		Retroreflectivity Model Parameters		
Retroreflectivity Model	Model Parameter	Yellow Left Edge Line	White Lane Line	White Right Edge Line
Linear	A	582	604	451
	B	-0.757	-1.22	-0.838
Exponential	A	593	636	499
	B	-0.002	-0.004	-0.005
Power	A	2410	8290	8100
	B	-0.384	-0.722	-0.783
Natural Logarithmic	A	1140	1442	1055
	B	-148	-225	-161

6.2.2 Aptness of the Retroreflectivity Models

After determining the retroreflectivity model parameters, the quality of the fit of the regression models was assessed using two statistical measures: the coefficient of determination, r^2, and the mean squared error, *MSE*. This subsection discusses each of these fit parameters. Similar to the previous subsection, only the results obtained for 3M 380WR ES durable tape installed on surface is presented.

6.2.2.1 Coefficient of Determination, r^2

The coefficient of determination, r^2, is an indicative measure of the level of variability in the observed data that can be explained by the model. The following equation is used to calculate the coefficient of determination, r^2:

$$r^2 = 1 - \frac{SSE}{SST} \tag{6.1}$$

where,

$$SSE = \sum \left(y_i - \hat{y}_i \right)^2 \tag{6.2}$$

$$SST = \sum \left(y_i - \bar{y} \right)^2 \tag{6.3}$$

Here, y_i are the measured data points; $\hat{y}_i$ are the predicted values of the dependent variable; $\bar{y}$ represents the sample mean; *SSE* is the error sum of squares, which measures the amount of variation in observed data that is unexplained by the model; and *SST* is the total sum of squares, which measures the total amount of variation in the observed data from the sample mean.

As previously mentioned, r^2 is a statistical measure that represents how well the regression model predicts the future outcomes. In general, the higher the r^2 value, the better the fit will be for a given model. The range of values for r^2 will fall between 0 and 1. An r^2 value of 1 indicates that all observed data points lie exactly on the regression model. However, a lower r^2 value indicates that the data points are further from the model.

Tables 6.4 and 6.5 summarize the r^2 values obtained for the dry and wet retroreflectivity data, respectively, for the 3M 380WR ES durable tape. The results in these tables show that the exponential and the natural logarithmic models had the highest r^2 values compared to the power and linear models for both dry and wet conditions. The tables also show that the r^2 values obtained for the yellow left edge lines were lower than those obtained for other line types. Since the yellow left edge lines are subjected to much lower traffic wear than the other lines, the retroreflectivity values did not change much over the course of the evaluation period, leading to the conclusion that a poor correlation exists between the independent variable (age) and the dependent variable (retroreflectivity). It can also observed be that r^2 values obtained for wet retroreflectivity data are higher than the ones collected under dry conditions. This is a consequence of the fact that the retroreflectivity data collected under wet conditions showed greater variation than data collected under dry conditions.

Table (6.4): r^2 Values Obtained by Fitting Various Models to the Dry Retroreflectivity Data of 3M 380WR ES Durable Tape Installed on Surface

	r^2 values		
Retroreflectivity Model	Yellow Left Edge Line	White Left Lane Line	White Right Edge Line
Linear	0.6737	0.6593	0.8211
Exponential	0.5376	0.7937	0.7117
Power	0.5059	0.7599	0.6325
Natural Logarithmic	0.7229	0.7519	0.8176

Table (6.5): r^2 Values Obtained by Fitting Various Models to the Wet Retroreflectivity Data of 3M 380WR ES Durable Tape Installed on Surface

	r^2 values		
Retroreflectivity Model	Yellow Left Edge Line	White Left Lane Line	White Right Edge Line
Linear	0.667	0.6586	0.6989
Exponential	0.617	0.8694	0.786
Power	0.6616	0.8939	0.7543
Natural Logarithmic	0.8346	0.8674	0.8518

6.2.2.2 Mean Squared Errors

The mean squared error, *MSE*, is another statistical measure to determine the goodness of fit of a mathematical model to the data points. The following equation is used to calculate *MSE*:

$$MSE = \frac{SSE}{N-(k+1)} \tag{6.4}$$

where *SSE* is the error sum of squares, *N* is the number of data points, and *k* is the number of model parameters. The *MSE* represents the deviation by which the predicted value differs from the quantity to be estimated, normalized by the total number of observations minus the number of model parameters plus one, which are the degrees of freedom lost in estimating the model parameters. A lower value of *MSE* indicates a better quality of fit; an *MSE* of 0 is ideal but is practically never possible.

Tables 6.6 and 6.7 present a summary of the resulting *MSE* values for the 3M 380WR ES durable tape. These values correspond to the retroreflectivity model parameters summarized in Tables 6.2 and 6.3, respectively. As can be seen from Tables 6.6 and 6.7, the exponential model has the lowest *MSE* values. This confirms earlier observations, based on the r^2 values, regarding the aptness of the exponential model. It is noted though that all models had relatively high MSE values. This is probably due to the fact that a small number of data points were used in fitting the models.

Table (6.6): *MSE* Values Obtained by Fitting Various Models to the Dry Retroreflectivity Data of 3M 380WR ES Durable Tape Installed on Surface

	MSE values		
Retroreflectivity Model	Yellow Left Edge Line	White Left Lane Line	White Right Edge Line
Linear	31528	94077	84577
Exponential	22174	95684	80723
Power	34414	117800	91302
Natural Logarithmic	29961	114312	86880

Table (6.7): *MSE* Values Obtained by Fitting Various Models to the Wet Retroreflectivity Data of 380WR ES Durable Tape Installed on Surface

	MSE values		
Retroreflectivity Model	Yellow Left Edge Line	White Left Lane Line	White Right Edge Line
Linear	240870	26365	12264
Exponential	9314	17506	8140
Power	5487	8176	7441
Natural Logarithmic	5757	172379	194692

6.4 Prediction of Pavement Marking Service Life

In the previous sections, the retroreflectivity deterioration of the pavement marking materials was captured by fitting four mathematical models (linear, exponential, power, and natural logarithmic) to the observed data points. Various statistical measures were then implemented to determine the aptness of these models. Based on the observations made from the coefficient of determination, r^2, and the mean squared error, *MSE*, it was concluded that the exponential model and the linear model had the best quality of fit. However, this conclusion is limited to the period during which the retroreflectivity measurements were made. Therefore, to gain insight regarding the ability of the abovementioned four models to predict future retroreflectivity, retroreflectivity predictions were plotted versus Age for an extended period of time to determine whether the predicted performance is reasonable and consistent with common pavement marking retroreflectivity deterioration trends. The selection of a mathematical model that can accurately predict future retroreflectivity performance is critical since the objective in this chapter is to estimate the service life of pavement marking, which is defined as the time required for retroreflectivity to fall below a threshold value where the pavement marking material is no longer considered effective as a delineation system. In this context, a minimum in-service retroreflectivity of 150 mcd/m^2/lux was chosen for white pavement markings and a minimum in-service retroreflectivity of 100 mcd/m^2/lux was chosen for yellow pavement markings. As discussed in Chapter 2, these two threshold values have been repeatedly used in the literature. Because yellow edge lines are subjected to less wear by traffic, service life prediction based on yellow line performance will not necessarily indicate how marking materials would perform under high traffic conditions. Therefore, the white edge lines that were subjected to a higher traffic volume are believed to be more realistic.

Figures 6.1 through 6.6 present the predicted retroreflectivity versus age for the materials installed along the white edge lines. The deterioration trend of pavement marking retroreflectivity for both dry and wet conditions are represented by a black solid and a black broken line, respectively. The red solid line represents the threshold value, and a pavement marking will be considered ineffective if its retroreflectivity falls below this line.

As can be seen from these figures, dry retroreflectivity of most of the materials stayed above the threshold value during the entire performance evaluation period except for thermoplastic installed on surface. A little over one year from the installation, dry retroreflectivity of thermoplastic installed on surface went below the threshold value. However, it should be noted that when installed in grooves, this material met the minimum dry retroreflectivity criteria through the end of the evaluation period. This may be attributed to the tendency of a groove to protect glass beads from the wear and tear of traffic and snow plows.

It can also be observed from Figures 6.1 through 6.6 that under wet conditions, none of the materials on the right edge lines were effective for more than one year. 3M 380WR ES durable had the longest service life of all materials under both dry and wet conditions. When installed on the surface, 3M AWP initially met the threshold value but lost most of its retroreflectivity within a short period of time. Thermoplastic was unable to meet the threshold value under wet conditions at any point during the evaluation.

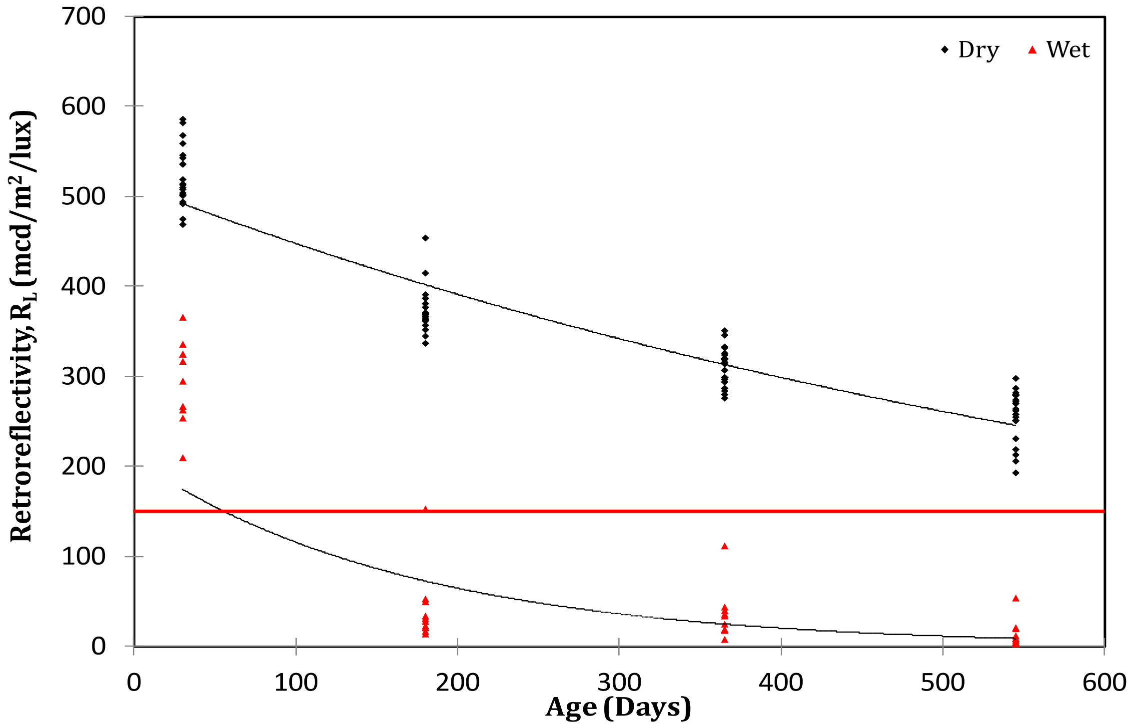


Figure (6.1): Individual Retroreflectivity Readings for 3M AWP Installed on Surface for White Edge Line

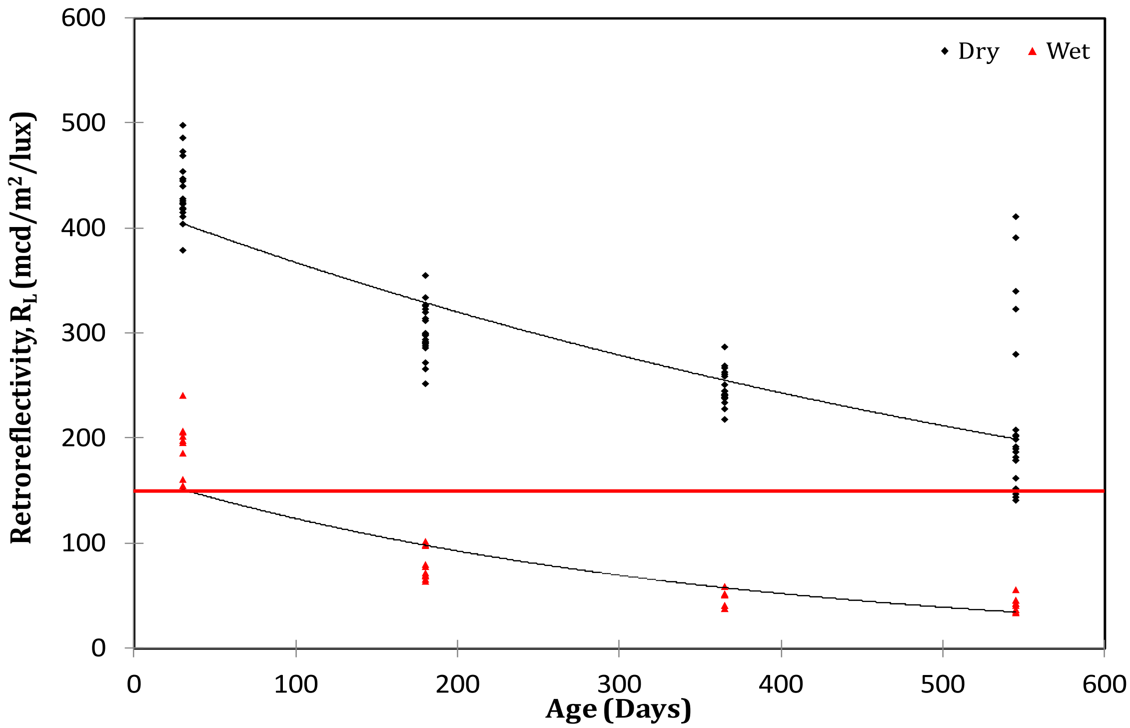


Figure (6.2): Individual Retroreflectivity Readings for 3M AWP Installed on Rumble Strips for White Edge Line

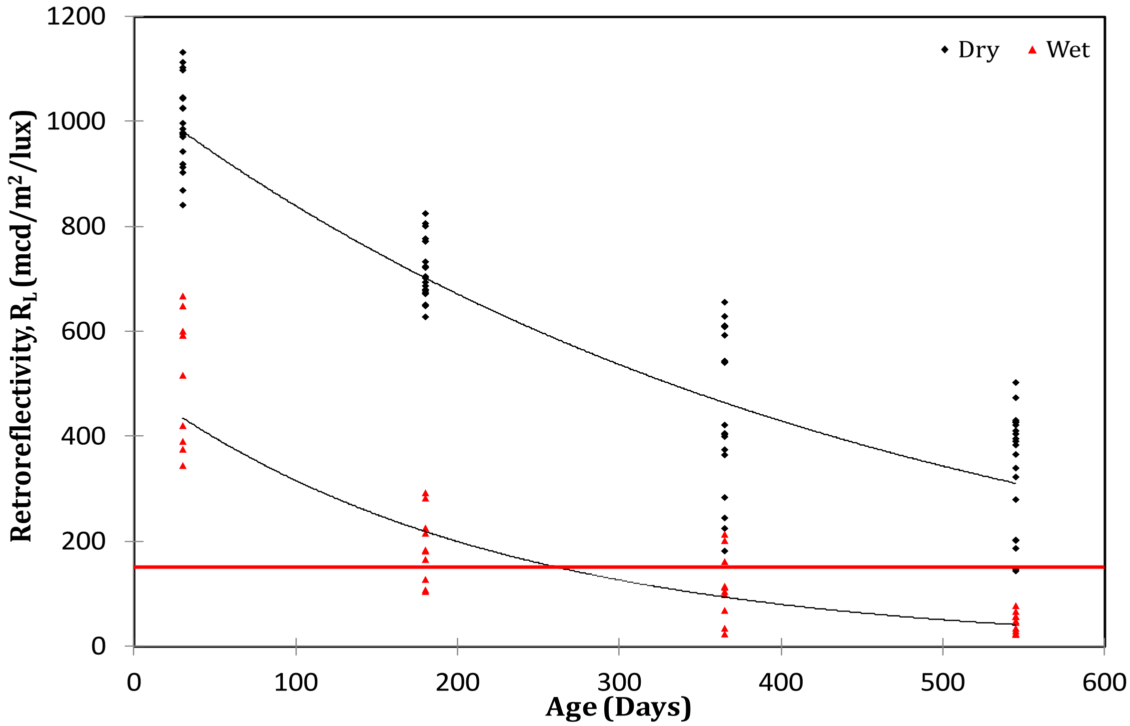


Figure (6.3): Individual Retroreflectivity Readings for 3M 380WR ES Durable Tape Installed on Surface for White Edge Line

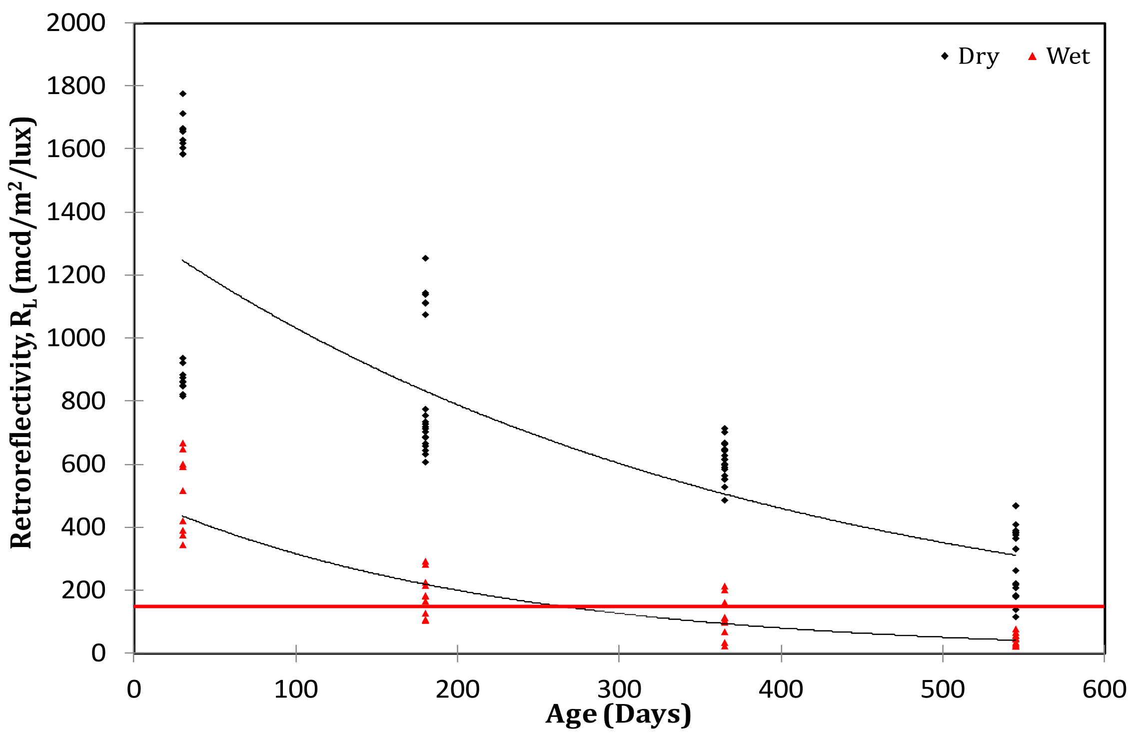


Figure (6.4): Individual Retroreflectivity Readings for 3M 380WR ES Durable Tape Installed in Groove for White Edge Line

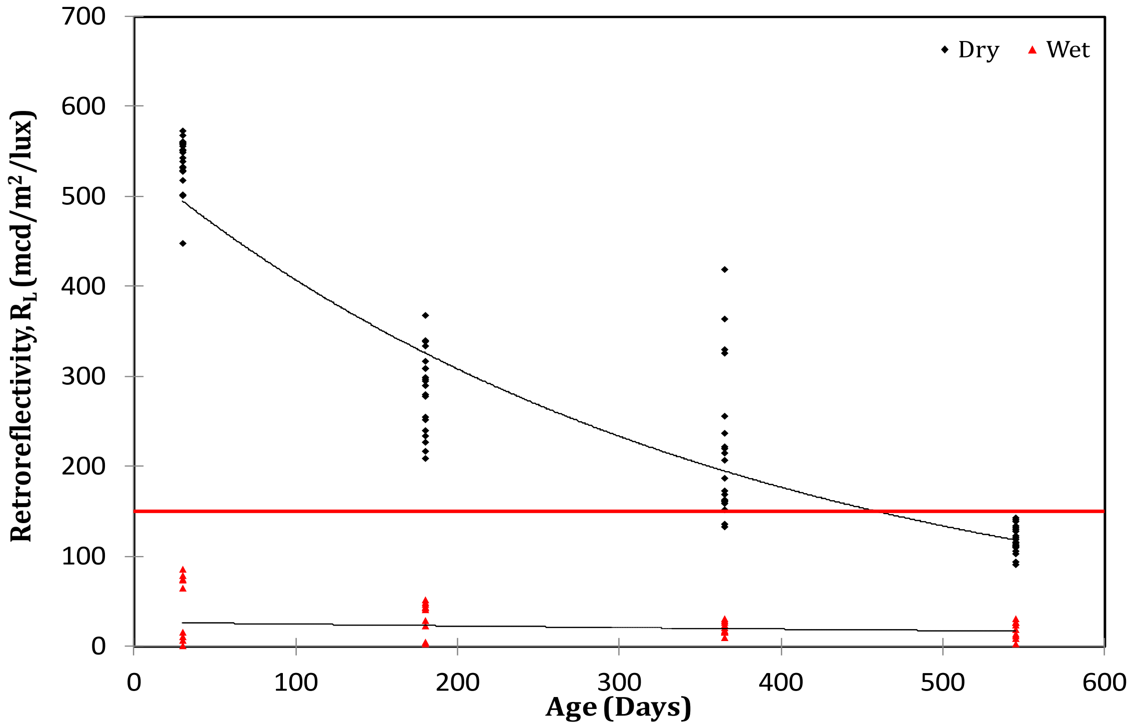


Figure (6.5): Individual Retroreflectivity Readings for Thermoplastic Installed on Surface for White Edge Line

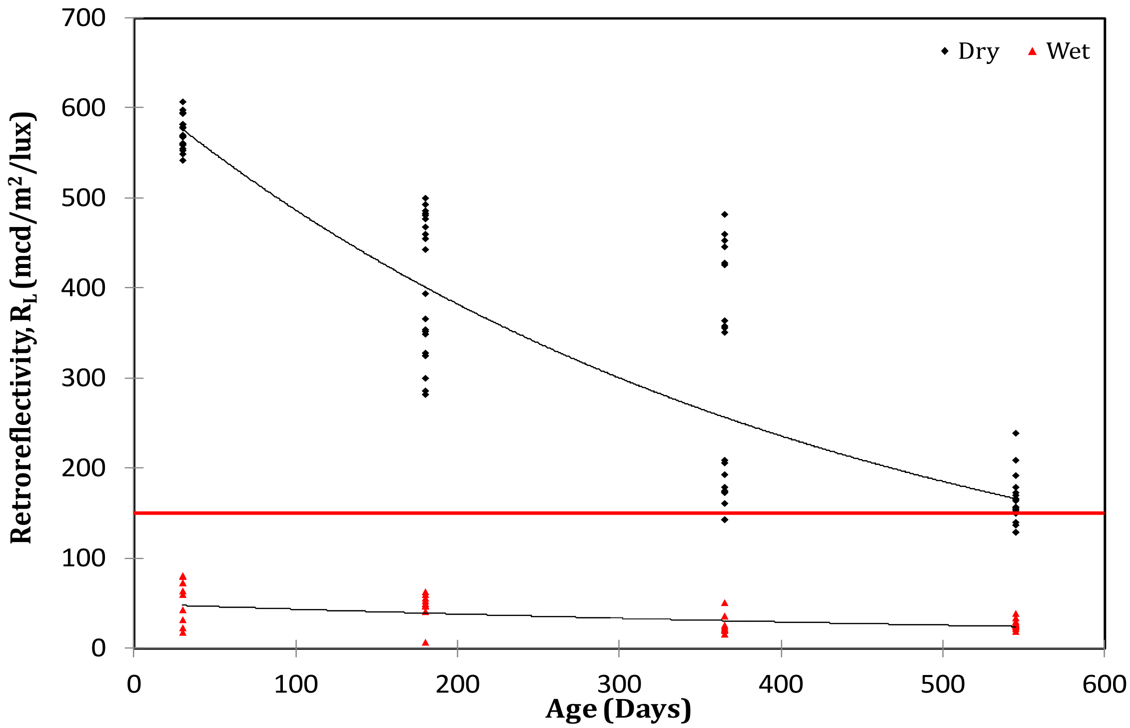


Figure (6.6): Individual Retroreflectivity Readings for Thermoplastic Installed in Groove for White Edge Line

Table 6.8 summarizes the predicted values of estimated service life for all evaluated materials. It can be observed from Table 6.8 that a longer service life is predicted for yellow edge lines and white lane lines than for white edge lines. This finding was expected, since white edge lines are subjected to a higher traffic and will thus deteriorate at a higher rate.

Table (6.8): Predicted Service Life (yrs)

Treatment Type	Line Type	Dry	Wet
3M AWP on Rumble Strips	YEL	3.3	< 0.5
3M AWP on Surface	WLL	3.1	< 0.5
3M AWP on Rumble Strips	**WEL**	**2.8**	**< 0.5**
3M 380WR ES on Surface	YEL	6	2.4
	WLL	2.7	0.9
	WEL	**2.6**	**0.6**
3M 380WR ES in Groove	YEL	7.7	2.3
	WLL	4	0.6
	WEL	**2**	**0.8**
Thermoplastic in Groove	YEL	10.8	< 0.5
	WLL	6.5	< 0.5
	WEL	**1.9**	**< 0.5**
3M AWP on Surface	YEL	2.8	< 0.5
Thermoplastic on Surface	WLL	1.8	< 0.5
3M AWP on Surface	**WEL**	**3.3**	**< 0.5**
Thermoplastic on Surface	YEL	1.6	< 0.5
	WLL	1.8	< 0.5
	WEL	**1.1**	**< 0.5**

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CHAPTER VII
LIFE CYCLE COST ANALYSIS

7.1 Introduction

In the previous chapters, performance evaluation results for all evaluated pavement marking materials were analyzed and discussed, and the service life of the evaluated materials was estimated through the use of various mathematical models. This chapter will focus on determining the cost effectiveness of the evaluated materials through a life cycle cost analysis.

7.2 Life Cycle Cost Analysis Inputs

Life cycle cost analysis (LCCA) is an economic evaluation technique that can be used to assess the feasibility of different pavement markings over a period of time. LCCA is particularly useful when a project has several alternatives that must fulfill a certain set of requirements where the alternatives are different from each other in terms of initial installation cost, operating, and maintenance cost, and a comparison is required to identify the option that optimizes the net savings. The method used in this study accounts for the total discounted dollar amount for the initial cost of installed materials, removal of the marking material at the end of its service life (if necessary), and operation and maintenance costs for reinstalling marking materials.

The following equation is used to determine the cost effectiveness of each material by calculating its present value, *PV*:

$$PV = A_o + \sum A_t \left(\frac{1}{1+i}\right)^t \tag{7.1}$$

where A_o is the initial material and installation cost, A_t is the maintenance cost incurred at time t; and i is the discount rate. The present value represents the current worth of present and future cash flows at the beginning of the analysis period. This amount accounts for the initial and future costs incurred during the analysis period at a discount rate that reflects the annual change in monetary value. In general, a discount rate of 4% is used in life cycle cost analysis.

In this study, an analysis period of 6 years and a 4% discount rate were used. This analysis was performed using one maintenance strategy. It included annual restriping with traffic paint from the end of service life until the end of the sixth year.

Table 7.1 presents the material installation, grooving and removal costs used in this project. These costs are based on the actual contract awarded by ODOT. As mentioned earlier, the test location was a divided highway with two lanes, two edge lines, and one lane line in each direction. As can be seen from this table, reasonable estimates of the pavement markings service lives were included in the analysis. These estimates are based on the performance of each material on the white edge line, which is subjected to the highest traffic volumes. From this table, it can be seen that 3M 380WR ES durable tapes were the most expensive material to install, followed by 3M AWP and thermoplastic. It can also be noticed that the installation cost for the edge lines was much higher than that for the lane lines. This is due to the fact that edge lines are continuous, whereas lane lines are installed in 10 ft segments spaced 30 ft apart.

Table (7.1): Average Cost and Service Life Values Used in the Analysis

Material Type	Assumed Service Life (Years)	Installation Cost ($/mile)			Removal Cost ($/mile)
		Grooving	Edge Line	Lane Line	
3M All Weather Paint	1 to 2	N/A	1,990	1,290	N/A
WR Durable Tapes (On Surface)	3 to 5	N/A	12,702	4,607	3,960
WR Durable Tapes (In Grooves)	4 to 5	4,478	12,702	4,607	3,960
Thermoplastic (On Surface)	1 to 3	N/A	1,680	850	N/A
Thermoplastic (In Grooves)	1 to 3	4,478	1,680	850	N/A
Raised Pavement Markers	6	N/A	N/A	1,023	264
Traffic Paint	1	N/A	500	250	N/A

7.3 Results and Limitations of the Life Cycle Cost Analysis

The results obtained from the life cycle cost analysis are summarized in Table 7.2. The present values shown in this table were calculated for each material over a range of possible service life values. As mentioned earlier, the maintenance strategy used in this project included using the pavement marking until the end of its service life, followed by annual restriping with traffic paint through the end of the analysis period. As can be seen from this table, RPMs had the lowest present value followed by thermoplastic installed on surface, 3M AWP, thermoplastic installed in groove, and 3M 380WR ES durable tape. It can also be noticed that the present value of each material is primarily governed by its initial installation cost.

The results shown herein are limited to the dry performance of the materials, which is not necessarily indicative of the performance of the materials under wet conditions. Furthermore, the analysis was performed over a range of possible service life values that may not reflect the actual performance of the materials. It also did not consider the potential risk to the maintenance crew or the administrative cost from initiating the restriping of the markings.

Table (7.2): Life Cycle Cost Analysis Results

Material Type	Assumed Service Life (Years)	Present Value ($/mile)	
		Edge Line	Lane Line
3M AWP	1	4,611	2,601
	2	4,130	2,360
3M 380WR ES on Surface	3	17,505	8,966
	4	17,321	8,609
	5	16,368	8,265
3M 380WR ES in Groove	3	22,378	13,444
	4	21,799	13,087
	5	21,241	12,743
Thermoplastic on Surface	1	4,301	2,161
	2	3,820	1,920
	3	3,358	1,689
Thermoplastic in Groove	1	8,779	6,639
	2	8,298	6,938
	3	7,836	6,167
RPMs	6	N/A	1,232

CHAPTER VIII
SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

8.1 Summary

The objective of this study was to determine the feasibility of using several alternative pavement marking materials as a replacement for RPMs in Ohio. The alternative materials included 3M AWP, 3M 380WR ES durable tape, and thermoplastic. These materials were installed in six different treatments along interstate I-70 in Licking County, Ohio, at a location that receives an annual snowfall of 20 to 30 inches and has an AADT of approximately 44,000 vehicles per day with about 30% truck traffic. The test location had two lanes per direction with three line types: yellow edge line, white lane line and white edge line.

Marking materials were evaluated in terms of dry and wet retroreflectivity, dry and wet nighttime visibility (visibility distance), daytime color, and durability for a period of approximately 1.5 years. A Delta LTL-X retroreflectometer was used to measure retroreflectivity and a MiniScan XE Plus colorimeter was used to obtain color ratings. Visibility distances were observed at night under both dry and natural rain conditions from a stationary vehicle by having an evaluator count the number of RPMs that were visible and multiplying the result by 120 or by counting the number of lane lines that were visible and multiplying by 40 ft.

Results obtained during the periodic evaluations were analyzed to assess the performance of the evaluated materials. The service life of each marking material was then predicted using various mathematical models to estimate the time required for both dry and wet retroreflectivity values to drop below threshold criteria (150 mcd/m^2/lux for white markings and 100 mcd/m^2/lux for yellow markings). Service life predictions were then used to determine the cost effectiveness of these materials through a life cycle cost analysis.

8.2 Conclusions

The following conclusions were drawn based on the periodic performance evaluation results and their subsequent analysis:

- The 3M AWP had relatively high initial dry and wet retroreflectivity. However, it lost most of its wet retroreflectivity during the first winter season. This was the case for both 3M AWP installed on the surface and on rumble strips. Therefore, this product would require regular restriping to maintain a reasonable level of wet visibility, which would not be cost effective.

- The 3M 380WR ES durable tape lost most of its wet visibility during the first and second winter seasons. Therefore, it would not be cost effective to use this relatively expensive material as a replacement for RPMs used to guide motorists under inclement weather conditions.
- When installed on the surface, the 3M 380WR ES durable tape was caught and removed by snow plows. Therefore, this material must be installed in groove to protect it from snow plowing activities.
- RPMs provided the longest dry and wet night visibility distances throughout this study. Hence, they are more effective in providing guidance to drivers at night under both dry and wet conditions than the alternative marking materials evaluated in this study.

8.3 Recommendations

Based on the conclusions above, it is recommended that ODOT continues to use RPMs in Ohio to provide wet night visibility. However, ODOT is advised to continue checking the condition of the RPMs from time to time, especially on aged asphalt pavements, to ensure proper adhesion to the pavement surface. RPMs not only guide motorists under inclement weather conditions, but also help snowplow truck drivers detect the center of the roadway when roads are covered with snow. While there have been rare incidents where RPMs have detached from the aged pavement surface, it is believed that RPMs prevent countless crashes during inclement weather conditions.

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Appendix A

Supplement Specification 1047

Durability of Long Line Pavement Marking

Durability is the rating of the adherence of the pavement marking material to the sound pavement surface, based on the percentage of the material remaining adhered. Durability is not an assessment of the thickness of the material or retention of optical elements, but rather an analysis of the amount of bare, sound pavement showing that was once covered with pavement marking material.

Durability is an objective assessment, although there exists no mechanical means to reliably and quickly measure durability in the field. Therefore, the field assessment of pavement marking durability must be made by trained evaluators.

The evaluation process is conducted as follows: Several trained evaluators observe the test line by viewing vertically from above. An assessment of the durability is made by each. The durability rating is agreed upon in the field by a consensus of the evaluators.

If line deterioration is inconsistent throughout the length of the test section, several line segments should be evaluated. Each segment should be a minimum of ten feet in length, and no less than 2% of the total length of the line. The durability rating is the lowest rating for any line segment, as agreed upon by a consensus of the evaluators.

Portions of the line subjected to unusual wear, such as at driveways or from line tracking prior to final curing, should be categorically excluded from the durability assessment. In addition, failures within the pavement must be recognized and discounted when assessing the durability of the pavement marking.

In all cases, the durability rating is expressed as an integer value.

Durability	
Rating	**Percentage of Line Remaining**
10	100
9	90
8	80
7	70
6	60
5	50

Durability	
Rating	**Percentage of Line Remaining**
4	40
3	30
2	20
1	10
0	0

Night Visibility of Long Line Pavement Marking
Dry and Wet Conditions

Night visibility rating is based on the visibility of the pavement marking line in feet from a stationary position on dry and wet pavement. The pavement markings will be evaluated by trained evaluators in a vehicle when viewed under low beam headlight illumination at night. The rating scales for night visibility will be as follows:

c. Dry nighttime visibility: a night visibility rating on dry pavement will be given in feet by looking to see how far the long line pavement markings are visible.

d. Wet nighttime visibility: a night visibility rating on wet pavement will be given in feet by looking to see how far the long line pavement markings are visible.

On this project lane lines are installed ten feet (10 feet) long with thirty feet (30 ft) gap. From a stationary position midway between lane lines the rating will be given as follows:

Description	**Rating**
1 lane line is visible	40 ft
2 lane lines are visible	80 ft
3 lane lines are visible	120 ft
4 lane lines are visible	160 ft
5 lane lines are visible	200 ft
6 lane lines are visible	240 ft
7 lane lines are visible	280 ft
8 lane lines are visible	320 ft
9 lane lines are visible	360 ft
10 lane lines are visible	400 ft
11 lane lines are visible	440 ft
12 lane lines are visible	480 ft

Lane lines are increasingly more difficult to differentiate from each other as the distance from the vehicle increases. Small changes in vertical curvature can exacerbate or mitigate this effect. Observers are cautioned to take vertical curvature into account, as even a small sag vertical curve can create the impression of increased visibility distance when none may actually exist. From a practical standpoint, on a flat section of roadway, lane line differentiation is limited to a maximum of about 10 to 12 lane lines (400 to 480 feet).

When assessing edge line visibility, the lane lines should be used as a gauge to estimate distance.

RPM Nighttime Visibility
Dry and Wet Conditions

Night visibility rating is based on the visibility of the number of raised pavement markers (RPMs) in feet from a stationary position on dry and wet pavement. RPMs are installed on the lane line at 120 feet spacing. From a stationary position at 120 feet away from first RPM the rating will be given as follows:

a. Dry nighttime visibility: a night visibility rating on dry pavement will be given in feet by looking to see how many RPMs are visible.

b. Wet nighttime visibility: a night visibility rating on wet pavement will be given in feet by looking to see how many RPMs are visible.

On this project RPMs are installed on the lane line at 120 feet spacing. From a stationary position at 120 feet away from first RPM the rating will be given as follows:

Description	Rating
1 RPM is visible	120 ft
2 RPMs are visible	240 ft
3 RPMs are visible	360 ft
4 RPMs are visible	480 ft
5 RPMs are visible	600 ft
6 RPMs are visible	720 ft

Raised pavement markers (RPMs) are increasingly more difficult to differentiate from each other as the distance from the vehicle increases. Small changes in vertical curvature can exacerbate or mitigate this effect. Observers are cautioned to take vertical curvature into account, as even a small sag vertical curve can create the impression of increased visibility distance when none may actually exist. From a practical standpoint, on a flat section of roadway, RPM differentiation is limited to a maximum of about 5 to 6 RPMs (600 to 720 feet).

PAVEMENT MARKING MATERIALS
FIELD SERVICE TESTING PROCEDURE

Color Box

To test the pavement marking colors either in the field or in the lab, the color coordinates listed in Table A.1 [based on Daytime Geometry - 45/0 (0/45), CIE illuminant D65 and CIE 1931 (2 **E**) standard observer] shall be used.

Table A.1
Color Requirements

	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

Appendix B

Comparison between Color Readings of Evaluated Materials and ODOT Color Specifications

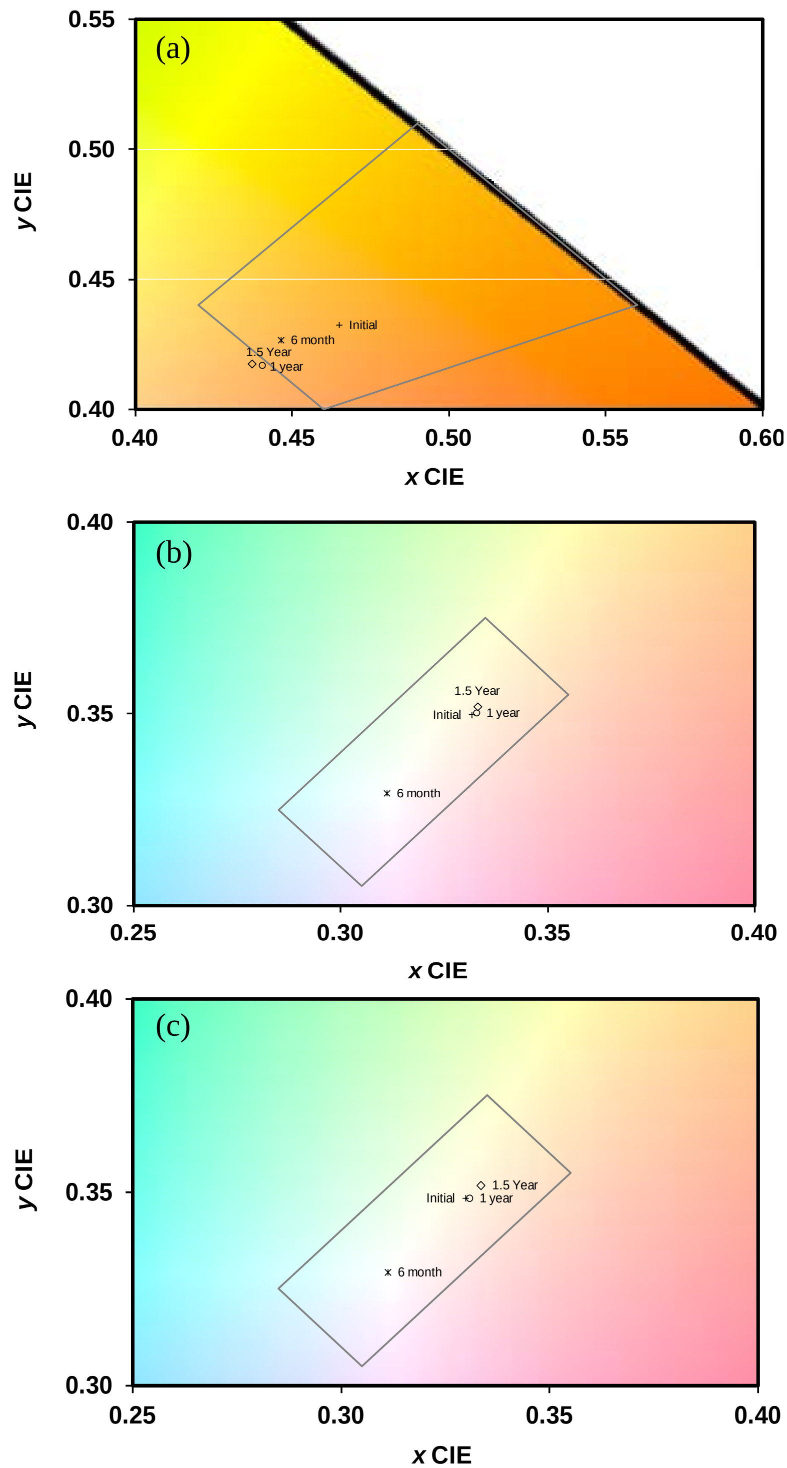


Figure (B.1): Comparison between 3M AWP Color Readings and ODOT Color Specifications: a) Yellow Edge Line (Installed on Rumble Strips), b) White Lane Line (Installed on Surface), and c) White Edge Line (Installed on Rumble Strips)

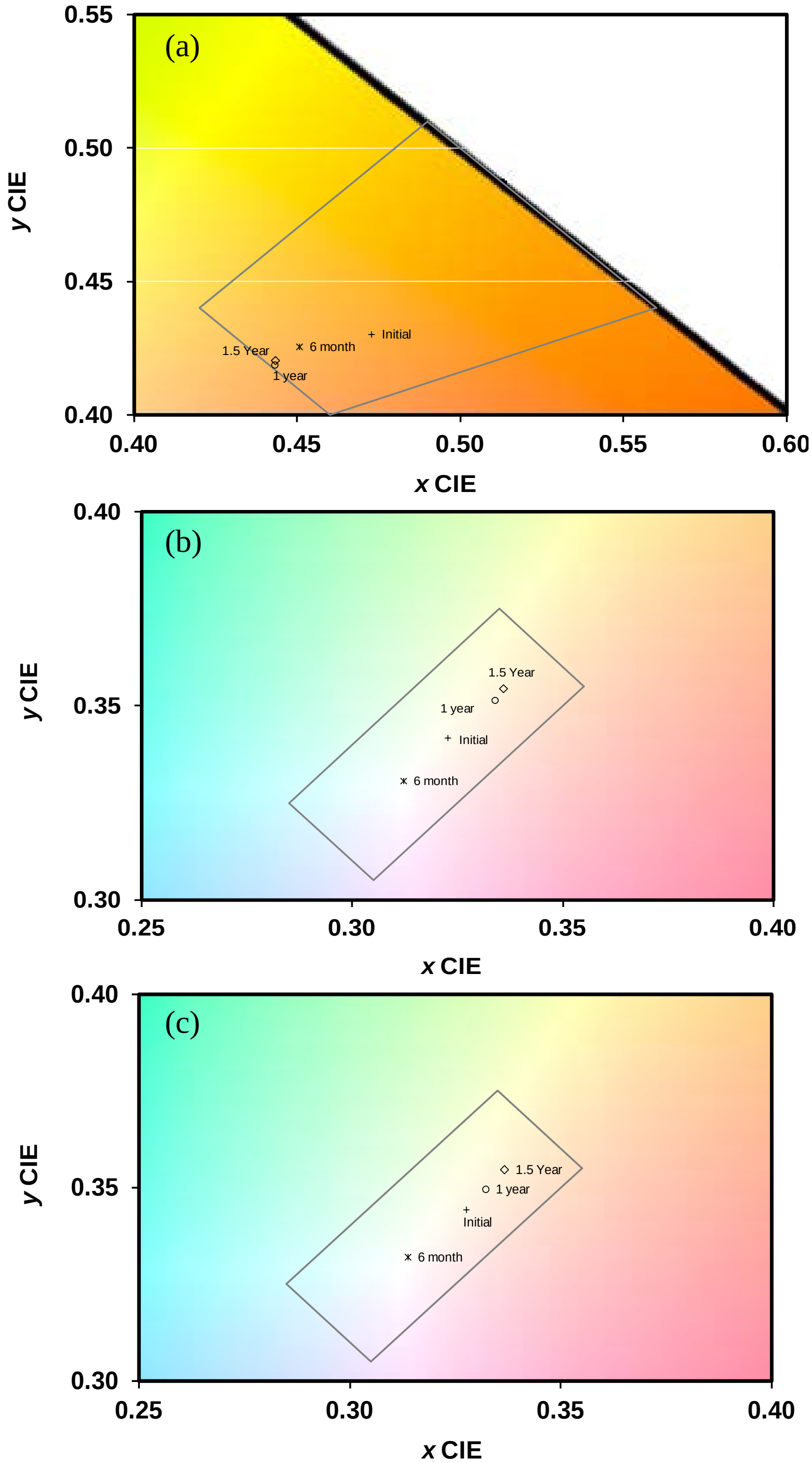


Figure (B.2): Comparison between 3M AWP Color Readings and ODOT Color Specifications: a) Yellow Edge Line (Installed on Rumble Strips), b) White Lane Line (Installed on Surface), and c) White Edge Line (Installed on Rumble Strips)

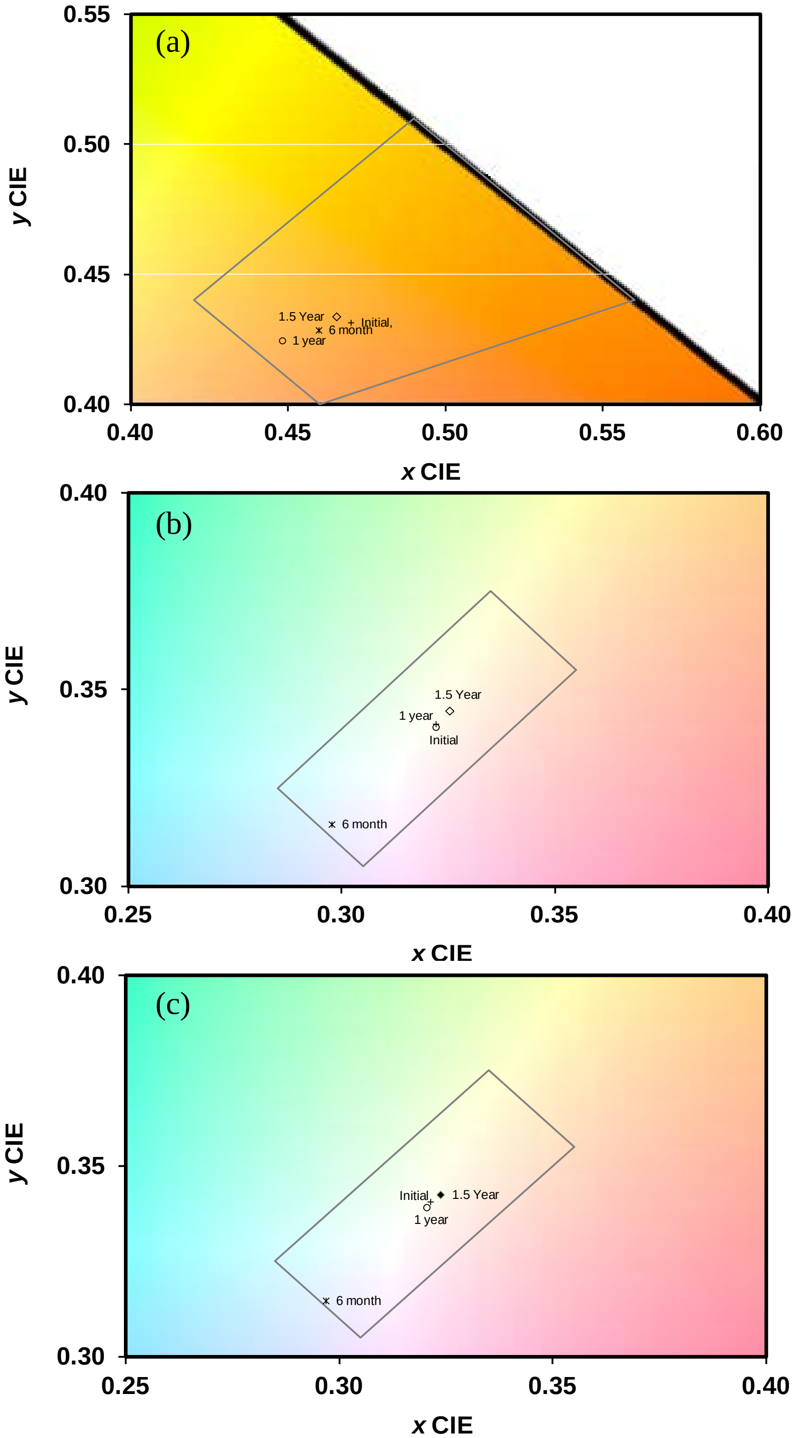


Figure (B.3): Comparisons between 3M 380WR ES Tape Color Readings and ODOT Color Specifications: a) Yellow Edge Line (Installed on Surface), b) White Lane Line (Installed on Surface), and c) White Edge Line (Installed on Surface)

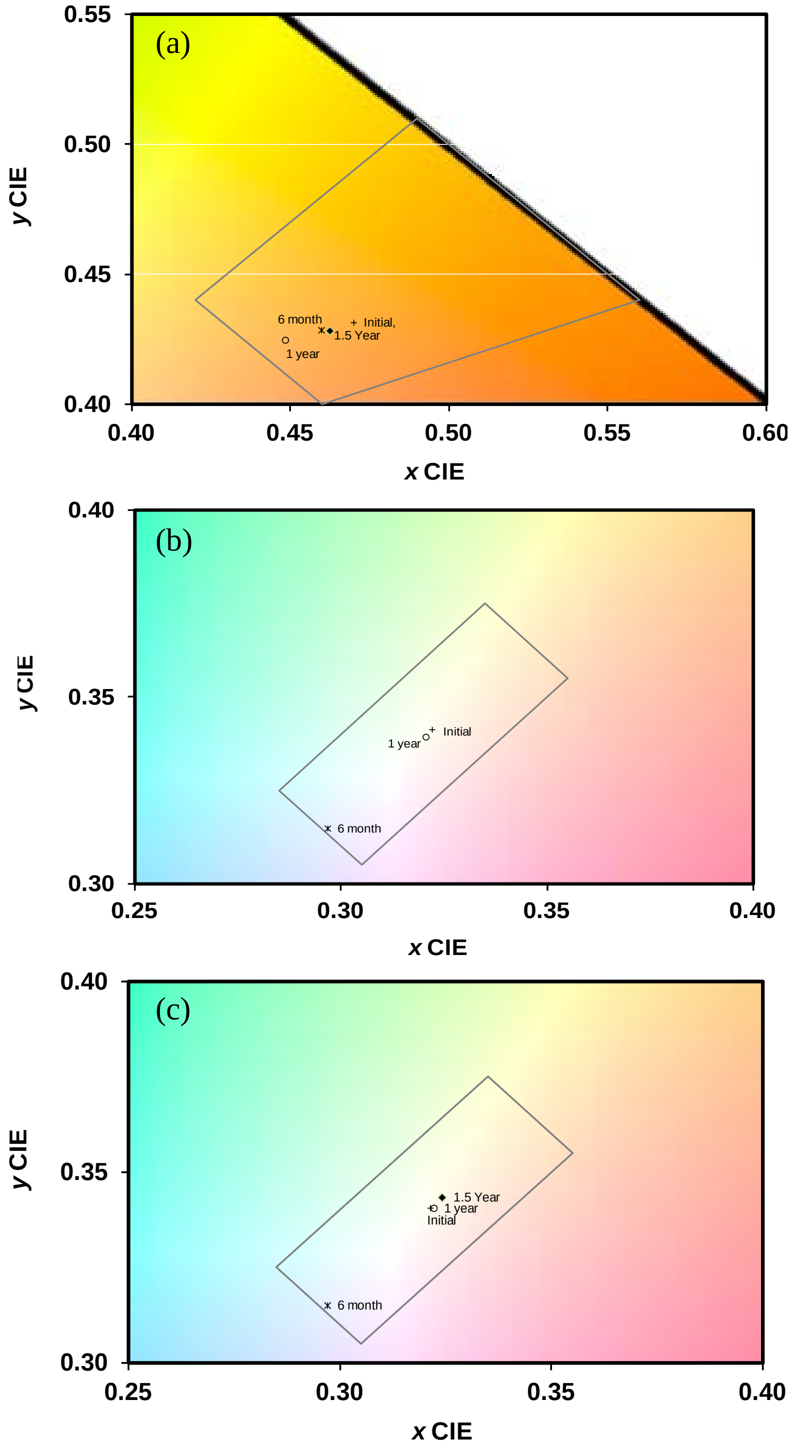


Figure (B.4): Comparisons between 3M 380WR ES Tape Color Readings and ODOT Color Specifications: a) Yellow Edge Line (Installed on Surface), b) White Lane Line (Installed on Surface), and c) White Edge Line (Installed on Surface)

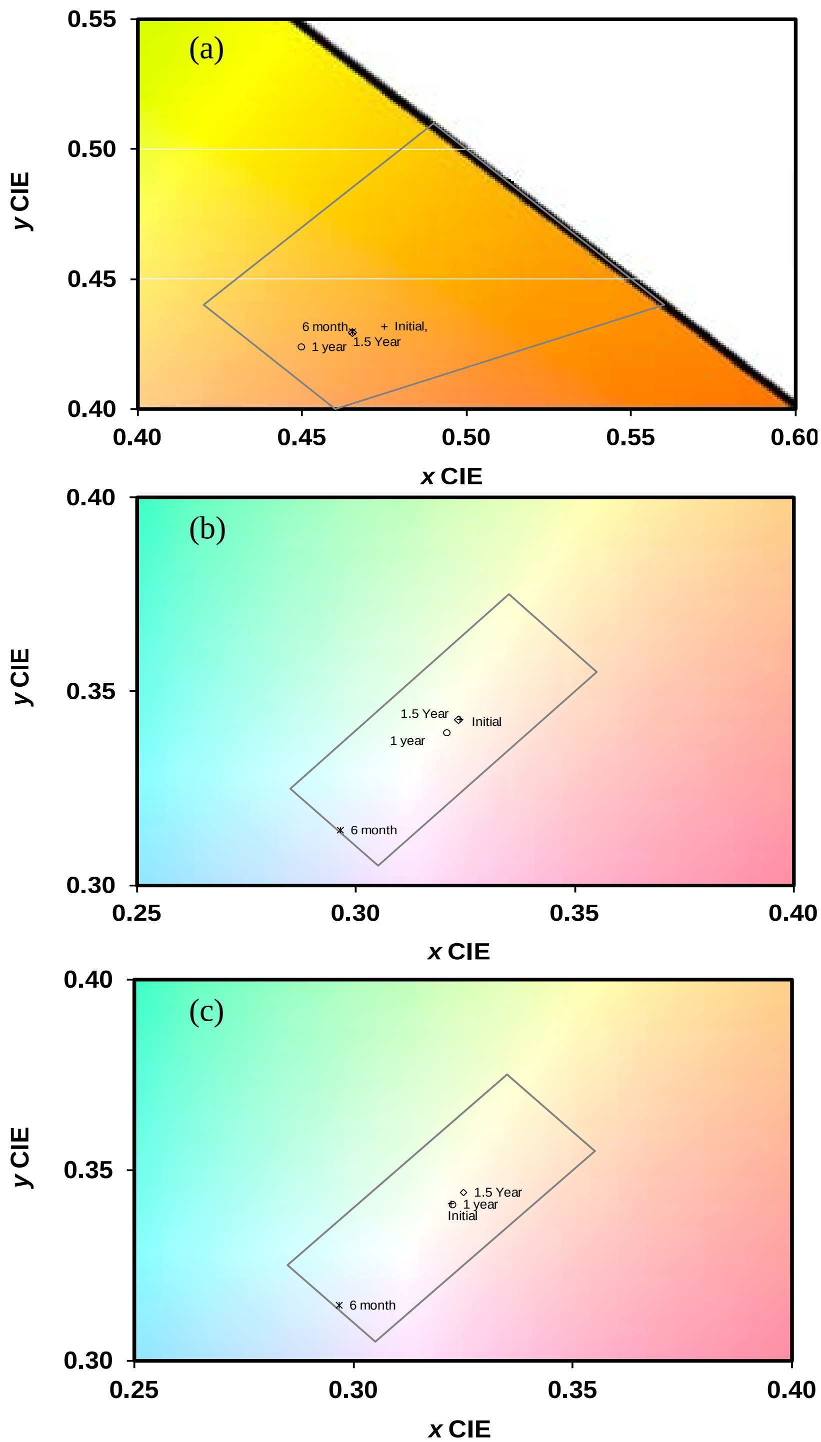


Figure (B.5): Comparisons between 3M 380WR ES Tape Color Readings and ODOT Color Specifications: a) Yellow Edge Line (Installed in Groove), b) White Lane Line (Installed in Groove), and c) White Edge Line (Installed in Groove)

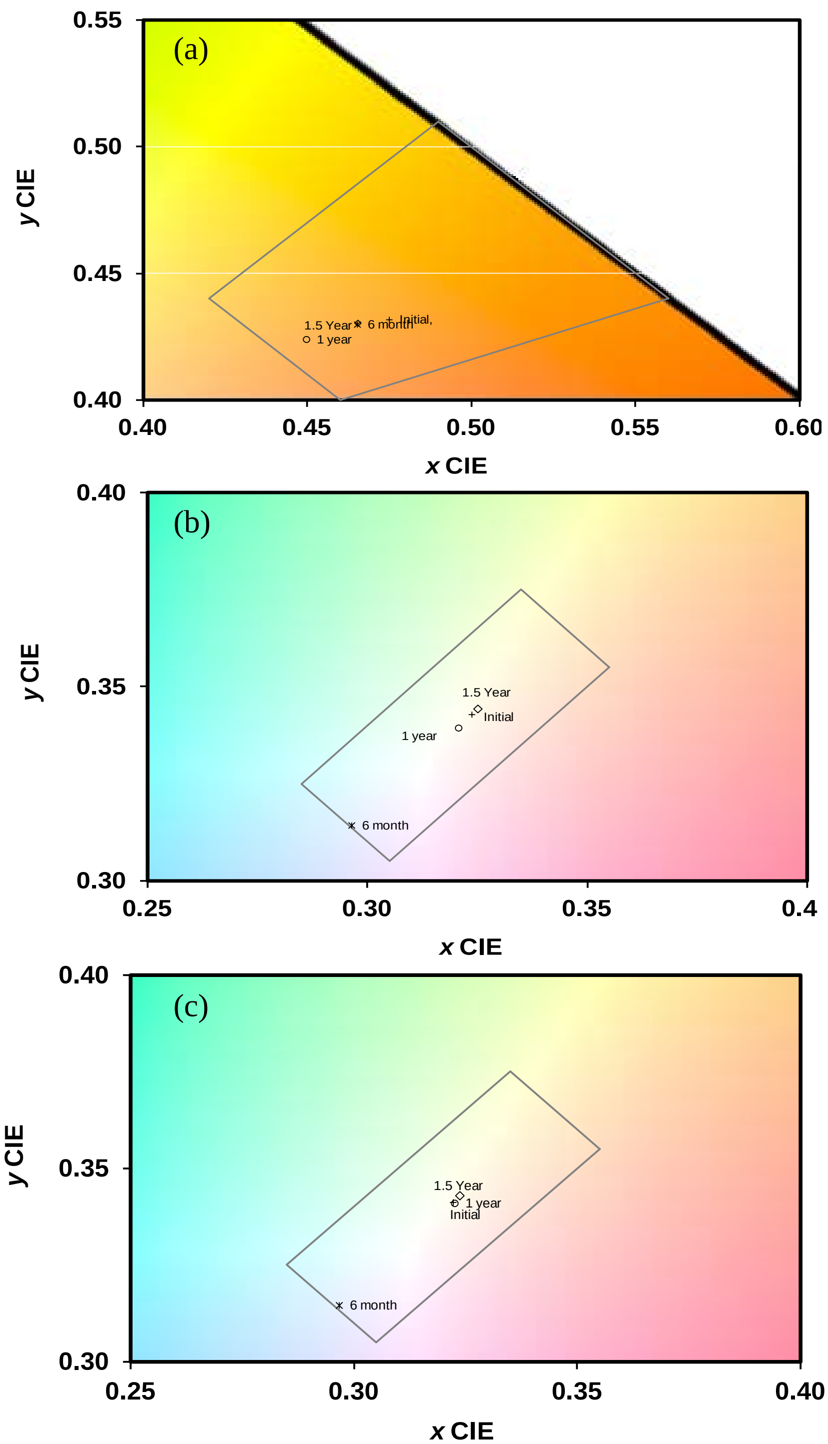


Figure (B.6): Comparisons between 3M 380WR ES Tape Color Readings and ODOT Color Specifications: a) Yellow Edge Line (Installed in Groove), b) White Lane Line (Installed in Groove), and c) White Edge Line (Installed in Groove)

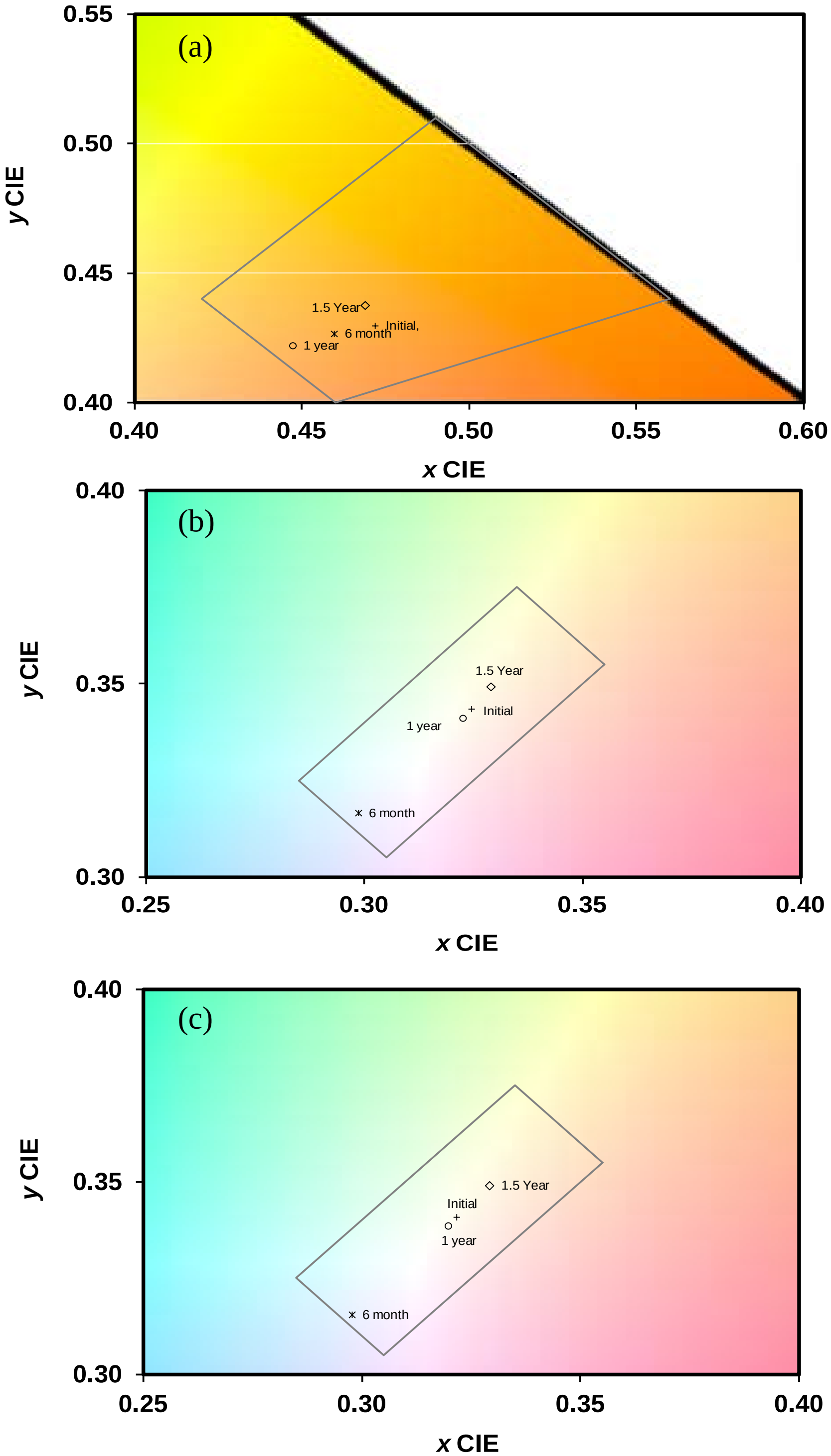


Figure (B.7): Comparisons between Thermoplastic Color Readings and ODOT Color Specifications: a) Yellow Edge Line (Installed in Groove), b) White Lane Line (Installed in Groove), and c) White Edge Line (Installed in Groove)

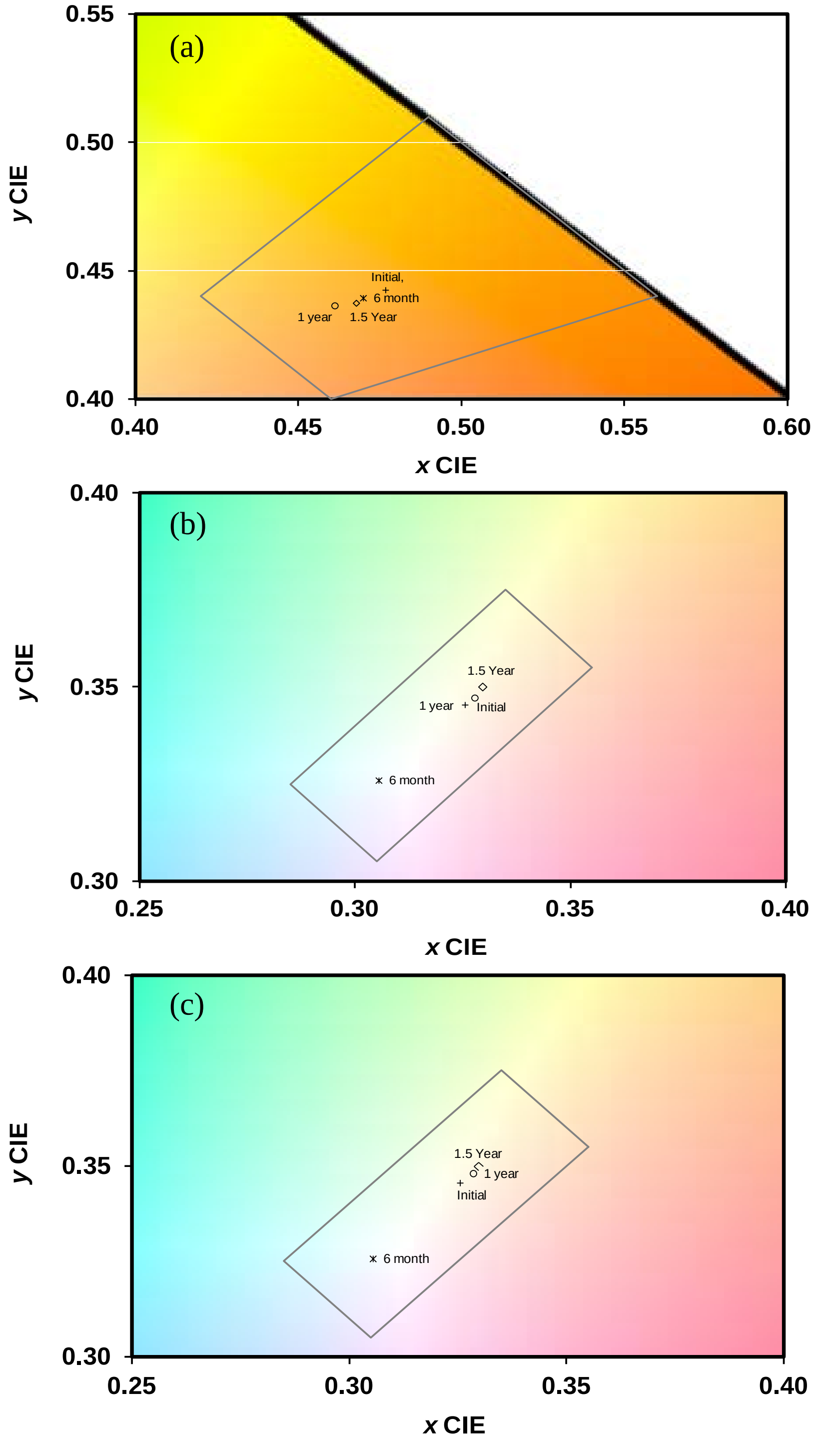


Figure (B.8): Comparisons between Thermoplastic Color Readings and ODOT Color Specifications: a) Yellow Edge Line (Installed in Groove), b) White Lane Line (Installed in Groove), and c) White Edge Line (Installed in Groove)

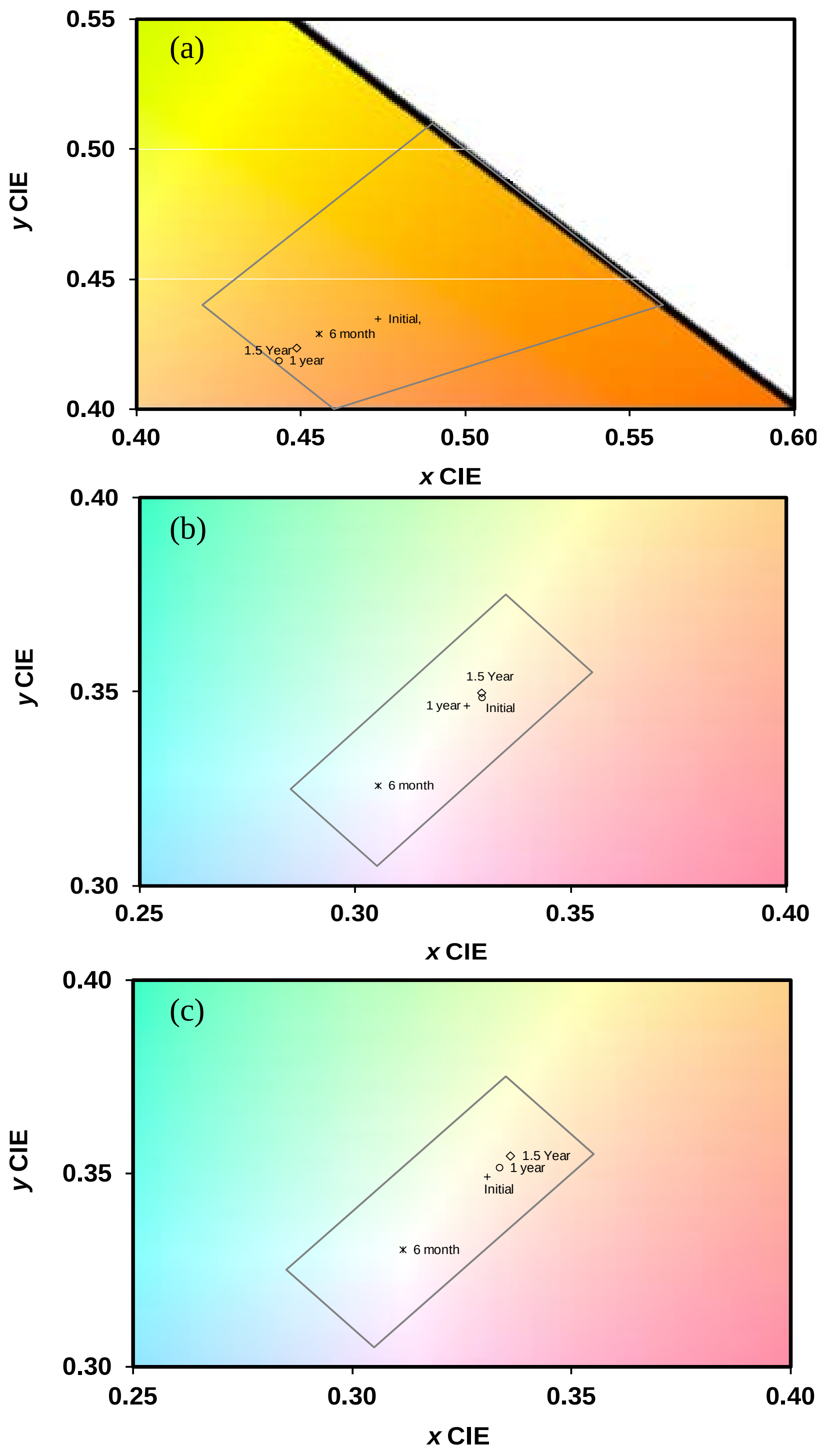


Figure (B.9): Comparisons between Color Readings and ODOT Color Specifications: a) Yellow Edge Line (3M AWP on Surface), b) White Lane Line (Thermoplastic in Groove), and c) White Edge Line (3M AWP on Surface)

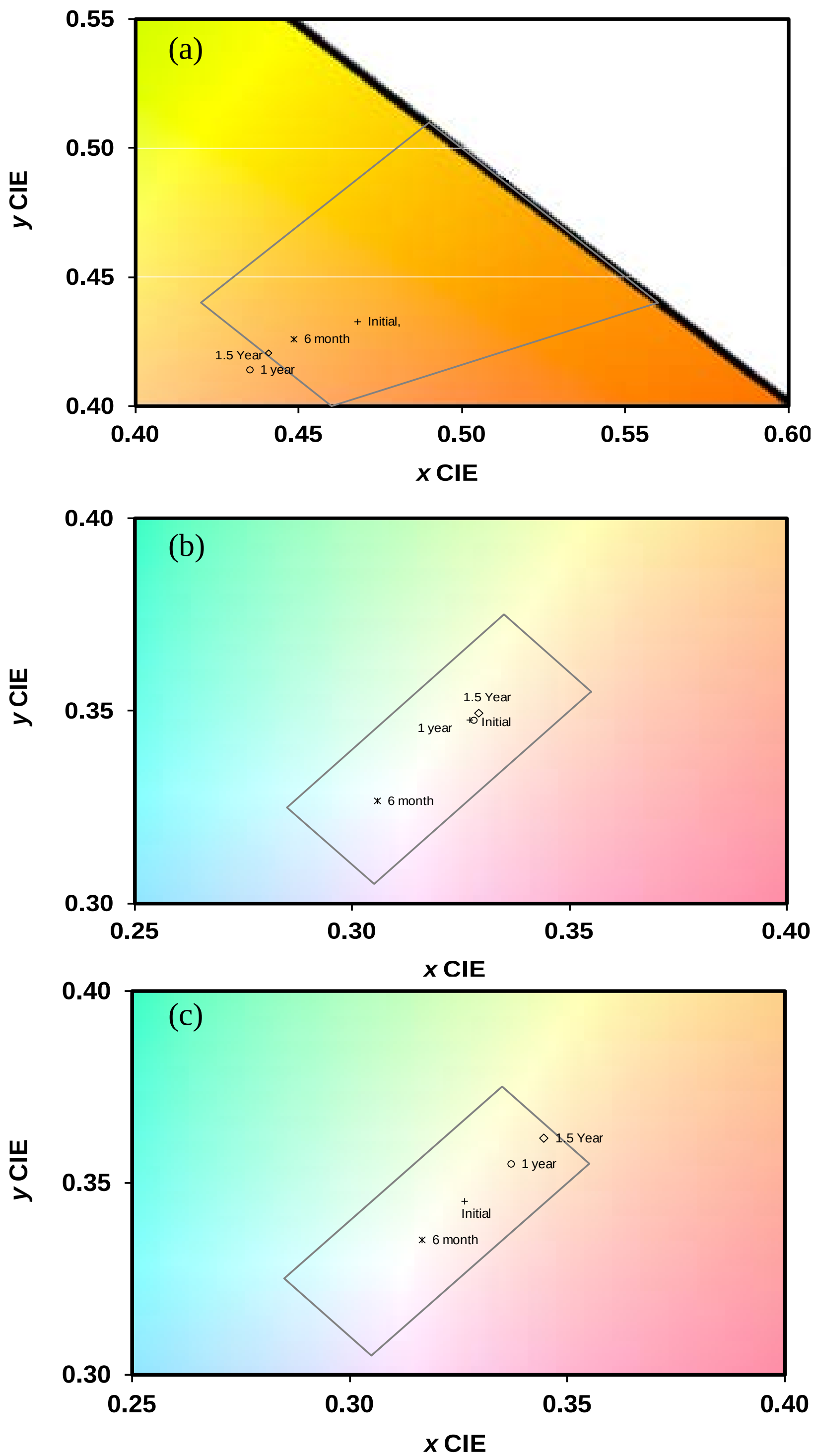
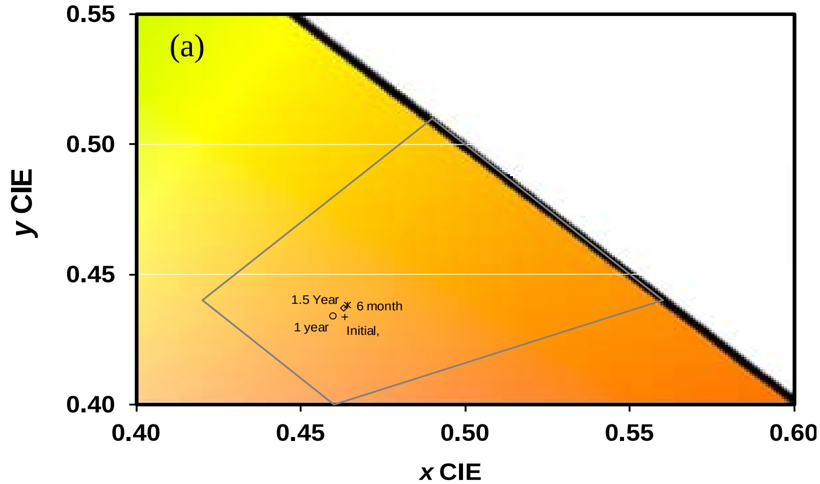
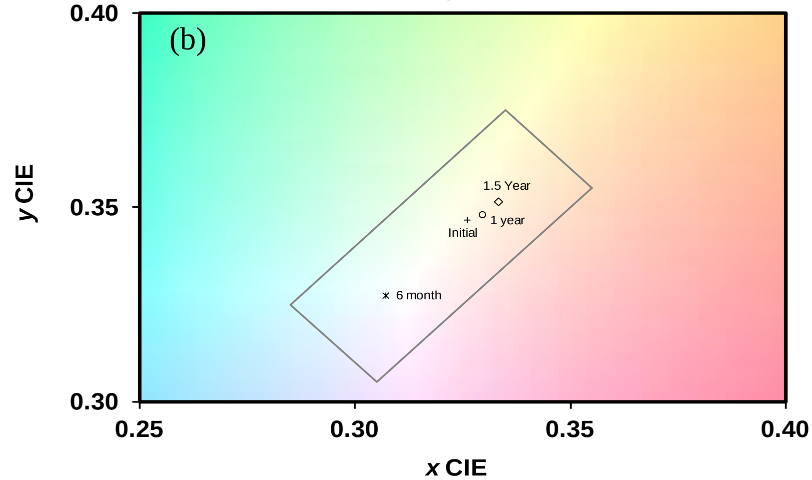


Figure (B.10): Comparisons between Color Readings and ODOT Color Specifications: a) Yellow Edge Line (3M AWP on Surface), b) White Lane Line (Thermoplastic in Groove), and c) White Edge Line (3M AWP on Surface)





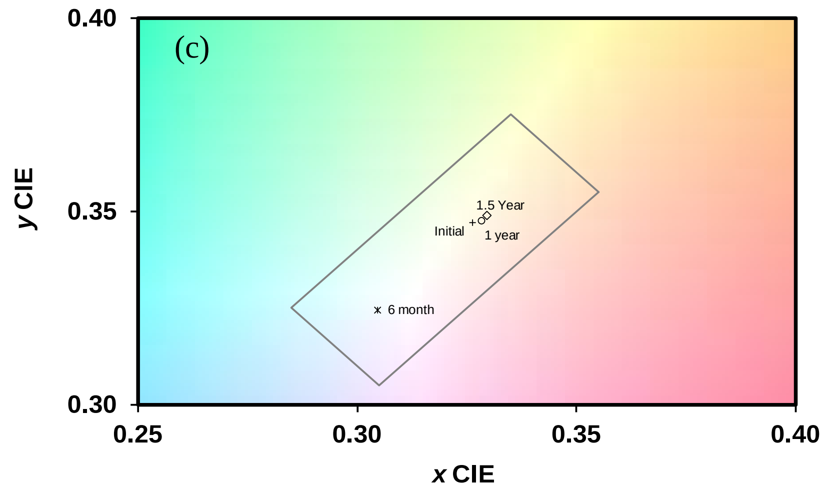


Figure (B.11): Comparisons between Thermoplastic Color Readings and ODOT Color Specifications: a) Yellow Edge Line (Installed on Surface), b) White Lane Line (Installed on Surface), and c) White Edge Line (Installed on Surface)

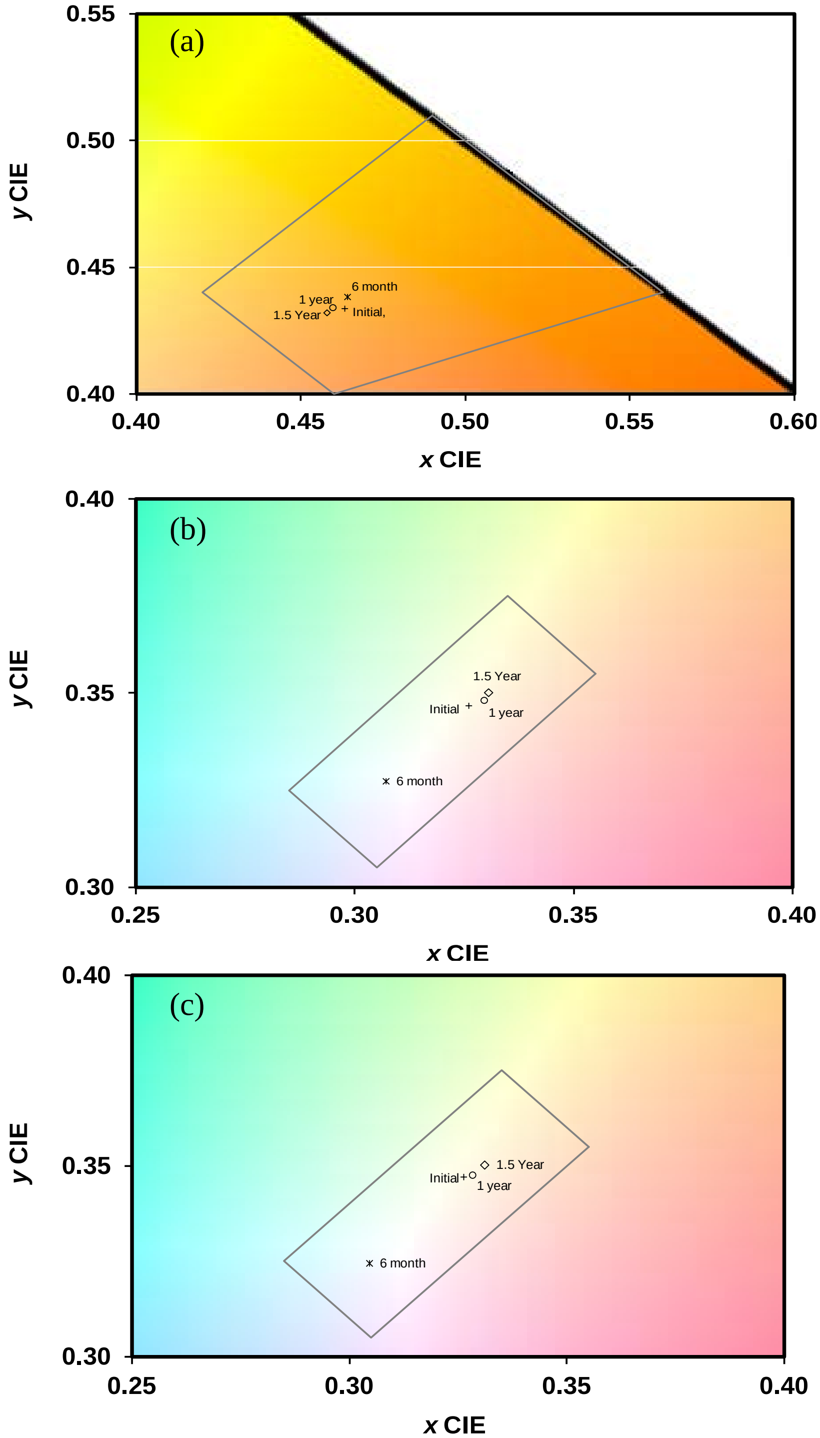


Figure (B.12): Comparisons between Thermoplastic Color Readings and ODOT Color Specifications: a) Yellow Edge Line (Installed in Groove), b) White Lane Line (Installed in Groove), and c) White Edge Line (Installed in Groove)

Appendix C

Durability Ratings of Evaluated Materials

Table (C.1): Durability Ratings of All the Materials

Treatment Type	Line Type	Initial	6-Month	1 Year	1.5 Years
3M AWP on Rumple Strips	Yellow Edge Line	10	10	10	10
3M AWP on Surface	White Lane Line	10	10	10	10
3M AWP on Rumple Strips	White Edge Line	10	10	10	10
3M 380WR ES Durable Tape on Surface	Yellow Edge Line	10	10	10	0
3M 380WR ES Durable Tape on Surface	White Lane Line	10	10	10	0
3M 380WR ES Durable Tape on Surface	White Edge Line	10	10	10	0
3M 380WR ES Durable Tape in Groove	Yellow Edge Line	10	10	10	10
3M 380WR ES Durable Tape in Groove	White Lane Line	10	10	10	10
3M 380WR ES Durable Tape in Groove	White Edge Line	10	10	10	10
Thermoplastic in Groove	Yellow Edge Line	10	10	10	10
Thermoplastic in Groove	White Lane Line	10	10	10	10
Thermoplastic in Groove	White Edge Line	10	10	10	10
3M AWP on Surface	Yellow Edge Line	10	10	10	9
Thermoplastic on Surface	White Lane Line	10	10	10	10
3M AWP on Surface	White Edge Line	10	10	10	9
Thermoplastic on Surface	Yellow Edge Line	10	10	10	10
Thermoplastic on Surface	White Lane Line	10	10	10	10
Thermoplastic on Surface	White Edge Line	10	10	10	10