Long Term Striping Alternatives for Bridge Decks

Ala R. Abbas, Ph.D.
Amal Mohi
Justin Butterfield
Department of Civil Engineering
The University of Akron
Akron, OH 44325-3905

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16. Abstract

This study evaluated the performance of the following pavement marking materials on Portland cement concrete bridge decks:

- Waterborne traffic paint: Ennis fast dry waterborne traffic paint
- Thermoplastic: Swarcotherm alkyd
- Preformed thermoplastic: Premark Plus and Premark Contrast
- Slow cure epoxy: IPS HPS-2, PolyCarb Mark 55.2, and Epoplex LS 60
- Fast cure epoxy: PolyCarb Mark 55.4 and Epoplex LS 70
- Polyurea: IPS HPS-5, PolyCarb Mark 75, and Epoplex Glomarc 90
- Modified urethane: IPS HPS-4
- Methyl methacrylate: Ennis Duraset 1 and Duraset Pathfinder
- High performance durable tapes: 3M 380WR ES, 3M 380WR-5 ES, and 3M 270 ES

The main objectives were to compare the performance evaluation results of these materials to milestone performance criteria, augment these results with performance data from the National Transportation Product Evaluation Program (NTPEP), estimate the service life of the pavement markings, and compare these materials based on their life cycle costs.

Based on the performance evaluation results and the subsequent analysis findings, it is recommended to use the following products on Portland cement concrete bridge decks: Ennis fast dry waterborne traffic paint (for bridges with low to medium traffic volumes or as part of a mainline asphalt pavement striping project), LS 60, HPS-2, Mark 55.2, Mark 55.4, HPS-4, and HPS-5. Grooving has been shown to improve the performance of some of these materials such as Ennis fast dry waterborne traffic paint. Therefore, it is recommended to consider this surface preparation technique in the installation of pavement markings on Portland cement concrete bridge decks that are subjected to high traffic.

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Prepared by:

Ala R. Abbas, Ph.D.
Assistant 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

Co-Authors:

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

Mr. Justin Butterfield
Undergraduate Assistant
The University of Akron
Department of Civil Engineering
Akron, Ohio 44325-3905

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LONG TERM STRIPING ALTERNATIVES FOR BRIDGE DECKS

ABSTRACT

The performance of several pavement markings, including waterborne traffic paint (Ennis fast dry waterborne traffic paint), thermoplastic (Swarcotherm alkyd), preformed thermoplastic (Premark Plus and Premark Contrast), slow cure epoxy (HPS-2, Mark 55.2, and LS 60), fast cure epoxy (Mark 55.4 and LS 70), polyurea (HPS-5, Mark 75, and Glomarc 90), modified urethane (HPS-4), methyl methacrylate (Duraset 1 and Duraset Pathfinder), and high performance durable tapes (3M 380WR ES, 3M 380WR-5 ES, and 3M 270 ES), was evaluated on sixteen concrete bridge decks located in Ashland and Richland counties in ODOT District 3 along interstate I-71. All bridges are connected to mainline asphalt pavement where the interstate has three lanes per direction, with an average daily traffic (ADT) of about 42,000 vehicles per day.

Each material was installed in four locations along the three lanes of the interstate. Yellow was installed on the left edge line and white was installed on the two lane lines and the right edge line. All materials were installed in 150-mil (3.8 mm) grooves. The groove depth selected was the same as the transverse tines depth on the bridge decks in order to ensure that all traces of the old thermoplastic have been completely removed; and thus, eliminate its effect on the newly installed products.

The performance evaluation period lasted for slightly over two years. The performance evaluation plan included measuring retroreflectivity using two handheld LTL-X retroreflectometers and color using a MiniScan XE Plus colorimeter. It also included rating daytime color, nighttime visibility, and durability according to Supplemental 1047 (dated April 18, 2008). In addition, a pocket magnifier was used to examine glass bead retention as it varied over time.

The performance evaluation results obtained during the periodic evaluations were compared to preselected milestone performance criteria and augmented with NTPEP data from the Pennsylvania and Wisconsin test decks. The service life of each marking material was predicted using different mathematical models that estimated the time required for retroreflectivity to drop to a threshold value of 150 mcd/m^2/lux for white markings and 100 mcd/m^2/lux for yellow markings. The service life predictions were then used to calculate the life cycle costs of the marking materials in order to determine their cost effectiveness.

Based on the performance evaluation results and the subsequent analysis findings, the following conclusions and recommendations were made:

- Three slow cure epoxies were evaluated in this study, namely IPS HPS-2, PolyCarb Mark 55.2, and Epoplex LS 60. All three products performed satisfactorily over the two-year performance evaluation period, with an expected service life of about 3 to 5 years. From among these products, only LS 60 is currently included in ODOT "Approved List" of pavement markings. Hence, it is recommended to add both HPS-2 and Mark 55.2 to this list.
- Two pavement marking materials showed the potential of lasting for more than five years under high traffic, namely IPS HPS-5 polyurea and Epoplex Glomarc 90 polyurea. These products, however, did not compare favorably with the less expensive slow cure epoxies based on the life cycle cost analysis results. Therefore, it will not be cost effective to use them on a large scale. Another concern regarding Glomarc 90 is that Epoplex has recently changed the bead systems used in this product. Therefore, additional evaluation may be necessary for this material with the new bead systems. Still, it is recommended to include HPS-5 polyurea in ODOT "Approved List" on a conditional basis by limiting its use to a number of projects per year that involve Portland cement concrete surfaces subjected to high traffic.
- The third polyurea product PolyCarb Mark 75 did not perform as satisfactorily as the other two polyurea products. Therefore, it is not recommended to include this material in ODOT "Approved List."
- Given their very high initial cost, durable tapes did not seem to offer clear advantage over the less expensive slow cure epoxies under dry conditions. One of the durable tapes, 3M 380WR ES series, contains specially designed optics to improve its performance under wet night conditions. Additional research is needed to evaluate the performance of this tape under such conditions.
- The performance of HPS-4 modified urethane was comparable to that of slow cure epoxies. This material is slightly more expensive. Yet, it dries much faster, which makes it desirable for areas with high traffic volumes since it requires less traffic control. Therefore, it is recommended to conditionally approve this material.

- Epoplex LS 70 slow cure epoxy failed due to durability in less than eight months. Therefore, it is not recommended to approve using this material.
- Even though PolyCarb Mark 55.4 fast cure epoxy is currently included in ODOT "Approved List," this product had one of the highest retroreflectivity deterioration rates. Therefore, it is recommended to review recent projects striped with this material to determine whether to keep it or remove it from the "Approved List."
- The performance of the preformed thermoplastic Premark Plus and Premark Contrast was comparable to the performance of the less expensive slow cure epoxies over the two-year performance evaluation period. Therefore, it is not recommended to use these materials for longitudinal applications on Portland cement concrete bridge decks.
- Poor installation of Duraset 1 methyl methacrylate resulted in poor performance. Additional evaluation may be required to assess the performance of this material. At the present, it is not recommended to include it in ODOT "Approved List".
- The performance of Duraset Pathfinder methyl methacrylate was comparable to that of the less expensive slow cure epoxies. Therefore, it is not recommended to include it in ODOT "Approved List."
- Interestingly, even though Ennis fast dry waterborne traffic paint did not meet most milestone retroreflectivity criteria set forth for the more durable products, its performance was reasonably acceptable (retroreflectivity is greater than 150 mcd/m^2/lux for white markings and 100 mcd/m^2/lux for yellow markings) even after two years from installation. This material is typically applied on the surface rather than in groove. However, in this study, it was installed in 150-mil (3.8 mm) grooves similar to the rest of the materials. One disadvantage of doing so is that the lines became completely invisible under wet night conditions once the grooves were filled with water. This was not necessarily the case for thicker materials and materials that had patterned structures.
- Some of the evaluated materials such as HPS-2, HPS-4, Mark 55.2, and Mark 55.4 had acceptable yellow color even though their color readings were very close to the bottom corner of ODOT yellow color specification box. On the other hand, some of the evaluated materials had white color readings well within ODOT white color specification box, but did not have acceptable color contrast. This calls into question the applicability of ODOT color specifications to determine pavement marking daytime color acceptability.

- Finally, grooving has been shown to improve the performance of some of the pavement markings such as Ennis fast dry waterborne traffic paint. Therefore, it is recommended to consider this surface preparation technique in the installation of pavement markings on Portland cement concrete bridge decks that are subjected to high traffic.

Major limitations of this study include:

- All materials evaluated in this project were installed in 150-mil (3.8 mm) grooves. The performance of these materials will probably be different if they were applied on the surface.
- Pavement marking performance under dry conditions is not necessarily indicative of their performance under wet conditions. The 3M 380WR ES wet reflective durable tape, for example, is designed to improve retroreflectivity under wet conditions. However, this factor was not taken into consideration in this study. Therefore, additional research is needed to evaluate the performance of this tape under such conditions.
- The life cycle cost analysis procedure employed in this project did not address the impact of frequent striping using less durable pavement markings on traffic flow and the potential risk to maintenance crew. These factors must be taken into consideration in determining which pavement marking material type to use.

In summary, it is recommended to use the following products on Portland cement concrete bridge decks: Ennis fast dry waterborne traffic paint (for bridges with low to medium traffic volumes or as part of a mainline asphalt pavement striping project), LS 60, HPS-2, Mark 55.2, Mark 55.4, HPS-4, and HPS-5. Grooving has been shown to improve the performance of some of these materials such as Ennis fast dry waterborne traffic paint. Therefore, it is recommended to consider this surface preparation technique in the installation of pavement markings on Portland cement concrete bridge decks that are subjected to high traffic. To this end, it is recommended to add the following products to ODOT “Approved List” of pavement markings: IPS HPS-2, PolyCarb Mark 55.2, IPS HPS-4, and IPS HPS-5.

CHAPTER 1
INTRODUCTION

1.1 Problem Statement

Ohio Department of Transportation (ODOT) uses a number of materials for pavement marking including waterborne and alkyd traffic paint, polyester, thermoplastic, preformed tapes, epoxy, and heat-fused preformed thermoplastic; which are addressed in 2008 Construction and Material Specifications (C&MS) Items 640 and 740. Material selection is presented in Table 397-1 of the 2002 Traffic Engineering Manual (TEM), whereby the material type is chosen according to the remaining life of the pavement surface, type of line (longitudinal line or auxiliary), type of pavement surface (asphalt or concrete), and average daily traffic (ADT). According to this table, durable markings such as thermoplastic and epoxy are more likely to be applied on highways with high traffic volumes and pavements with a remaining surface life in excess of four years, while non-durable markings such as traffic paint and polyester are recommended for restriping. Furthermore, thermoplastic markings are specified for new asphalt pavements and epoxy markings are specified for new concrete pavements. This constraint, however, has significant financial impacts on projects that include concrete bridge decks connected to mainline asphalt pavements. The additional cost in such projects is resulted from paying the contractor an extra cost to use thermoplastic for asphalt and epoxy for concrete, or from dividing the project into two separate projects; one for the asphalt portion and another for the concrete portion. Due to these financial concerns, thermoplastic, which has poor durability on concrete surfaces, is currently being applied to the concrete bridge decks as well as the mainline asphalt pavements. This often results in premature debonding in the bridge stripes compared to those on the adjoining asphalt pavement. This deficiency raises major safety concerns regarding these bridges, and leads to low performance ratings as measured using various performance indicators in force by ODOT.

As a result, ODOT invited the marking industry to provide alternative marking materials and installation techniques to be tested on Portland cement concrete bridge decks along interstate I-71 in District 3; and initiated this project to evaluate the effectiveness of the proposed combinations. In particular, ODOT is interested in identifying those materials that can last more than five years.

1.2 Objectives of the Study

The specific objectives of this research project are enumerated below:

1. Develop a comprehensive performance evaluation plan for pavement markings;
2. Evaluate the performance of different marking materials on Portland cement concrete bridge decks using qualitative as well as quantitative measures;
3. Compare the performance of these materials based on durability, daytime color, and nighttime visibility performance;
4. Augment the performance evaluation results with data from the National Transportation Product Evaluation Program (NTPEP);
5. Compare these materials based on cost-effectiveness; and
6. Recommend changes to current ODOT practices and specifications to address the research findings.

1.3 Report Organization

This report is organized into ten chapters. Chapter 2 presents a literature review of subjects pertinent to this study. Chapter 3 offers an overview of ODOT pavement marking practices. Product information and installation techniques for the various marking materials evaluated in this study are summarized in Chapter 4. Chapter 5 outlines the performance evaluation plan according to which the field evaluations were conducted. Performance evaluation results are presented in Chapter 6; and augmented with data from the NTPEP program in Chapter 7. Chapter 8 deals with the estimation of the pavement markings service life. Chapter 9 focuses on calculating the life-cycle costs of the various marking systems. Conclusions regarding the performance of each material and recommendations for future implementation are available in Chapter 10.

CHAPTER 2
LITERATURE REVIEW

2.1 Background

Pavement marking is the process of striping a pavement surface using a material that is visible during daytime and has retro-reflective properties during nighttime. It includes longitudinal markings (centerlines, lane lines, and edge lines), transverse markings (stop lines, yield lines, and crosswalk markings), and special markings (arrows, words, symbol markings, red or blue raised pavement markers, cross-hatching, dotted lines, reversible lane markings, two-way left turn lane markings, speed hump markings, and parking space markings), which are defined in the Ohio Manual on Uniform Traffic Control Devices (OMUTCD).

Pavement markings play an important role in providing guidance to motorists. They have the potential to reduce crashes during both daylight and darkness under normal and adverse weather conditions (Migletz and Graham 2002). A wide range of pavement marking materials are available, including waterborne and alkyd traffic paints, polyester, thermoplastic, preformed thermoplastic, epoxy, polyurea, modified urethane, methyl methacrylate, and durable tapes (Migletz and Graham 2002; Gates et al. 2003). These 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).

This project focuses on the performance of pavement marking materials on Portland cement concrete surfaces. The following sections offer a synthesis of literature review on key topics related to pavement markings. Due to rapid changes in pavement marking materials and technologies, the discussion presented herein will focus on documents published within the last ten years. Special attention will be given to publications dealing with the performance of pavement markings on concrete surfaces.

2.2 Performance Evaluation of Pavement Markings

Pavement marking performance is affected by several factors, including marking material type and color; type and size of glass beads; surface preparation and quality of installation; type and age of pavement surface; environmental conditions; type and number of snowplow activities; highway geometry; traffic volume; and type of vehicle mix.

Pavement markings have been evaluated using two main criteria, durability and visibility (Migletz and Graham 2002; Gates et al. 2003). The former refers to the resistance of the marking material to abrasion from traffic and snow removal activities; while the latter relates to the contrast in color between the marking material and the underlying pavement surface during the day and at night. As will be discussed next, these attributes have been characterized using subjective and objective evaluation techniques. As their names imply, subjective evaluations are made by experienced evaluators who use their judgment in rating the performance of the pavement marking according to predefined guidelines. Meanwhile, objective evaluations are conducted using an instrument such as a retroreflectometer or a colorimeter. Readings obtained using these instruments can be used to determine whether the performance of the material is acceptable or not.

2.2.1 Durability

Pavement marking durability is mainly determined by the type and quality of the binder or resin used in the marking material; and its ability to adhere to the underlying pavement surface.

Pavement marking durability is commonly assessed by visually rating the percentage of material remaining on the surface by a trained evaluator on a scale of 0 to 10, where 0 indicates that the material has been completely lost and 10 means that 100% of the material is remaining. The rating is commonly reported as an integer (with no fractions). Due to the subjective nature of the evaluation, durability ratings can vary based on the person administering the test.

Alternatively, durability has been measured by testing the bond strength between the marking material and the pavement surface using a pull out test. This test is conducted by gluing a cylindrical piece of metal to the surface of the marking material and applying a tensile force on the assembly until the pavement marking detaches from the pavement surface. In order to ensure that failure does not occur at the interface between the metal piece and the marking surface where the glue is applied, the marking surface shall be free of dirt and moisture. In these tests, durability is reported in pounds per square inch (psi) or some other stress unit.

Pavement marking durability is highly dependent on the material type. Paints, for example, tend to degrade faster than other durable materials such as thermoplastics and epoxies. In addition, the degradation rate is dependent on the pavement type, pavement surface texture, surface preparation, traffic volume, and weather conditions and corresponding snow removal practices (Thomas and Schloz 2001).

2.2.2 Visibility

Visibility is described using daytime appearance and nighttime performance of the marking material. The former is dictated by the quality of pigmentation in the baseline marking materials and hence is commonly referred to as *color*, while the latter is generally provided through the use of round transparent glass beads that are partially embedded in the marking material and is commonly referred to as *retroreflectivity*.

Similar to durability, these two properties have been evaluated using subjective and objective evaluating techniques. In-depth comparison between these two techniques, including the advantages and disadvantages, is presented in Chapter 5. In brief, subjective evaluations are made by experienced evaluators who use their judgment in rating the performance of the pavement marking according to predefined guidelines. Meanwhile, objective evaluations are conducted using an instrument such as a colorimeter or a retroreflectometer. Readings obtained using these instruments are discussed next in detail.

2.2.2.1 Color

Pavement marking color is quantitatively measured using a colorimeter, which provides coordinates in Commission Internationale de l'Eclairage (CIE) color units. These coordinates can be plotted on a CIE chromaticity diagram, as shown in Figure (2.1), to determine the color of the pavement marking. In this figure it can be noticed that as *x* increases, the red quality of the color increases; and as *y* increases, the green quality of the color increases. One additional reading that is measured using spectro-colorimeters, but is not presented in this figure is the Y reading, which describes how bright or luminous the object is. As will be presented later in this report, color specifications can be superimposed on this diagram and be used along with the CIE color coordinates to determine whether color of the pavement marking meets specifications or not.

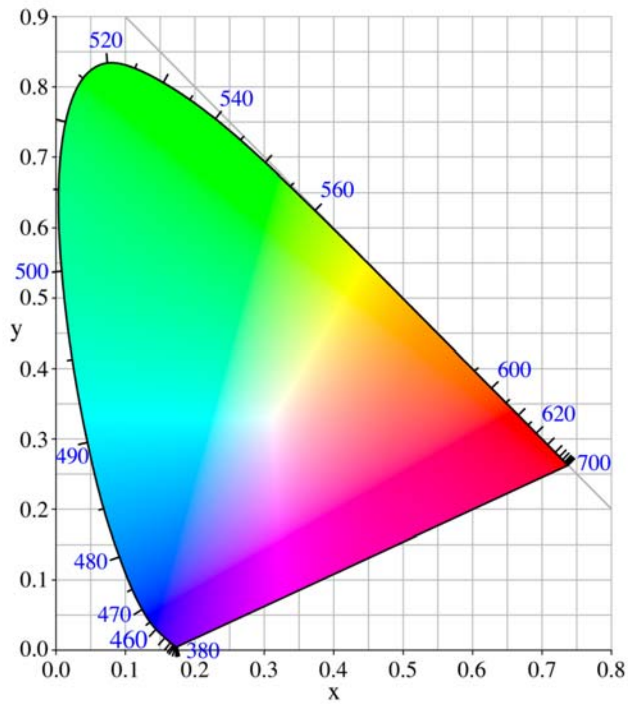

Figure (2.1): CIE Chromaticity Diagram.

In general, most pavement markings tend to have acceptable color performance if installed properly. Common practices that may lead to unacceptable color properties include the use of some epoxies that are highly sensitive to ultraviolet light; overheating of thermoplastic materials; use of some lead-free yellow markings that are not stable; and use of large beads in ample quantities, which attracts dirt, grease, deicing compounds, and other contaminants.

2.2.2.2 Retroreflectivity

Pavement marking retroreflectivity is defined as the reflection of the incident light from the vehicle headlight beams to the drivers' eyes after striking the marking material. As mentioned earlier, pavement marking retroreflectivity is generally provided through the use of round transparent glass beads that are partially embedded in the marking material (Figure 2.2). The effectiveness of the glass beads in providing nighttime visibility depends on the characteristics of the glass beads themselves in terms of size, refraction index, clarity, and roundness as well as the application rate and quality of installation. It is widely held that fifty to sixty percent of the glass bead diameter must be embedded in the marking material in order to achieve optimum retroreflectivity.

Retroreflectivity is typically quantified using the coefficient of retro-reflected luminance, R_L, represented in millicandelas per square meter per lux (mcd/m^2/lux). This coefficient is calculated by dividing the luminance or the amount of light available for seeing or reflected in a particular direction, by the luminous flux defined as the rate of flow of light over time (Thomas and Schloz 2001).

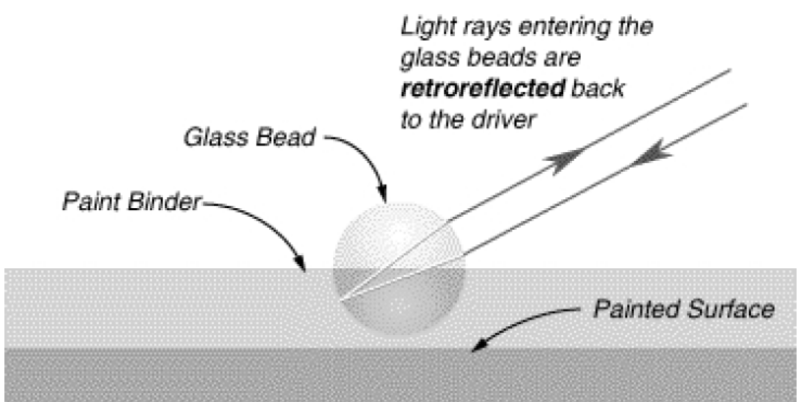

Figure (2.2): Glass Bead Retroreflection (After: Thomas and Schloz 2001).

Retroreflectivity is measured using handheld and mobile reflectometers that vary in cost, required manpower, data accuracy, equipment reliability, and compliance with current standards (Migletz and Graham 2002). Example handheld reflectometers include LTL 2000, LTL-X, Mirolux 12, Mirolux Plus 30, Black Box, Ecolux, MP-30, MX-30, Gamma Scientific 2000, and Retrolux Model 1500; and example mobile reflectometers include ECODYN and Laserlux (Migletz and Graham 2002; Thomas and Schloz 2001; Migletz et al. 1999). Figure (2.3) presents the standard 30-m geometry (entrance angle of 88.76° and observation angle of 1.05°) used for measuring nighttime retro-reflectivity (Migletz and Graham 2002). This geometry exemplifies the driver's ability to view the marking at a location that is 30-m ahead of the vehicle. The fact that not all reflectometers use this geometry partly explains the variations among these instruments (Migletz et al. 1999).

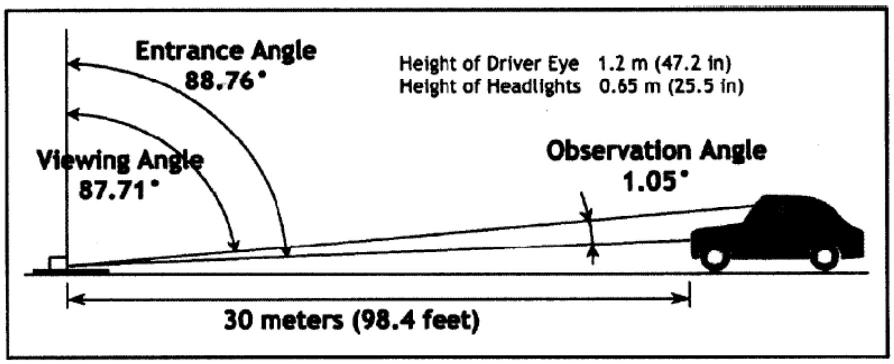

Figure (2.3): Standard 30-m Measurement Geometry for Pavement Marking Retroreflectivity (After: Migletz and Graham 2002; Source: Hawkins et al. 2000).

2.3 Pavement Marking Materials

The section offers a brief overview of the pavement marking material types evaluated in this study. These materials include traffic paint, thermoplastic, preformed thermoplastic, epoxy, polyurea, modified urethane, methyl methacrylate, and durable tapes. The information for these products was obtained from several references. In particular, TxDOT (2004), Gates et al. (2003), Migletz and Graham (2002), and Thomas and Schloz (2001) were very useful in writing this section. Table (2.1) offers a comparison between these materials in terms of cost, typical service life, surface preparation requirements, need for lane closure, and performance on concrete pavements; based on data and information presented in Gates et al. (2003). Chapter 3 offers an overview of the pavement marking materials used by ODOT. Additional information regarding the specific products evaluated in this project is available in Chapter 4 and Appendix B.

2.3.1 Traffic Paint

Traffic paint is the most commonly used pavement marking material due to its low cost. Compared to other pavement markings, this material is the least durable as it wears off more rapidly, leading to a quick drop in retroreflectivity. The typical service life of traffic paint is about one year. Newer formulations of high-build traffic paint have been reported to improve performance (Hawkins et al. 2007). Still, this material is more likely to be used on highways with low to medium traffic volumes, and be restriped on a regular schedule.

Two types of traffic paints are available, waterborne (or water-based) and solvent-based traffic paints. The former is also referred to as latex paint. Both are single component paints that can be applied without adding anything to them. The former consists of emulsion resins, while the latter contains a solvent-based resin. Recent years have seen increased used of waterborne traffic paints because they are more environmentally friendly and are easier to handle than solvent-based traffic paints. Yet, the drying time of most waterborne traffic paints is much longer than that of solvent-based paints.

2.3.2 Thermoplastic

Thermoplastic consists of four components: binder, pigment, glass beads, and filler material. Two types of thermoplastics are available, namely hydrocarbon and alkyd. The former is a petroleum derivative and hence, is susceptible to oil, while the latter is a naturally occurring resin which can resist oil, but is sensitive to heat and therefore needs to be carefully controlled during application (Thomas and Schloz 2001). The thermoplastic is applied to the pavement in three ways, namely the extrusion method, the ribbon application technique, and the spraying method (Thomas and Schloz 2001). Satisfactory results have been reported for its use on asphalt pavements. Several States, however, do not allow its use on their concrete pavements due to durability concerns (Migletz and Graham 2002). Gates et al. (2003) attributed the superior adhesion quality between the thermoplastic and the asphalt surface to the thermal bonding mechanism that takes place between these two materials, resulting in bond strengths equivalent to that of the cohesive strength within the asphalt. On the other hand, it was argued that the adhesion between the thermoplastic and the concrete surface is controlled by an inferior mechanical bonding mechanism that is based on the mere seepage of the molten thermoplastic material into the pores of the concrete at the time of the installation. The resulting interlocking is weakened by the frequent contraction and expansion of the concrete, leading to the frequently reported premature debonding between these two materials. This bonding could be enhanced by applying a primer material on the concrete surface before the thermoplastic is applied.

2.3.3 Preformed Thermoplastic

Preformed thermoplastic is a thermoplastic that has been formed to its final shape in a controlled production facility. This material consists of surface applied glass beads to provide initial retroreflectivity and intermixed glass beads to improve retained retroreflectivity once its thickness wears down due to abrasion from traffic. Both glass beads are added during production. The former glass beads are larger in size than the latter. Due to its high initial cost, this material has primarily been used for transverse (e.g., stop lines, yield lines, and crosswalk markings) and special (e.g., arrows, symbol markings, and parking space markings) markings.

This material is marketed as durable product that can be applied on surface or in groove. It can be used on concrete and asphalt surfaces. A sealer is required when installed on concrete surfaces or on aged asphalt surfaces. Preformed thermoplastic is installed by placing all parts in their desired location with no gaps between them and heating the surface using a propane torch until the thermoplastic melts and adheres to the underlying surface.

2.3.4 Epoxy

Epoxies are two-component thermosetting materials. The first component contains resin, pigment, extenders, and fillers. The second component contains a hardener that acts as a catalyst to accelerate setting time. Depending on the type of catalyst and pavement temperature upon application, two types of epoxies are available, namely slow-curing epoxies that require in general more than 40 minutes to dry and fast-curing epoxies that can dry in less than 30 seconds, but are considerably more expensive (Gates et al. 2003).

This material has good durability performance on both asphalt and concrete surfaces, but it provides better retro-reflectivity performance on concrete pavements than asphalt pavements (Gates et al. 2003). As will be discussed later, potential problems with this material include low durability in weaving areas, color instability under intense ultraviolet exposure, and incompatibility with existing marking material (Gates et al. 2003). Furthermore, epoxies should be applied at a temperature between 60 and 80°F (15.6 and 26.7^{o}C), which limit their use to certain months within the year (Thomas and Schloz 2001).

Recently, polymers have been added to epoxy markings resulting in so called hybridized epoxy (or hybridized polymer). It is not uncommon to refer to this material simply as epoxy since it contains epoxy resin and is applied using standard epoxy equipment. Hybridized epoxy producers market this material as a material that combines the durability (resistance to traffic) of epoxies and contains polymers that enhance the resistance to ultra violet exposure.

2.3.5 Polyurea

Polyurea is a two-component liquid marking material. The first component consists of polyurea resin and pigmentation, while the second component contains a curing agent. This material is promoted as a high quality durable product that can be used on concrete and asphalt surfaces. Its producers claim that it has low sensitivity to ultraviolet light, is not affected by humidity, can be applied at ambient temperatures as low as 40°F (4.4^{o}C), and dries in three to eight minutes at all temperatures (Thomas and Schloz 2001). The previous properties imply that this material has a relatively long installation season due to the low installation temperature requirement and requires less traffic control than other slow curing products due to the fast drying time. The main disadvantage of this material, however, is its high initial cost (material cost plus installation), which is resulted from the need for special application equipment that is different than the more commonly available standard epoxy equipment.

2.3.6 Modified Urethane

Modified urethane is a 100% solid two-component system. The first component consists of modified urethane resin and pigmentation, while the second component contains a curing agent. This material is relatively new to pavement marking. There is currently one manufacturer that produces modified urethanes, which is Innovative Performance Systems (IPS); (Thomas and Schloz 2001). This material is slightly more expensive than epoxies, but less expensive than polyurea as it can be applied using standard epoxy equipment. Main advantages of this product as claimed by its producer are low sensitivity to ultraviolet light and fast drying time (Thomas and Schloz 2001).

2.3.7 Methyl Methacrylate

Methyl methacrylate is two-component durable pavement marking. The first component consists of methacyrlate resin intermixed with glass beads to enhance retroreflectivity and blended with fine aggregates for better skid resistance, while the second component contains a liquid or powder catalyst. The two components are mixed together immediately before application. They can be sprayed or extruded onto the pavement surface at temperatures as low as 40°F (4.4°C). This material can be used on concrete and asphalt surfaces. To improve initial retroreflectivity, surface applied glass beads are used. Methyl methacrylate has been reported to have high durability under extreme weather conditions that involve high snow removal activities and high traffic volumes (Gates et al. 2003; Thomas and Schloz 2001). Its main disadvantages include the slow curing time of thirty minutes, the high initial cost, and the need for special installation equipment.

2.3.8 Durable Tapes

Several types of durable tapes are available. The discussion presented herein is limited to high performance polymeric tapes similar to those evaluated in this study that are manufactured by 3M Stamark™. These tapes consist of a base bead-filled pliant polymer layer topped with polyurethane coating intermixed with microcrystalline ceramic beads. They have a patterned structure with raised near vertical surfaces to improve retroreflectivity under wet weather conditions.

Most durable tapes are precoated with a pressure sensitive adhesive on the bottom surface. They can be applied by inlay application (embedded in fresh hot asphalt), overlay application (applying tape on existing surface), or overlaid on a grooved surface. For overlay applications, an additional adhesive may be required. The typical setting time for the adhesive is about two to three minutes, during which the tape is placed on the adhesive resting on its back and tampered using a tamper cart. The pavement can be open to traffic immediately after the tape is thoroughly tamped. Most tapes shall be installed when the surface temperature is greater than 60 to 70°F (15.6 to 21.1°C), which restricts their use to certain times within the year. Extended season tapes like the ones used in this project, however, may be installed at temperatures as low as 40°F (4.4°C).

In general, durable tapes have been reported to have very high initial retroreflectivity and high durability even under excessive traffic conditions. Their main disadvantages, however, are high initial cost, slow application procedures, and the added cost of removal at the end of their service life because they are not compatible with other pavement markings commonly used for restriping. As such, their use as longitudinal marking has been mainly recommended for urban areas with very high traffic volumes or for transverse lines (Gates et al. 2003).

Table (2.1): Comparison of Pavement Marking Material Performance on Concrete Pavements (Based on Information and Data Presented in Gates et al. 2003)[†].

Marking Material	Avg. Contracted Cost ($/LF) [a]	Typical Service Life (years)	Surface Preparation	Lane Closure?	Comments
TxDOT Thermoplastic	0.20	2	- Blast Clean [b] - Primer may be necessary	No	- May not bond well to concrete without suitable primer/sealer
Concrete Thermoplastic	0.35	1-5	- Blast Clean [b] - Primer may be necessary	No	- Some States reported poor adhesion to concrete, while others reported adequate performance - No-track time of 30 sec
Epoxy	0.4	3-5	- Blast Clean [b]	Yes	- Performs well on concrete and asphalt in terms of durability, but provides better retroreflectivity on concrete. - Incompatible with other pavement marking materials, limiting their usefulness for re-striping. - Susceptible to fading under intense sunlight (i.e., color instability). - Low durability in weaving areas - No-track time of 40 min for slow-curing epoxies and 30 sec for the more expensive fast-curing epoxies
Preformed Tape	2.6	4-8	- Full Removal	Yes	- Extremely expensive and time consuming to install - Moisture sensitivity - Strict application procedures - Most tape producers offer a warranty on their products

[†] Based on feedback from 19 State highway agencies.
[a] Includes material cost, surface preparation cost, and removal cost for all materials (excluding paint).
[b] Full removal of existing marking is necessary if existing marking is debonding from the pavement, new and existing markings are incompatible, or existing marking is too thick.

Table (2.1): Comparison of Pavement Marking Material Performance on Concrete Pavements (Based on Information and Data Presented in Gates et al. 2003); (Continued)[†].

Marking Material	Avg. Contracted Cost ($/LF) [a]	Typical Service Life (years)	Surface Preparation	Lane Closure?	Comments
Polyurea	1.0	Up to 5 years [c]	- Blast Clean [b]	No	- High initial cost - May require special equipment - Dries faster than slow-curing epoxies, and has better color stability under ultra-violet exposure
Methyl Methacrylate	2.6	Up to 5 years [c]	- Blast Clean [b]	Yes	- Good durability especially at cold temperatures - Very little use nationwide
Modified Urethane	0.6	Up to 4 years	- Blast Clean [b]	No	- Very little use nationwide
Waterborne Paints	0.1	Up to 1 year [d]	- Blast Clean [b]	No	- Commonly used as a temporary marking material - Water-based paints require more time to dry than solvent-based paints, and are more environmentally friendly. - Low initial cost - Short service life
Ceramic Buttons	0.6	Up to 3 years [e]	- Full Removal	Yes	- Good durability on concrete - Provide no retro-reflectivity

[†] Based on feedback from 19 State highway agencies.
[a] Includes material cost, surface preparation cost, and removal cost for all materials (excluding paint).
[b] Full removal of existing marking is necessary if existing marking is debonding from the pavement, new and existing markings are incompatible, or existing marking is too thick.
[c] Based on limited data.
[d] Not recommended for high traffic volumes.
[e] Based on high traffic volumes.

2.4 Pavement Marking Material Selection

Significant progress has taken place during the last two decades in producing quality pavement marking materials that have good performance on concrete surfaces (Migletz and Graham 2002). In an effort to identify superior materials under prevailing traffic and weather conditions, several States have experimented with different marking materials on their pavements including, but not limited to, Alaska (Lu 1995), Washington (Lagergren et al. 2005, Lagergren et al. 2006), South Dakota (Becker and Marks 1993), Michigan (Lee et al. 1999), Iowa (Thomas and Schloz 2001), Pennsylvania (Henry et al. 1990), Virginia (Cottrell and Hanson 2001), South Carolina (Swygert 2002), and Texas (Gates et al. 2003). Active ongoing programs of similar nature include the well-known National Transportation Product Evaluation Program (NTPEP) sponsored by the American Association of State Highway and Transportation Officials (AASHTO). The following is a summary of some of these studies.

In a study funded by Texas Department of Transportation (TxDOT), Gates et al. (2003) investigated the effectiveness of different marking materials and corresponding application procedures on concrete pavements. This study was originally initiated by TxDOT to seek superior marking alternatives to the non-retroreflective, yet durable, ceramic buttons that were extensively used in Texas prior to May 2000, when the TxDOT officials revised the Signs and Markings Volume of the TxDOT Traffic Operations Manual and strongly discouraged their use. Based on a survey that included 19 State highway agencies, it was reported that the following materials have either been used or experimented with on concrete pavements: thermoplastic, epoxy, preformed tape, polyurea, methyl methacrylane, modified urethane, waterborne paint, and ceramic buttons.

By reviewing the advantages and disadvantages of each material, the researchers recommended using the following marking materials on concrete roads in Texas:

- preformed tape for long-term applications under very heavy traffic;
- epoxy materials for long-term applications under the majority of traffic conditions; and
- thermoplastic only for short-term applications with low to medium traffic.

Several studies reported similar conclusions regarding the performance of preformed tapes under heavy traffic (e.g., Thomas and Schloz 2001, Lu 1995). Some studies, however, suggested that this material may not be cost-effective due to high initial cost (e.g., Becker and Marks 1993); and that some tapes, especially the thick ones, may be caught by snowplows

(Lagergren et al. 2006, Lagergren et al. 2005, Becker and Marks 1993). Moreover, while most studies indicated high initial retro-reflectivity for this material, some studies reported poor reflectivity performance after certain period of time (e.g., Lee et al. 1999, Attaway 1989). Preformed tapes, however, significantly vary in quality and therefore, performance results reported in the literature should be handled with caution. In addition, several tape manufacturers offer warranties on their products, which guaranties good performance during the warranty period and significantly reduces any financial risks associated with their use during that period.

In another study (Lagergren et al. 2005, Lagergren et al. 2006), Washington State Department of Transportation (WSDOT) in cooperation with several pavement marking manufacturers conducted an evaluation that included a variety of materials for use on interstate I-90 over the Snoqualmie Pass in the Cascade Mountains; 50 miles (80.5 km) east of Seattle. The objective of this study was to improve the service life of pavement markings on concrete surfaces in snow removal areas. The following materials were evaluated: thermoplastics, methacrylate, polyurea, preformed tapes, and modified urethane. The marking materials were applied in insets in order to protect them from snowplowing, chains, and studded tires. Retroreflectivity was measured using a Delta LTL-X retroreflectometer, and durability was characterized using ASTM Test Method D913. Based on the findings of the interim evaluation, the following actions were taken:

- Polyurea outperformed modified urethane and due to similarities, the latter was not pursued.
- Some methacrylate materials had low retroreflectivity readings and hence, were excluded, while others were satisfactory, and thus were pursued to be included in the specifications.
- Some preformed tapes performed satisfactorily, while others had issues with durability.

2.5 Minimum Retroreflectivity Requirements

Over the last two decades, there has been a concentrated effort to establish minimum acceptable retroreflectivity requirements for pavement markings (Zwahlen and Schnell 2000; Schnell and Zwahlen 2000; Loetterle et al. 2000; Parker and Meja 2004; Debaillon et al. 2007). Two approaches have been used for this purpose. The first approach is based on gauging drivers' perception of pavement marking retroreflectivity by having a number of participants drive on different roads of varying retroreflectivity levels and obtaining their feedback regarding the visibility on these roads. The second approach is based on developing a relationship between pavement marking retroreflectivity and drivers' detection distances using static or dynamic experiments, and determining the minimum retroreflectivity requirement for different operating speeds at a distance corresponding to a predefined preview time. The latter is defined as the time required for drivers to perceive and react to pavement markings.

An example study that used the first approach is that of Loetterle et al. (2000). This study was funded by Minnesota Department of Transportation (MnDOT). It involved 194 participants who drove state-owned vehicles on a driving course of state and county roads and rated the visibility of the pavement markings as A-Excellent, B-Very good, C-Acceptable, D-Not acceptable, or E-Completely unacceptable. The visibility ratings were assimilated into two groups of acceptable (A, B, and C) and unacceptable (D and E); and were compared to retroreflectivity data obtained using Laserlux mobile retroreflectometer. As shown in Figure (2.4), a high correlation was observed between the drivers' perception and measured retroreflectivity. Based on this figure, the researchers concluded that the threshold value of acceptability versus unacceptability was between 80 and 120 mcd/m^2/lux. They recommended using the more conservative threshold value of 120 mcd/m^2/lux in developing MnDOT new pavement marking management program.

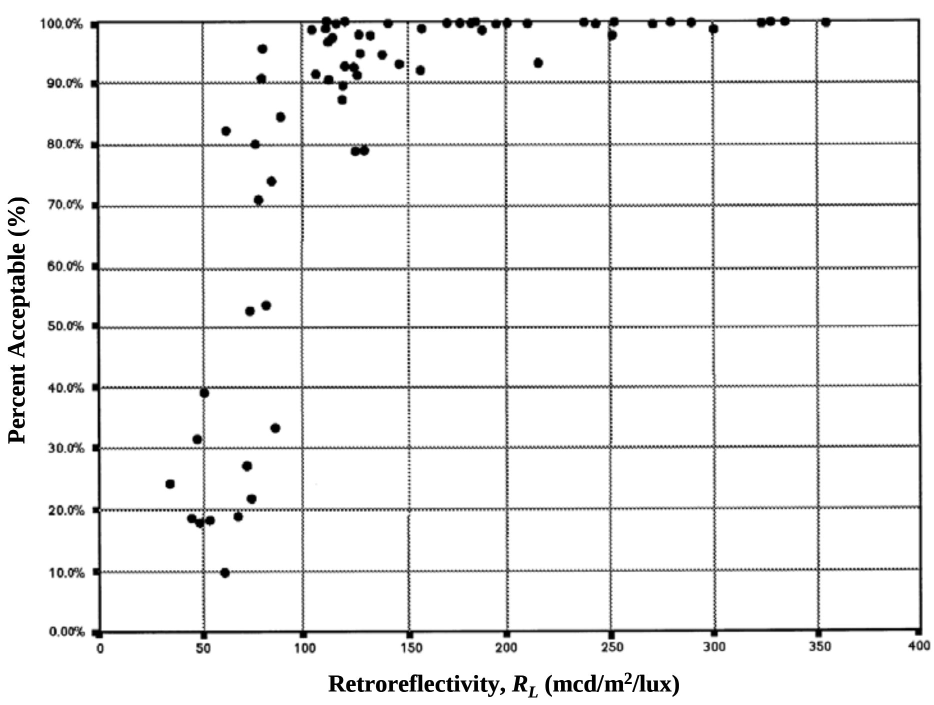

Figure (2.4): Percent Acceptable versus Pavement Marking Retroreflectivity Measured using Laserlux Mobile Retroreflectometer (After: Loetterle et al. 2000).

A similar approach was followed in a more recent study by Parker and Meja (2004) funded by New Jersey Department of Transportation (NJDOT). This study involved 64 participants who drove their own vehicles along a 32 mile (51.5 km) route of public roads and rated the visibility of pavement markings on a scale of 1 to 5 (5 being the most desirable). The subjective ratings were compared to retroreflectivity measurements obtained using Laserlux mobile retroreflectometer as illustrated in Figure (2.5). The researchers concluded that the threshold value of acceptable versus unacceptable retroreflectivity was between 70 and 170 mcd/m^2/lux. In order to increase public satisfaction, the researchers recommended restriping pavement markings when their retroreflectivity drops below 130 mcd/m^2/lux.

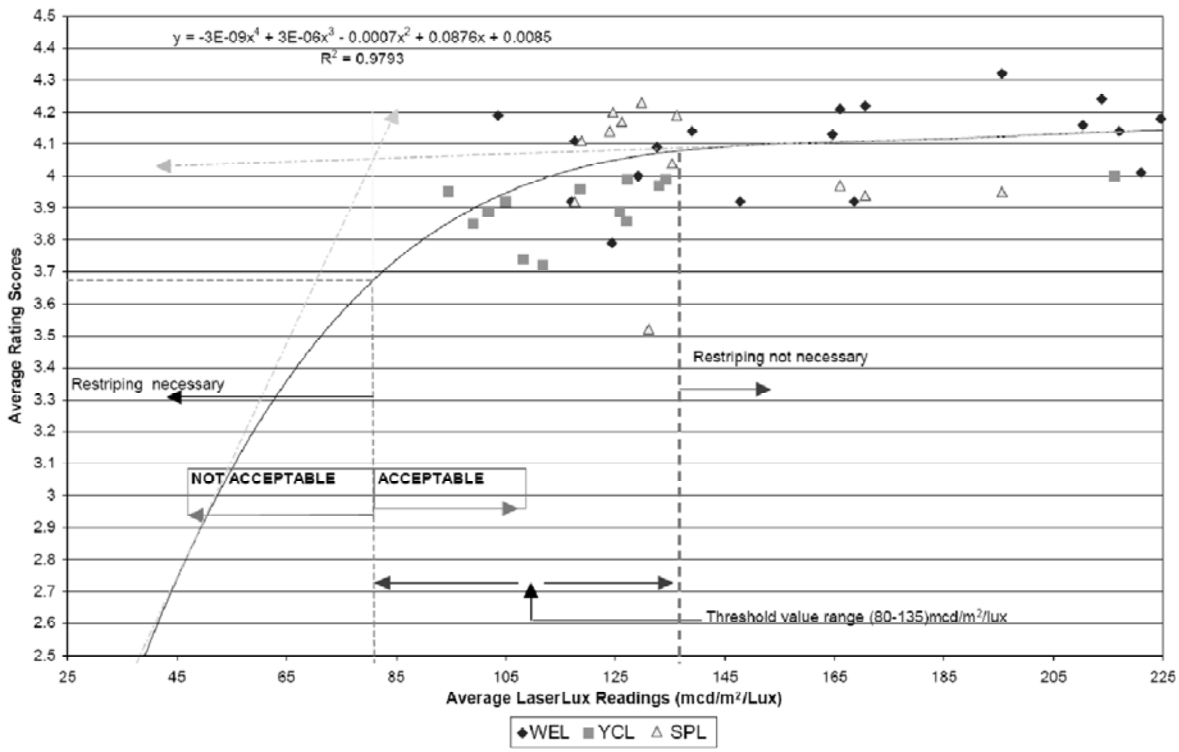

Figure (2.5): Average Participant Rating versus Marking Retroreflectivity Measured using Laserlux Mobile Retroreflectometer for White Edge Line (WEL), Yellow Centerline (YCL), and Skip Line (SPL); (After: Parker and Meja 2004).

Alternatively, minimum retroreflectivity recommendations have been established according to a more rigorous approach that is based on developing a relationship between retroreflectivity and drivers' detection distances using significantly larger number of observations from static or dynamic experiments. Among the first efforts that used this approach was that of Zwahlen's research group at the Human Factors and Ergonomics Laboratory at Ohio University (Zwahlen and Schnell 2000; Schnell and Zwahlen 2000). This work was based on a pavement marking visibility model called Computer Aided Road Marking Visibility Evaluator (CARVE), which was calibrated using data from previous field studies conducted at Ohio University during the 1990s. The recommended minimum retroreflectivity values for fully marked roads at different vehicle speeds in the presence and absence of raised pavement markers (RPMs) using this model are presented in Table (2.2). As can be noticed in this table, a preview time of 3.65 sec was used for roads without RPMs and a preview time of 2.0 sec was used for roads with RPMs.

Table (2.2): Minimum Required Pavement Marking Retroreflectivity Recommendations for Fully Marked Roads (After: Zwahlen and Schnell 2000).

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

Note: The minimum R_L values for the yellow centerline are 76 percent of those listed below for the white edgeline. R_L [mcd/m^2/lx] at the30 m ASTM geometry, entrance angle = 88.7°, observation angle = 1.05°.

Later research studies noted that the 3.65-sec preview time was one of the longest preview times recommended in the literature (Debaillon et al. 2007), which explains the relatively high retroreflectivity recommendations in the absence of RPMs. Furthermore, Bahar et al. (2006) nicely pointed out that the concept of preview time implies a static driving behavior rather than an adaptive one. The authors argued that drivers change their speed as a function of visibility and road conditions and do not maintain a constant speed. Hence, preview time requirements and subsequently minimum retroreflectivity requirements can be relaxed if this fact was taken into consideration.

An extension to the CARVE model was accomplished as part of a newer model developed by the Operator Performance Laboratory at the University of Iowa called Target Visibility Predictor (TARVIP). As compared to the CARVE model, the TARVIP model was calibrated using more recent data to account for changes in pavement marking materials, vehicle headlamps, and types of pavement surfaces (Debaillon et al. 2007). Minimum retroreflectivity recommendations based on this model are presented in Table (2.3). A preview time of 2.2 sec was used in obtaining these retroreflectivity values.

Table (2.3): Minimum Retroreflectivity Values Suggested by Deabillon et al. (2007).

Roadway Marking Configuration	Without RRPMs			With RRPMs
	≤ 50 mi/h	55–65 mi/h	≥ 70 mi/h	
Fully marked roadways (with center line, lane lines, and/or edgeline, as needed)*	40	60	90	40
Roadways with center lines only	90	250	575	50

* Applies to both yellow and white pavement markings.
1 mi/h = 1.61 km/h

In summary, several research studies have attempted to develop minimum retroreflectivity requirements for pavement markings. Factors like roadway classification, roadway marking configuration, vehicle type and speed, pavement marking color, presence of RPMs, and presence of roadway lighting were considered in establishing such criteria. In general, most studies suggested higher retroreflectivity requirements in the absence of RPMs and for roadways with high speed limits. Besides, some studies suggested higher retroreflectivity requirement for white markings than for yellow markings.

Finally, in addition to the aforementioned minimum retroreflectivity proposals, several threshold retroreflectivity values have been used in the literature for white and yellow markings. Table (2.4) presents some of these values. As can be seen in this table, a minimum retroreflectivity value of either 100 or 150 mcd/m^2/lux is most common for this purpose.

Table (2.4): Threshold Retroreflectivity Values used in the Literature.

	Threshold Retroreflectivity ($mcd/m^2/lux$)	
Publication	White	Yellow
Abboud and Bowman (2002)	150	150
Thamizharasan et al. (2003)	100	100
Gates et al. (2003)	100	100
Fitch (2007)	100	100
Martin et al. (1996)	100	100
Smadi et al. (2008) for Iowa DOT	150	100

CHAPTER 3
OVERVIEW OF ODOT PAVEMENT MARKING PRACTICES

3.1 Introduction

The Ohio Department of Transportation (ODOT) uses various types of materials for pavement marking. The primary types are paint, polyester, thermoplastic, and epoxy. These four materials account for more than 97 percent of the pavement markings market share by cost in Ohio. In addition, ODOT uses preformed tapes and heat-fused preformed thermoplastics that account for the remaining portion. Figures (3.1) and (3.2) present ODOT's annual expenditure on pavement markings for fiscal years 2004, 2005, 2006, and 2007; and the corresponding pavement marking miles striped during these years. This information is based on the "Summary of Contracts Awarded" made available by ODOT Office of Estimating for the above indicated years. It includes projects on the national and local highway systems. Mileage does not include symbols or removal of pavement marking.

As can be noticed in these figures, ODOT spends on average about 23.8 million dollars per year to stripe about 44.0 thousand miles (70.8 thousand kilometers) of pavement markings. The fluctuation in the annual expenditure from one year to another observed in Figure (3.1) can be partly explained by the number of pavement marking miles striped during these years (Figure 3.2) and by the larger amounts of polyester used during the peak years as can be seen in Figures (3.3) and (3.4). This probably is due to the fact that some districts use polyester in restriping their existing pavement markings according to a regular pavement marking maintenance schedule (every two years in this case).

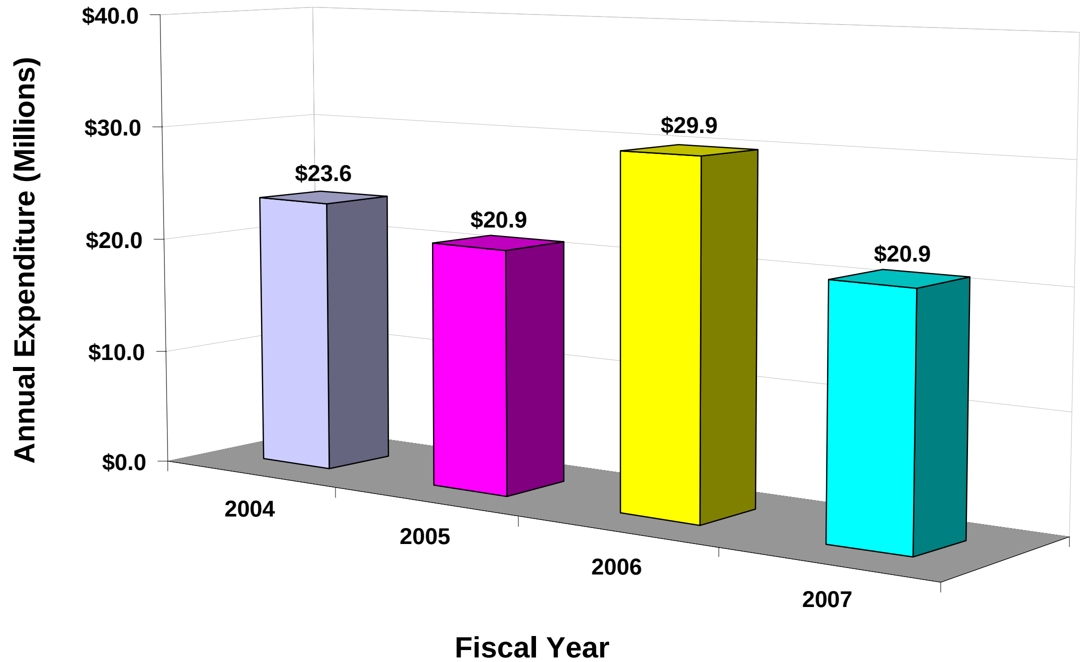

Figure (3.1): ODOT Annual Expenditure on Pavement Markings.

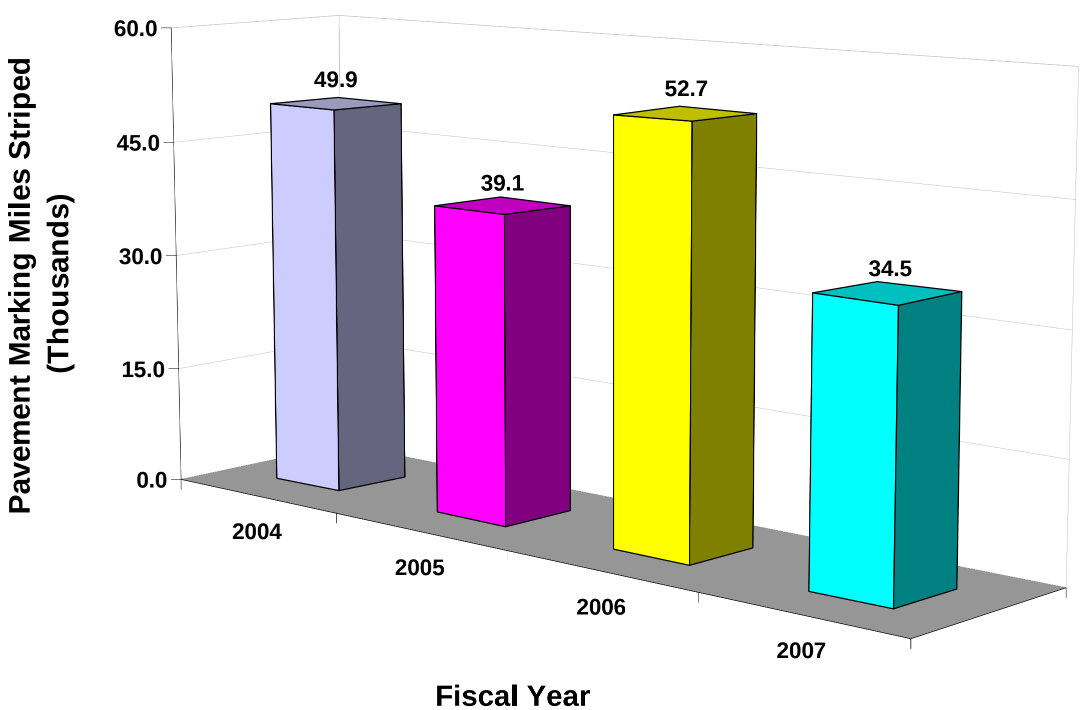

Figure (3.2): Annual Pavement Marking Miles Striped by ODOT.

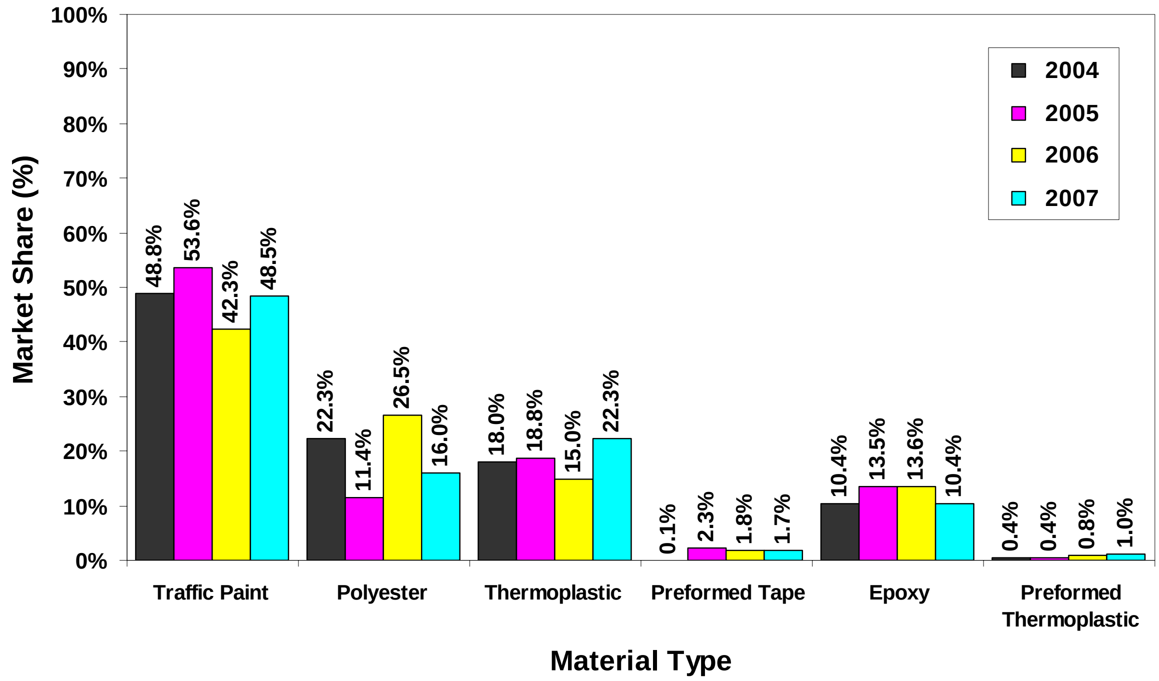

Figure (3.3): Percentage Market Share by Cost for Marking Materials used by ODOT.

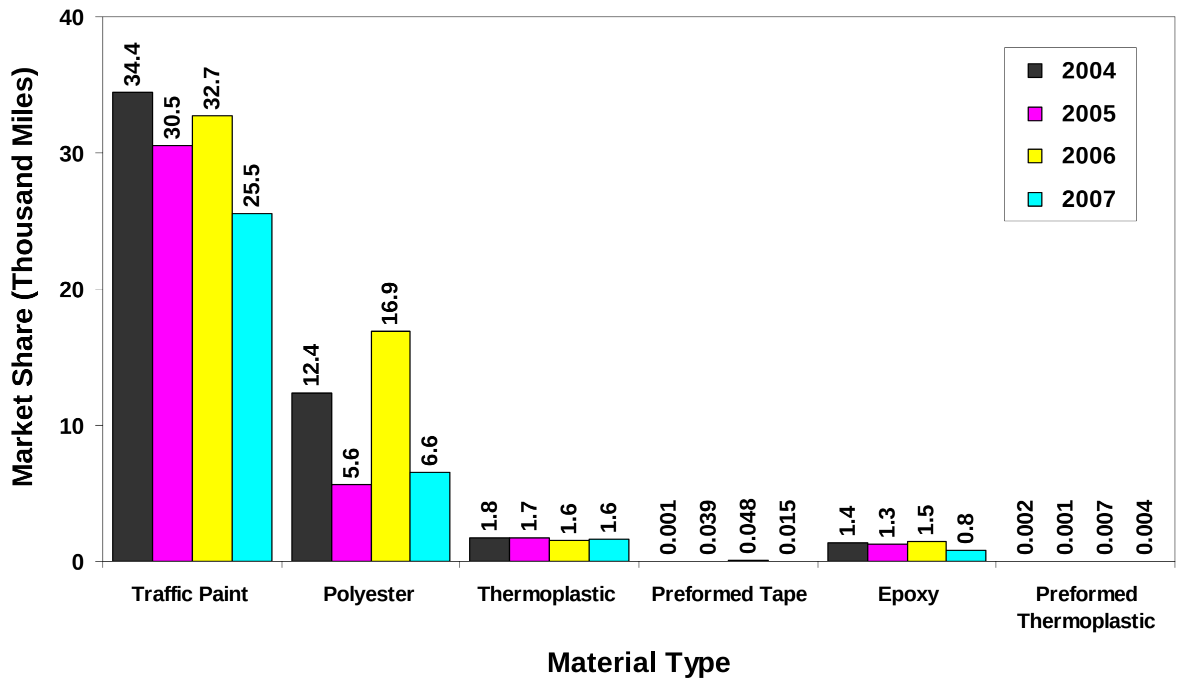

Figure (3.4): Market Share by Mileage for Marking Materials used by ODOT.

3.2 ODOT Pavement Marking Specifications

Pavement marking application specifications and pavement marking material specifications are documented in 2008 ODOT Construction and Material Specifications (C&MS) Items 640 and 740, respectively. As discussed in Item 641 (Pavement Marking – General), ODOT employs prescriptive-based pavement marking specifications that restrict the contractor to using certain materials, equipment, and application procedures. The contractor is required to use equipment that can apply solid, broken, or dotted lines uniformly and in a timely manner. Long lines are applied using a standard line width of 4 inches (100 mm). Broken lines are required to be applied in 40 ft (12.2 m) cycles with 30 ft (9.1 m) gap and 10 ft (3.0 m) marking. All long line pavement markings must be installed using application equipment equipped with a Data Logging System (DLS) when the length of the line exceeds 0.5 miles (0.8 km). Below are some of the items that the DLS must record:

- Weight and/or volume amount of material used by color;
- Weight of glass beads;
- Pavement surface temperature;
- Air temperature;
- Dew point;
- Humidity; and
- Average material application rate and film thickness over the striped section.

The DLS sheet must be given to the engineer by the next working day after the operation. The engineer will then check the application rates of the material and glass beads to determine any deficiencies. In order to receive the full bid amount for the material that is being placed, the contractor must follow the instructions set forth in the C&MS manual. If the contractor does not fulfill these specifications, the pay can be reduced or in severe cases the material shall be replaced by a newer material that meets the specifications set by the department. For traffic paint, polyester, thermoplastic, and epoxy, the pay is adjusted up to a deficiency of 20 percent; anything over 20 percent is unsatisfactory.

ODOT has recently acquired several LTL-X handheld retroreflectometers for use by its district offices. However, there is no minimum requirement in the current specifications for initial retroreflectivity. Therefore, retroreflectivity is not used as part of the quality assurance of pavement markings.

3.3 Pavement Marking Materials Used by ODOT

The following subsections present a brief overview of the current specifications for different pavement marking materials used by ODOT.

3.3.1 Item 642 – Traffic Paint

ODOT uses two types of traffic paints, Type 1 (water-based traffic paint) and Type 2 (alkyd traffic paint). Type 1 is commonly used for new installations, while Type 2 is more common for restriping. Type 1 is applied at a thickness of 20 mils (0.51 mm). It must be applied at ambient temperatures of 50°F (10.0^{o}C) or higher. Type 2 is applied at a thickness of 15 mils (0.38 mm) on old pavement and 25% more on new pavement. It may be applied at temperatures below 50°F (10.0^{o}C) if needed. Both types use Type A glass beads (ODOT C&MS Item 740.09). The glass beads are applied at a minimum rate of 12 pounds (5.44 kg) of glass beads per gallon (3.79 liter) of Type 1 paint and at a minimum rate of 8 pounds (3.63 kg) of glass beads per gallon (3.79 liter) of Type 2 paint. This material shall be applied using equipment capable of applying the traffic paint and the glass beads at the time of installation.

3.3.2 Item 643 – Polyester

Polyester must be applied at an ambient temperature of 50°F (10.0^{o}C) or higher. If markings are required and temperatures are consistently under 50°F (10.0^{o}C), Type 2 alkyd paint may be used as a substitute to polyester. Polyester is applied at a thickness of 15 mils (0.38 mm) with a minimum application rate of 18 lbs (8.16 kg) of Type B glass beads (ODOT C&MS Item 740.09) per gallon (3.79 liter) of polyester. This material shall be applied using equipment capable of mixing the polyester components at the required proportions and applying the glass beads at the time of installation.

3.3.3 Item 644 – Thermoplastic

If thermoplastic is applied onto a pavement surface that is less than six months old, air and surface temperatures shall be at least 50°F (10.0^{o}C) and rising. However, if applied onto a pavement surface that is older than one year, the air and surface temperatures shall be at least 70°F (21.1^{o}C) and rising. Another temperature that must be checked by the inspector prior to application is that of the thermoplastic. It must range between 400 and 440°F (204.4 and

226.7°C). Thermoplastic is applied at a thickness of 125 mils (3.2 mm). In addition to the intermixed glass beads, Type C glass beads are surface applied at a minimum rate of 8 lbs (3.63 kg) of glass beads per 100 square feet (9.3 m^2) of marking area.

3.3.4 Item 645 – Preformed Tapes

ODOT uses three types of preformed tapes, Type A (permanent tapes – Types A1, A2, and A3 of 90-mil (2.3 mm), 60-mil (1.5 mm), and 20-mil (0.51 mm) minimum thicknesses, respectively, including any pre-coated adhesive), Type B (Type II non-removable work zone markings of 15-mil (0.38 mm) minimum thickness), and Type C (Type I removable work zone markings of 30-mil (0.76 mm) minimum thickness). All these tapes must be applied according to their manufacturers' installation instructions. As will be discussed in Chapter 4, two durable tapes, namely 3M 380WR ES Series and 3M 270 ES Series, were evaluated in this project. Both tapes are classified as Type A3 tapes according to the previous definition.

3.3.5 Item 646 – Epoxy

Epoxy markings must be applied when air and pavement temperatures are above 50°F (10.0°C). Prior to the application of epoxy, 95 percent of all existing pavement markings must be removed by grinding or scarifying. For new asphalt surface 48 hours must pass before epoxy markings can be applied. On concrete surface 30 days must pass before the application can proceed. Epoxy is applied at a thickness of 20 mils (0.51 mm) on old pavements and at a thickness of 25 mils (0.63 mm) on new pavements. Epoxy uses Type D glass beads (ODOT C&MS Item 740.09) which consist of ODOT specified Size I (comparable to AASHTO M247 Type 3) and Size II (comparable to AASHTO M247 Type 1) beads. The glass beads are applied in a double-drop where the larger glass beads (Size I) are applied first followed immediately by the smaller glass beads (Size II). The glass beads shall be applied at a minimum combined application rate of 25 lbs (11.33 kg) of both glass beads sizes per gallon (3.79 liter) of epoxy. Epoxy shall be applied using equipment capable of thoroughly mixing the epoxy components at the required proportions and applying the glass beads in a double-drop at the desired application rates at the time of installation.

3.3.6 Item 647 – Heat-Fused Preformed Thermoplastic

ODOT uses two types of heat-fused preformed thermoplastics, Type A (pre-heated – Type A90 and Type A125 of 90-mil (2.3 mm) and 125-mil (3.2 mm) thicknesses, respectively) and Type B (post-heated – Type B90 and B125 of 90-mil (2.3 mm) and 125-mil (3.2 mm) thicknesses, respectively). Both types shall contain intermixed glass beads and hence no drop-on glass beads are required. A sealer may be required on concrete surfaces and on old asphalt pavements.

Type A materials are installed by first preheating the pavement surface to 300°F (149.9°C). Then, placing and heating the material to 400°F (204.4°C). Heating is carried out using a propane torch. An infrared thermometer is used to check all temperature requirements. As for Type B materials, there is no need to preheat the pavement surface unless to ensure that the surface is free of moisture. The material can be placed on a dry surface without pre-heating until it bubbles and slightly changes in color. No infrared thermometer is required to check the temperature.

Heat-fused preformed thermoplastics have been only used by ODOT for auxiliary markings such as symbols, legends, and crosswalks. This study explores the potential use of Flint Premark Plus and Premark Contrast preformed thermoplastic as longitudinal lines on Portland cement concrete bridge decks.

3.4 Prequalification of Pavement Marking Materials

Pavement marking materials are included in ODOT "Approved List" according to Supplemental 1047 (dated April 18, 2008), which describes the evaluation and acceptance procedures by which ODOT maintains this list. According to this document, pavement marking producers shall provide ODOT Pavement Striping Committee with performance data (if available) from previous evaluation studies as well as cost estimates for products submitted for potential inclusion this list. The Pavement Striping Committee will then decide whether ODOT has no interest in the submitted product, additional field evaluation data is necessary for prequalification, the material is conditionally approved, or the material is fully approved. The additional field evaluation data can include results from the National Transportation Product Evaluation Program (NTPEP) Pennsylvania and Wisconsin Test Decks, in-house evaluations to be conducted in Ohio, or any other study. This document also provides color requirements for white and yellow markings (Table 3.1 and Figure 3.5) and guidelines for rating pavement marking durability, daytime color, and nighttime visibility in field evaluation studies in Ohio. These guidelines were revised as part of this project and used as an integral component of a comprehensive performance evaluation plan as documented in Chapter 5. Finally, this document includes provisions for removing products – that do not perform satisfactorily in the field – from the “Approved List”; and reapproving removed products upon identifying the reasons for failure and correcting the problem.

Table (3.1): ODOT Color Requirements for White and Yellow Markings.

	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

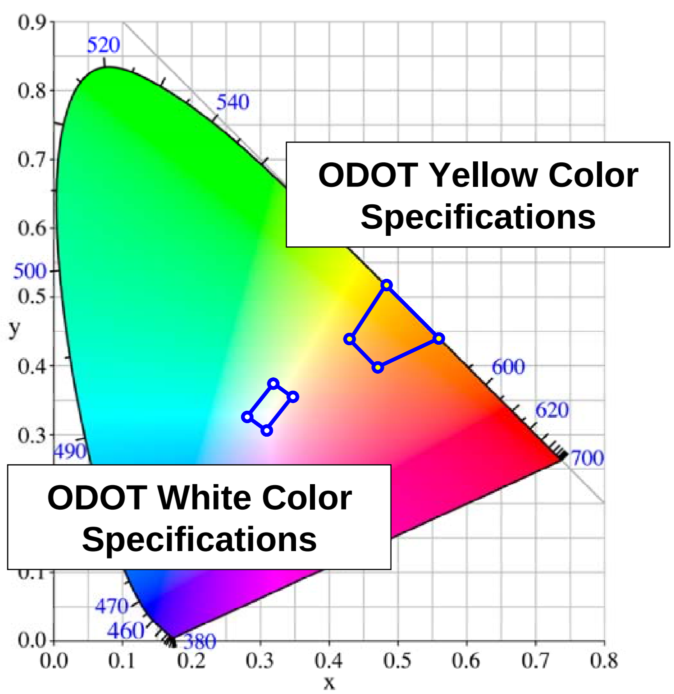

Figure (3.5): ODOT Color Requirements for White and Yellow Markings Plotted on a CIE Chromaticity Diagram (Point Locations are not to Scale).

3.5 Pavement Marking Material Selection

Pavement marking materials are selected in Ohio according to Table 397-1 of 2002 ODOT Traffic Engineering Manual (TEM). This table is presented as Table (3.2) in this chapter. As illustrated in this table, ODOT uses various parameters such as remaining life of pavement surface, type of line (longitudinal line or auxiliary), type of pavement surface (asphalt or concrete), average daily traffic (ADT), and ambient temperature in recommending which marking material to use. Durable markings such as thermoplastics and epoxies are more likely to be applied on highways with high traffic volumes and pavements with a remaining surface life in excess of four years, while non-durable markings such as traffic paint and polyester are recommended for restriping. Furthermore, thermoplastic markings are specified for new asphalt pavements and epoxy markings are specified for new concrete pavements.

It should be noted though that actual marking material selection practices vary from one district to another. For example, some districts rely heavily on using more durable products such as thermoplastic and epoxy, while others mainly use less durable products such as traffic paint and polyester. Districts that use less durable markings are more likely to replace the markings on a regular schedule.

Table (3.2): Pavement Marking Material Selection (After: ODOT TEM 2002).

Table 397-1. Material Selection for Pavement Marking and Expected Life** in Years

a. Long Line Pavement Marking – 2 Lane or General System (See next page for related notes.)				
Remaining Pavement Surface Life *	Asphalt		Concrete	
	ADT < 5,000	ADT > 5,000	ADT < 5,000	ADT > 5,000
0 - 2 years	Water-Based Paint 1	Polyester 2 Spray Thermo 2 Water-Based Paint 1	Polyester 2 Water-Based Paint 1	Polyester Spray 2 Thermo 2 Water-Based Paint 1
3 - 4 years	Polyester 3 Spray Thermo 2 Water-Based Paint 1	Polyester 2 Spray Thermo 2 Water-Based Paint 1	Spray Thermo 2 Water-Based Paint 1	Epoxy 4 Spray Thermo 2 Water-Based Paint 1
> 4 years	Thermo 4 Polyester 3	Epoxy 4 Thermo 4 Polyester 2 Spray Thermo 2	Epoxy 4 Spray Thermo 2 Water-Based Paint 1	Epoxy 4
New Surface i) <40° F ii) 40 to 50° F iii) > 50° F	 Alkyd Paint 1 Water-Based Paint 1 Thermo 4	 Alkyd Paint 1 Water-Based Paint 1 Thermo 4	 Alkyd Paint 1 Water-Based Paint 1 Epoxy 4	 Alkyd Paint 1 Water-Based Paint 1 Epoxy 4

b. Long Line Pavement Marking – Multilane or Priority System (See next page for related notes.)				
Remaining Pavement Surface Life *	Asphalt		Concrete	
	ADT < 5,000	ADT > 5,000	ADT < 5,000	ADT > 5,000
0 - 2 years	Polyester 2 Water-Based Paint 1	Polyester 2 Spray Thermo 2 Water-Based Paint 1	Polyester 2 Water-Based Paint 1	Polyester 2 Spray Thermo 2 Water-Based Paint 1
3 - 4 years	Polyester 3 Spray Thermo 2 Water-Based Paint 1	Polyester 2 Spray Thermo 2 Water-Based Paint 1	Polyester 2 Spray Thermo 2 Water-Based Paint 1	Epoxy 4 Spray Thermo 2
> 4 years	Thermo 4 Polyester 3 Spray Thermo Water- 2 Based Paint 1	Epoxy 4 Thermo 4 Polyester 2	Epoxy 4 Spray Thermo 2	Epoxy 4
New Surface i) <40° F ii) 40 to 50° F iii) > 50° F	 Alkyd Paint 1 Water-Based Paint 1 Thermo 4	 Alkyd Paint 1 Water-Based Paint 1 Thermo 4	 Alkyd Paint 1 Water-Based Paint 1 Epoxy 4	 Alkyd Paint 1 Water-Based Paint 1 Epoxy 4

Table (3.2): Pavement Marking Material Selection (After: ODOT TEM 2002); (Continued).

Table 397-1. Material Selection for Pavement Marking and Expected Life in Years (continued)

c. Auxiliary Pavement Marking – 2-Lane and Multilane or Priority System				
Remaining Pavement Surface Life *	**Asphalt**		**Concrete**	
	ADT < 5,000	ADT > 5,000	ADT < 5,000	ADT > 5,000
0 - 2 years	Water-Based Paint 1	Water-Based Paint 1	Spray Thermoplastic 2 Alkyd Paint 1 Water-Based Paint 1	Heat Fused Preformed Tape 2 Spray Thermoplastic 2 Alkyd Paint 1 Water-Based Paint 1
3 - 4 years	Heat Fused Preformed Tape 4 Polyester 1-2	Heat Fused Preformed Tape 2	Heat Fused Preformed Tape 3 Thermoplastic 2 Spray Thermoplastic 2 Water-Based Paint 1	Heat Fused Preformed Tape 2
> 4 years	Heat Fused Preformed Tape 4 Polyester 1-2 Water-Based Paint 1	Heat Fused Preformed Tape 2	Heat Fused Preformed Tape 3 Thermoplastic 2 Spray Thermoplastic 2	Heat Fused Preformed Tape 2
New Surface i) <40° F ii) 40 to 50° F iii) > 50° F	Same as used for long lines	Same as used for long lines	Same as used for long lines	Same as used for long lines

Notes:

* Remaining pavement surface life is the life before resurfacing, reconstruction or before crack sealant will cover the pavement markings.

** The expected life of edge line pavement marking is typically 20 to 30 percent longer as compared to center line and lane line pavement markings expected life as shown in this table.

1. Spray thermoplastic works well for retracing existing thermoplastic. For other materials, check with material suppliers.
2. Auxiliary markings not regularly run over by traffic will last 1.5 to 2 times longer.
3. Surface preparation may be required to remove old markings as recommended by supplier.
4. Remove curing compound completely from new concrete surfaces - follow CMS Item 641.05.
5. Polyester pavement marking material is addressed in CMS Item 643. Since it adheres best to a worn surface, polyester is not to be placed until new asphalt pavement has been open to traffic at least fourteen days. Polyester pavement marking material shall only be used on CMS Item 446 or 448 pavements. This material shall not be used on the following asphalt concrete surfaces due to poor bonding qualities: open graded courses, slurry seal, Supplemental Specification (SS) 805 Rubberized Sand Asphalt, and SS 807 Latex Modified Emulsified Asphalt Pavement Course. Any Asphalt Concrete (Item Special) should be questioned before considering placement of polyester material on it.
6. Primer is required for thermoplastic when used on concrete.
7. Due to the high cost of preformed material, it should only be considered for use where extra long life is needed or in certain applications, such as bridge decks where thermoplastic has not adhered well.
8. Epoxy should only be used on pavements in good condition after surface preparation has been accomplished per manufacturer recommendations.

CHAPTER 4
PRODUCT INFORMATION AND INSTALLATION

4.1 Introduction

In June 2006, several marking materials were installed on sixteen monolithic Portland cement concrete bridge decks located in Ashland and Richland counties in ODOT District 3 along interstate I-71. Eight of these bridges are located along the northbound direction and eight along the southbound direction. All bridges are connected to mainline asphalt pavement where the interstate has three lanes per direction. They range in length from about 200 to 400 ft (60 to 120 m). These bridges were constructed between 1996 and 2002 and were striped with extruded thermoplastic. Most of the thermoplastic was no longer in place on these bridges prior to the beginning of this project. Meanwhile, the thermoplastic on the adjacent asphalt varied from recent to five years old.

By analyzing the traffic data along interstate I-71 for the period from July 2006 through June 2008, the following observations were made:

- The average annual daily traffic (AADT) for both directions is about 42,000 vehicles per day;
- Traffic is equally distributed between the northbound and the southbound (i.e., about 21,000 vehicles per day per direction);
- Traffic is concentrated in the middle and the far right lanes with about 9,900 and 6,900 vehicles per day per lane, respectively; and
- Traffic is significantly lower in the far left lane with about 4,200 vehicles per day per lane.

4.2 Material Types

Table (4.1) provides a brief description of the marking materials used in the evaluation along with the name of their producers. As can be seen in this table, a wide variety of pavement marking materials were evaluated. The fast dry waterborne traffic paint that is commonly used by ODOT District 3 Roadway Services was selected as a control material. From among these materials, the following are already included in ODOT Approved List: Ennis fast dry waterborne paint, Swarcotherm thermoplastic, Epoplex LS 60, Poly-Carb Mark 55.4, Flint Premark Plus, and 3M Series 380WR ES tapes. Poly-Carb Mark 55.2 was removed from this list effective August

26, 2004. Flint Premark Plus has only been used by ODOT for auxiliary markings. This study explores the potential use of this material as a longitudinal pavement marking on Portland cement concrete bridge decks.

Appendix A presents pictures of these materials when they were almost one year old. Appendix B provides detailed information about each product summarized in an easy to follow table format. This information was collected from the products technical bulletins, material safety data sheets (MSDS), and other supporting documents related to special handling and installation instructions issued by the producers. Special attention is given to material composition, surface preparation, and installation specifications. It should be noted, however, that most documents were obtained in early stages of this project (end of 2006). Therefore, some of this information might have changed. For example, two proprietary bead systems were used in Glomarc 90 that was evaluated in this study, namely Clusterbead® and Visibead® Plus II. However, Epoplex has recently changed the bead systems used in Glomarc 90. The recently released product data and general application specification documents for Glomarc 90 (03/08) replaces these two proprietary bead systems with a new bead system called VISIMAX™. Nevertheless, the information in Appendix B is based on the material installed and evaluated as part of this study not on the new product information.

4.3 Material Installation

Table (4.2) presents the location along interstate I-71 where each material was installed. The location of these bridges was selected so that the performance evaluation on all sixteen bridges can be conducted within a reasonable period of time. It is noted that each material was installed in four locations along the three lanes of the interstate. Yellow was installed on the left edge line and white was installed on the two lane lines and the right edge line. Based on the traffic data presented earlier, yellow markings on the left edge lines have probably been subjected to less traffic than white markings on the remaining lines.

Table (4.1): List of Products Evaluated in this Project.

Producer	Product Trade Name	Product Description
Epoplex	LS 60	Slow cure epoxy
	LS 70	Fast cure hybridized epoxy
	Glomarc 90	Polyurea with two proprietary bead systems
Flint Trading, Inc.	Premark Plus	Preformed thermoplastic
	Premark Contrast	7-inch (175 mm) wide preformed thermoplastic contrast
3M Stamark™	3M 380WR ES	Extended season high performance wet reflective tape
	3M 380WR-5 ES	Extended season high performance wet reflective contrast tape
	3M 270 ES	Extended season pavement marking tape
POLY-CARB, Inc.	Mark 55.2	Slow cure hybridized epoxy
	Mark 55.4	Fast cure hybridized epoxy
	Mark 75	Polyurea
Innovative Performance Systems, LLC (IPS)	HPS-2	Slow cure epoxy
	HPS-4	Modified urethane
	HPS-5	Polyurea
Ennis Paint, Inc.	Duraset 1	Externally plasticized methyl methacrylate
	Duraset Pathfinder	Internally plasticized methyl methacrylate
	Ennis waterborne paint	Fast dry waterborne paint
Swarco Industries, Inc.	Swarcotherm alkyd	Alkyd-based thermoplastic marking compound

Table (4.2): Bridge Deck Information and Material Installation.

				Product Name			
Deck #	Mile Post	Direction	Bridge	Yellow Left Edge Line	White Left Lane Line	White Right Lane Line	White Right Edge Line
01	MP 186	SB	Jerome Fork	381WR ES	380WR-5 ES	380WR-5 ES	380WR ES
02	MP 186	SB	Hess Ditch	Premark Plus	Premark Contrast	Premark Contrast	Premark Plus
03	MP 176	SB	Crider Rd.	HPS-2	HPS-2	HPS-2	HPS-2
04	MP 176	SB	US 30	HPS-4	HPS-4	HPS-4	HPS-4
05	MP 173	SB	Mt. Zion Rd.	Mark 55.2	Mark 55.2	Mark 55.2	Mark 55.2
06	MP 173	SB	Rock Fork	Mark 75	Mark 75	Mark 75	Mark 75
07	MP 173	SB	SR 39 RXR	Mark 55.4	Mark 55.4	Mark 55.4	Mark 55.4
08	MP 169	SB	Hanley Rd.	Swarcotherm	Swarcotherm	Swarcotherm	Swarcotherm
09	MP 173	NB	SR 39 RXR	LS 60	LS 60	Epoplex LS 60	LS 60
10	MP 173	NB	Rock Fork	Glomarc 90	Glomarc 90	Glomarc 90	Glomarc 90
11	MP 173	NB	Mt. Zion Rd.	LS 70	LS 70	LS 70	LS 70
12	MP 176	NB	US 30	HPS-5	HPS-5	HPS-5	HPS-5
13	MP 176	NB	Crider Rd.	Duraset 1	Duraset Pathfinder	Duraset Pathfinder	Duraset 1
14	MP 178	NB	SR 603	Fast dry waterborne paint	Fast dry waterborne paint	Fast dry waterborne paint	Fast dry waterborne paint
15	MP 186	NB	Hess Ditch	Premark Plus	Premark Plus	Premark Plus	Premark Plus
16	MP 186	NB	Jerome Fork	270 ES	270 ES	270 ES	270 ES

Table (4.3) lists the installation dates of the materials. It is noted that an incorrect formulation of LS 70 was originally installed on June 6, 2006. Epoplex representative reported the mix up to ODOT District 3 Pavement Marking Engineers before the installation. It was agreed to reinstall this material should it fails prematurely and it did. To that end, the material was removed and the correct formulation was reinstalled on November 28, 2006.

The installation for Flint preformed thermoplastic, 3M durable tapes, and Ennis methyl methacrylate was conducted by their producers; thermoplastic was installed as part of a striping project that involved a 6-mile (9.7 km) mainline asphalt section; waterborne paint was installed by ODOT District 3 Roadway Services crew; and the remaining liquid materials were competitively bid and installed by a company headquartered in Waukesha, Wisconsin called Century Fence.

All materials were installed in 150-mil (3.8 mm) grooves, which were prepared by Century Fence for all bridge decks. The groove width was one to two inches (25 to 50 mm) wider than the width of the pavement marking. Small grooving equipment with saw blade cutting heads was used in preparing the grooves on bridge decks # 1 and # 2. However, to expedite the grooving process, larger grooving equipment with grinder cutting head was used for the remaining bridge decks. As presented in Appendix B, not all products require grooving as part of their installation specifications. Furthermore, not all materials required a groove depth of 150 mils (3.8 mm). However, it was decided to use this groove depth, which is the same as the depth of the transverse tines on the bridge decks, to ensure that all traces of the old thermoplastic have been completely removed; thus, eliminate its effect on the newly installed products. Figure (4.1) and (4.2) present pictures of a bridge deck before and after grooving.

Table (4.3): Product Installation Dates.

Producer	Product Trade Name	Installation Date
Epoplex	LS 60	June 6, 2006
	LS 70	November 28, 2006 †
	Glomarc 90	June 6, 2006
Flint Trading, Inc.	Premark Plus	June 2, 2006
	Premark Contrast	June 1, 2006
3M Stamark™	3M 380WR ES	June 2, 2006
	3M 380WR-5 ES	June 2, 2006
	3M 270 ES	June 2, 2006
POLY-CARB, Inc.	Mark 55.2	June 6, 2006
	Mark 55.4	June 6, 2006
	Mark 75	June 6, 2006
Innovative Performance Systems, LLC (IPS)	HPS-2	June 7, 2006
	HPS-4	June 7, 2006
	HPS-5	June 7, 2006
Ennis Paint, Inc.	Duraset 1	June 13, 2006
	Duraset Pathfinder	June 13, 2006
	Ennis waterborne paint	June 13, 2006
Swarco Industries, Inc.	Swarcotherm alkyd	June 30, 2006

† Epoplex LS 70 was initially installed on June 6, 2006. It was later removed and reinstalled on November 28, 2006 due to premature failure.

Figure (4.1): Traces of Old Thermoplastic on One of the Bridge Decks.

Figure (4.2): 150-mil (3.8 mm) Groove.

The target thickness and glass bead application rates are presented in Table (4.4). As can be noticed in this table, the target thickness for waterborne traffic paint was 20 mils (0.51 mm); the target thickness for all liquid markings (epoxy, modified urethane, and polyurea) was 25 mils (0.63 mm); the target thickness for Swarcotherm thermoplastic was 125 mils (3.2 mm); the target thickness for Duraset 1 was about 90 mils (2.3 mm); and the target thickness for Duraset Pathfinder was about 200 mils (5.1 mm) at the peaks. In addition, the thickness of Flint preformed thermoplastic tapes was 125 mils (3.2 mm) and that of 3M durable tapes was about 35 to 40 mils (0.9 to 1.0 mm) at the base and about 90 to 95 mils (2.3 to 2.4 mm) at the raised profiles. The previous thicknesses are consistent with ODOT C&MS Item 640 where applicable.

Two types of glass beads meeting the requirements of AASHTO M247 for Type 1 and Type 4 were used (double drop) for all liquid markings except Glomarc 90, for which two proprietary bead systems were used (Clusterbead® and Visibead® Plus II produced by Prismo LTD and Potters Industries, respectively); Type 1 glass beads were used for waterborne traffic paint, Duraset 1, and Duraset Pathfinder; and Type C glass beads were used for Swarcotherm thermoplastic. Some of these materials (Duraset 1, Duraset Pathfinder, and Swarcotherm thermoplastic) also contained intermixed glass beads. As for Flint preformed thermoplastic and 3M durable tapes, the reflective media in these products is controlled during production. Flint Premark Plus and Premark Contrast consist of large surface applied and small intermixed glass beads. Meanwhile, 3M durable tapes contain intermixed microcrystalline ceramic beads. 3M wet reflective tapes also include specially designed optics to improve wet retroreflectivity.

Table (4.4): Target Thickness and Glass Bead Application Rates.

<table>
<tr><th>Material Type</th><th>Product Name</th><th>Target Thickness</th><th>Target Glass Bead Application Rate(s)</th></tr>
<tr><td>Waterborne Paint</td><td>Ennis Fast Dry</td><td>20 mils (0.51 mm)</td><td>12 lbs/gallon (1.44 kg/liter) of Type 1</td></tr>
<tr><td rowspan="5">Epoxy</td><td>LS 60</td><td>25 mils (0.63 mm)</td><td>12 lbs/gallon (1.44 kg/liter) of Type 4 and 12 lbs/gallon (1.44 kg/liter) of Type 1</td></tr>
<tr><td>LS 70</td><td>25 mils (0.63 mm)</td><td>12 lbs/gallon (1.44 kg/liter) of Type 4 and 12 lbs/gallon (1.44 kg/liter) of Type 1</td></tr>
<tr><td>Mark 55.2</td><td>25 mils (0.63 mm)</td><td>12 lbs/gallon (1.44 kg/liter) of Type 4 and 12 lbs/gallon (1.44 kg/liter) of Type 1</td></tr>
<tr><td>Mark 55.4</td><td>25 mils (0.63 mm)</td><td>12 lbs/gallon (1.44 kg/liter) of Type 4 and 12 lbs/gallon (1.44 kg/liter) of Type 1</td></tr>
<tr><td>HPS-2</td><td>25 mils (0.63 mm)</td><td>12 lbs/gallon (1.44 kg/liter) of Type 4 and 12 lbs/gallon (1.44 kg/liter) of Type 1</td></tr>
<tr><td>Modified Urethane</td><td>HPS-4</td><td>25 mils (0.63 mm)</td><td>12 lbs/gallon (1.44 kg/liter) of Type 4 and 12 lbs/gallon (1.44 kg/liter) of Type 1</td></tr>
<tr><td rowspan="3">Polyurea</td><td>Glomarc 90</td><td>25 mils (0.63 mm)</td><td>5 lbs/gallon (0.60 kg/liter) of Clusterbead® and 12 lbs/gallon (1.44 kg/liter) of Visibead® Plus II</td></tr>
<tr><td>Mark 75</td><td>25 mils (0.63 mm)</td><td>12 lbs/gallon (1.44 kg/liter) of Type 4 and 12 lbs/gallon (1.44 kg/liter) of Type 1</td></tr>
<tr><td>HPS-5</td><td>25 mils (0.63 mm)</td><td>12 lbs/gallon (1.44 kg/liter) of Type 4 and 12 lbs/gallon (1.44 kg/liter) of Type 1</td></tr>
<tr><td>Thermoplastic</td><td>Swarcotherm Alkyd</td><td>125 mils (3.2 mm)</td><td>8 lbs (3.63 kg) of Type C glass beads per 100 square feet (9.3 m^2) of marking area in addition to intermixed glass beads</td></tr>
<tr><td rowspan="2">Methyl Methacrylate</td><td>Duraset 1</td><td>About 90 mils (2.3 mm)</td><td>8 lbs (3.63 kg) of Type 1 glass beads per 100 square feet (9.3 m^2) of marking area in addition to intermixed glass beads</td></tr>
<tr><td>Duraset Pathfinder</td><td>about 200 mils (0.63 mm) at the peaks</td><td>8 lbs (3.63 kg) of Type 1 glass beads per 100 square feet (9.3 m^2) of marking area in addition to intermixed glass beads</td></tr>
</table>

The installation was monitored by ODOT District 3 Pavement Marking Engineers and representatives from ODOT Central Office. The following comments are made regarding the material installation:

- 3M durable tapes:
  - Three 3M durable tapes were evaluated in this study, namely 380WR ES, 380WR-5 ES, and 270 ES.
  - The symbols WR, ES, and -5 in the names of these products refer to wet reflective, extended season, and contrast tape, respectively.
  - P-50 surface preparation adhesive was used in the installation of these tapes (Figure 4.3). This adhesive is recommended for long line applications, but not required during the installation season for extended season tapes produced by 3M. The adhesive was applied using a roller as shown in Figure (4.4).
  - The tapes were applied when the adhesive felt tacky and it had a matte finish instead of glossy appearance.
  - The 3M tapes came in 300 ft (91 m) rolls. The 3M 380WR ES and the 3M 270 ES tapes had a standard line width of four inches (100 mm). The 3M 380WR-5 ES tape had a width of seven inches (175 mm) that included a base line width of four inches (100 mm) and 1.5 inch (37.5 mm) black contrasting border on each side.
  - These tapes were rolled on the right and left edge lines using a manual highway tape applicator (Figure 4.5) and placed manually on the skip lane lines (Figure 4.6).
  - To ensure proper adhesion to the underlying pavement surface, the tapes were tamped using tamper carts that weighed more than 200 lbs (90.7 kg); (Figure 4.7).
  - Two tamper carts of different wheel sizes were used to tamper the 4-inch (100 mm) standard and the 7-inch (175 mm) contrast tapes (Figure 4.8).
  - The pavement was open to traffic as soon as the tapes were applied and thoroughly tamped.
- Flint preformed thermoplastic:
  - Premark Plus and Premark Contrast came in 3 ft (0.9 m) flat packs. Premark Plus had a standard line width of four inches (100 mm). Premark Contrast had a total width of seven inches (175 mm) that included a base line width of four inches (100 mm) and 1.5 inch (37.5 mm) black contrasting border on each side.

- As per the manufacturer specifications regarding the application of Premark Plus and Premark Contrast on concrete surfaces, TopMark sealer was used for these products on all lines on Bridge Decks # 2 and # 15 (Figure 4.9), except on the Right Lane Line of Bridge Deck # 2 in order to observe the effect of not using a sealer on the performance of these materials.
- The sealer was applied using a spray applicator and spread using a small roller as shown in Figure (4.10).
- As per the manufacturer installation instructions, Premark Plus and Premark Contrast were installed immediately after the sealer was applied without waiting for it to cure.
- Premark Plus and Premark Contrast were heated using handheld propane heat torches and a propane fueled wheel cart, as shown in Figures (4.11) and (4.12), respectively.
- Following the installation, the lines seemed to have adequate bonding with the concrete surface. However, a change in color was noticed due to overheating especially on the yellow lines.
- The lines were opened to traffic shortly after the installation was completed.

- Liquid marking materials (epoxy, modified urethane, and polyurea):
  - As shown in Figure (4.13), standard epoxy equipment was used in the installation of epoxy (LS 60, LS 70, Mark 55.2, Mark 55.4, and HPS-2) and modified urethane (HPS-4) products; and another piece of equipment – different than the first one – capable of spraying polyurea was used for Glomarc 90, Mark 75, and HPS-5.
  - As mentioned previously, two types of glass beads (Type 1 and Type 4) were used for all liquid markings (epoxy, modified urethane, and polyurea) except Glomarc 90. Type 4 glass beads are significantly larger in diameter than Type 1 glass beads. These sizes are different than what is commonly used by ODOT for epoxy markings. As discussed previously in Chapter 3, ODOT C&MS Item 740.09 Part D specifies two types of glass beads (Size I and Size II) for epoxies. Size II is comparable to Type 1 in size, whereas Size I is comparable to Type 3, which is smaller than Type 4.
  - Type 1 and Type 4 glass beads were applied in a double-drop where Type 4 was applied first followed immediately by Type 1 from a different bead dispenser (Figure 4.14).
  - To achieve a uniform line thickness, the installation equipment was operated at a constant speed while moving on the bridge. This was achieved by starting the equipment from a

distance and increasing its speed until it stabilized prior to reaching the bridge.

  - In general, the achieved thickness was slightly higher than the target thickness for all liquid markings, but still within acceptable tolerance limits. The variability in the glass beads application rates, however, was more pronounced as evident from the glass bead amounts and distributions on the lines. The latter is very hard to control to be the same for all materials.
- Ennis Duraset 1 and Duraset Pathfinder
  - Duraset 1 was used for the right and left edge lines (white and yellow, respectively). It was extruded using a push cart as shown in Figure (4.15). In addition to the intermixed glass beads contained in this material, surface applied Type 1 glass beads were dropped on manually using a gardener watering pot as shown in Figure (4.16).
  - This material hardened in a relatively short period of time, which did not allow the surface applied glass beads to properly embed on its surface. As a result, this material had poor initial and retained retroreflectivity as will be discussed in the following chapters.
  - Duraset Pathfinder was used for the right and left white lane lines. It was applied using the splatter method where the Pathfinder pattern is generated by a rotating spindle as shown in Figure (4.17). This material appears solid when viewed by drivers at normal operating speeds; however, when viewed from a close distance it has an agglomerate pattern as shown in Figure (4.18). As can be seen in this picture, the thickness of this material varies from one location to another. The thickness of the final product at the peaks was about 200 mils (5.1 mm).
  - It is claimed that the specific structure of Duraset Pathfinder allows water to drain easily and therefore improves wet night reflectivity.
  - Silane coated methyl methacrylate compatible glass beads were used in the installation.
- Ennis waterborne traffic paint:
  - Standard traffic paint equipment was used in the installation of Ennis fast dry waterborne traffic paint on Bridge Deck # 14.
- Swarcotherm thermoplastic:
  - A sealer was used prior to the application of Swarcotherm alkyd on Bridge Deck # 8.
  - Standard thermoplastic equipment capable of heating and extruding thermoplastics was used in the installation.

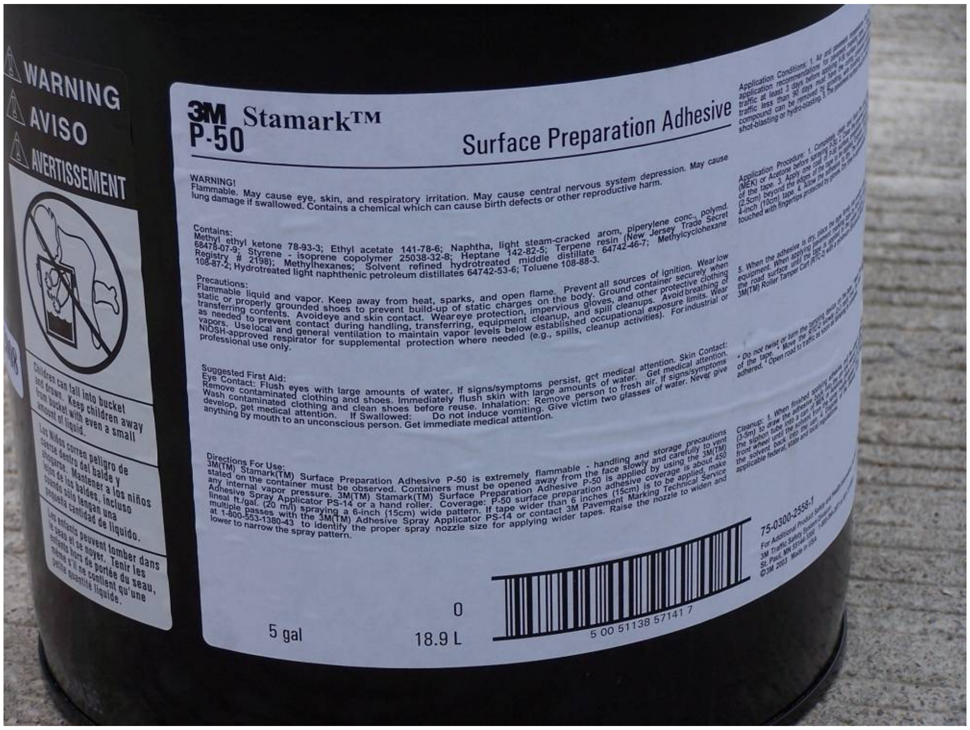

Figure (4.3): P-50 Surface Preparation Adhesive used for 3M Durable Tapes.

Figure (4.4): Application of P-50 Surface Preparation Adhesive.

Figure (4.5): Installation of 3M Durable Tape on Edge Line.

Figure (4.6): Manual Placement of 3M Durable Tape on Lane Line.

Figure (4.7): Tampering of 3M Durable Tapes.

Figure (4.8): 4-inch (Right) and 7-inch (Left) Tamper Carts.

Figure (4.9): TopMark Sealer used for Flint Premark Plus and Premark Contrast.

Figure (4.10): Application of TopMark Sealer.

Figure (4.11): Propane Heat Torch Used for Premark Plus and Premark Contrast.

Figure (4.12): Propane Fueled Wheel Cart Used for Premark Plus and Premark Contrast.

Figure (4.13): Standard Epoxy Equipment followed by another for Polyurea Installation.

Figure (4.14): Double Drop Application of Type 1 and Type 4 Glass Beads (Type 4 is Applied First Followed by Type 1).

Figure (4.15): Extrusion of Duraset 1 using a Push Cart.

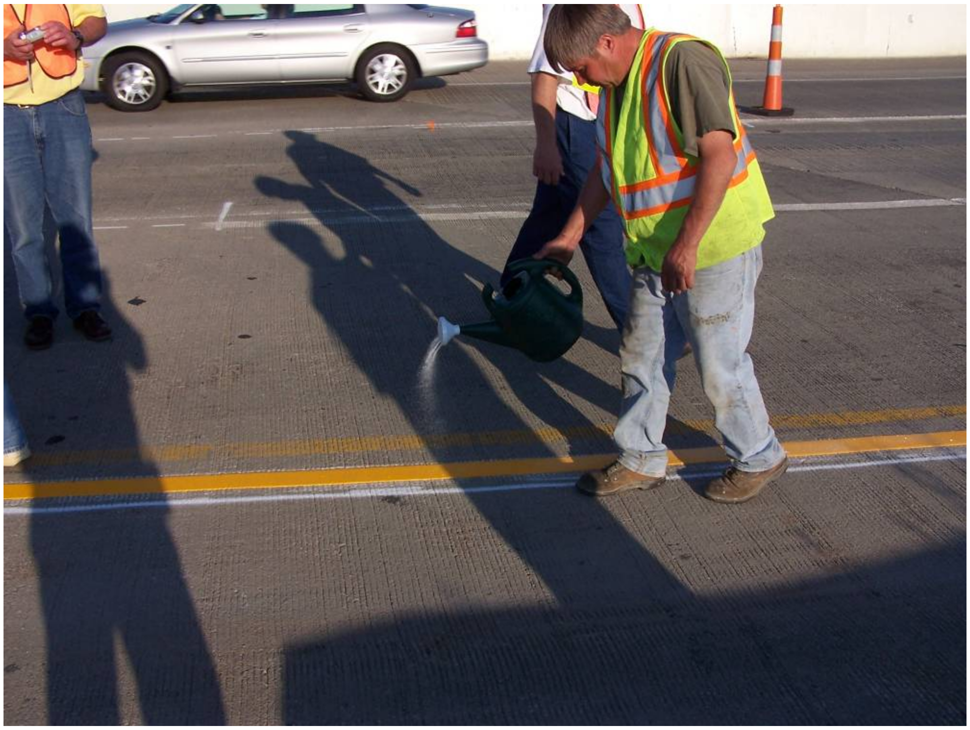

Figure (4.16): Manual Application of Type 1 Glass Beads on Duraset 1.

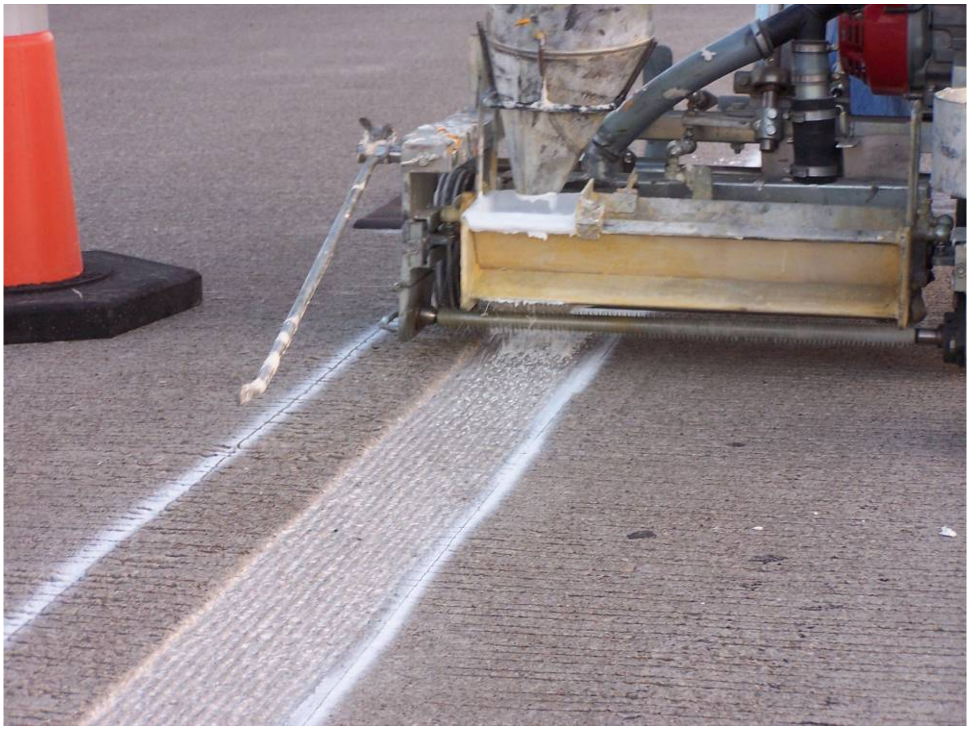

Figure (4.17): Application of Duraset Pathfinder using the Splatter Method.

Figure (4.18): Splatter Pattern of Duraset Pathfinder.

CHAPTER 5
PERFORMANCE EVALUATION PLAN

5.1 Introduction

Pavement markings must maintain certain levels of durability, retroreflectivity, and color to effectively serve as a delineation system. These attributes are commonly characterized using subjective and objective evaluation techniques. As their names imply, subjective evaluations are made by experienced evaluators who use their judgment in rating the performance of the pavement marking according to predefined guidelines. Meanwhile, objective evaluations are conducted using an instrument such as a retroreflectometer or a colorimeter, and hence are less affected by the individual conducting the evaluation. Readings obtained using these instruments can be used to determine whether the performance of the pavement marking is acceptable or not.

There are advantages and disadvantages to both evaluation techniques. The obvious advantage of subjective evaluations is that they can be performed without the need for a specialized instrument, which may be expensive to acquire. In addition, they are not limited by the limitations of available instruments. As a consequence, subjective evaluations may include properties that may be hard to measure in a quick and reliable manner. For example, it is easier and less time consuming to subjectively rate durability than to quantify it using alternative mechanical means such as image analysis. Subjective evaluations, however, are highly variable since they are dependent on the judgment of the evaluator and the prevailing conditions during the evaluation. For example, among the factors known to affect nighttime visibility of pavement markings are pavement surface type and color, vehicle type, vehicle headlamps, driver age, preview time (or vehicle speed), windshield transmission, highway lighting, weather conditions, and glare from oncoming traffic (Debaillon et al. 2007). Therefore, all these factors shall be taken into consideration in determining the nighttime visibility performance of pavement markings.

Objective evaluations, on the other hand, are conducted using an instrument. Hence, they are less dependent on the individual conducting the evaluation, provided that proper calibration and operation instructions are followed. In most cases, the instrument can be operated by one person, which reduces the cost of the evaluation. However, the main disadvantage of objective evaluations is that they are limited by the limitations of available instruments, which may not be capable of measuring all aspects of pavement marking performance in a quick and reliable manner. Another disadvantage of objective evaluations pertains to the common practice of averaging color and retroreflectivity readings to describe the overall color or retroreflectivity quality of the pavement marking. These readings are spot measurements and their average may not reflect the overall quality of the pavement marking even if several readings are taken. For example, a line having very bright and very dull portions may produce an average retroreflectivity value that is acceptable. Yet, this line is less desirable than a line with consistently average retroreflectivity values. This drawback can be addressed by analyzing the variability in the individual retroreflectivity readings or by developing a subjective evaluation procedure that accounts for this variability as will be presented in the following sections.

Based on the previous discussion, both evaluation techniques are necessary to evaluate the overall performance of pavement markings. In this study, retroreflectivity was measured using two LTL-X handheld retroreflectometers; color was measured using a MiniScan XE Plus colorimeter; and daytime color, nighttime visibility, and durability were evaluated according to Supplemental 1047 (dated April 18, 2008). In addition, a pocket magnifier was used to examine glass bead retention as it varied over time.

5.2 Performance Evaluation Conduct

The periodic field evaluations were conducted approximately every thirty days over a period of about two years. They were limited to dry conditions when the lines were clear of dirt and deicing salt. This restriction limited the ability to conduct the evaluation during the period from November to April. Each evaluation lasted for about twelve to fourteen hours, during which both daytime and nighttime performance measurements and ratings were made.

State-owned vehicles were used in the evaluation, which was conducted by ODOT District 3 Pavement Marking Engineers, representatives from ODOT Central Office, and the Principal Investigator. In general, six to eight evaluators were present during the evaluation. Two graduate assistants from the University of Akron also assisted with recording retroreflectivity and color readings during the evaluations. In addition, an invitation was sent to pavement marking manufacturers, glass bead producers, and engineers from other districts in ODOT to attend the evaluation.

The evaluation involved two edge lines and two lane lines. These lines were evaluated in two passes; the first pass covered the left edge line and the left lane line and the second pass covered the right edge line and the right lane line; or the other way around. This required closing either the far right or the far left lane during the evaluation. Traffic control was provided by ODOT District 3. It consisted of two truck-mounted crash attenuators with flashing arrow panels and two pick-up trucks holding the sign “Left/Right Lane Closed”. The pick up trucks were placed on the shoulders of the interstate and the crash attenuators were placed behind the evaluation vehicles – one on the right or left lane and one on the shoulder. The spacing between the crash attenuator and the evaluation vehicle was minimized to deter traffic from driving in between. The placement of the crash attenuators and the pick up trucks followed Ohio Manual of Uniform Traffic Control Devices (OMUTCD) Figure 6H-35 for Mobile Operation on Multi-Lane Road (Section TA-35) with some modifications to account for the frequent temporary lane closures.

5.3 Performance Evaluation Measures

As mentioned previously, the performance evaluation plan included measuring retroreflectivity using two handheld LTL-X retroreflectometers and color using a MiniScan XE Plus colorimeter. It also included rating daytime color, nighttime visibility, and durability according to Supplemental 1047 (dated April 18, 2008). In addition, a pocket magnifier was used to examine glass bead retention as it varied over time. Each of these performance measures is covered separately in the following subsections. The performance evaluation results (measurements and ratings) collected during the periodic evaluations were complied in an Excel spreadsheet for further analysis as will be presented in the following chapters.

5.3.1 Retroreflectivity

Retroreflectivity was measured using two LTL-X handheld retroreflectometers. These devices were operated by ODOT personnel who were also responsible for the periodic calibration as per the manufacturer instructions. Retroreflectivity was measured in every periodic evaluation. An effort was made to collect ten (10) retroreflectivity readings per line per field evaluation. In some cases, only five (5) readings were taken instead of ten (10) due to battery malfunction with one of the devices. In other occasions, no readings were taken due to rain or due to lane closure for a nearby bridge paint. To obtain a representative retroreflectivity value, the readings were obtained across the width of the bridge deck.

5.3.1.1 LTL-X Retroreflectometer

The LTL-X retroreflectometer is developed by Delta Light and Optics and distributed in the US by Flint Trading, Inc. It measures pavement marking retroreflectivity in accordance with CEN and ASTM standards. This device uses 30-m geometry in simulating the roadway being illuminated by the headlights of a car. Retroreflectivity is a reading that represents the amount of light that is reflected back to the motorists from the pavement marking. Retroreflectivity for pavement markings is measured in millicandelas per square meter per lux (mcd/m^2/lux). This value is also known as the coefficient of retroreflected luminance, R_L.

The illumination system in the LTL-X is powered by a xenon lamp in the top of the tower. The generated light is collimated using a lens and deflected through a mirror in the bottom of the tower towards the pavement marking. The light illuminates a field of approximately 200 mm by 45 mm. The same mirror is used to direct the reflected light from the road back into a receptor where retroreflectivity is measured. The instrument automatically compensates for any leakage from the light trap that occurs during the testing.

The LTL-X retroreflectometer is portable and ideal for collecting field data. In order to acquire accurate retroreflectivity readings, the surface must be level and clean of any debris. This device is equipped with a data log system that can print out all data results at the end of a testing session. Multiple readings can be automatically averaged for more accurate results. Its display shows the date and time, measurement number, retroreflectivity measurement, the average of a series of measurements, and other data related to the test at hand. This device comes with an optional Global Positioning System (GPS) that can be used to determine the location of the testing site.

Figure (5.1) presents a picture of the LTL-X retroreflectometer. Figure (5.2) illustrates using this device to measure pavement marking retroreflectivity. As can be seen in this picture, retroreflectivity is measured by placing the LTL-X on the pavement marking in a stationary mode while a reading is made.

Figure (5.1): LTL-X Retroreflectometer (http://www.flinttrading.com).

Figure (5.2): Measuring Retroreflectivity using an LTL-X Retroreflectometer.

5.3.2 Color

Color was measured using a MiniScan XE Plus (Model 4500L) spectrocolorimeter. This model has a large view area with 31.8 mm measurement port. It employs 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 device was operated by ODOT personnel who were also responsible for the periodic calibration as per the manufacturer instructions. Color was measured approximately every three months. Five (5) color readings were collected per line. In some occasions, no readings were taken due to rain or due to lane closure for a nearby bridge paint. To obtain a representative color value, the readings were obtained across the width of the bridge deck.

5.3.2.1 MiniScan XE Plus

The MiniScan XE Plus is a portable sprectrocolorimeter which measures color in the CIE xyY scale. This device is produced by Hunter Associates Laboratory, Inc. This system describes color using three parameters x, y, and Y. The x and y parameters describe the color of the object at hand. The Y component describes how bright or luminous the object is. As x increases, the red quality of the color increases. As y increases, the green quality of the color increases. These coordinates can be plotted on a graph that is bounded by a horseshoe curve which represents the wavelengths of the light waves, as shown previously in Figure (2.1).

The Miniscan XE Plus can be connected to a computer or a printer; and a software is available that allows the user to plot the data and analyze it further. The colorimeter can average up to twenty five readings at a time and it can show spectral and color plots after data has been taken. This instrument can store color specifications for the object of interest before color measurements are made. The color values can then be displayed as a difference from the specifications set earlier.

Figure (5.3) presents a picture of the Miniscan XE Plus colorimeter. Figure (5.4) illustrates using this device to measure pavement marking color. As can be seen in this picture, color is measured by placing the Miniscan XE Plus on the pavement marking in a stationary mode while a reading is made.

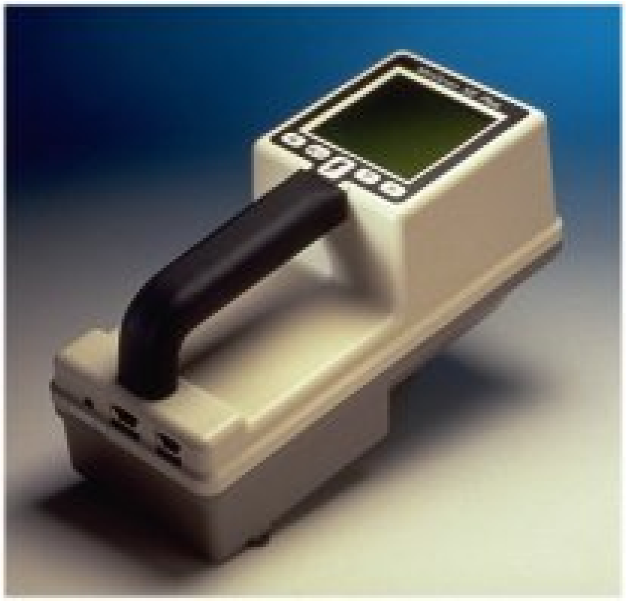

Figure (5.3): MiniScan XE Plus (http://www.hunterlab.com).

Figure (5.4): Measuring Color using MiniScan XE Plus.

5.3.3 Daytime Color

Daytime color was evaluated according to Supplemental 1047, Appendix C (Figure 5.5). This evaluation involved rating the vividness of the white markings and the richness of the yellow markings as observed by a trained evaluator from a distance of 100 ft (30 m) on a scale of 0 to 10. A scale of 0 indicates that the material is very dull in color, while a scale of 10 indicates that the material is very vivid and rich in appearance. As explained in this figure, daytime color is affected by several factors including the pavement surface type and age, weather conditions, and the viewing angle of the observer with respect to the incident rays from the sun.

5.3.4 Nighttime Visibility

Nighttime visibility was evaluated according to Supplemental 1047, Appendix D (Figure 5.6). The evaluation commenced fifteen to thirty minutes after sunset. In this evaluation, a trained evaluator subjectively rated the appearance of pavement markings on dry pavement at night from a vehicle operated under low beam headlight illumination. The evaluation vehicles were driven slowly through the bridge deck on either the far right or the far left lane, which allowed evaluating two lines in the one pass. As shown in Figure (5.6), the evaluation consisted of rating three attributes of the pavement markings:

- Uniformity: The ability of the line to provide a consistent, unvarying appearance along its length and across its width (on a scale of 0 to 4).
- Retroreflectivity: The brightness of the line in the return of incident illumination (on a scale of 0 to 3).
- Nighttime Color: The vividness of the white markings and the richness of the yellow markings when seen with retroreflected light (on a scale of 0 to 3).

The nighttime visibility rating was calculated as the sum of the three ratings for these three attributes. It was expressed as an integer value.

As mentioned previously, nighttime visibility of pavement markings is affected by several factors, including the pavement surface type and color, vehicle type, vehicle headlamps, driver age, preview time (or vehicle speed), windshield transmission, highway lighting, weather conditions, and glare from oncoming traffic. All these factors might have contributed to the variability in nighttime visibility ratings in this study.

Based on the previous, this rating procedure accounts for other attributes in addition to retroreflectivity. Therefore, it is not expected that there will be a direct relationship between average retroreflectivity values and nighttime visibility ratings. This rating procedure was revised as part of this study from an older version that did not include any provisions for uniformity and nighttime color. The rationale behind revising this rating procedure was to take note of those materials that had deficiencies in these two aspects.

5.3.5 Durability

Durability was evaluated according to Supplemental 1047, Appendix E (Figure 5.7). This evaluation was conducted in the most deteriorated location on the bridge deck, including the approach slab. In this evaluation, the percentage of pavement marking remaining on a line segment of ten feet (3.0 m) in length was visually assessed by several trained evaluators and reported as a consensus rating on a scale of 0 (the material has been completely lost) to 10 (100% of the material is remaining). The durability rating was reported as an integer value.

As will be discussed in the following chapters, a material is assumed to have failed once its durability rating drops down to eight. Therefore, durability ratings below this value are of less importance.

In general, this rating procedure was found satisfactory when more than five percent of the material is lost enough to drop the durability rating to nine or less. However, it was limited in its ability to identify materials that had minor chipping of less than or equal to five percent since durability is reported as an integer and any material with ninety five percent or more remaining is rated as a ten. Given that chipping in its initial stages is an early sign of failure, a photo log of chipped materials was collected and maintained for documentation purposes.

5.3.6 Glass Bead Retention

Finally, a pocket magnifier was used to inspect the glass bead distribution and retention as it varied over time (Figure 5.8). Observations made during the periodic field evaluations were noted and compared to close up pictures collected throughout the project. Figure (5.9) presents an example close up picture that shows the details of the glass beads as seen using the pocket magnifier.

Appendix C

Daytime Color of Long Line Pavement Marking

The color rating is a subjective field assessment of the vividness of the white markings and the richness of the yellow markings when viewed under dispersed daylight conditions on dry pavement, in accordance with the table below.

Ideally, color should be assessed under uniformly overcast conditions. If it is necessary to conduct evaluations under clear or partly cloudy conditions, the color assessment should be made with the sun as near transit as practical, as the angle of the incident rays of the sun can have a significant effect on the appearance of the color of the pavement markings. Viewing the line with the sun behind and low on the horizon should be avoided, as this can impart a level of retroreflectivity to the pavement marking. Under certain circumstances, especially during the fall and winter, when the sun is low on the horizon even at transit, it may be necessary to view the line in the opposite direction to avoid excessive retroreflectivity imparted from the sun.

The evaluation process is conducted as follows: A trained evaluator observes the line from a distance of 100 feet (±10 feet), and rates the color as per the table below. For lane lines, this distance can be approximated by standing midway between two lane lines, and looking beyond the nearest two lane lines to the third.

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

Daytime Color (line viewed at a distance of 100 feet)	
10	White and yellow are very vivid and rich in appearance, and are very effective in delineation
9 8 7	White and yellow are very distinctive and definite in color
6 5 4	White and yellow appear somewhat grayish; yellow may appear to have a brownish or greenish tint
3 2 1	White and yellow are dull and grayish; yellow may appear to be green, brown or off-white
0	White and yellow appear very dull

Figure (5.5): Guidelines for Evaluating Daytime Color.

Appendix D

Night Visibility Rating of Long Line Pavement Marking

Night visibility is a subjective rating based on the appearance of the pavement marking line on dry pavement to a trained evaluator in a vehicle when viewed under low beam headlight illumination at night. The night visibility rating consists of an evaluation of three distinct attributes:

Uniformity – The ability of the line to provide a consistent, unvarying appearance along its length and across its width.
Retroreflectivity – The brightness of the line in the return of incident illumination.
Nighttime Color – The vividness of the white markings and the richness of the yellow markings when seen with retroreflected light.

The rating scales for each of these attributes is described in the tables below.

The evaluation process is conducted as follows: With appropriate traffic control in place, slowly drive through the test section at night with low beam headlights, and observe the test line. First, rate the uniformity of the line appearance. Second, rate the line retroreflectivity. Finally, rate the color. Add up the three individual scores to get a composite rating for the line.

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

Uniformity	
+4	Line is completely consistent in appearance, with no distinguishable variations
+3	Line is generally consistent in appearance, with minimal variations
+2	Line is generally consistent in appearance, but with distinctly brighter and darker areas
+1	Line is inconsistent in appearance, with distinctly brighter and darker areas
0	Line is very inconsistent in appearance and may appear blotchy

Retroreflectivity	
+3	Line is very bright
+2	Line is bright
+1	Line appears adequate, but with unimpressive brightness
0	Line has minimal brightness; line is discernable but only marginally effective

Nighttime Color	
+3	White appears as very clean reflected light; yellow is distinctive and definite in color
+2	White and yellow appear somewhat grayish; yellow may appear to have a brownish or greenish tint
+1	White and yellow are dull and grayish; yellow may appear to be green, brown or off-white
0	White and yellow appear very dull

Figure (5.6): Guidelines for Evaluating Nighttime Visibility.

Appendix E

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

Figure (5.7): Guidelines for Evaluating Durability.

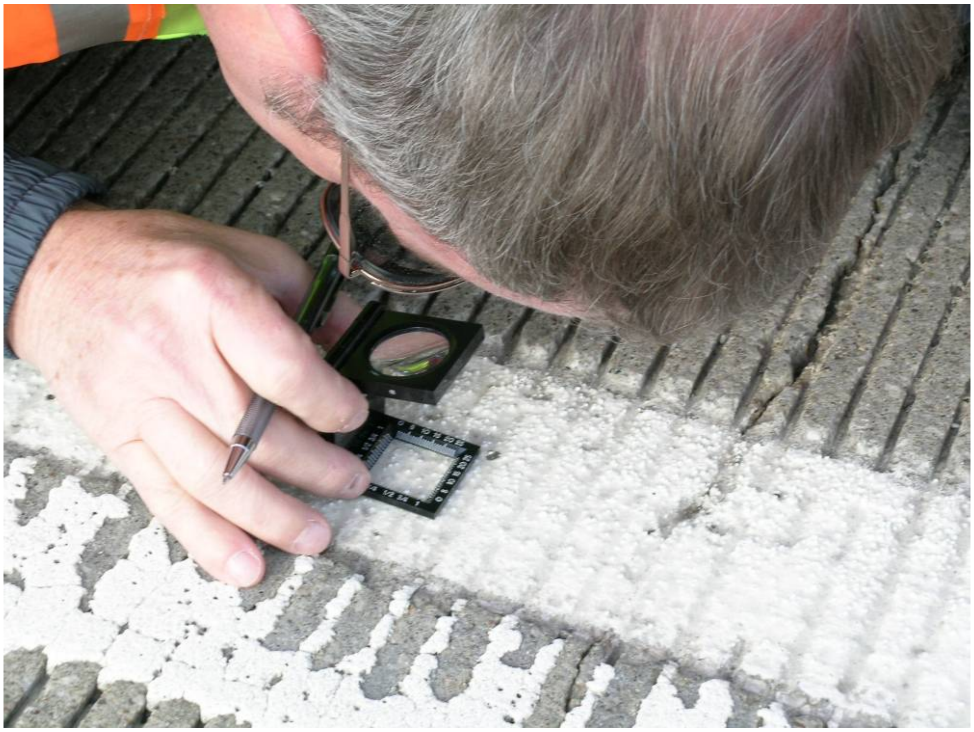

Figure (5.8): Glass Bead Inspection using a Pocket Magnifier.

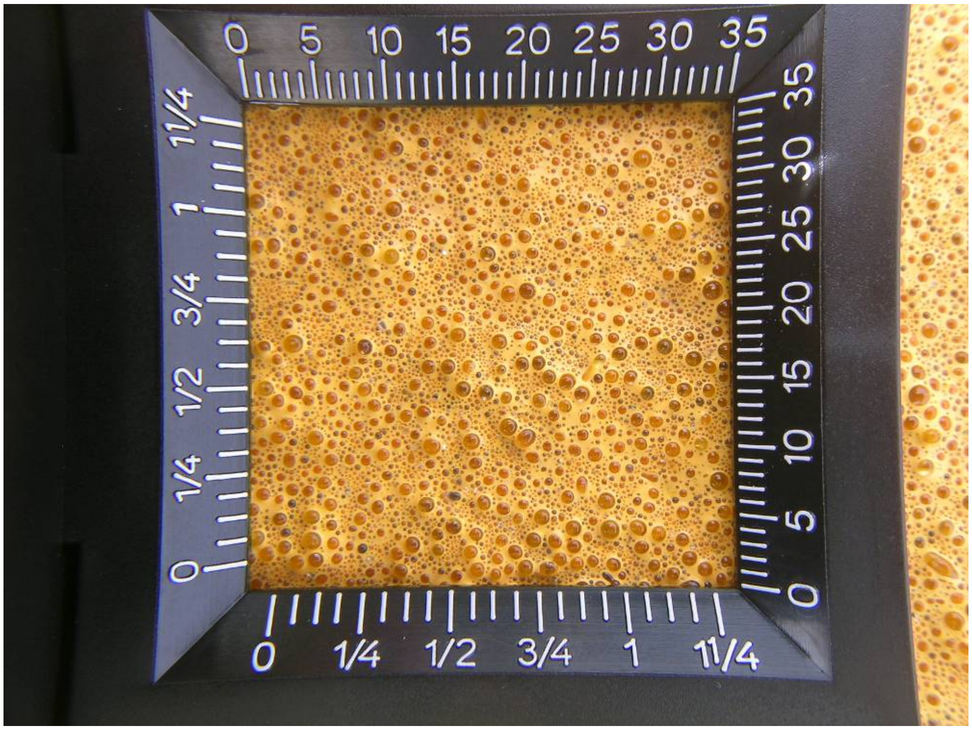

Figure (5.9): Glass Bead Distribution as seen using a Pocket Magnifier.

CHAPTER 6
PERFORMANCE EVALUATION RESULTS

6.1 Introduction

This chapter provides a summary of the performance evaluation results obtained during the periodic evaluations. Retroreflectivity measurements are summarized and compared with milestone criteria for initial, 1-yr, and 2-yr performance. Color readings are compared with ODOT specifications for white and yellow markings. Durability, daytime color, and nighttime visibility ratings are presented. Materials with low subjective ratings are highlighted and discussed in more detail. Finally, glass bead retention is characterized by assessing the amounts of large glass beads lost after one year and after two years.

6.2 Summary of Results

6.2.1 Retroreflectivity

Table (6.1) summarizes initial, 1-yr, and 2-yr retroreflectivity for all materials, organized in the same order of the bridge decks on which they were installed. These values correspond to the average of ten (in some cases five) retroreflectivity readings obtained using two LTL-X retroreflectometers on July 2006 (initial), May 2007 (1-yr), and May 2008 (2-yr). This table also provides a comparison between retroreflectivity and milestone criteria for initial (250 mcd/m^2/lux for yellow markings and 300 mcd/m^2/lux for white markings), 1-yr (200 mcd/m^2/lux for yellow markings and 250 mcd/m^2/lux for white markings), and 2-yr performance (150 mcd/m^2/lux for yellow markings and 200 mcd/m^2/lux for white markings). Retroreflectivity measurements not meeting the corresponding criteria are highlighted. These criteria were selected based on threshold retroreflectivity values of 100 mcd/m^2/lux for yellow markings and 150 mcd/m^2/lux for white markings. It was assumed that most of the evaluated materials will last more than three years and that their retroreflectivity will drop at a rate of 50 mcd/m^2/lux per year. Therefore, for a material to meet these threshold values at the end of the third year, its initial retroreflectivity shall be greater than 100+3x50 = 250 and 150+3x50 = 300 mcd/m^2/lux for yellow and white markings, respectively. Figures (6.1) through (6.12) offer similar comparisons in a graphical form.

The following is a summary of conclusions based on the analysis of the retroreflectivity measurements and observations related to retroreflectivity made during the periodic evaluations:

- White markings had higher initial retroreflectivity than yellow markings for all materials except 3M 380WR ES and 3M 380WR-5 ES. Yet, the initial retroreflectivity of white 3M 380WR ES and 3M 380WR-5 ES was significantly higher than yellow 3M 381WR ES when retroreflectivity was measured in the opposite direction to traffic, which indicates that these tapes have preferred directionality with respect to retroreflectivity. This directionality is believed to be resulted from the presence of a knob on the edge of one side of the raised profiles of these tapes as shown in Figure A.1 in Appendix A. When placed in the same direction to traffic, these protrusions scatter light rays emitted from moving vehicles; and thus reduce the retroreflectivity of this material. Therefore, for optimum performance, it is recommended to place these knobs in the opposite direction to traffic when installing these tapes. In this project, the yellow 3M 381WR ES tape was installed in the preferred direction, whereas the white 3M 380WR ES and 3M 380WR-5 ES tapes were not, which explains why the initial retroreflectivity of the yellow tape was higher than the white tapes.
- White right edge lines deteriorated at a higher rate than white (left and right) lane lines, which in turn deteriorated at a higher rate than yellow left edge lines. This trend is probably due to higher traffic in the right and middle lanes than in the left lane and higher truck concentration in the right lane than in the middle lane.
- Glomarc 90 polyurea had the highest initial, 1-yr, and 2-yr retroreflectivity; and HPS-5 polyurea had the lowest retroreflectivity deterioration rate (year-to-year drop in retroreflectivity). The high retroreflectivity values for Glomarc 90 are attributed to the presence of two proprietary bead systems, namely Clusterbead® and Visibead® Plus II, which are larger than the other glass beads used for the rest of the materials. The low deterioration rate of HPS-5 retroreflectivity is probably due to the high durability of this material and its good bonding with concrete surfaces.
- Duraset 1 methyl methacrylate had the lowest initial retroreflectivity for both yellow and white markings. As discussed earlier in Chapter 4, these low retroreflectivity values are attributed to the fact that this material hardened in a relatively short period of time during the installation, which did not allow the surface applied glass beads to properly embed on its surface. On the other hand, the performance of Duraset Pathfinder methyl methacrylate,

which was applied using the splatter method, was satisfactory.

- The highest retroreflectivity deterioration rate (year-to-year drop in retroreflectivity) was observed for Mark 55.4 and 3M 270 ES white right edge lines.
- The more expensive 3M 380WR ES tape performed better than the less expensive 3M 270 ES tape especially on the highly trafficked white right edge line.
- All thermoplastic materials had low initial retroreflectivity for yellow markings, which is probably due to overheating and sinking of some of the larger glass beads in the molten thermoplastic during the installation.
- In general, retroreflectivity decreased over time for all materials except conventional and preformed thermoplastics, for which retroreflectivity increased after installation for all lines then decreased for the white edge and lane lines. The increase in retroreflectivity resulted from the exposure of the intermixed glass beads and some of the larger glass beads that sank in the molten thermoplastic during installation once the lines wore down due to traffic.
- Premark Contrast (Bridge Deck # 2; Lane Lines) had better retained retroreflectivity after two years than Premark Plus (Bridge Deck # 15; Lane Lines). The comparison is based on the performance of the lane lines only since Premark Contrast was not installed on the edge lines.
- Interestingly, even though Ennis fast dry waterborne traffic paint did not meet most milestone retroreflectivity criteria set forth for the more durable products, its performance was reasonably acceptable (retroreflectivity is greater than 150 mcd/m^2/lux for white and 100 mcd/m^2/lux for yellow markings) even at the end of the second year. One disadvantage of installing this material in 150-mil (3.8 mm) grooves similar to the rest of the materials is that the lines become completely invisible under wet conditions once the grooves are filled with water from rain. This was not necessarily the case for thicker materials and materials that had patterned structures.
- Comparable retroreflectivity performance was obtained from HPS-2, Mark 55.2, and LS 60 slow cure epoxies. Mark 55.2 performed the best on the yellow left edge line and the white lane lines, while LS 60 performed the best on the white right edge line. HPS-2 performance was in the middle for all lines. In addition, the performance of HPS-4 modified urethane was comparable to these three materials. The performance of Mark 55.4 fast cure epoxy, on the other hand, was worse on the yellow and white edge line, but comparable on the lane lines;

and the performance of LS 70 fast cure epoxy was unsatisfactory due to poor durability.

- The performance of the three polyurea products (Glomarc 90, Mark 75, and HPS-5) widely varied. As mentioned earlier, Glomarc 90 had the highest initial, 1-yr, and 2-yr retroreflectivity, with all retroreflectivity measurements exceeding 500 mcd/m^2/lux at all times. Meanwhile, Mark 75 had acceptable initial retroreflectivity for yellow and very high initial retroreflectivity for white. However, its 1-yr and 2-yr retroreflectivity performance was comparable, if not lower, to the less expensive epoxy products. Finally, HPS-5 had acceptable initial retroreflectivity for yellow and very high initial retroreflectivity for white. It also had very high retained retroreflectivity for both white and yellow markings. Interestingly, the retroreflectivity of yellow HPS-5 increased over time from an initial value of 339 mcd/m^2/lux to about 400 mcd/m^2/lux after one year and did not change much afterwards. This increase in retroreflectivity can be justified as follows: (1) Retroreflectivity measurements were not taken at exactly the same locations on the bridge decks. The effect of such variability is usually outweighed by the drop in retroreflectivity due to wearing from traffic and snowplowing. However, since yellow markings in this project were not subjected to high traffic, this factor could be significant. (2) Some of the larger glass beads were embedded more than 50 to 60%, which is believed to be the optimum embedment for retroreflectivity performance; and over time once the lines wore down the retroreflectivity of these glass beads increased. (3) More glass beads than necessary were used during the installation, which resulted in so called shadowing effect that hindered the initial retroreflectivity of this material.
- Based on initial retroreflectivity of yellow left edge lines, the performance of the evaluated materials can be ranked from best to worst as follows: Glomarc 90, 3M 380WR ES, Mark 55.2, HPS-2, 3M 270 ES, LS 60, HPS-4, Mark 55.4, Mark 75, HPS-5, Premark Plus (Bridge Deck # 15), LS 70, Ennis Fast Dry Waterborne Paint, Premark Plus (Bridge Deck # 2), Swarcotherm, and Duraset 1.
- Based on 2-yr retroreflectivity of yellow left edge lines, the performance of the evaluated materials can be ranked from the best to worst as follows: Glomarc 90, 3M 380WR ES, Mark 55.2, HPS-4, HPS-5, HPS-2, Mark 75, Premark Plus (Bridge Decks # 2 and 15), 3M 270 ES, LS 60, Mark 55.4, Ennis Fast Dry Waterborne Paint, and Duraset 1.
- Based on initial retroreflectivity of white right edge lines, the performance of the evaluated

materials can be ranked from the best to worst as follows: Glomarc 90, HPS-5, Mark 75, Mark 55.4, HPS-4, HPS-2, Premark Plus (Bridge Deck # 2), Mark 55.2, 3M 380WR ES, Premark Plus (Bridge Deck # 15), LS 60, 3M 270 ES, LS 70, Swarcotherm, Ennis Fast Dry Waterborne Paint, and Duraset 1.

- Based on 2-yr retroreflectivity of white right edge lines, the performance of the evaluated materials can be ranked from the best to worst as follows: HPS-5, Glomarc 90, 3M 380WR ES, HPS-4, LS 60, HPS-2, Mark 55.2, Mark 75, Duraset 1, Premark Plus (Bridge Decks # 2 and 15), Mark 55.4, Ennis Fast Dry Waterborne Paint, and 3M 270 ES.
- By comparing the initial and the 2-yr retroreflectivity values, it is concluded that high initial retroreflectivity is not always an indication of good retained retroreflectivity.
- The variation in the individual retroreflectivity readings was determined using the coefficient of variation. This statistical quantity is calculated by dividing the standard deviation of a set of data by their mean. Consequently, the closer are the data points to each other, the lower is the coefficient of variation; and the wider is the spread of the data points about their mean, the higher is the coefficient of variation. In this project, it was noticed that Premark Plus and Premark Contrast had the highest coefficient of variation of all materials. For example, the coefficient of variation (expressed as a percentage) of white Premark Plus on the right edge line of Bridge Deck # 2 two years after installation was 8.9%; and that of yellow Premark Plus on the left edge line of Bridge Deck # 2 was 44.7%. Similar results of 19.1% and 42.3% were also obtained for white and yellow Premark Plus, respectively, on Bridge Deck # 15.
- Other materials that had high coefficients of variability (greater than 20%) after two years include white 3M 380WR ES on the right edge line of Bridge Deck # 1, white LS 60 on the right edge line of Bridge Deck # 9, white Duraset 1 on the right edge line of Bridge Deck # 13. The rest of the lines had a coefficient of variation less than or equal to 15%.
- Finally, the following materials met the milestone retroreflectivity criteria set forth in this project: 3M 380WR ES, Premark Plus (except for initial yellow retroreflectivity on Bridge Deck # 2), Premark Contrast, HPS-2, HPS-4, Mark 55.2, Mark 75, Mark 55.4, LS 60, Glomarc 90, HPS-5, and Duraset Pathfinder; while the following materials did not meet these criteria: LS 70, Duraset1, Ennis Fast Dry Waterborne Traffic Paint, and 3M 270 ES.

Table (6.1): Summary of Retroreflectivity Measurements and Comparison with Milestone Criteria for Initial (250 mcd/m²/lux for Yellow and 300 mcd/m²/lux for White), 1-yr (200 mcd/m²/lux for Yellow and 250 mcd/m²/lux for White), and 2-yr Retroreflectivity (150 mcd/m²/lux for Yellow and 200 mcd/m²/lux for White); (Retroreflectivity Measurements not Meeting the Corresponding Criteria are Highlighted).

		Retroreflectivity (mcd/m²/lux)			
Product	**Age**	**Y-LEL[1]**	**W-LLL[2]**	**W-RLL[3]**	**W-REL[4]**
3M 380WR ES	Initial	638	550	572	594
	1-yr	587	446	473	539
	2-yr	492	314	336	352
Premark Contrast	Initial	**184**	626	688	663
	1-yr	282	590	654	470
	2-yr	375	559	532	215
HPS-2	Initial	480	706	648	682
	1-yr	349[‡]	472	486	404
	2-yr	407	422	415	307
HPS-4	Initial	451	711	695	737
	1-yr	459	563	540	605
	2-yr	431	466	387	343
Mark 55.2	Initial	516	697	710	636
	1-yr	486	565	536	372
	2-yr	433	503	498	292
Mark 75	Initial	423	783	747	775
	1-yr	405	486	399	386
	2-yr	387	337	277	247
Mark 55.4	Initial	425	728	706	766
	1-yr	378	473	482	259
	2-yr	320	386	398	200
Swarcotherm[†]	Initial	**169**	**282**	342	371
	1-yr	225	402	379	303
	2-yr	**--**	**--**	**--**	**--**

[1] Y-LEL: Yellow Left Edge Line
[2] W-LLL: White Left Lane Line
[3] W-RLL: White Right Lane Line
[4] W-REL: White Right Edge Line
[†] Material failed due to durability
[‡] This value is an outliner as indicated by an average retroreflectivity reading of 453 mcd/m²/lux in the previous month and an average retroreflectivity reading of 444 mcd/m²/lux in the following month.

Table (6.1): Summary of Retroreflectivity Measurements and Comparison with Milestone Criteria for Initial (250 mcd/m²/lux for Yellow and 300 mcd/m²/lux for White), 1-yr (200 mcd/m²/lux for Yellow and 250 mcd/m²/lux for White), and 2-yr Retroreflectivity (150 mcd/m²/lux for Yellow and 200 mcd/m²/lux for White); (Retroreflectivity Measurements not Meeting the Corresponding Criteria are Highlighted); (Continued).

		Retroreflectivity (mcd/m²/lux)			
Product	**Age**	**Y-LEL[1]**	**W-LLL[2]**	**W-RLL[3]**	**W-REL[4]**
LS 60	Initial	461	619	640	514
	1-yr	422	390	481	396
	2-yr	333	324	395	332
Glomarc 90	Initial	695	1193	1239	1142
	1-yr	609	826	786	684
	2-yr	529	727	691	526
LS 70[†]	Initial	**249**	326	320	447
	1-yr	309	267	258	**193**
	2-yr	**--**	**--**	**--**	**--**
HPS-5	Initial	339	681	641	794
	1-yr	404	560	549	587
	2-yr	411	503	483	527
Ennis MMA	Initial	**82**	508	480	**280**
	1-yr	**83**	347	327	**236**
	2-yr	**92**	320	276	223
Ennis Paint	Initial	**202**	310	305	330
	1-yr	**179**	**229**	**207**	**237**
	2-yr	151	**166**	**139**	**150**
Premark Plus	Initial	317	715	814	579
	1-yr	400	780	851	570
	2-yr	385	433	410	215
3M 270 ES	Initial	466	527	517	486
	1-yr	421	430	436	**228**
	2-yr	356	362	362	**127**

[1] Y-LEL: Yellow Left Edge Line
[2] W-LLL: White Left Lane Line
[3] W-RLL: White Right Lane Line
[4] W-REL: White Right Edge Line
[†] Material failed due to durability

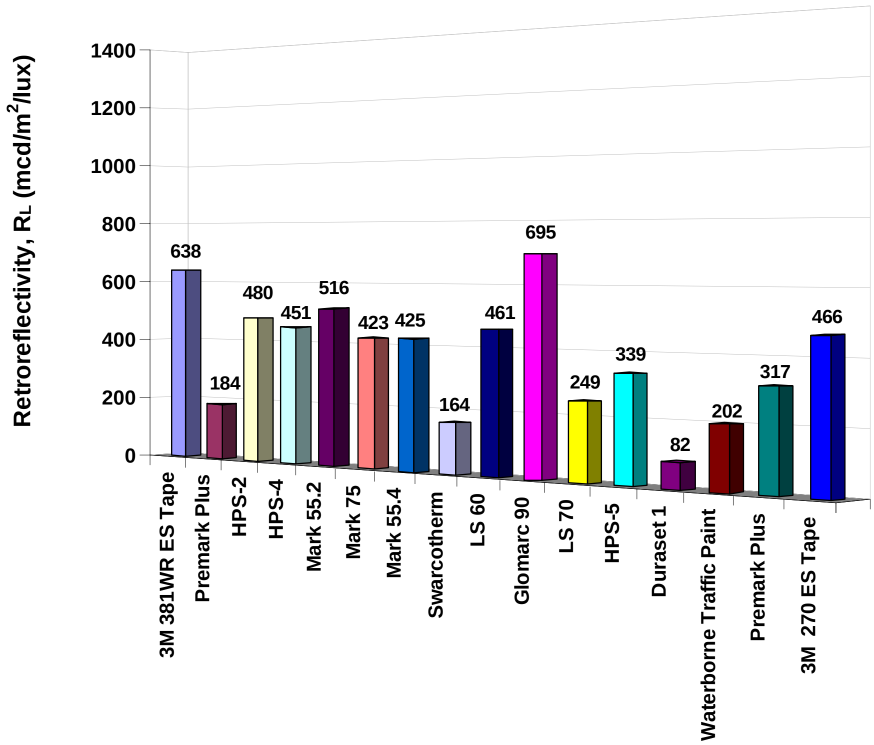

Figure (6.1): Initial Retroreflectivity of Yellow Left Edge Lines.

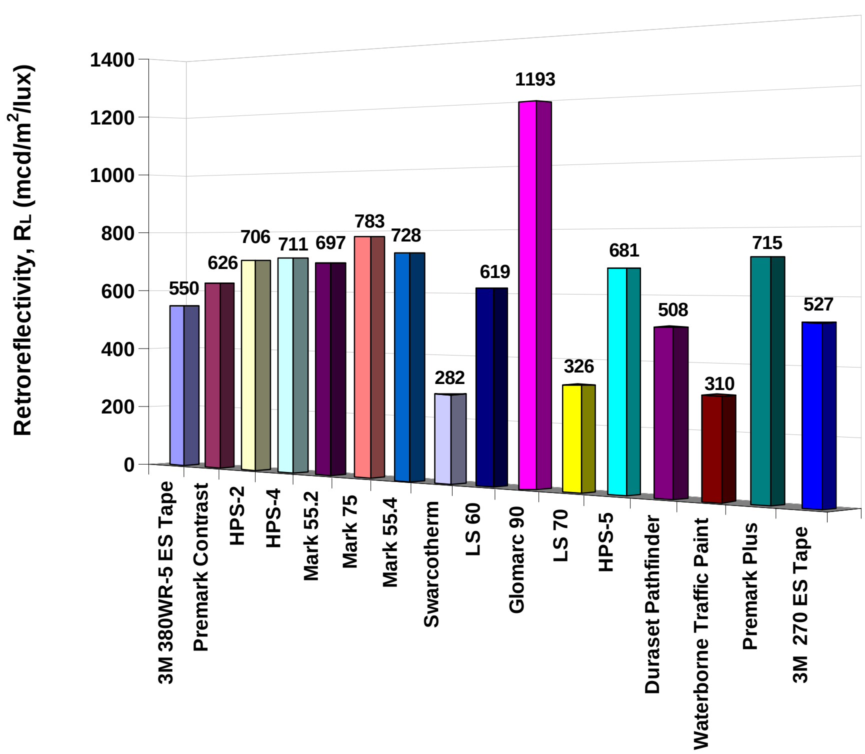

Figure (6.2): Initial Retroreflectivity of White Left Lane Lines.

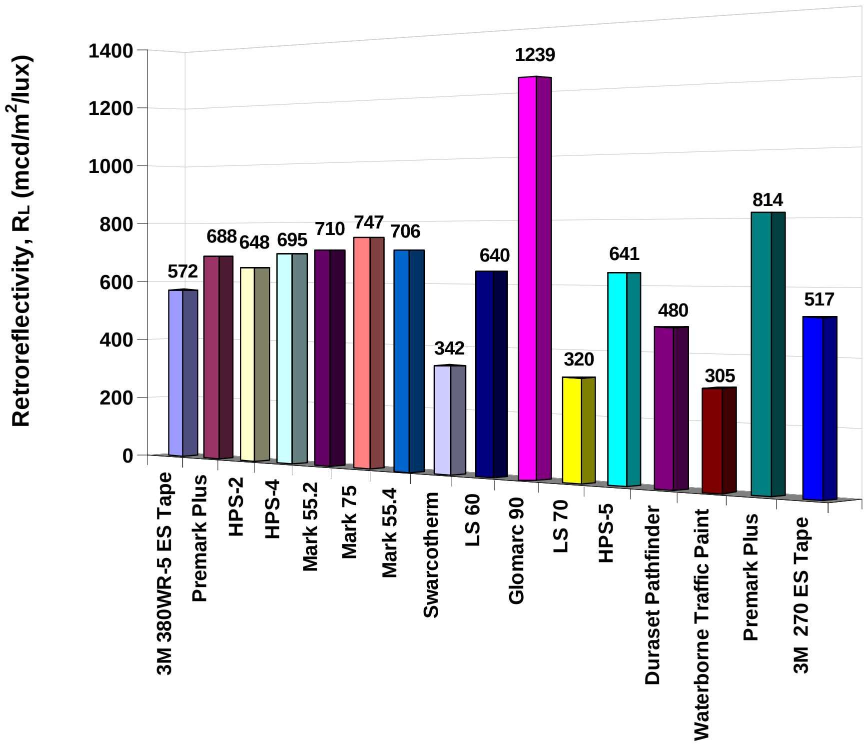

Figure (6.3): Initial Retroreflectivity of White Right Lane Lines.

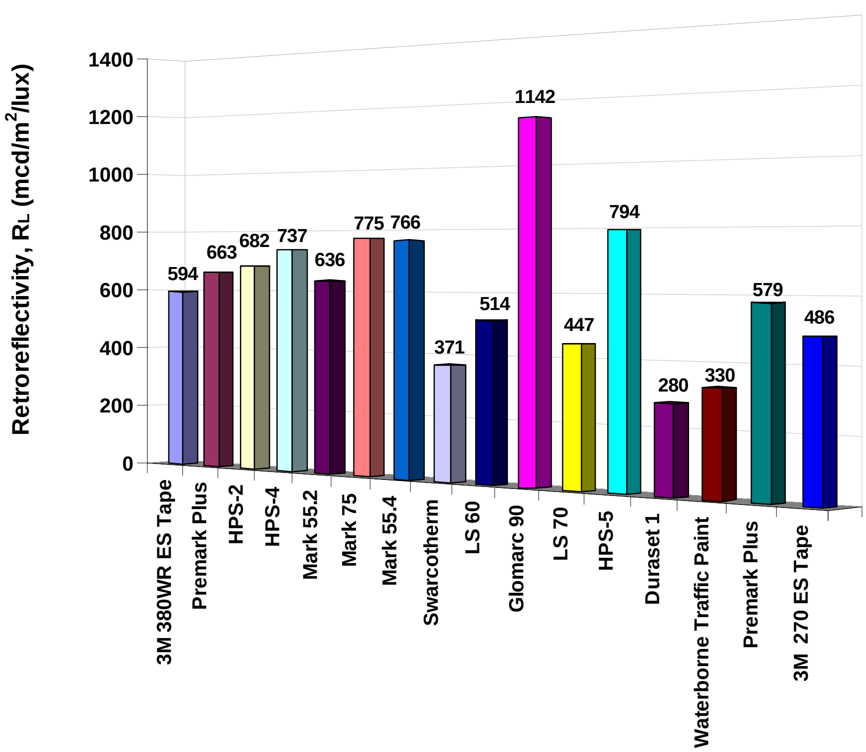

Figure (6.4): Initial Retroreflectivity of White Right Edge Lines.

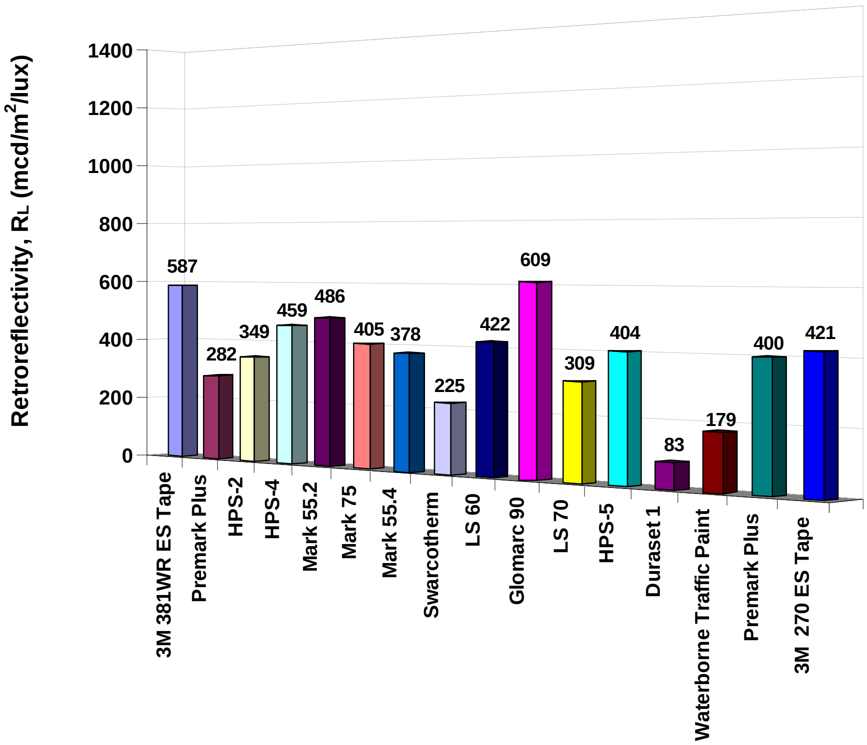

Figure (6.5): 1-yr Retroreflectivity of Yellow Left Edge Lines.

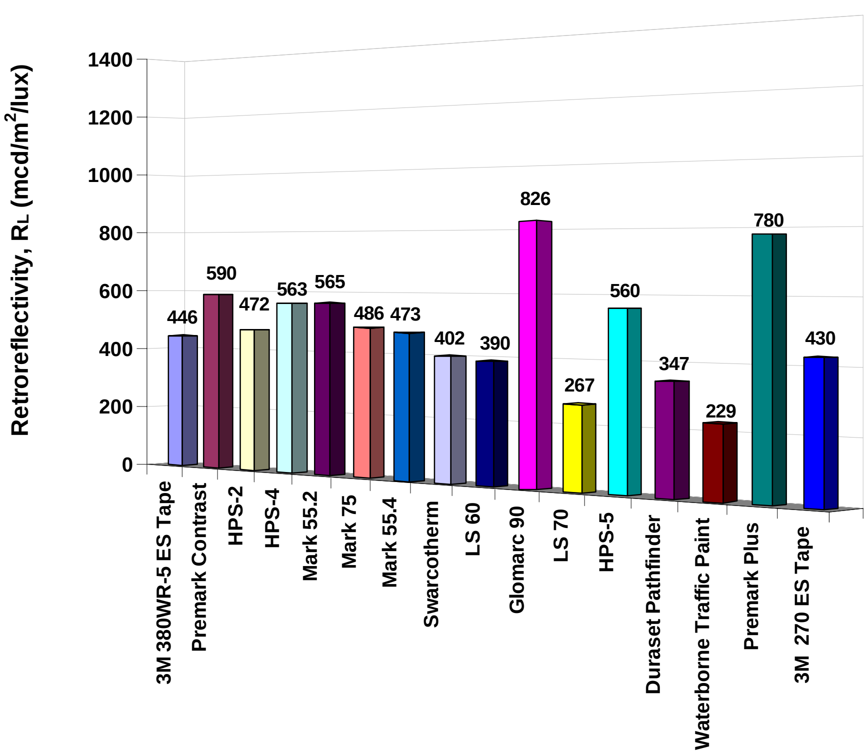

Figure (6.6): 1-yr Retroreflectivity of White Left Lane Lines.

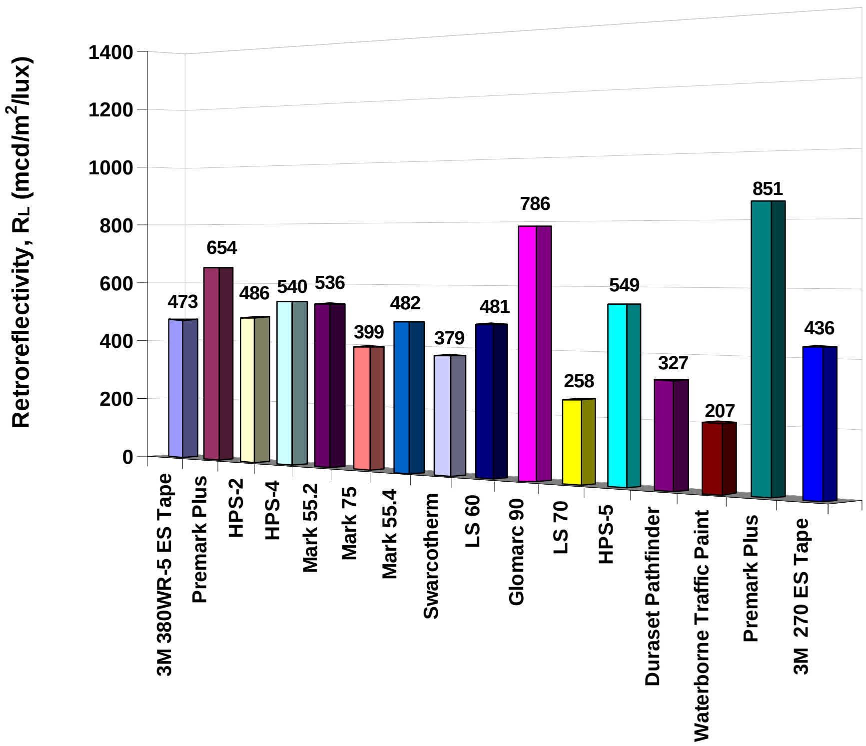

Figure (6.7): 1-yr Retroreflectivity of White Right Lane Lines.

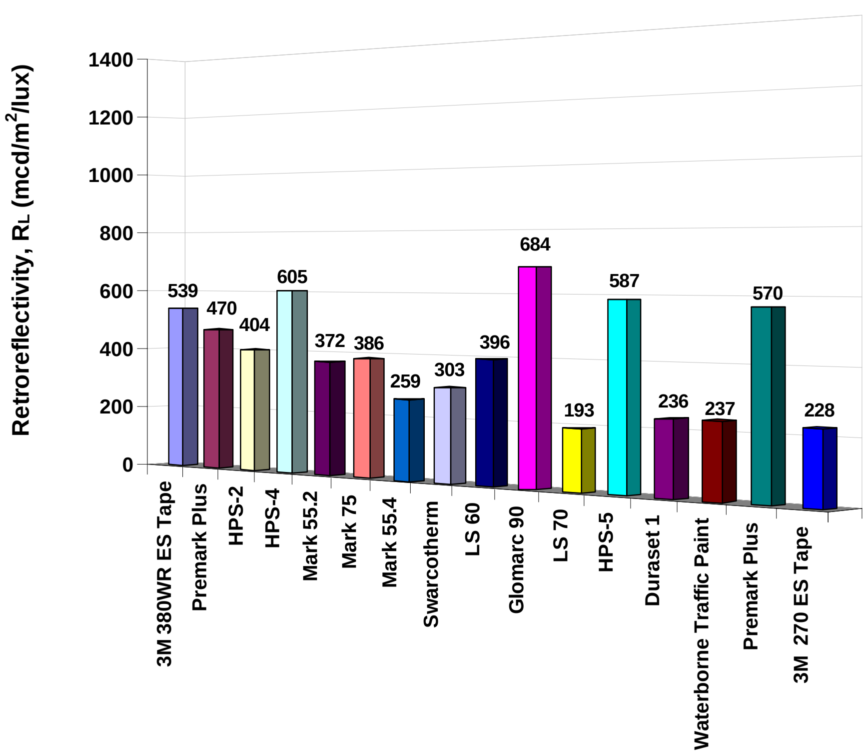

Figure (6.8): 1-yr Retroreflectivity of White Right Edge Lines.

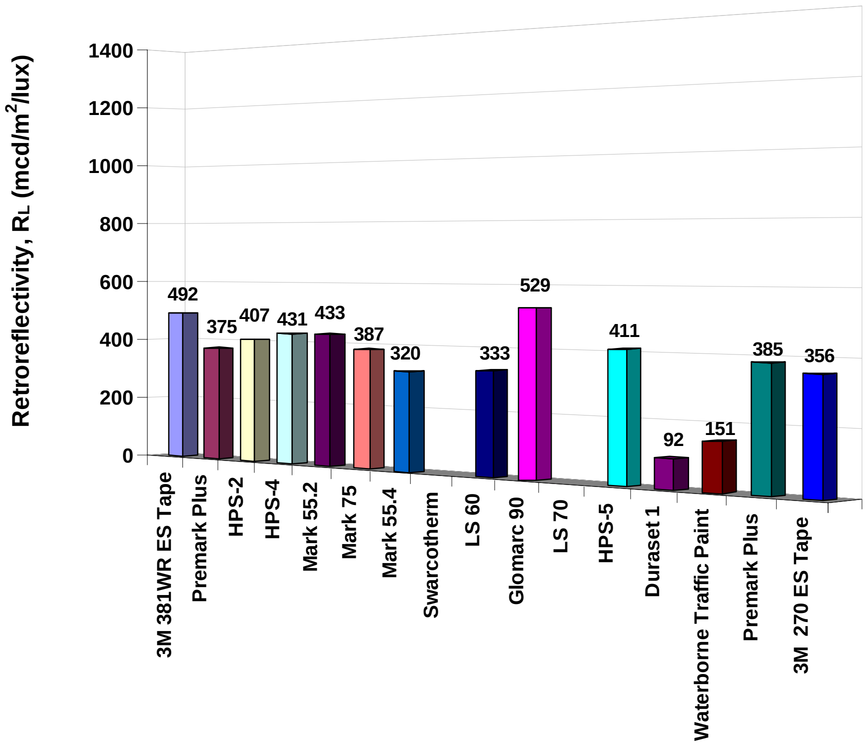

Figure (6.9): 2-yr Retroreflectivity of Yellow Left Edge Lines.

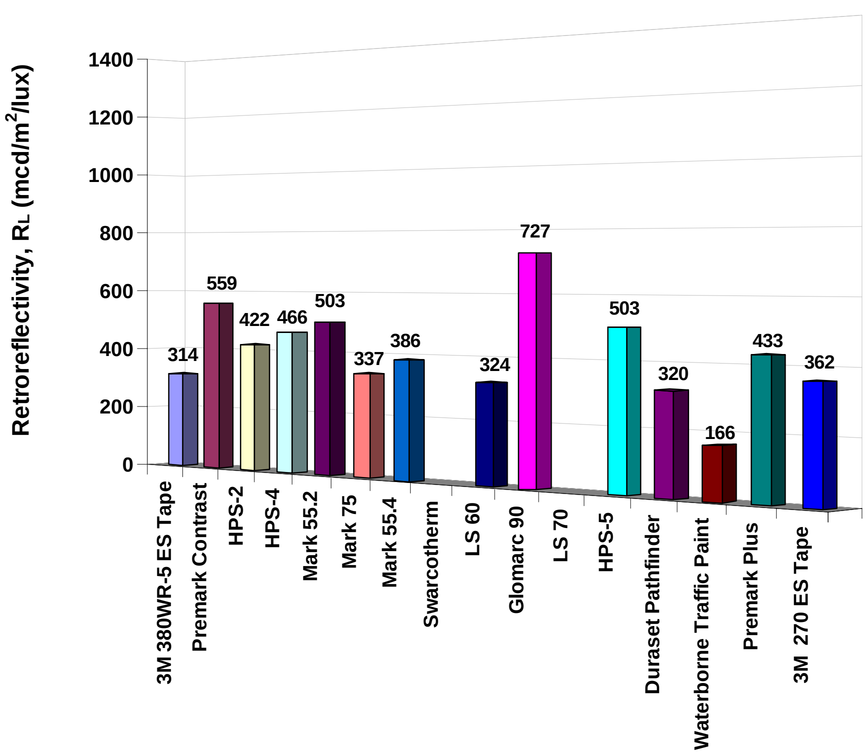

Figure (6.10): 2-yr Retroreflectivity of White Left Lane Lines.

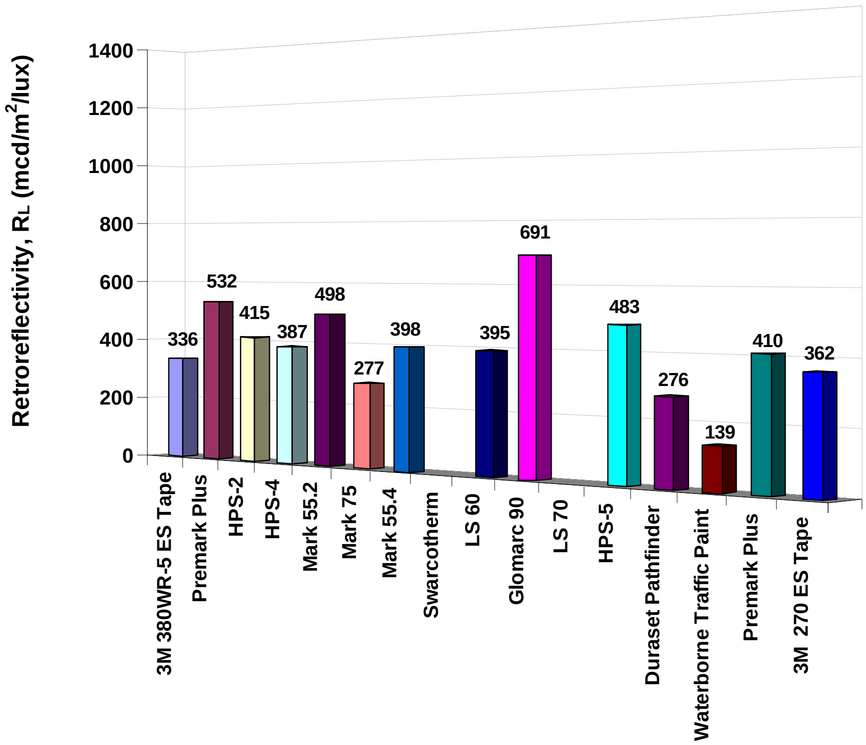

Figure (6.11): 2-yr Retroreflectivity of White Right Lane Lines.

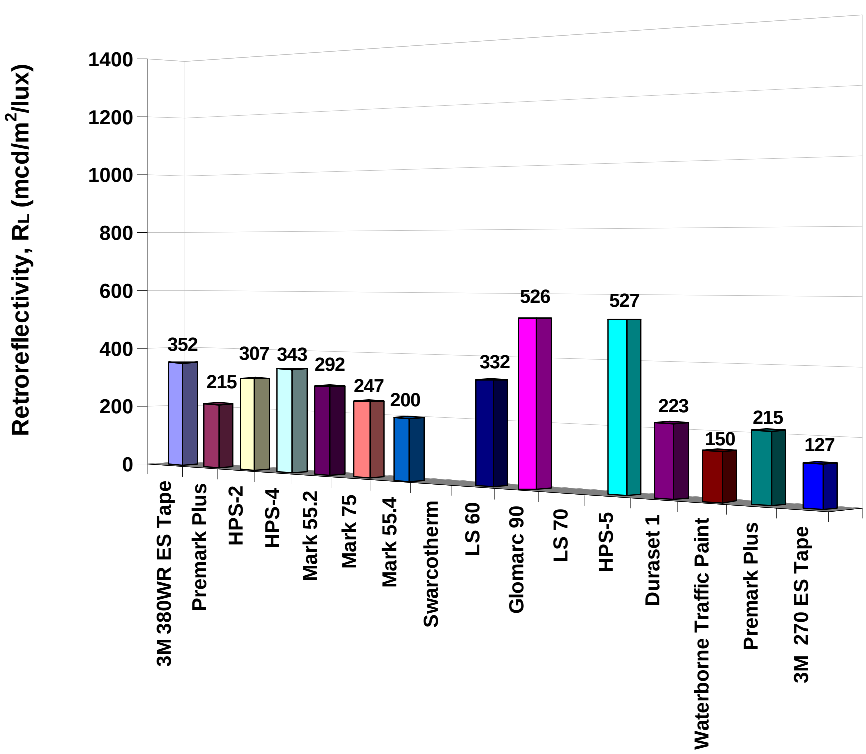

Figure (6.12): 2-yr Retroreflectivity of White Right Edge Lines.

6.2.2 Color

Table (6.2) presents a comparison between color readings measured using a MiniScan XE Plus colorimeter and ODOT color specifications for yellow and white markings (Table 3.1). Figures (6.13) through (6.28) provide similar comparisons in a graphical form whereby both color readings defined by their *x* and *y* CIE coordinates and ODOT color specifications for yellow and white markings are plotted on CIE chromaticity diagrams.

To determine whether a color reading meets ODOT specifications or not, a set of formula were defined in Microsoft Excel to mathematically determine whether the color reading falls within the corresponding specification box or not. Results from the Excel spreadsheet were visually verified using Figures (6.13) through (6.28) and summarized in Table (6.2).

The following is a summary of conclusions made based on the analysis of the color data and observations made during the periodic evaluations:

- All materials met ODOT specifications for white color markings. However, several materials (Premark Plus, Premark Contrast, HPS-2, HPS-4, Mark 75, LS 60, Glomarc 90, LS 70, HPS-5, and Ennis Fast Dry Waterborne Traffic Paint) did not meet the specifications for yellow color. Among these materials HPS-2, Mark 75, Glomarc 90, HPS-5, LS 70, and Ennis Fast Dry Waterborne Traffic Paint failed to meet ODOT yellow color specifications towards the end of the second year, but were acceptable before that time.
- The change in color took place in the following forms:
    - Overheating of preformed thermoplastics such as Premark Plus, which resulted in an irreversible color change of yellow markings;
    - Dirt accumulation and color darkening especially at the location of large glass beads that got knocked off as was the case for HPS-4 modified urethane;
    - Change in color due to ultraviolet light sensitivity as was the case for some epoxy materials;
    - Color fading as was the case for Mark 75, Glomarc 90, and HPS-5 polyurea products; and
    - Significant wearing of marking material and subsequent loss of color such as was the case for Ennis fast dry waterborne traffic paint.
- It is noted though that some of the evaluated materials such as HPS-2, HPS-4, Mark 55.2, and Mark 55.4 had acceptable yellow color even though their color readings were very close

to the bottom corner of ODOT yellow color specification box. On the other hand, some of the evaluated materials had white color readings well within ODOT white color specification box, but did not have acceptable color contrast, which calls into question the applicability of ODOT color specifications to determine pavement marking daytime color acceptability.

Table (6.2): Comparison between Color Readings Measured using a MiniScan XE Plus Colorimeter and ODOT Color Specifications for Yellow and White Markings.

	Did Color Reading Meet ODOT Color Specifications throughout the Evaluation Period?			
Product	**Y-LEL[1]**	**W-LLL[2]**	**W-RLL[3]**	**W-REL[4]**
3M 380WR ES	Yes	Yes	Yes	Yes
Premark Contrast	**No**	Yes	Yes	Yes
HPS-2	**No**†	Yes	Yes	Yes
HPS-4	**No**	Yes	Yes	Yes
Mark 55.2	Yes	Yes	Yes	Yes
Mark 75	**No**†	Yes	Yes	Yes
Mark 55.4	Yes	Yes	Yes	Yes
Swarcotherm	Yes	Yes	Yes	Yes
LS 60	**No**	Yes	Yes	Yes
Glomarc 90	**No**†	Yes	Yes	Yes
LS 70	**No**	Yes	Yes	Yes
HPS-5	**No**†	Yes	Yes	Yes
Ennis MMA	Yes	Yes	Yes	Yes
Ennis Paint	**No**†	Yes	Yes	Yes
Premark Plus	**No**	Yes	Yes	Yes
3M 270 ES	Yes	Yes	Yes	Yes

[1] Y-LEL: Yellow Left Edge Line
[2] W-LLL: White Left Lane Line
[3] W-RLL: White Right Lane Line
[4] W-REL: White Right Edge Line
† Color failed to meet ODOT specifications towards the end of the second year, but was acceptable before that time.

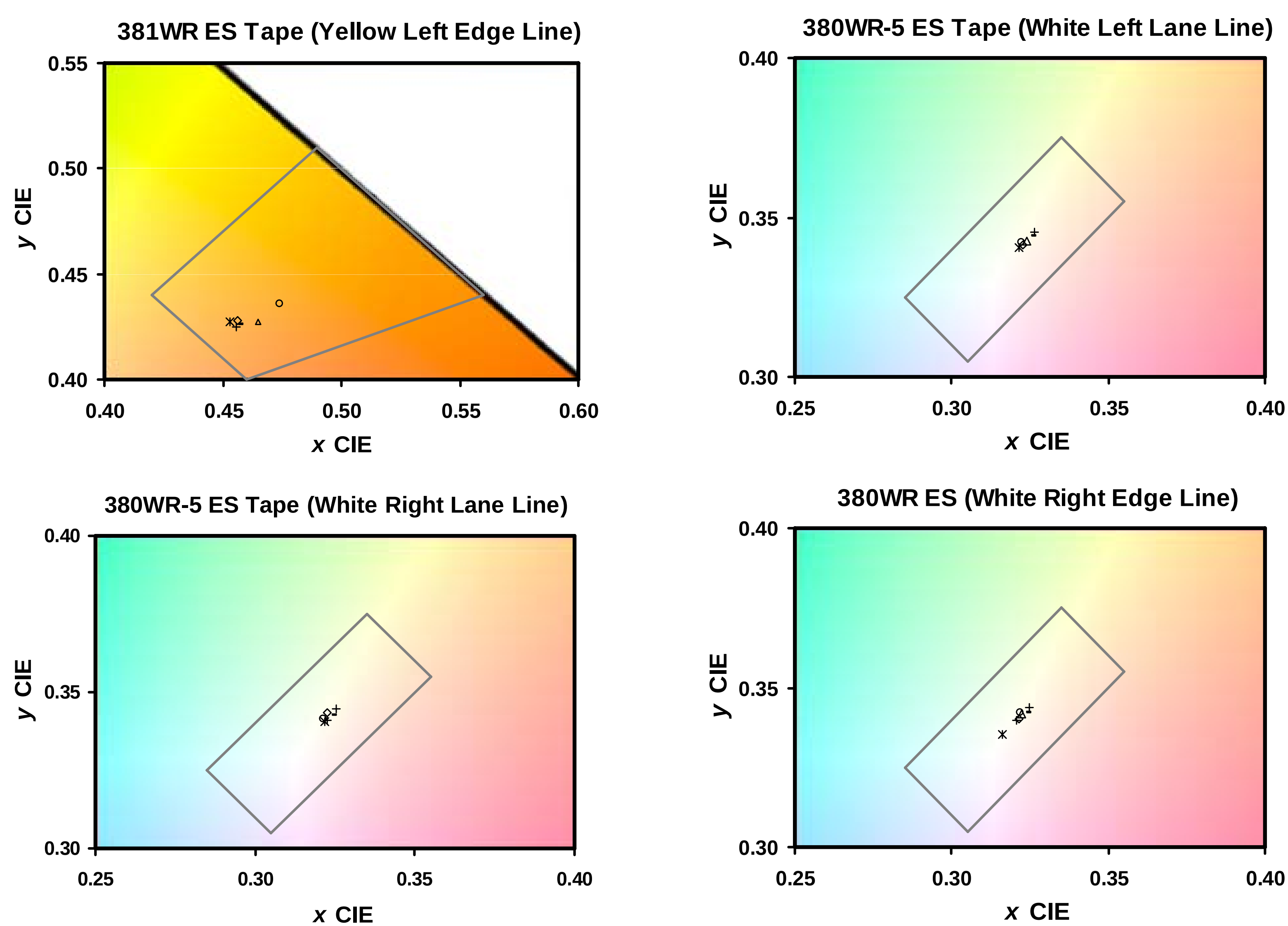

Figure (6.13): Comparison between 3M 380WR ES and 380WR-5 ES Series Tapes Color and ODOT Color Specifications for Yellow and White Markings (Bridge Deck #1).

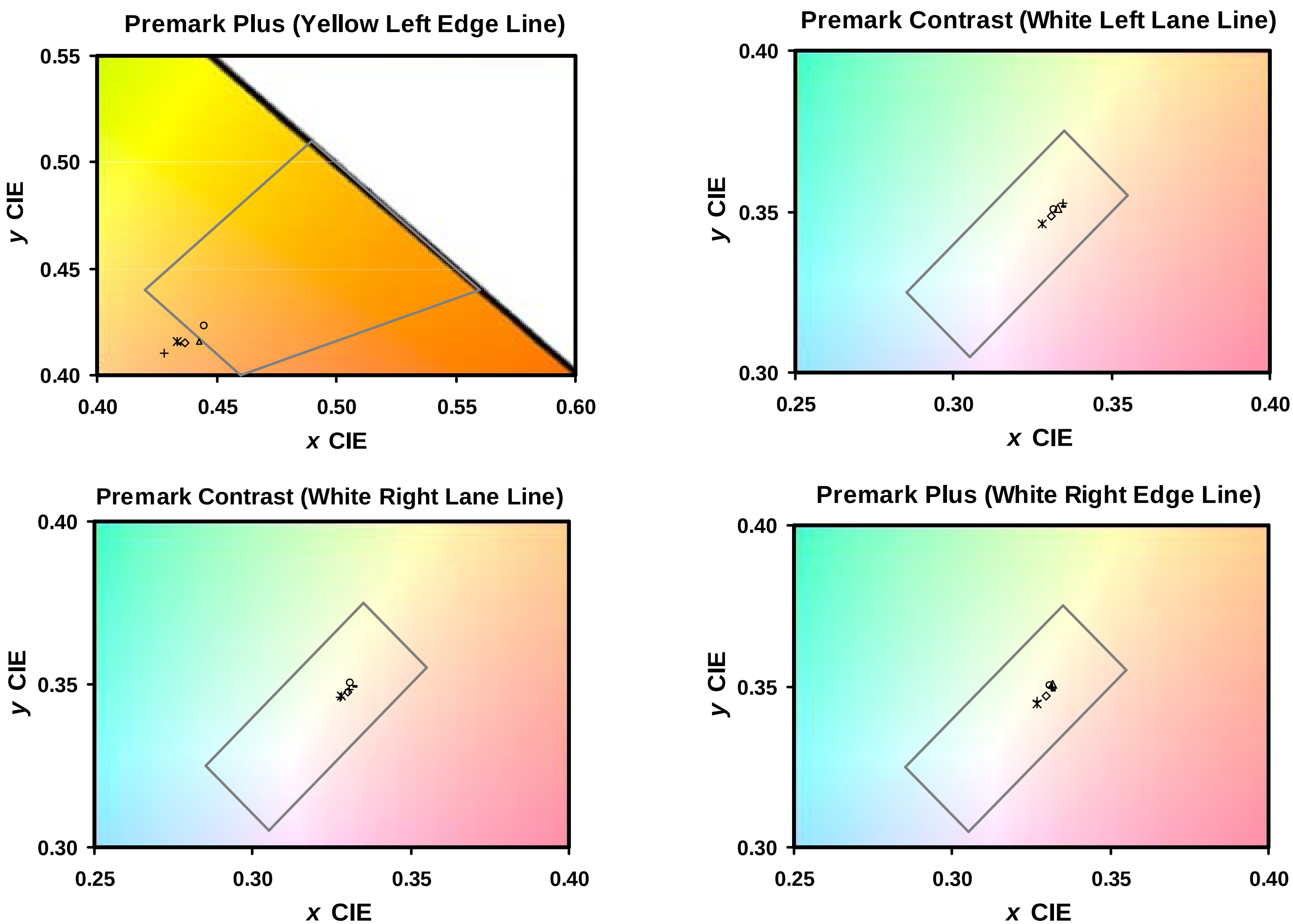

Figure (6.14): Comparison between Premark Plus and Premark Contrast Color and ODOT Color Specifications for Yellow and White Markings (Bridge Deck #2).

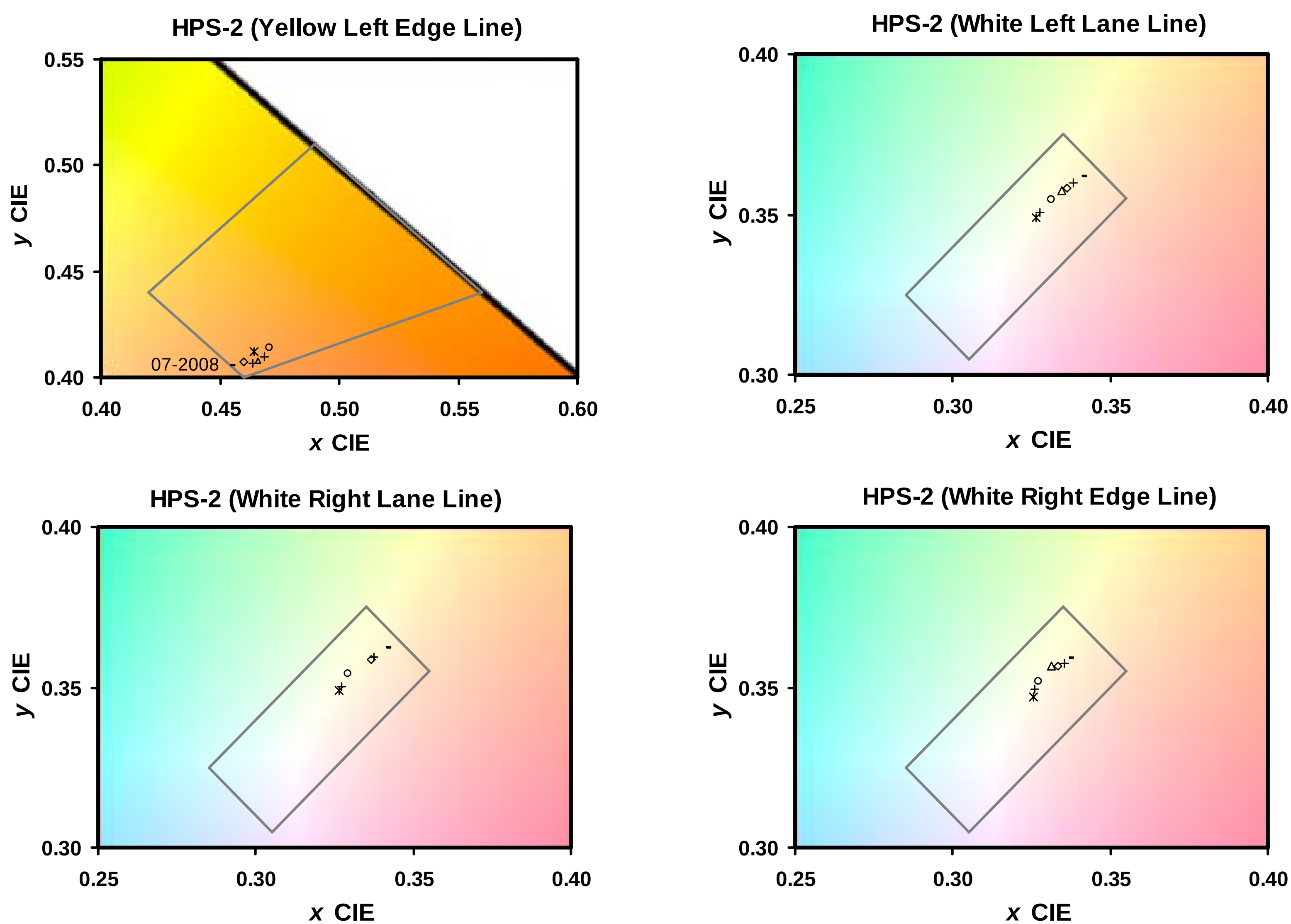

Figure (6.15): Comparison between HPS-2 Color and ODOT Color Specifications for Yellow and White Markings (Bridge Deck #3).

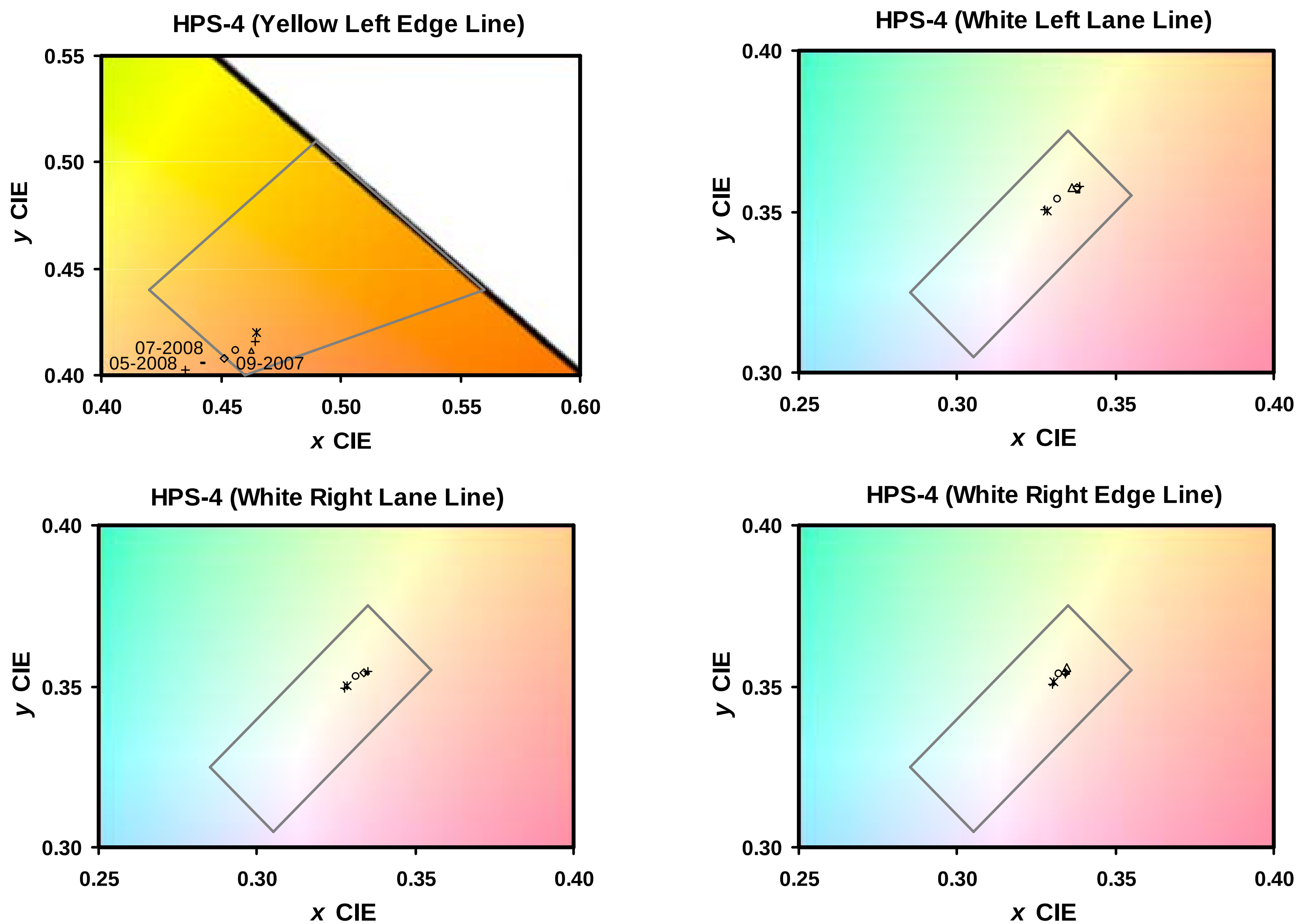

Figure (6.16): Comparison between HPS-4 Color and ODOT Color Specifications for Yellow and White Markings (Bridge Deck #4).

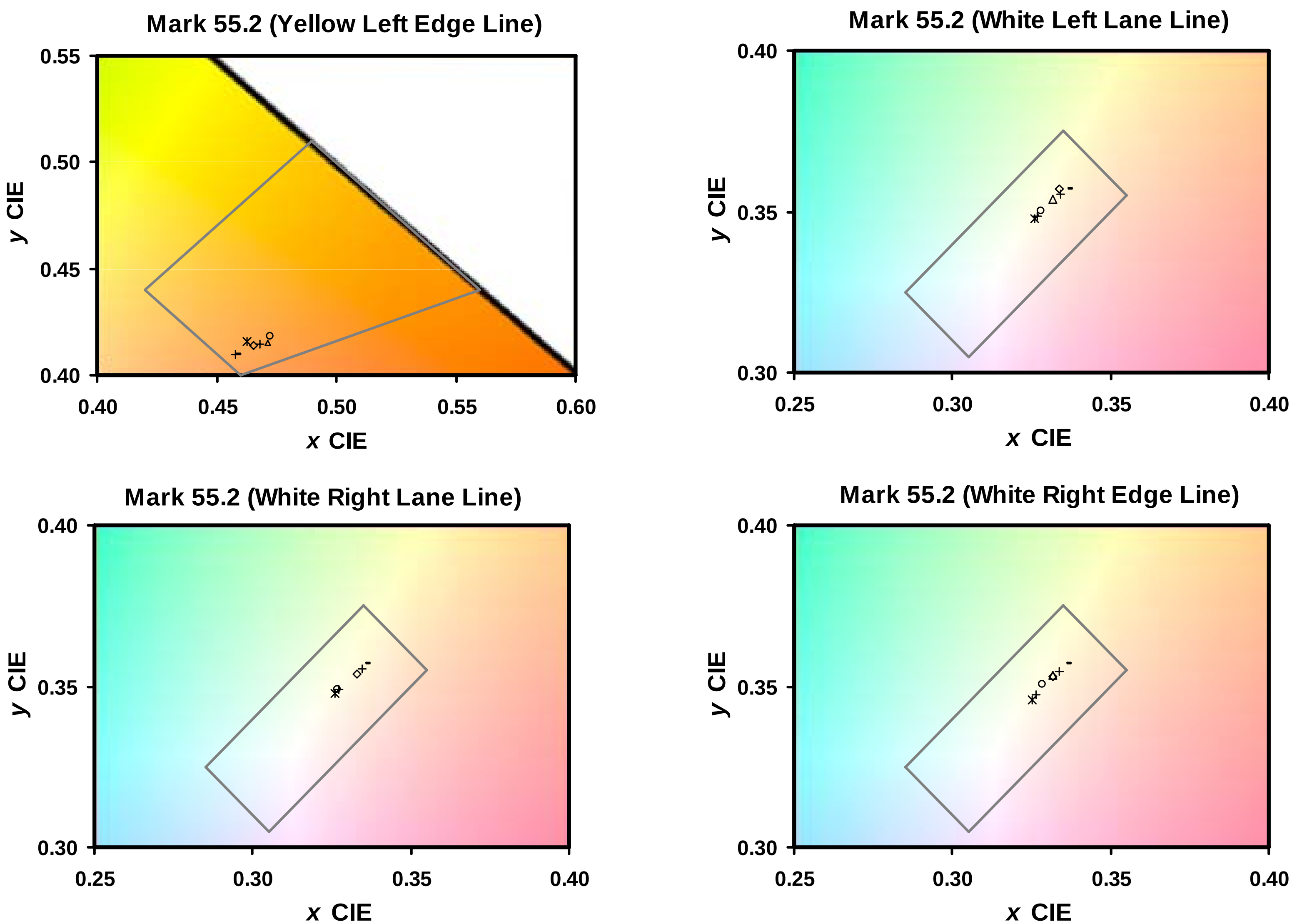

Figure (6.17): Comparison between Mark 55.2 Color and ODOT Color Specifications for Yellow and White Markings (Bridge Deck #5).

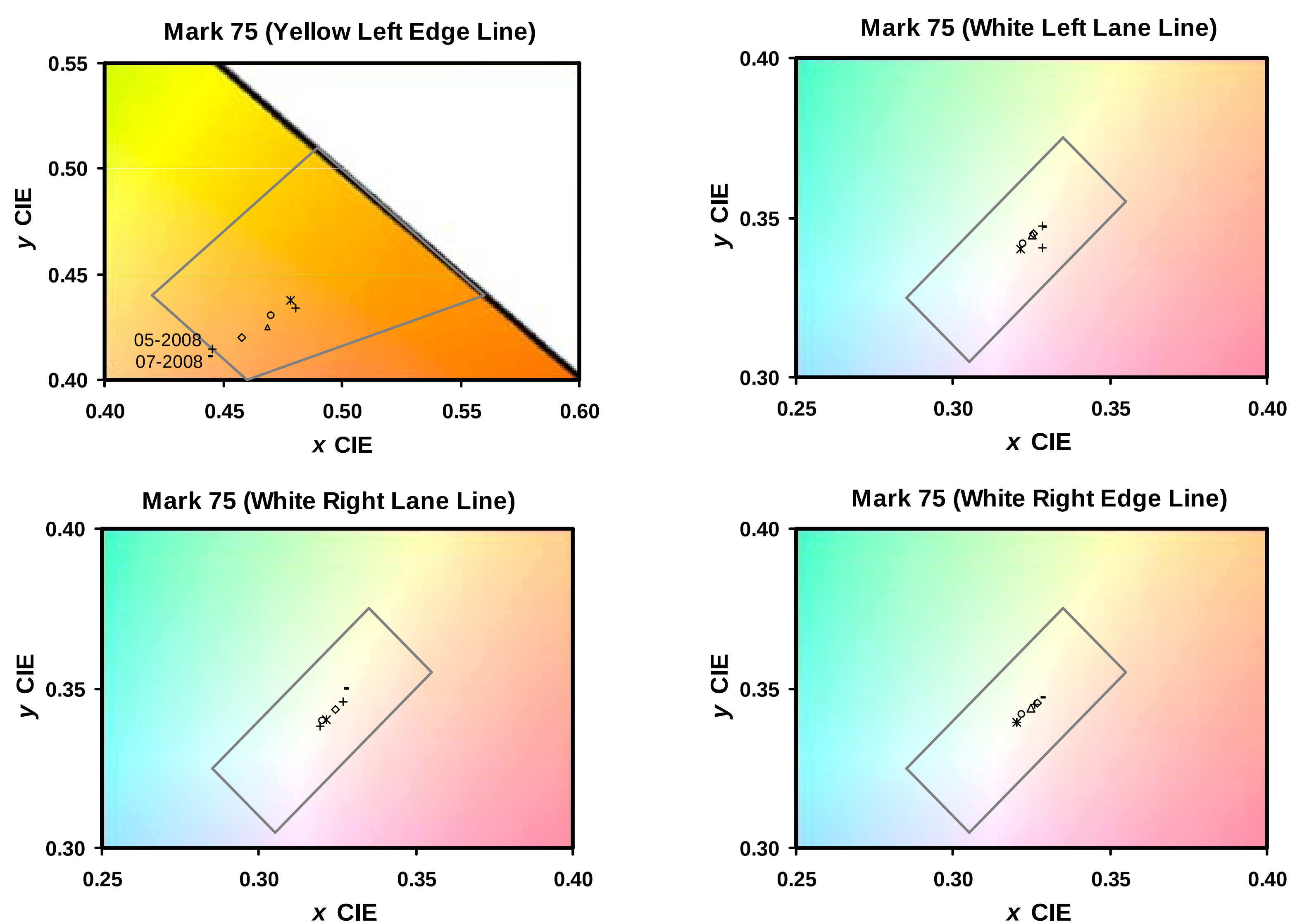

Figure (6.18): Comparison between Mark 75 Color and ODOT Color Specifications for Yellow and White Markings (Bridge Deck #6).

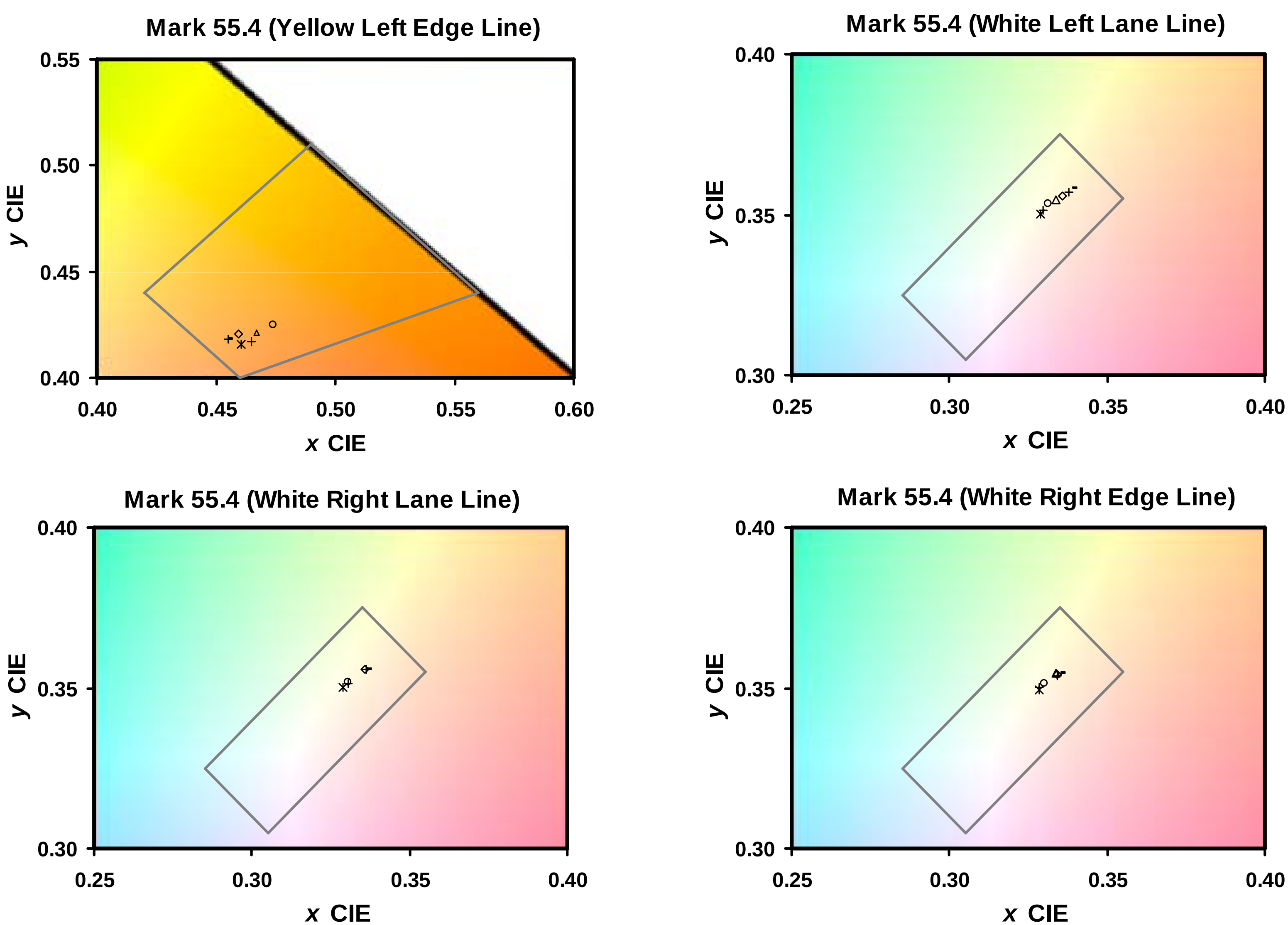

Figure (6.19): Comparison between Mark 55.4 Color and ODOT Color Specifications for Yellow and White Markings (Bridge Deck #7).

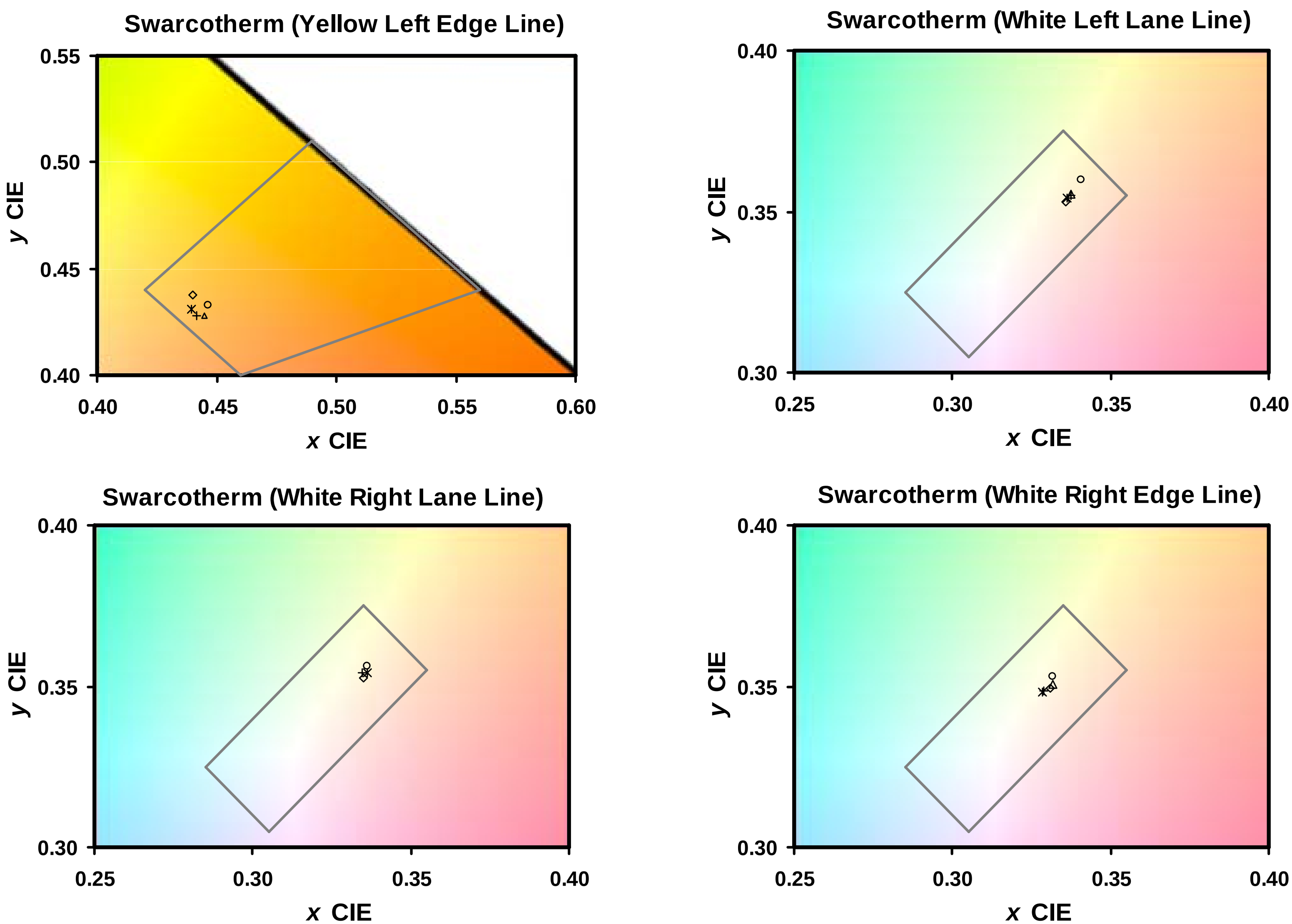

Figure (6.20): Comparison between Swarcotherm Color and ODOT Color Specifications for Yellow and White Markings (Bridge Deck #8).

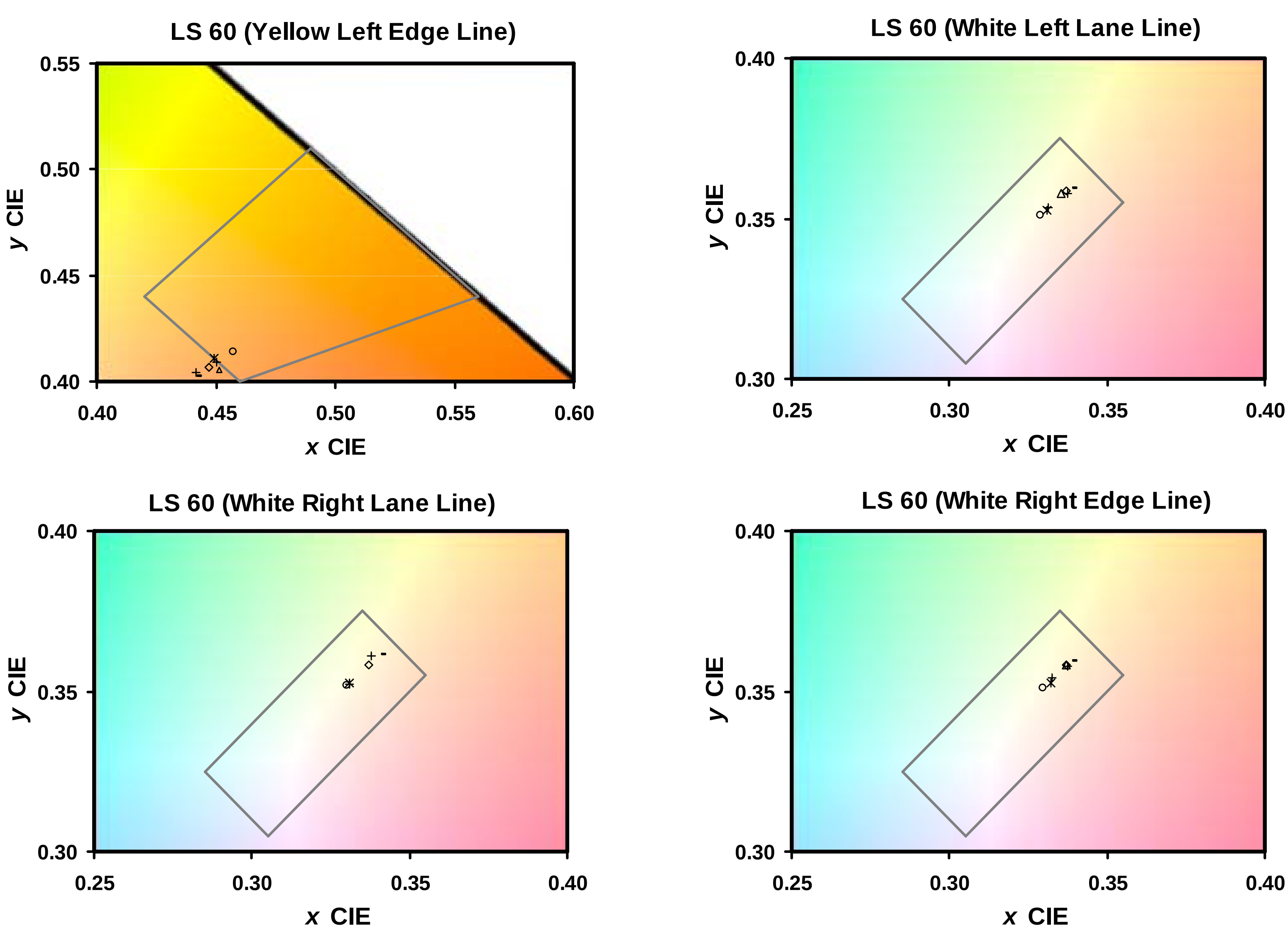

Figure (6.21): Comparison between LS 60 Color and ODOT Color Specifications for Yellow and White Markings (Bridge Deck #9).

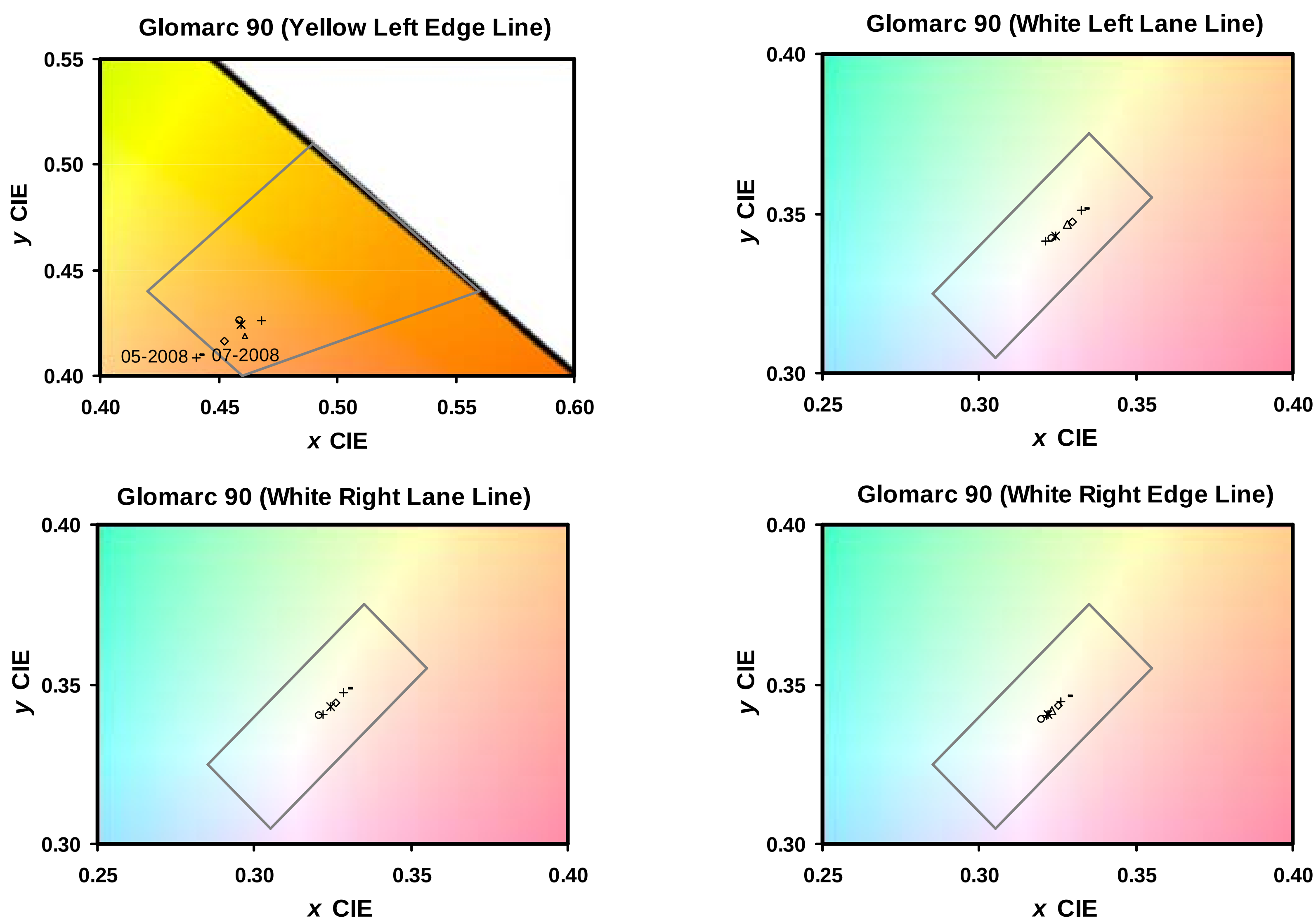

Figure (6.22): Comparison between Glomarc 90 Color and ODOT Color Specifications for Yellow and White Markings (Bridge Deck #10).

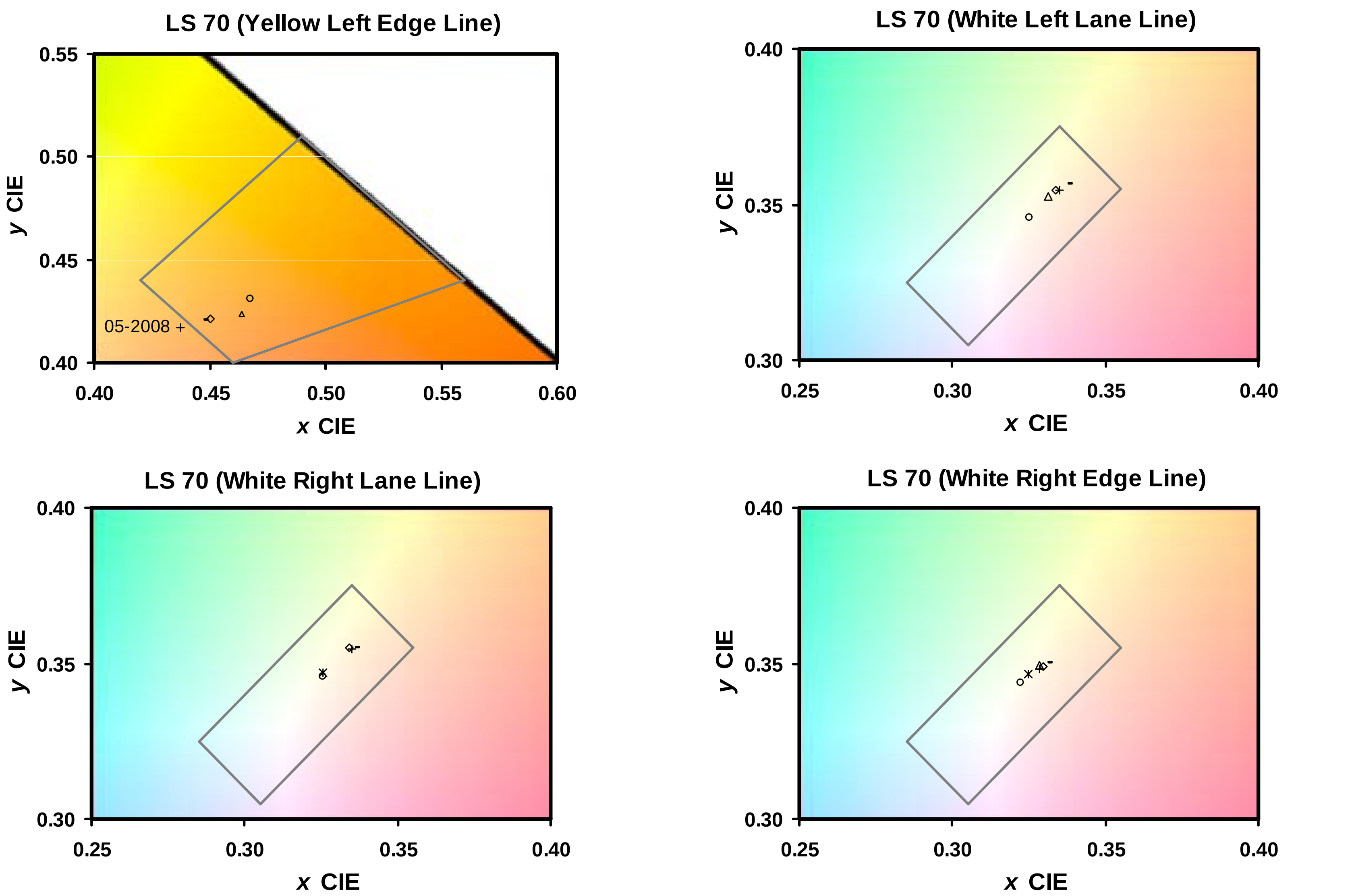

Figure (6.23): Comparison between LS 70 Color and ODOT Color Specifications for Yellow and White Markings (Bridge Deck #11).

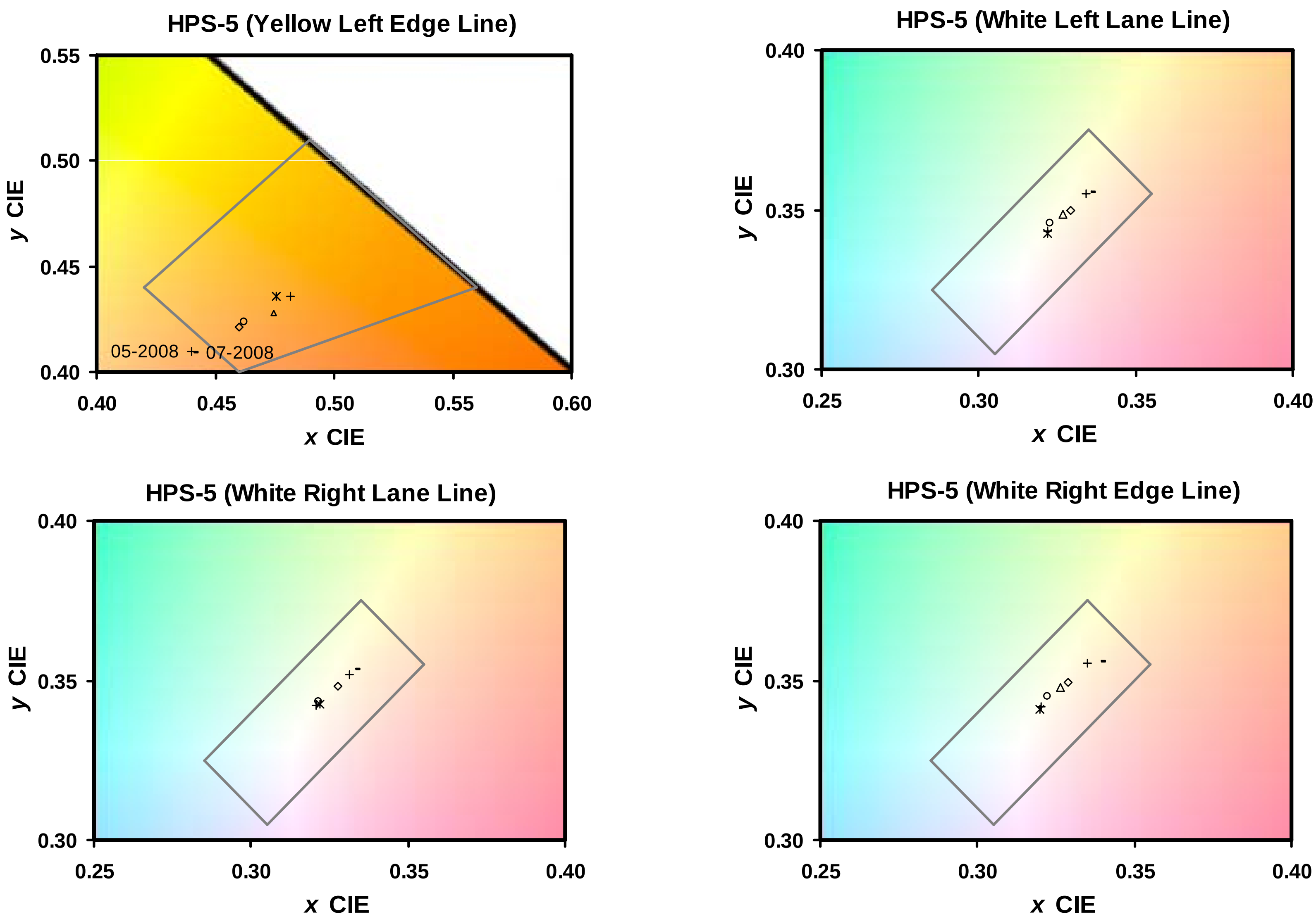

Figure (6.24): Comparison between HPS-5 Color and ODOT Color Specifications for Yellow and White Markings (Bridge Deck #12).

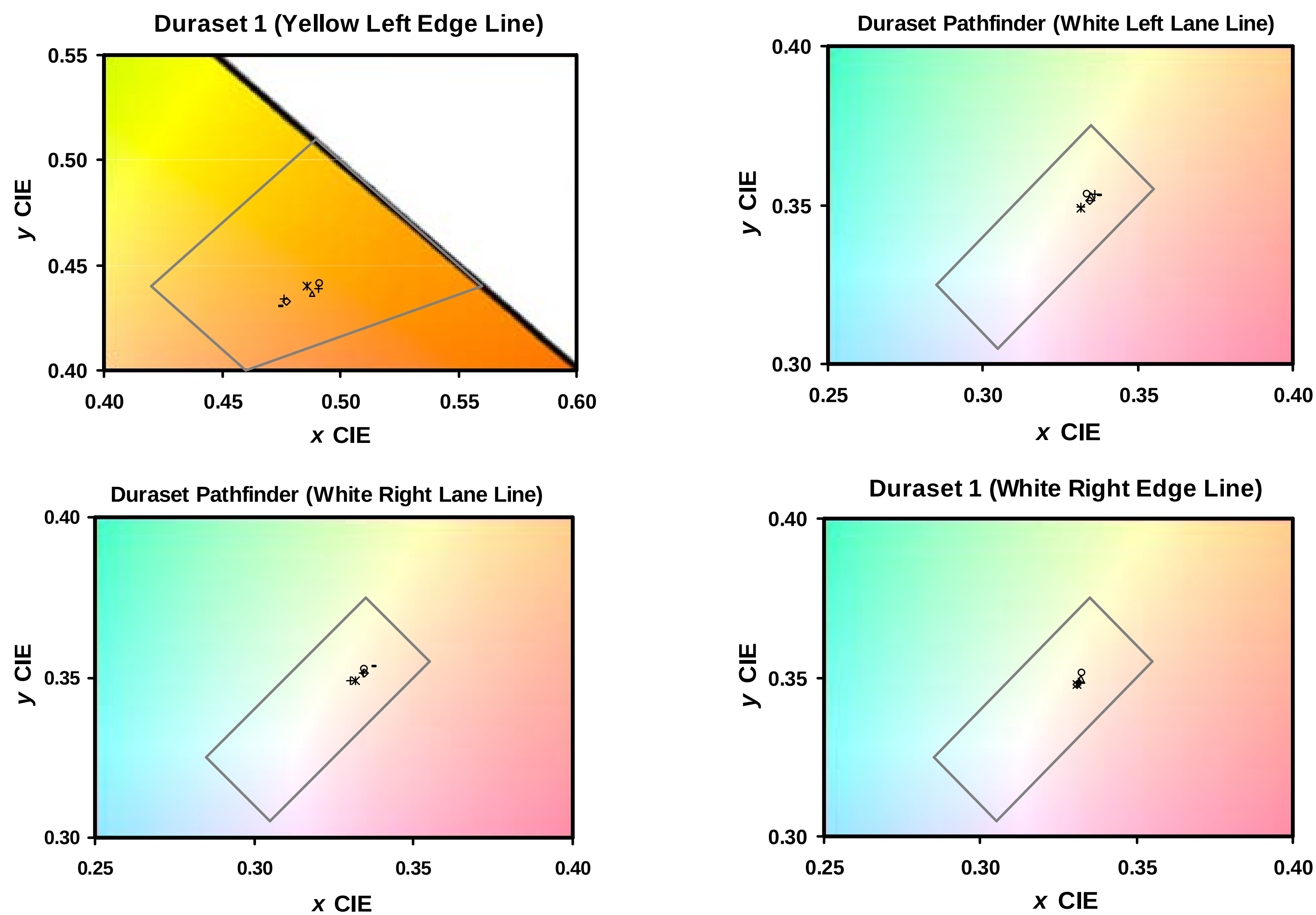

Figure (6.25): Comparison between Duraset 1 and Duraset Pathfinder Color and ODOT Color Specifications for Yellow and White Markings (Bridge Deck #13).

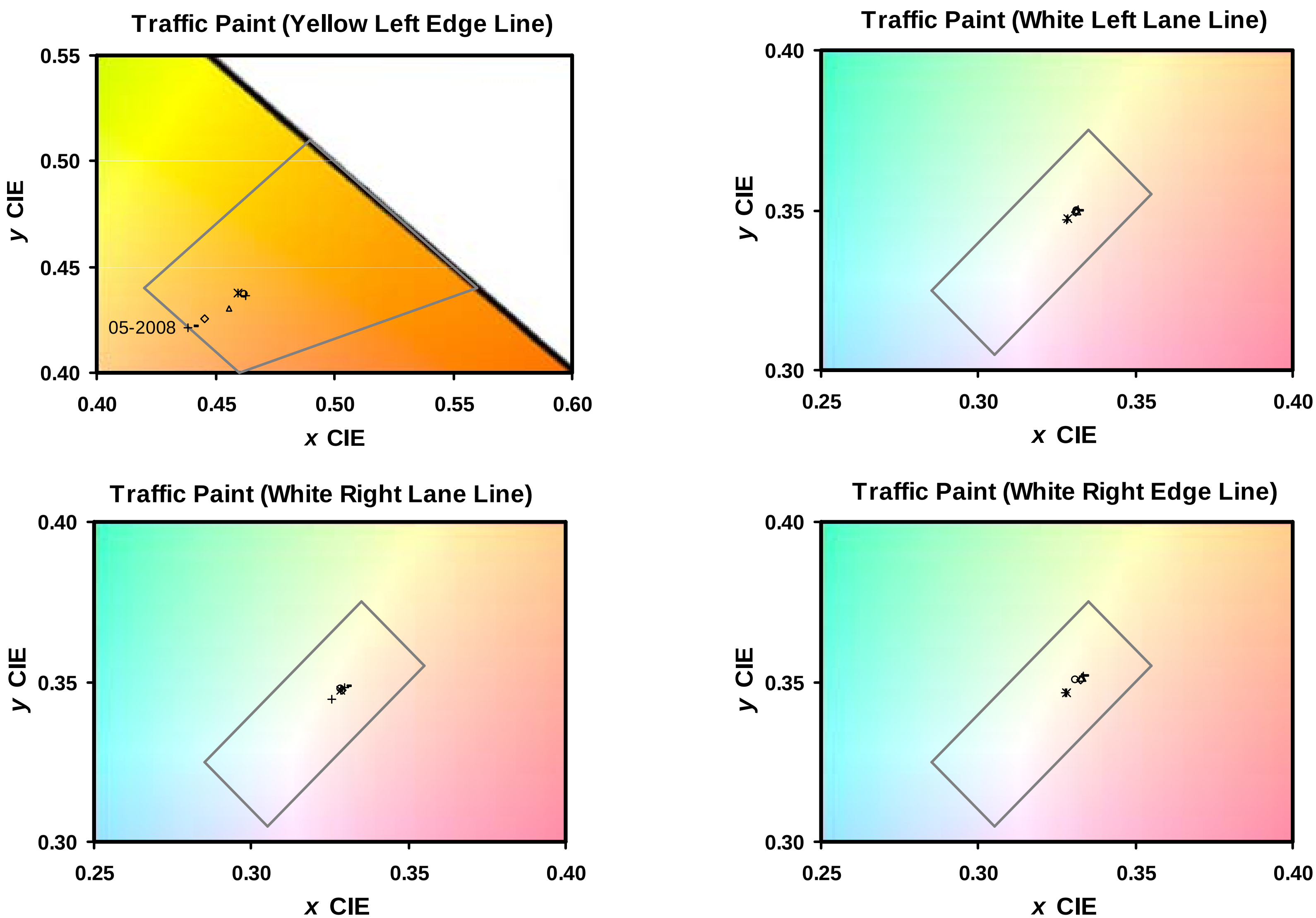

Figure (6.26): Comparison between Waterborne Traffic Paint Color and ODOT Color Specifications for Yellow and White Markings (Bridge Deck #14).

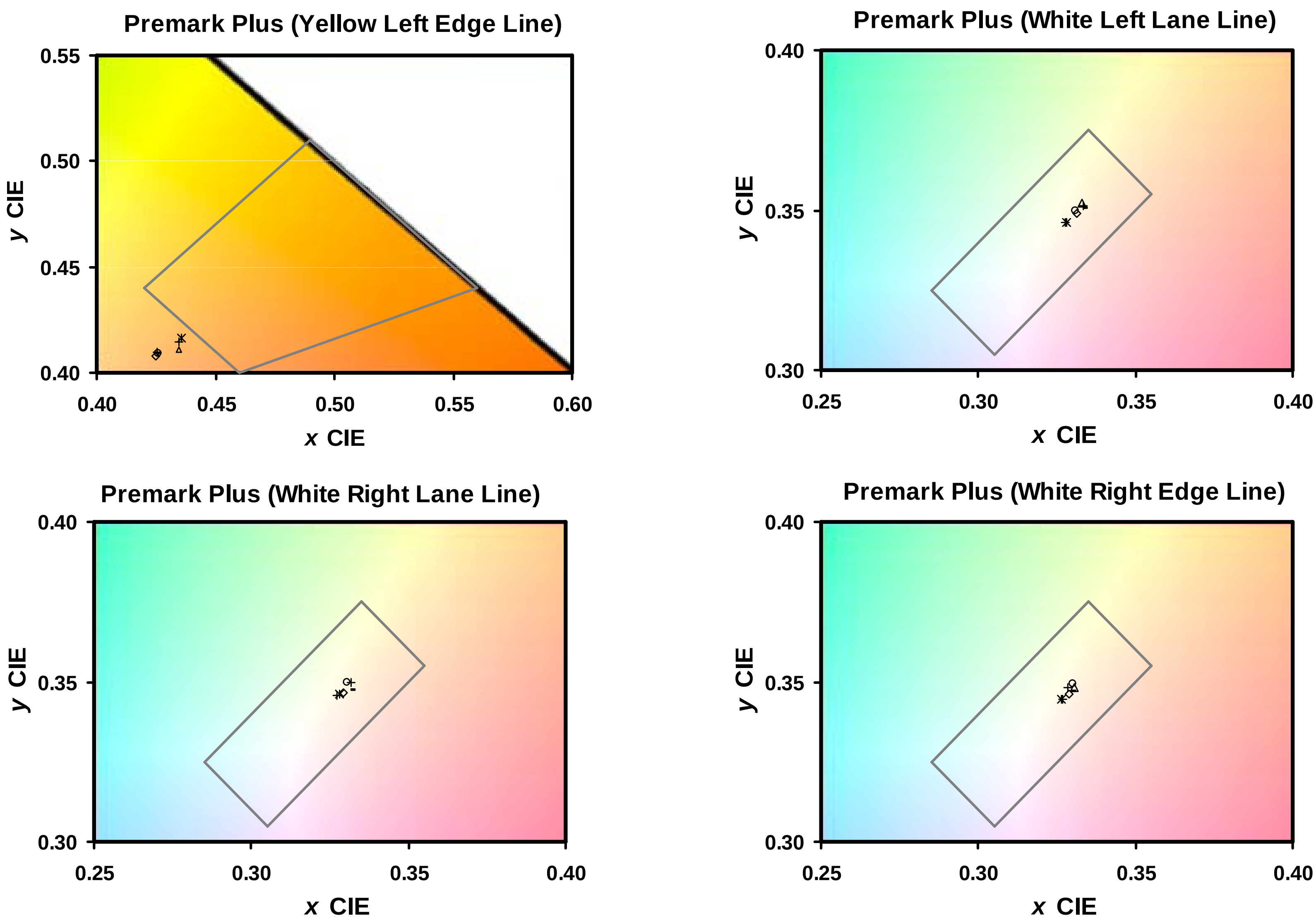

Figure (6.27): Comparison between Premark Plus Color and ODOT Color Specifications for Yellow and White Markings (Bridge Deck #15).

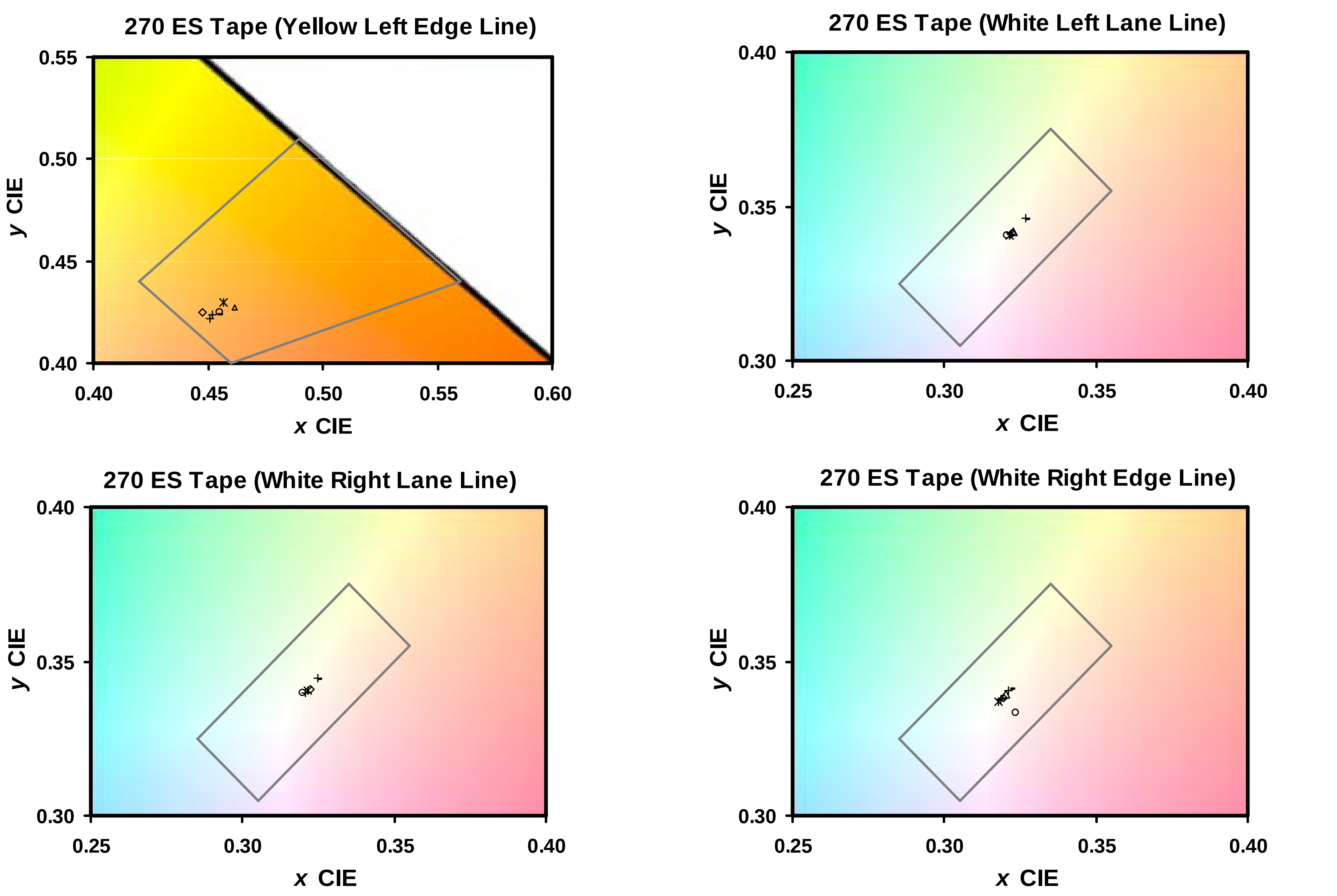

Figure (6.28): Comparison between 3M 270 ES Tape Color and ODOT Color Specifications for Yellow and White Markings (Bridge Deck #16).

6.2.3 Durability, Daytime Color, and Nighttime Visibility

The following is a summary of conclusions based on the subjective evaluation results presented in Tables (6.3), (6.4), and (6.5) for durability, daytime color, and nighttime visibility, respectively, and observations made during the periodic evaluations:

- Durability
  - The durability of most materials did not drop below a rating of ten over the duration of this project, which is probably due to installing all materials in 150-mil (3.8 mm) grooves. As mentioned earlier, this groove depth was selected in order to ensure that all traces of the old thermoplastic have been completely removed; and thus, eliminate its effect on the newly installed products.
  - Among the materials that failed due to durability are:
    - Swarcotherm alkyd: Swarcotherm showed significant debonding in less than nine months (i.e., immediately following the first winter) even though a sealer was used. From that point forward the percentage of material remaining decreased rapidly to the point that almost all lines were gone prior to the end of 2007 (i.e., in less than eighteen months). Swarcotherm debonded in relatively thick pieces, which were rich in glass beads. As such, retroreflectivity readings made on the remaining portions of the lines were acceptable. In fact, retroreflectivity increased over time due to the intermixed glass beads for all lines except for the white right edge line, which probably was subjected to more abrasion from traffic and snow plows.
    - LS 70 fast cure hybridized epoxy: An incorrect formulation of LS 70 was originally installed on June 6, 2006. This material was later removed and reinstalled on November 28, 2006. Nonetheless, this material had very poor durability. It fully debonded from the approach slab of the right edge line in less than nine months; and failed on the rest of the lines shortly thereafter. The drop in durability was also accompanied by a noticeable darkening in color.
    - Premark Contrast when a sealer was not used: As per Flint Trading, Inc. installation instructions for Premark Contrast, a sealer must be used when installing this material on concrete surfaces. In order to investigate the effect of not using this sealer on the performance of this material, it was decided to install Premark Contrast with and without sealer on the left and right lane lines, respectively, of Bridge Deck # 2. As

expected, the Premark Contrast that was applied without sealer had poor durability (Figure 6.29); durability dropped to eight in about one year and to five in about two years; whereas the Premark Contrast that was applied with sealer remained intact throughout the duration of this study (Figure 6.30), which emphasizes the importance of using the recommended sealer on concrete surfaces prior to the application of this material.

- In general, the durability rating procedure was found satisfactory when more than five percent of the material is lost enough to drop the durability rating to nine or less. However, it was limited in its ability to identify materials that had minor chipping of less than or equal to five percent since durability is reported as an integer and any material with ninety five percent or more remaining is rated as a ten. Given that chipping in its initial stages is an early sign of failure, a photo log of chipped materials was collected and maintained for documentation purposes.
- Among the materials that had minor signs of chipping at the end of the second year are:
  - Ennis fast dry waterborne traffic paint: At the end of the second year, this material wore down significantly, but not to the point where the concrete surface got exposed. Therefore, it continued to receive a durability rating of ten even though it was approaching its service life. Still, this material exceeded its expected service life, which is probably due to being installed in groove.
  - Glomarc 90 polyurea: This material showed very minor signs of chipping as early as the end of the first year. The rate of chipping, however, did not increase during the second year, which explains why this material continued to receive a durability rating of ten.

- Daytime color
  - Table (6.4) presents initial, 1-yr, and 2-yr daytime color ratings for all materials. Materials with daytime color ratings less than 7 are highlighted.
  - The three polyurea products (Mark 75, Glomarc 90, and HPS-5) had the highest daytime color ratings over the duration of this study; followed by the epoxies (excluding LS 70), the modified urethane, the methyl methacrylate, the waterborne traffic paint, and the durable tapes; then the conventional and preformed thermoplastics.
  - One advantage of the polyurea products in terms of color is that they had a dirt repellent

glossy surface, which provided them with better contrast with the underlying gray concrete surface and improved their color during winter when other lines were full of dirt and deicing salt.

- Different conclusions can be made based on these ratings than based on the color readings presented in Section (6.2.2).
  - As noticed in this table, the following yellow materials: HPS-2, HPS-4, Mark 75, LS 60, Glomarc 90, HPS-5, and Ennis Fast Dry Waterborne Traffic Paint received acceptable daytime color ratings even though they did not meet ODOT color specifications for yellow markings.
  - Meanwhile, the following white materials: 3M 380WR ES, Premark Plus, Premark Contrast, Swarcotherm alkyd, and LS 70 did not receive acceptable daytime color ratings even though they met ODOT color specifications for white markings.
  - The previous calls into question the ability of ODOT color specifications for white and yellow markings to differentiate between materials based on their daytime color when installed on Portland cement concrete surfaces.

- Nighttime visibility
  - The nighttime visibility evaluation consisted of rating three attributes of the pavement markings: uniformity (on a scale of 0 to 4), retroreflectivity (on a scale of 0 to 3), and nighttime color (on a scale of 0 to 3). The nighttime visibility rating was calculated as the sum of the three ratings for these three attributes.
  - Based on the previous, it is not expected that there will be high correlation between retroreflectivity readings measured using an LTL-X retroreflectometer and nighttime visibility ratings since the latter accounts for retroreflectivity uniformity and nighttime color.
  - Among the materials that received low nighttime visibility ratings (less than seven) are:
    - Premark Plus and Premark Contrast: These two materials had very bright and very dark areas that are believed to be the result of excessive heating during installation. Furthermore, white and yellow lines appeared dull and grayish in color.
    - Swarcotherm alkyd: This material had initially low nighttime visibility and yellow appeared grayish. However, its visibility improved once the lines wore down due to abrasion from traffic and the intermixed glass beads got exposed. Nevertheless, this

material had very poor durability, which resulted in full detachment from the bridge deck surface in less than eighteen months.

- Ennis Duraset 1 methyl methacrylate: As mentioned previously, this material hardened in a relatively short period of time, which did not allow the surface applied glass beads to properly embed on its surface. As a result, this material had poor initial and retained retroreflectivity.
- Ennis fast dry waterborne paint: Following initial installation, this material had acceptable nighttime color and very uniform retroreflectivity. Over time, the performance of this material deteriorated especially on the yellow left edge line, which resulted in a drop in retroreflectivity with a subsequent reduction in nighttime visibility.

Table (6.3): Initial, 1-yr, and 2-yr Durability Ratings
(Durability Ratings Less than 10 are Highlighted).

		Durability Rating (on a Scale of 0 to 10)			
Product	**Age**	**Y-LEL[1]**	**W-LLL[2]**	**W-RLL[3]**	**W-REL[4]**
3M 380WR ES	Initial	10	10	10	10
	1-yr	10	10	10	10
	2-yr	10	10	10	10
Premark Contrast	Initial	10	10	10	10
	1-yr	10	10	**8†**	10
	2-yr	10	10	**5†**	10
HPS-2	Initial	10	10	10	10
	1-yr	10	10	10	10
	2-yr	10	10	10	10
HPS-4	Initial	10	10	10	10
	1-yr	10	10	10	10
	2-yr	10	10	10	10
Mark 55.2	Initial	10	10	10	10
	1-yr	10	10	10	10
	2-yr	10	10	10	10
Mark 75	Initial	10	10	10	10
	1-yr	10	10	10	10
	2-yr	10	10	10	10
Mark 55.4	Initial	10	10	10	10
	1-yr	10	10	10	10
	2-yr	10	10	10	10
Swarcotherm	Initial	10	10	10	10
	1-yr	**9**	**9**	**8**	**8**
	2-yr	**0**	**0**	**0**	**0**

[1] Y-LEL: Yellow Left Edge Line
[2] W-LLL: White Left Lane Line
[3] W-RLL: White Right Lane Line
[4] W-REL: White Right Edge Line
† No sealer was used for this line

Table (6.3): Initial, 1-yr, and 2-yr Durability Ratings

(Durability Ratings Less than 10 are Highlighted); (Continued).

		Durability Rating (on a Scale of 0 to 10)			
Product	**Age**	**Y-LEL[1]**	**W-LLL[2]**	**W-RLL[3]**	**W-REL[4]**
LS 60	Initial	10	10	10	10
	1-yr	10	10	10	10
	2-yr	10	10	10	10
Glomarc 90	Initial	10	10	10	10
	1-yr‡	10	10	10	10
	2-yr‡	10	10	10	10
LS 70	Initial	10	10	10	10
	1-yr	10	10	**7**	**0**
	2-yr†	**0**	**4**	**3**	**0**
HPS-5	Initial	10	10	10	10
	1-yr	10	10	10	10
	2-yr	10	10	10	10
Ennis MMA	Initial	10	10	10	10
	1-yr	10	10	10	10
	2-yr	10	10	10	10
Ennis Paint	Initial	10	10	10	10
	1-yr	10	10	10	10
	2-yr‡	10	10	10	10
Premark Plus	Initial	10	10	10	10
	1-yr	10	10	10	10
	2-yr	10	10	10	10
3M 270 ES	Initial	10	10	10	10
	1-yr	10	10	10	10
	2-yr	10	10	10	10

[1] Y-LEL: Yellow Left Edge Line
[2] W-LLL: White Left Lane Line
[3] W-RLL: White Right Lane Line
[4] W-REL: White Right Edge Line
† Ratings are based on the last periodic evaluation
‡ Minor signs of chipping were evident

Table (6.4): Initial, 1-yr, and 2-yr Daytime Color Ratings

(Daytime Color Ratings Less than 7 are Highlighted).

		Average Daytime Color Rating (on a Scale of 0 to 10)			
Product	**Age**	**Y-LEL[1]**	**W-LLL[2]**	**W-RLL[3]**	**W-REL[4]**
3M 380WR ES	Initial	8.3	8.4	9.1	8.9
	1-yr	8.2	8.2	7.5	7.0
	2-yr	7.7	8.0	8.0	**6.9**
Premark Contrast	Initial	8.0	7.9	8.9	8.6
	1-yr	7.7	8.3	7.3	**6.5**
	2-yr	**6.1**	7.4	**6.4**	**6.3**
HPS-2	Initial	9.3	7.6	8.4	8.4
	1-yr	9.2	8.8	8.0	8.0
	2-yr	8.7	8.4	8.4	8.4
HPS-4	Initial	9.4	8.4	9.3	9.1
	1-yr	9.5	9.0	8.3	8.7
	2-yr	9.0	8.1	7.9	7.9
Mark 55.2	Initial	9.4	8.6	10.0	10.0
	1-yr	9.7	9.3	8.8	9.0
	2-yr	9.9	9.1	8.9	9.0
Mark 75	Initial	9.6	10.0	10.0	10.0
	1-yr	9.7	10.0	9.7	9.7
	2-yr	9.7	9.7	9.1	9.3
Mark 55.4	Initial	9.0	9.0	9.1	9.1
	1-yr	9.2	9.2	8.2	8.0
	2-yr	9.4	9.0	8.4	8.4
Swarcotherm	Initial	8.0	**5.4**	7.1	7.9
	1-yr	7.2	**6.2**	**6.0**	**6.5**
	2-yr[†]	**--**	**--**	**--**	**--**

[1] Y-LEL: Yellow Left Edge Line
[2] W-LLL: White Left Lane Line
[3] W-RLL: White Right Lane Line
[4] W-REL: White Right Edge Line
[†] Material failed due to durability in less than two years

Table (6.4): Initial, 1-yr, and 2-yr Daytime Color Ratings

(Daytime Color Ratings Less than 7 are Highlighted); (Continued).

		Average Daytime Color Rating (on a Scale of 0 to 10)			
Product	**Age**	**Y-LEL[1]**	**W-LLL[2]**	**W-RLL[3]**	**W-REL[4]**
LS 60	Initial	8.9	9.1	8.9	8.9
	1-yr	8.7	8.8	8.3	8.7
	2-yr	9.0	8.7	8.1	7.9
Glomarc 90	Initial	9.7	8.9	9.3	9.4
	1-yr	9.8	9.7	9.5	9.7
	2-yr	9.3	9.6	9.3	9.3
LS 70	Initial	8.9	9.7	9.6	9.3
	1-yr	8.3	7.8	**6.3**	**4.5**
	2-yr[†]	**6.7**	**5.8**	**5.7**	**3.3**
HPS-5	Initial	9.7	9.7	9.4	9.6
	1-yr	9.2	9.2	9.2	9.2
	2-yr	9.4	9.3	9.1	9.3
Ennis MMA	Initial	9.3	8.9	9.0	8.9
	1-yr	9.0	8.5	8.7	8.2
	2-yr	9.4	9.0	7.9	7.9
Ennis Paint	Initial	8.9	8.3	8.9	8.9
	1-yr	7.2	7.2	7.8	7.3
	2-yr	7.4	8.1	7.9	7.9
Premark Plus	Initial	8.4	8.9	9.4	9.3
	1-yr	**5.8**	**6.5**	**5.5**	**6.2**
	2-yr	**5.0**	7.3	**6.6**	**6.1**
3M 270 ES	Initial	9.6	9.4	9.0	9.0
	1-yr	8.8	9.0	9.0	8.8
	2-yr	9.4	9.9	9.0	7.9

[1] Y-LEL: Yellow Left Edge Line
[2] W-LLL: White Left Lane Line
[3] W-RLL: White Right Lane Line
[4] W-REL: White Right Edge Line
[†] Ratings are based on the last periodic evaluation; LS 70 was almost 19 months old

Table (6.5): Initial, 1-yr, and 2-yr Nighttime Visibility Ratings (Nighttime Visibility Ratings Less than 7 are Highlighted).

		Average Nighttime Visibility Rating (on a Scale of 0 to 10)			
Product	**Age**	**Y-LEL[1]**	**W-LLL[2]**	**W-RLL[3]**	**W-REL[4]**
3M 380WR ES	Initial	8.7	8.7	9.7	9.4
	1-yr	8.0	8.7	9.0	8.8
	2-yr	8.8	8.7	8.5	8.3
Premark Contrast	Initial	**5.6**	7.3	**5.7**	**6.1**
	1-yr	**5.8**	7.7	7.7	7.3
	2-yr	7.5	7.8	**6.3**	**5.0**
HPS-2	Initial	10.0	9.3	9.1	9.1
	1-yr	9.2	9.5	9.0	8.8
	2-yr	9.8	10.0	10.0	10.0
HPS-4	Initial	10.0	9.9	10.0	10.0
	1-yr	9.2	9.7	10.0	10.0
	2-yr	9.5	9.7	9.8	9.3
Mark 55.2	Initial	10.0	10.0	10.0	10.0
	1-yr	9.5	10.0	9.7	10.0
	2-yr	9.8	10.0	10.0	10.0
Mark 75	Initial	9.7	10.0	10.0	10.0
	1-yr	9.7	9.8	9.5	9.7
	2-yr	10.0	10.0	9.8	9.8
Mark 55.4	Initial	9.9	10.0	10.0	10.0
	1-yr	9.5	9.5	9.3	9.2
	2-yr	9.7	9.8	9.8	9.5
Swarcotherm	Initial	**6.1**	7.7	9.0	9.0
	1-yr	**6.7**	8.0	7.3	7.0
	2-yr[†]	**--**	**--**	**--**	**--**

[1] Y-LEL: Yellow Left Edge Line
[2] W-LLL: White Left Lane Line
[3] W-RLL: White Right Lane Line
[4] W-REL: White Right Edge Line
[†] Material failed due to durability in less than two years

Table (6.5): Initial, 1-yr, and 2-yr Nighttime Visibility Ratings
(Nighttime Visibility Ratings Less than 7 are Highlighted); (Continued).

		Average Nighttime Visibility Rating (on a Scale of 0 to 10)			
Product	**Age**	**Y-LEL[1]**	**W-LLL[2]**	**W-RLL[3]**	**W-REL[4]**
LS 60	Initial	9.7	9.4	9.3	9.1
	1-yr	8.8	9.3	8.8	8.5
	2-yr	8.3	9.0	9.2	8.7
Glomarc 90	Initial	10.0	10.0	10.0	10.0
	1-yr	9.5	9.3	10.0	10.0
	2-yr	9.8	10.0	10.0	10.0
LS 70	Initial	9.0	8.9	8.7	9.1
	1-yr	9.5	9.0	8.2	7.5
	2-yr†	**--**	**--**	**--**	**--**
HPS-5	Initial	8.9	9.9	10.0	10.0
	1-yr	9.3	9.5	9.8	9.5
	2-yr	10.0	10.0	10.0	10.0
Ennis MMA	Initial	**3.7**	9.4	9.3	**6.4**
	1-yr	**4.0**	8.7	8.0	**6.5**
	2-yr	**5.3**	9.5	8.7	**5.8**
Ennis Paint	Initial	7.7	9.1	9.1	9.4
	1-yr	7.3	8.0	8.3	8.3
	2-yr	**6.7**	7.5	7.5	8.0
Premark Plus	Initial	**5.9**	9.7	9.3	8.4
	1-yr	7.0	8.7	9.0	7.8
	2-yr	**6.2**	7.3	**6.2**	**4.3**
3M 270 ES	Initial	9.9	10.0	10.0	10.0
	1-yr	9.2	9.7	9.7	9.2
	2-yr	9.5	9.7	9.0	7.5

[1] Y-LEL: Yellow Left Edge Line
[2] W-LLL: White Left Lane Line
[3] W-RLL: White Right Lane Line
[4] W-REL: White Right Edge Line
† Material failed due to durability in less than two years

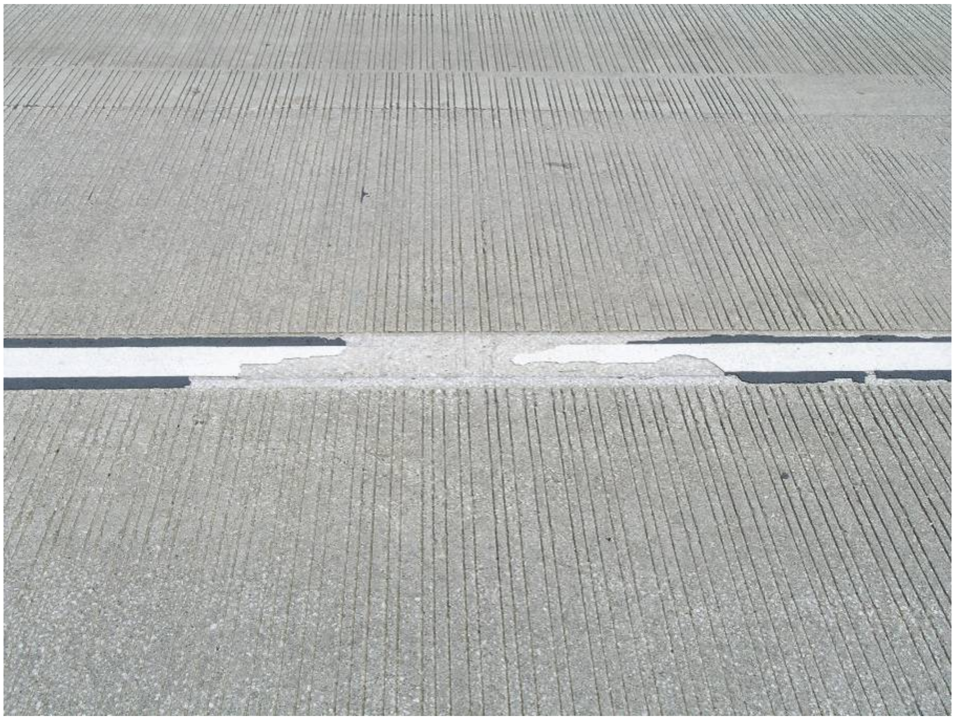

Figure (6.29): Premark Contrast without Sealer
(Bridge Deck # 2, Right Lane Line, Two Years).

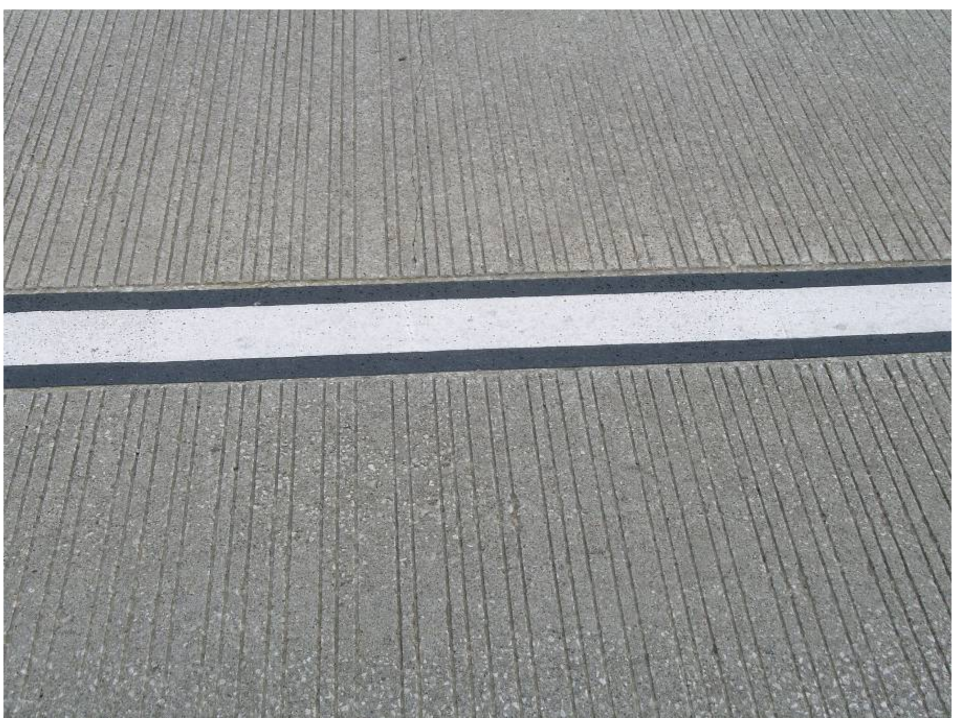

Figure (6.30): Premark Contrast with Sealer
(Bridge Deck # 2, Left Lane Line, Two Years).

6.2.4 Glass Bead Retention

Glass bead types and application rates have been presented previously in Chapter 4 Table (4.4). In summary, two types of glass beads meeting the requirements of AASHTO M247 for Type 1 and Type 4 were used (double drop) for all liquid markings (i.e., polyurea products, epoxies, and modified urethane) except Glomarc 90, for which two proprietary bead systems (Clusterbead® and Visibead® Plus II) were used; Type 1 glass beads were used for waterborne traffic paint, Duraset 1, and Duraset Pathfinder; and Type C glass beads were used for Swarcotherm thermoplastic. Some of these materials (Duraset 1, Duraset Pathfinder, and Swarcotherm thermoplastic) also contained intermixed glass beads. As for Flint preformed thermoplastic and 3M durable tapes, the reflective media in these products is controlled during production. Flint Premark Plus and Premark Contrast consist of large surface applied and small intermixed glass beads. Meanwhile, 3M durable tapes contain intermixed microcrystalline ceramic beads. 3M wet reflective tapes also include specially designed optics to improve wet retroreflectivity.

In this section, the percentage amount (by count) of the large glass beads (Clusterbead® and Visibead® Plus II for Glomarc 90 and Type 4 glass beads for the rest of the materials) lost after one and after two years are presented in Tables (6.6) and (6.7), respectively. These results are based on visual observations made during the periodic evaluations using a pocket magnifier; and verified using a photo log of close up pictures collected and maintained during the project (e.g., Figure 6.31). Based on the visual observations it was noticed that the amount of small glass beads lost was significantly lower than the amount of large glass beads lost. Therefore, only large glass bead retention results are presented in this section. Comparable results were obtained for right and left lane lines; therefore, average values are presented for both lines in one column.

Based on the results presented in Tables (6.6) and (6.7), it is concluded that polyurea products had the best glass bead retention followed by epoxies. Still, both materials had satisfactory glass bead retention. The previous conclusion resonates with the fact that some of the polyurea products such as HPS-5 had relatively high retained retroreflectivity even after two years.

On the other hand, HPS-4 modified urethane had very poor ability to retain large glass beads especially on the white right edge line, where traffic and subsequently drop in retroreflectivity were highest for all materials. Based on this observation, it was expected that this material would have very poor retained retroreflectivity on the white right edge line. Nevertheless, the retroreflectivity of this material on the white right edge line was slightly lower than that on the white lane lines, which lost significantly less large glass beads over the duration of this study. Based on the previous, it is concluded that higher small and large glass bead application rates than necessary were used during the installation of this material so that even when 60 to 70% of the large glass beads were lost, the small glass beads were still able to provide the required retroreflectivity. As a final point, the more significant effect of losing the large glass beads on the performance of HPS-4 was the change in color especially on the white right edge line which appeared darker than the rest of the lines when viewed from a close distance.

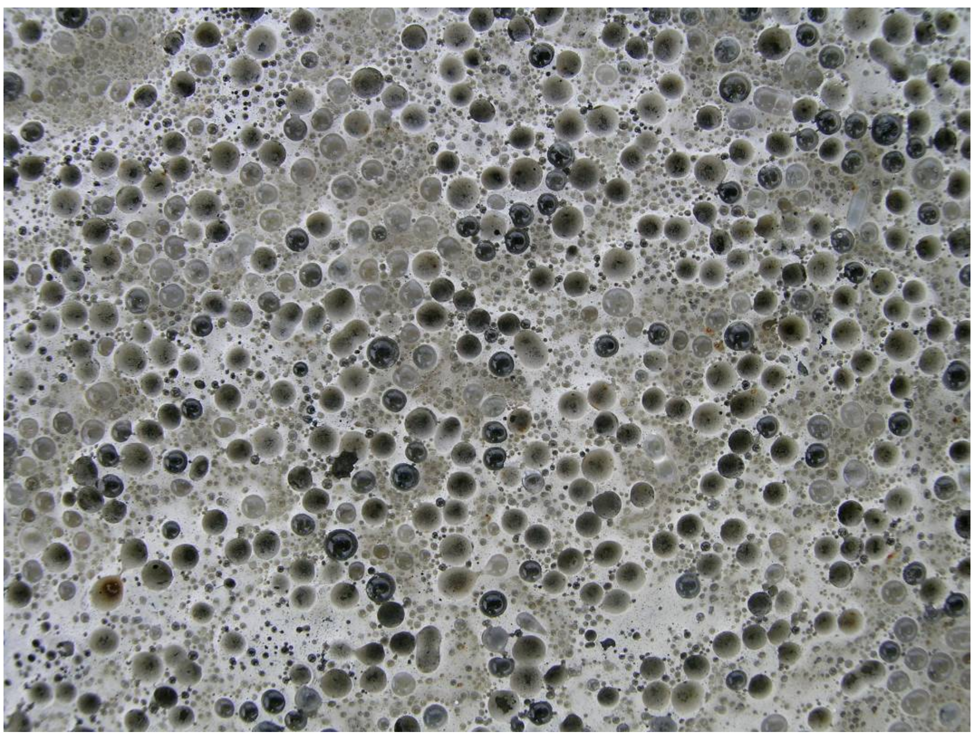

Figure (6.31): Example Close Up Picture of Two-Year Old HPS-4 Modified Urethane Installed on the White Right Edge Line of Bridge Deck # 4.

Table (6.6): Large Glass Bead Retention after One Year.

Material Type	Product Name	Glass Bead Type	Percentage of Large Glass Beads Lost (%)		
			Y-LEL	W-LL	W-REL
Modified Urethane	HPS-4	Type 4	2.5 – 5	5 – 7.5	**50 – 60**
Epoxy	HPS-2	Type 4	< 2.5	2.5 – 5	5 – 10
	Mark 55.2	Type 4	< 2.5	< 2.5	5 – 10
	Mark 55.4	Type 4	< 2.5	2.5 – 5	10 – 20
	LS 60	Type 4	< 2.5	2.5 – 5	2.5 – 5
	LS 70	Type 4	5 – 10	5 – 10	10 – 20
Polyurea	Mark 75	Type 4	< 2.5	< 2.5	5 – 10
	Glomarc 90	Clusterbead®	≈ 5	≈ 5	≈ 5
		Visibead® Plus II	< 2.5	< 2.5	2.5 – 5
	HPS-5	Type 4	< 2.5	< 2.5	< 2.5

[1] Y-LEL: Yellow Left Edge Line
[2] W-LL: White Lane Lines
[3] W-REL: White Right Edge Line

Table (6.7): Large Glass Bead Retention after Two Years.

			Percentage of Large Glass Beads Lost (%)		
Material Type	Product Name	Glass Bead Type	Y-LEL	W-LL	W-REL
Modified Urethane	HPS-4	Type 4	2.5 – 5	10 – 20	**60 – 70**
Epoxy	HPS-2	Type 4	2.5 – 5	2.5 – 5	**20 – 30**
	Mark 55.2	Type 4	< 2.5	2.5 – 5	**30 – 40**
	Mark 55.4	Type 4	≈ 5	5 – 10	**20 – 30**
	LS 60	Type 4	2.5 – 5	2.5 – 5	**30 – 40**
	LS 70	Type 4	Failed	Failed	Failed
Polyurea	Mark 75	Type 4	< 2.5	< 2.5	10 – 20
	Glomarc 90	Clusterbead®	≈ 5	5 – 10	5 – 10
		Visibead® Plus II	< 2.5	5 – 10	5 – 10
	HPS-5	Type 4	2.5 – 5	2.5 – 5	10 – 20

[1] Y-LEL: Yellow Left Edge Line
[2] W-LL: White Lane Lines
[3] W-REL: White Right Edge Line

CHAPTER 7
COMPARISON WITH NTPEP DATA

7.1 Introduction

The National Transportation Product Evaluation Program (NTPEP) is a pool funded Technical Service Program (TSP) founded in 1994 under the auspices of the American Association of State Highway and Transportation Officials (AASHTO). This program provides comprehensive field and laboratory evaluations on a variety of transportation-related products commonly used by AASHTO member departments. The main objective of this program is to assist state highway agencies in making informed decisions regarding the prequalification of these products; thus, improving the quality of available products and raising awareness of their availability (http://www.ntpep.org/).

Products evaluated under the NTPEP are classified into three main categories, namely traffic safety products (e.g., pavement markings and sign sheeting materials); construction materials (e.g., concrete admixtures and concrete curing compounds); and maintenance materials (e.g., bridge deck sealants and rapid set concrete patch materials). While these categories cover a very wide range of products and materials, this project is only concerned with pavement markings.

The NTPEP evaluates different types of pavement markings including temporary removable tapes and non-removable pavement marking products such as traffic paints, liquid pavement markings (e.g., epoxies, polyesters, polyurea, and methyl methacrylates), thermoplastics, preformed thermoplastics, and durable tapes. The discussion presented herein will be limited to non-removable pavement markings since they are the focus of this project.

The NTPEP employs a detailed consensus-based work plan, approved by at least two-thirds of the 52 AASHTO member states, in the evaluation of pavement markings. This work plan outlines the schedule of the evaluation, describes the installation procedure, and documents the laboratory and field test protocols that are involved in the evaluation. Performance evaluation results are disseminated through printed reports that are sent to NTPEP member states and are available online in an electronic format. The latter can be readily accessed using the NTPEP DataMine web tool (http://data.ntpep.org) that was developed under NCHRP Project 20-7 (Task 150) titled "A First Generation Query-Based Program to Aid in the Assessment of Pavement

Markings and Sign Sheeting Materials" (Ahmad 2003). This web tool allows lead state agencies hosting the evaluation to upload the evaluation results to a web-enabled database that can then be accessed by users to generate performance reports for specific products; thus, allowing side-by-side product comparison. It can also be used to export pavement marking performance data to Microsoft Excel as a spreadsheet or Microsoft Access as a database for further analysis.

State highway agencies vary in their reliance on NTPEP pavement markings data for product prequalification (NTPEP Oversight Committee, 2004). The level of use varies from not using the NTPEP data at all to fully relying on the NTPEP results to support product approval. As discussed previously, ODOT maintains its "Approved List" of pavement marking materials according to Supplemental 1047 (dated April 18, 2008). This supplemental specification has been revised over the last decade to allow using NTPEP data from Pennsylvania and Wisconsin Test Decks for product prequalification. In this chapter, performance evaluation results from this research project are augmented with NTPEP data from these two test decks. It is noted though that not all marking materials evaluated in this project have been previously evaluated under the NTPEP program. For completeness, an overview of the NTPEP pavement marking performance evaluation procedure is presented first. Performance evaluation measures collected during the field evaluations are discussed in detail.

7.2 NTPEP Pavement Marking Performance Evaluation

As mentioned previously, the NTPEP employs a detailed work plan that involves laboratory and field procedures in evaluating the performance of pavement markings. The laboratory evaluation consists of a number of ASTM and AASHTO test methods that are used to determine certain properties of the evaluated materials in the lab, and to "fingerprint" the chemical composition of these materials so that no changes can be made to them after testing. Different lab tests are specified for different types of materials. However, since few states can perform all lab tests required by the NTPEP, the NTPEP has attempted to use the same lab facilities for this purpose. For example, Pennsylvania was selected to conduct all laboratory evaluations on traffic paints and polyesters; Louisiana was selected to evaluate tapes; and New York selected to evaluate thermoplastics (http://www.ntpep.org/).

As for the field evaluation, the NTPEP uses several test decks that are widely distributed within the US to cover different environmental and traffic conditions (Figure 7.1). AASHTO member departments volunteer to host these test decks. Every spring the NTPEP solicits manufacturers to submit their products for evaluation. A testing fee is collected for this service and used to reimburse the host agency. Meanwhile, the administrative cost for operating the NTPEP program is covered by AASHTO member departments on a voluntary basis.

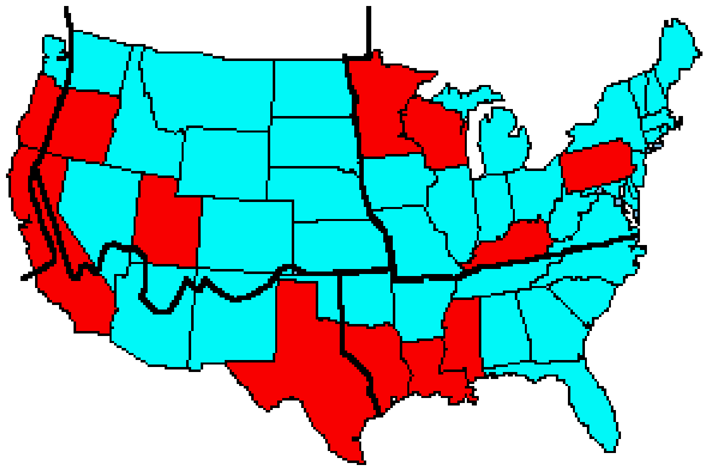

Figure (7.1): NTPEP Pavement Marking Test Decks (http://www.ntpep.org/).

The following is a list of recent NTPEP pavement marking test decks along with a brief description of prevailing conditions at each test deck (http://www.ntpep.org/):

- Minnesota ('97), Wisconsin ('99, '04,'07) (cold, dry, altitude)
- Pennsylvania ('96,'98,'00,'02,'05,'08) (cold, humid, altitude)
- Kentucky ('96) (cold/warm, humid)
- Texas ('96,'98), Mississippi ('99,'02,'04,'06), Alabama ('97) (hot, humid, gulf state)
- California ('00) (warm, wet, high ADT, urban)
- Oregon ('95) (warm, wet, altitude, studded tires)
- Utah ('01,'05) (cold, dry, high altitude, freeze/thaw)

From the previous list of test decks and as apparent in Figure (7.1), it can be noticed that the Pennsylvania test deck is most representative of Ohio conditions in terms of weather and traffic followed by the Kentucky and the Wisconsin test decks. Similar to Ohio all three states prohibit the use of studded tires. Yet, only one evaluation took place on the Kentucky test deck and this evaluation was conducted more than ten years ago, which suggests that this data is probably outdated and should not be included in the analysis. Therefore, only data from recent Pennsylvania and Wisconsin test decks will be used in this project. In particular, results from the NTPEP Pennsylvania (2000-2002, 2002-2005, and 2005-2007) and NTPEP Wisconsin (2004-2006) field evaluations will be presented in this chapter and compared with data obtained from ODOT District 3 bridge decks.

The field testing procedure for evaluating the performance of pavement markings on the NTPEP test decks is based on ASTM D713 titled "Standard Practice for Conducting Road Service Tests on 16 Fluid Traffic Marking Materials." According to this document, the evaluation shall take place on four-lane divided sections in an area where traffic is moderate (minimum Average Annual Daily Traffic or AADT of 5,000 vehicles per day) and free-rolling with no grades, curves, intersections, or access points; with full exposure to sunlight throughout the daylight hours and there is good drainage (ASTM 2008).

As can be seen in Figure (7.2), durable (non-removable) pavement markings are applied in a transverse direction along the highway; extending from the inner side of the edge line to the far side of the skip line without crossing an existing skip line. Four transverse lines of each product, placed in pairs in two locations, are evaluated. The test strips are applied at a width of 4 inches (100 mm). Pavement marking installation is conducted by the product producer and supervised by the host state. The transverse placement of these lines allows moving traffic to constantly come in contact with the lines along the right and left wheel paths, leading to more excessive wearing at these locations.

The NTPEP conducts the evaluation in two locations: the first location is commonly called the "skip" and the second location is commonly called the "left wheel" or simply the "wheel". The first location is taken within nine inches (225 mm) from the far left portion of the line and the second location is taken within eighteen inches (450 mm) of the left wheel path – nine inches (225 mm) on both sides of the location with greatest wear; refer to (Figure 7.2). Accordingly, the performance of the marking material in the "skip" area is representative of its performance when used as a longitudinal marking and the performance of the marking material in the "left wheel" area is representative of its performance when used as a transverse marking or as a longitudinal marking along curved roads where drivers frequently come in contact with the lines.

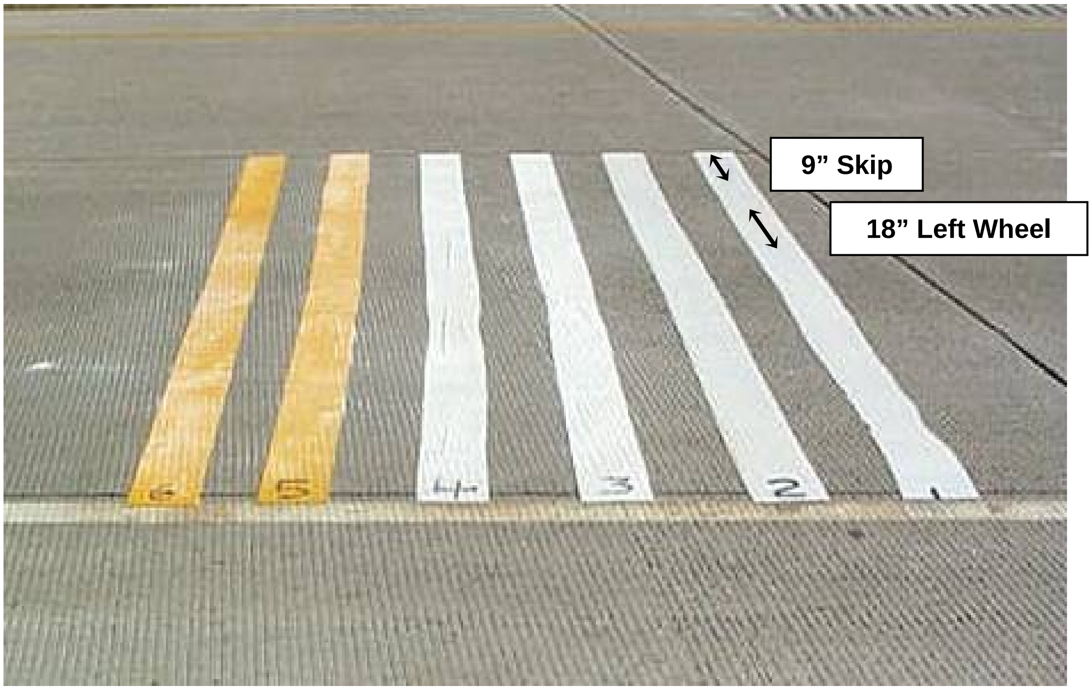

Figure (7.2): Transverse Placement of Pavement Markings on NTPEP Test Decks.

The NTPEP field evaluation is conducted in three phases: 1) Project organizations material installation, 2) Product monthly field evaluations, and 3) Product quarterly field evaluations. The first phase includes the organization and scheduling of the pavement markings installation as well as the initial product evaluation that is conducted within seven (7) days of application of all samples. The second phase includes evaluating the performance of the pavement marking approximately every thirty (30) days until the end of the first year. The third phase includes evaluating the performance of the pavement marking approximately every one hundred and twenty (120) days until the completion of the field evaluation. During these evaluations, each durable product is evaluated for retroreflectivity using a Delta LTL-X retroreflectometer or other acceptable device; durability is rated by visually assessing the percentage of material remaining on the surface on a scale of 0 to 10; daytime color is measured using Gardner 6805 color guide spectrophotometer, which provides coordinates in CIE color units and luminance factor measurements; nighttime color is determined using Delta LTL 2000Y retroreflectometer (yellow markings only); and wet-night retroreflectivity is measured in accordance with ASTM E2177 (if requested by the manufacturer). In addition to the previous, the NTPEP collects information regarding the site location (ADT, type, age, and special treatment of pavement surface material), product information (manufacturer name, class of material, binder, color, primer or other adhesives (if needed), and indication if material contains lead), application information (application equipment, equipment description, thickness, temperature of material, relative humidity, no-track time, and type and rate of application of beads), and information regarding snowfall and snowplow damage.

7.3 Overview of NTPEP Pennsylvania and Wisconsin Test Decks

The NTPEP Pennsylvania (PA) test deck is one of the most active pavement marking test decks in the NTPEP program. It is located along interstate I-80 in a mountainous area south of Williamsport, PA, where the interstate has two lanes per direction. This test deck consists of two sites, a concrete site along the eastbound and an asphalt site along the westbound. The concrete surface has transverse tines. The asphalt surface is made of heavy duty mix. The average daily traffic (ADT) is about 10,000. Both sites are subjected to moderate to heavy truck traffic.

The NTPEP Wisconsin (WI) test deck is located along U.S. 53 South in Chippewa Falls, WI, between County Trunk Highway S and State Trunk Highway 29. The evaluation is conducted in four-lane divided sections. Testing on asphalt is conducted near the north end of the test deck, while testing on concrete is conducted near the south end. The concrete surface is not tined. The asphalt surface is made of stone matrix asphalt (SMA) with 3/8 in (9.5 mm) maximum aggregate size. The average daily traffic (ADT) is in the range of 5,200 to 5,800.

Both NTPEP PA and WI test decks meet ASTM D713 guidelines regarding the location where the pavement marking evaluation shall take place; and hence are considered suitable for this purpose.

7.4 NTPEP Data Availability

Table (7.1) presents data availability on the NTPEP PA (2000-2002, 2002-2005, and 2005-2007) and WI (2004-2006) test decks for the materials evaluated in ODOT District 3. It can be noticed that from among the evaluated materials in ODOT District 3, ten (10) materials have been tested on at least one test deck and three (3) materials have been tested on both test decks, which allows comparing not only the ODOT District 3 test results with the NTPEP data, but also the NTPEP performance results between the two test decks.

Table (7.1): Data Availability on NTPEP PA and WI Test Decks for the Materials Evaluated in ODOT District 3 (W stands for White and Y stands for Yellow).

		NTPEP PA Test Deck			WI Test Deck
Deck #	**Material**	**2000 – 2002**	**2002 – 2005**	**2005 – 2007**	**2004 – 2006**
1	380WR ES	--	--	W, Y[1]	--
2	Premark Contrast	--	--	--	--
3	HPS-2	W, Y	--	W, Y	--
4	HPS-4	W, Y	--	W, Y	W, Y
5	Mark 55.2	--	--	--	--
6	Mark 75	--	--	--	--
7	Mark 55.4	--	W, Y	--	--
8	Swarcotherm	--	W, Y	--	--
9	LS 60	--	W, Y	--	--
10	Glomarc 90	--	--	--	--
11	LS 70	--	--	--	--
12	HPS-5	W	--	W, Y	W, Y
13	Duraset 1	--	--	--	--
13	Duraset Pathfinder	--	--	--	--
14	Ennis Paint	W, Y	--	--	--
15	Premark Plus	--	W, Y	W	W
16	3M 270 ES	--	--	W	--

[1]This data is for 3M 380WR not 3M 380WR ES. However, both tapes are composed of the same materials; the only difference is in the adhesive type on the back of the tapes.

7.5 Comparison with NTPEP Retroreflectivity Data

Recently, there has been an increased emphasis on using pavement marking retroreflectivity as the main indicator of pavement marking performance. This section presents a comparison between the retroreflectivity readings obtained from ODOT District 3 and those obtained from the NTPEP PA and WI test decks. The comparison is limited to the performance of the pavement markings on Portland cement concrete surfaces.

Prior to presenting the data, it might be worth noting some of the possible differences between these test locations that might affect the retroreflectivity performance:

- Grooving
- Traffic level (ADT)
- Number of lanes per direction (traffic distribution)
- Weather (snow plow activity)
- Material variation (e.g., wet film thickness and glass bead type and application rate)

Table (7.2) summarizes the initial, 1-year, 2-year, and 3-year retroreflectivity readings (if available) for each of the evaluated materials on ODOT District 3 and NTPEP PA and WI test decks. Similar comparisons are presented in Figures (7.3) through (7.35). The latter is probably more helpful in comparing the overall performance of the evaluated materials on these test locations since more data points are used to describe the retroreflectivity decay. This is particularly true in the case of initial retroreflectivity, which in several occasions increased until reaching a peak value then started to deteriorate.

By comparing the retroreflectivity readings in Table (7.2) and Figures (7.3) through (7.35), the following conclusions can be made:

- Different deterioration trends are noticed for white and yellow markings in ODOT District 3 than in the NTPEP. In ODOT District 3, the white right edge lines deteriorated at the highest rate, followed by the white (left and right) lane lines, then the yellow left edge lines. In the NTPEP, white and yellow markings are applied transversely to ensure that both markings are subjected to the same traffic. Still, for most materials, yellow markings deteriorated at a higher rate than white markings.
- The deterioration rate of yellow markings in ODOT District 3 was modest compared to that in NTPEP PA and WI test decks due to grooving and low traffic level (Figures 7.5, 7.7, 7.9, 7.11, 7.13, 7.15, 7.17, 7.19, 7.22, 7.24, and 7.28).
- The 2-yr white markings retroreflectivity in ODOT District 3 was in general consistent (especially on the right edge line) with the NTPEP PA test deck skip retroreflectivity (Figures 7.6, 7.10, 7.12, 7.16, 7.20, 7.21, 7.22, 7.29, 7.30, 7.31, 7.32, and 7.35), but slightly higher than the skip retroreflectivity in NTPEP WI test deck (Figures 7.14, 7.25, 7.33, and 7.34). This implies that the deterioration rate in NTPEP WI is slightly lower than the deterioration rate in NTPEP PA for the same material. This difference should be taken into

consideration by product prequalification specifications that utilize data from both NTPEP test decks such as ODOT Supplemental 1047.

- Higher initial retroreflectivity values were obtained for most liquid markings (e.g., HPS-2, HPS-4, Mark 55.4, LS 60, and HPS-5) in ODOT District 3 than in the NTPEP test decks. This could be due to variations in glass bead type and application rates.
- Significantly higher initial retroreflectivity was obtained for white 3M 380WR in NTPEP PA 2005-2007 than in ODOT District 3. This difference is due to the fact that this tape has higher retroreflectivity in one direction than the other; and that it was probably placed in its preferred direction in NTPEP PA 2005-2007 but not in ODOT District 3.
- The more expensive 3M 380WR tape performed better than the less expensive 3M 270 ES tape on the NTPEP test decks (Figures 7.3, 7.4, and 7.35). This observation is consistent with what have been observed in ODOT District 3 regarding the performance of these two tapes.
- The performance of yellow and white HPS-2 varied significantly between NTPEP PA 2000-2002 and NTPEP PA 2005-2007. Again, this difference could be attributed to material variability and variations in glass bead type and application rates. It is worth noting that HPS-2 was applied at a thickness of 14 to 22 mils (0.36 to 0.56 mm) in NTPEP PA 2000-2002 using 6 lbs (2.72 kg) per linear foot (0.3 linear meter) of Swarco Megalux M247 glass beads, while it was applied at a thickness of 18 to 20 mils (0.46 to 0.51 mm) in NTPEP PA 2005-2007 using Type 1 and Type 4 glass beads, both of which were applied by flooding. The performance of HPS-2 in ODOT District 3 was closer to NTPEP PA 2000-2002 than NTPEP PA 2005-2007 even though Type 1 and Type 4 glass beads were used in ODOT District 3.
- White Mark 55.4, which had very high deterioration rate on the right edge line in ODOT District 3, had an acceptable deterioration rate in NTPEP PA 2002-2005 where retroreflectivity after about 3 years was 197 mcd/m^2/lux.
- The performance of Swarcotherm alkyd on the NTPEP test decks was much better than its performance in ODOT District 3. The main difference was in durability. The durability of Swarcotherm at the end of the third year in NTPEP PA 2002-2005 was 9 for white and 7 for yellow. While the durability of white and yellow Swarcotherm in ODOT District 3 was almost zero in less than two years.
- White Epoplex LS 60 had significantly higher initial retroreflectivity in ODOT District 3 than in NTPEP PA 2002-2005. Yet, the retroreflectivity of this material in both locations

ranged between 300 and 400 mcd/m^2/lux after about 2 years from installation.

- The HPS-5 polyurea, which had the highest retained retroreflectivity in ODOT District 3, also had high retained retroreflectivity on the NTPEP test decks. For example, the skip retroreflectivity of white HPS-5 in NTPEP PA 2005-2007 was 316 mcd/m^2/lux after about 3 years, down from an initial retroreflectivity of 455 mcd/m^2/lux.
- Ennis fast dry waterborne traffic paint, which had an acceptable performance in ODOT District 3, had much better initial and retained retroreflectivity in NTPEP PA 2000-2002 (Figures 7.26 and 7.27).
- The performance of white Premark Plus in NTPEP PA and WI test decks was slightly higher than the performance of this material on the right edge lines of Bridge Decks # 2 and 15 in ODOT District 3, but lower than its performance on the right and left lane lines of Bridge Deck # 15 (Figures 7.29 and 7.34).

Table (7.2): Comparison between ODOT District 3 and NTPEP PA and WI Test Decks Retroreflectivity Results.

		Retroreflectivity (mcd/m²/lux)											
		ODOT District 3				PA 2000-2002		PA 2002-2005		PA 2005-2007		WI 2004-2006	
Product	**Age**	**Y-LEL[1]**	**W-LLL[2]**	**W-RLL[3]**	**W-REL[4]**	**Skip**	**Wheel**	**Skip**	**Wheel**	**Skip**	**Wheel**	**Skip**	**Wheel**
Yellow 3M 380WR ES	Initial	638	--	--	--	--	--	--	--	1130	1067	--	--
	1-yr	587	--	--	--	--	--	--	--	578	142	--	--
	2-yr	492	--	--	--	--	--	--	--	400	80	--	--
	3-yr	--	--	--	--	--	--	--	--	--	--	--	--
White 3M 380WR ES	Initial	--	550	572	594	--	--	--	--	1223	1161	--	--
	1-yr	--	446	473	539	--	--	--	--	721	179	--	--
	2-yr	--	314	336	352	--	--	--	--	498	114	--	--
	3-yr	--	--	--	--	--	--	--	--	--	--	--	--
Yellow HPS-2	Initial	480	--	--	--	408	379	--	--	238	226	--	--
	1-yr	349	--	--	--	321	102	--	--	181	106	--	--
	2-yr	407	--	--	--	297	66	--	--	188	86	--	--
	3-yr	--	--	--	--	--	--	--	--	168	67	--	--
White HPS-2	Initial	--	706	648	682	573	473	--	--	322	313	--	--
	1-yr	--	472	486	404	466	116	--	--	237	153	--	--
	2-yr	--	422	415	307	429	32	--	--	243	120	--	--
	3-yr	--	--	--	--	--	--	--	--	229	76	--	--

[1] Y-LEL: Yellow Left Edge Line
[2] W-LLL: White Left Lane Line
[3] W-RLL: White Right Lane Line
[4] W-REL: White Right Edge Line

Table (7.2): Comparison between ODOT District 3 and NTPEP PA and WI Test Decks Retroreflectivity Results (Continued).

		Retroreflectivity (mcd/m²/lux)											
		ODOT District 3				PA 2000-2002		PA 2002-2005		PA 2005-2007		WI 2004-2006	
Product	**Age**	**Y-LEL[1]**	**W-LLL[2]**	**W-RLL[3]**	**W-REL[4]**	**Skip**	**Wheel**	**Skip**	**Wheel**	**Skip**	**Wheel**	**Skip**	**Wheel**
Yellow HPS-4	Initial	451	--	--	--	308	322	--	--	329	324	316	367
	1-yr	459	--	--	--	202	58	--	--	224	116	338	132
	2-yr	431	--	--	--	108	61	--	--	215	87	212	86
	3-yr	--	--	--	--	--	--	--	--	178	73	--	--
White HPS-4	Initial	--	711	695	737	540	491	--	--	473	529	298	406
	1-yr	--	563	540	605	452	171	--	--	411	168	528	180
	2-yr	--	466	387	343	413	75	--	--	398	95	391	140
	3-yr	--	--	--	--	--	--	--	--	319	69	--	--
Yellow Mark 55.4	Initial	425	--	--	--	--	--	299	304	--	--	--	--
	1-yr	378	--	--	--	--	--	247	113	--	--	--	--
	2-yr	320	--	--	--	--	--	219	67	--	--	--	--
	3-yr	--	--	--	--	--	--	132	36	--	--	--	--
White Mark 55.4	Initial	--	728	706	766	--	--	380	410	--	--	--	--
	1-yr	--	473	482	259	--	--	356	155	--	--	--	--
	2-yr	--	386	398	200	--	--	328	96	--	--	--	--
	3-yr	--	--	--	--	--	--	197	57	--	--	--	--

[1] Y-LEL: Yellow Left Edge Line
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[3] W-RLL: White Right Lane Line
[4] W-REL: White Right Edge Line

Table (7.2): Comparison between ODOT District 3 and NTPEP PA and WI Test Decks Retroreflectivity Results (Continued).

		Retroreflectivity (mcd/m²/lux)											
		ODOT District 3				PA 2000-2002		PA 2002-2005		PA 2005-2007		WI 2004-2006	
Product	Age	Y-LEL[1]	W-LLL[2]	W-RLL[3]	W-REL[4]	Skip	Wheel	Skip	Wheel	Skip	Wheel	Skip	Wheel
Yellow Swarcotherm	Initial	169	--	--	--	--	--	281	289	--	--	--	--
	1-yr	225	--	--	--	--	--	198	74	--	--	--	--
	2-yr	--	--	--	--	--	--	229	27	--	--	--	--
	3-yr	--	--	--	--	--	--	219	12	--	--	--	--
White Swarcotherm	Initial	--	282	342	371	--	--	541	507	--	--	--	--
	1-yr	--	402	379	303	--	--	511	186	--	--	--	--
	2-yr	--	--	--	--	--	--	394	78	--	--	--	--
	3-yr	--	--	--	--	--	--	403	21	--	--	--	--
Yellow LS 60	Initial	461	--	--	--	--	--	245	252	--	--	--	--
	1-yr	422	--	--	--	--	--	284	85	--	--	--	--
	2-yr	333	--	--	--	--	--	226	51	--	--	--	--
	3-yr	--	--	--	--	--	--	153	35	--	--	--	--
White LS 60	Initial	--	619	640	514	--	--	325	345	--	--	--	--
	1-yr	--	390	481	396	--	--	347	130	--	--	--	--
	2-yr	--	324	395	332	--	--	303	70	--	--	--	--
	3-yr	--	--	--	--	--	--	227	48	--	--	--	--

[1] Y-LEL: Yellow Left Edge Line
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[3] W-RLL: White Right Lane Line
[4] W-REL: White Right Edge Line

Table (7.2): Comparison between ODOT District 3 and NTPEP PA and WI Test Decks Retroreflectivity Results (Continued).

		Retroreflectivity (mcd/m²/lux)											
		ODOT District 3				PA 2000-2002		PA 2002-2005		PA 2005-2007		WI 2004-2006	
Product	**Age**	**Y-LEL[1]**	**W-LLL[2]**	**W-RLL[3]**	**W-REL[4]**	**Skip**	**Wheel**	**Skip**	**Wheel**	**Skip**	**Wheel**	**Skip**	**Wheel**
Yellow HPS-5	Initial	339	--	--	--	--	--	--	--	374	384	303	360
	1-yr	404	--	--	--	--	--	--	--	291	150	366	189
	2-yr	411	--	--	--	--	--	--	--	247	80	299	122
	3-yr	--	--	--	--	--	--	--	--	177	50	--	--
White HPS-5	Initial	--	681	641	794	624	657	--	--	455	531	481	468
	1-yr	--	560	549	587	501	93	--	--	350	154	556	184
	2-yr	--	503	483	527	366	80	--	--	298	98	413	109
	3-yr	--	--	--	--	--	--	--	--	316	74	--	--
Yellow Ennis Paint	Initial	202	--	--	--	317	303	--	--	--	--	--	--
	1-yr	179	--	--	--	325	58	--	--	--	--	--	--
	2-yr	151	--	--	--	288	52	--	--	--	--	--	--
	3-yr	--	--	--	--	--	--	--	--	--	--	--	--
White Ennis Paint	Initial	--	310	305	330	460	392	--	--	--	--	--	--
	1-yr	--	229	207	237	392	101	--	--	--	--	--	--
	2-yr	--	166	139	150	342	67	--	--	--	--	--	--
	3-yr	--	--	--	--	--	--	--	--	--	--	--	--

[1] Y-LEL: Yellow Left Edge Line
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[3] W-RLL: White Right Lane Line
[4] W-REL: White Right Edge Line

Table (7.2): Comparison between ODOT District 3 and NTPEP PA and WI Test Decks Retroreflectivity Results (Continued).

		Retroreflectivity (mcd/m^2/lux)											
		ODOT District 3				PA 2000-2002		PA 2002-2005		PA 2005-2007		WI 2004-2006	
Product	Age	Y-LEL[1]	W-LLL[2]	W-RLL[3]	W-REL[4]	Skip	Wheel	Skip	Wheel	Skip	Wheel	Skip	Wheel
Yellow Premark Plus Deck # 15	Initial	317	--	--	--	--	--	346	345	--	--	--	--
	1-yr	400	--	--	--	--	--	268	74	--	--	--	--
	2-yr	385	--	--	--	--	--	153	89	--	--	--	--
	3-yr	--	--	--	--	--	--	138	70	--	--	--	--
White Premark Plus Deck # 15	Initial	--	715	814	579	--	--	648	686	625	560	657	582
	1-yr	--	780	851	570	--	--	552	94	547	204	641	396
	2-yr	--	433	410	215	--	--	278	91	379	151	422	141
	3-yr	--	--	--	--	--	--	173	89	129	117	--	--
Yellow 3M 270 ES	Initial	466	--	--	--	--	--	--	--	--	--	--	--
	1-yr	421	--	--	--	--	--	--	--	--	--	--	--
	2-yr	356	--	--	--	--	--	--	--	--	--	--	--
	3-yr	--	--	--	--	--	--	--	--	--	--	--	--
White 3M 270 ES	Initial	--	527	517	486	--	--	--	--	456	347	--	--
	1-yr	--	430	436	228	--	--	--	--	205	75	--	--
	2-yr	--	362	362	127	--	--	--	--	143	67	--	--
	3-yr	--	--	--	--	--	--	--	--	100	74	--	--

[1] Y-LEL: Yellow Left Edge Line
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[3] W-RLL: White Right Lane Line
[4] W-REL: White Right Edge Line

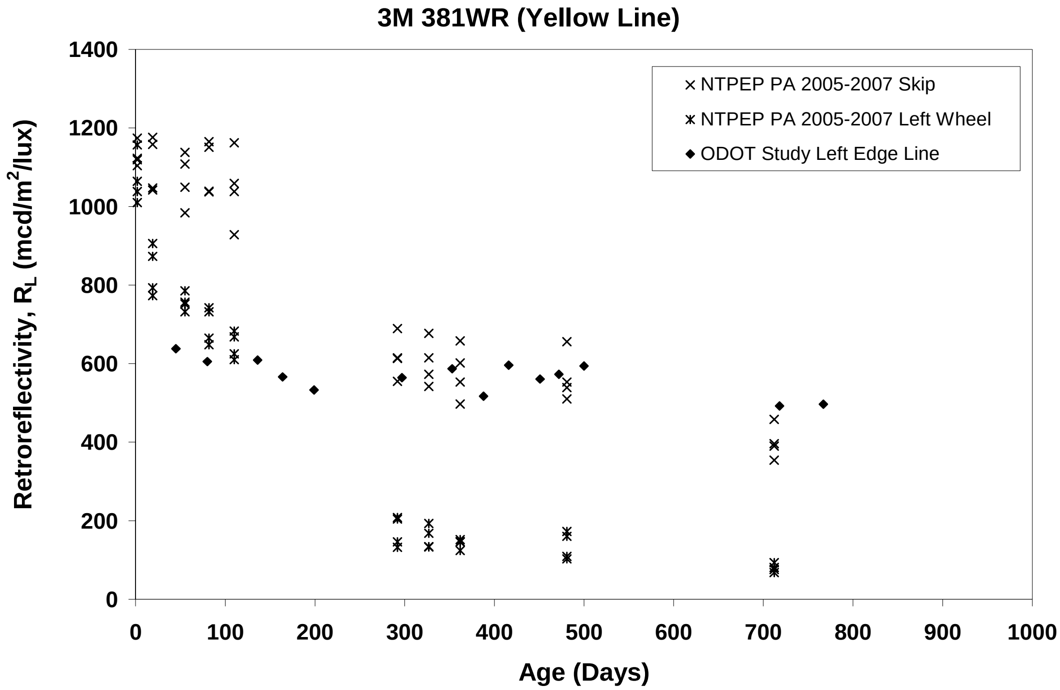

Figure (7.3): Comparison between ODOT District 3 and NTPEP PA 2005-2007 Retroreflectivity Data for Yellow 3M 381WR ES.

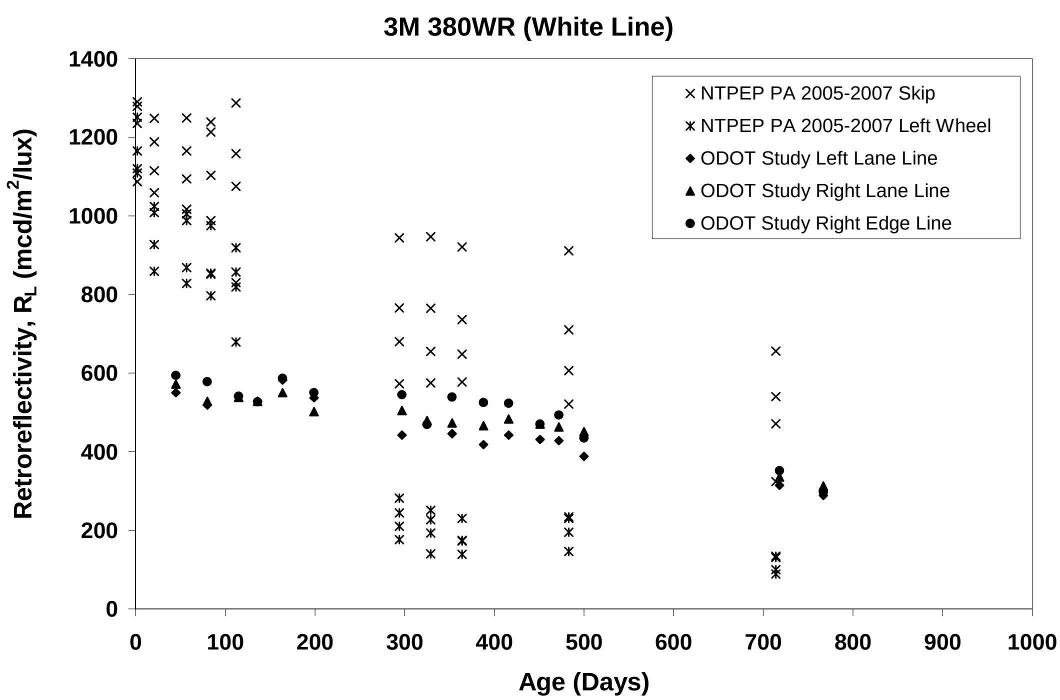

Figure (7.4): Comparison between ODOT District 3 and NTPEP PA 2005-2007 Retroreflectivity Data for White 3M 380WR ES.

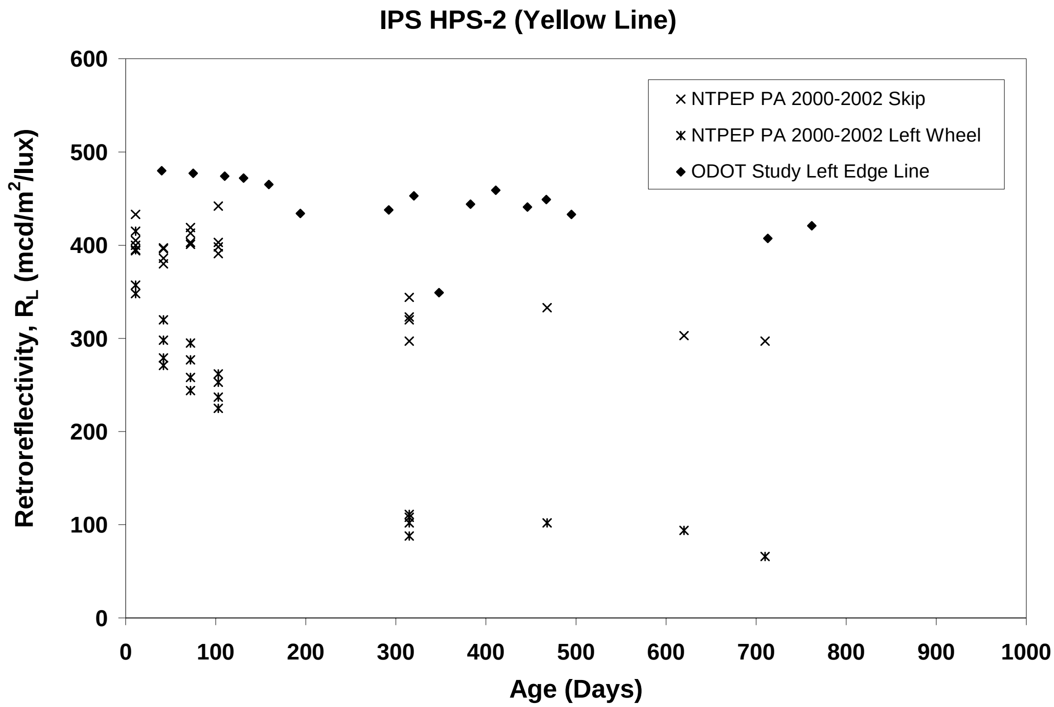

Figure (7.5): Comparison between ODOT District 3 and NTPEP PA 2000-2002 Retroreflectivity Data for White HPS-2.

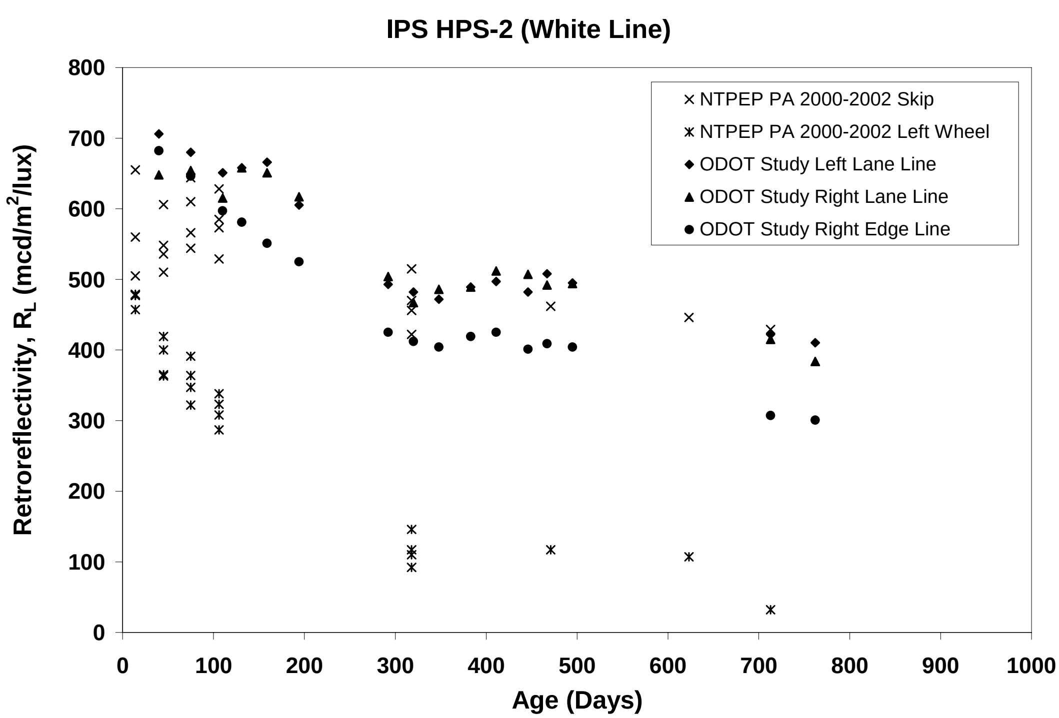

Figure (7.6): Comparison between ODOT District 3 and NTPEP PA 2000-2002 Retroreflectivity Data for White HPS-2.

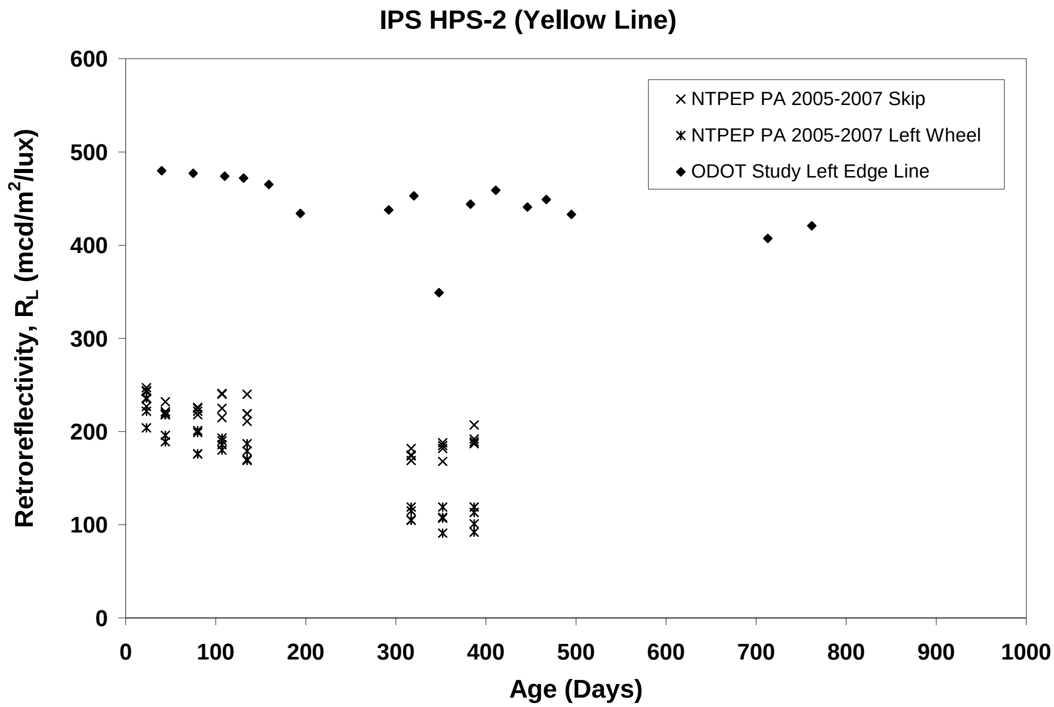

Figure (7.7): Comparison between ODOT District 3 and NTPEP PA 2005-2007 Retroreflectivity Data for Yellow HPS-2.

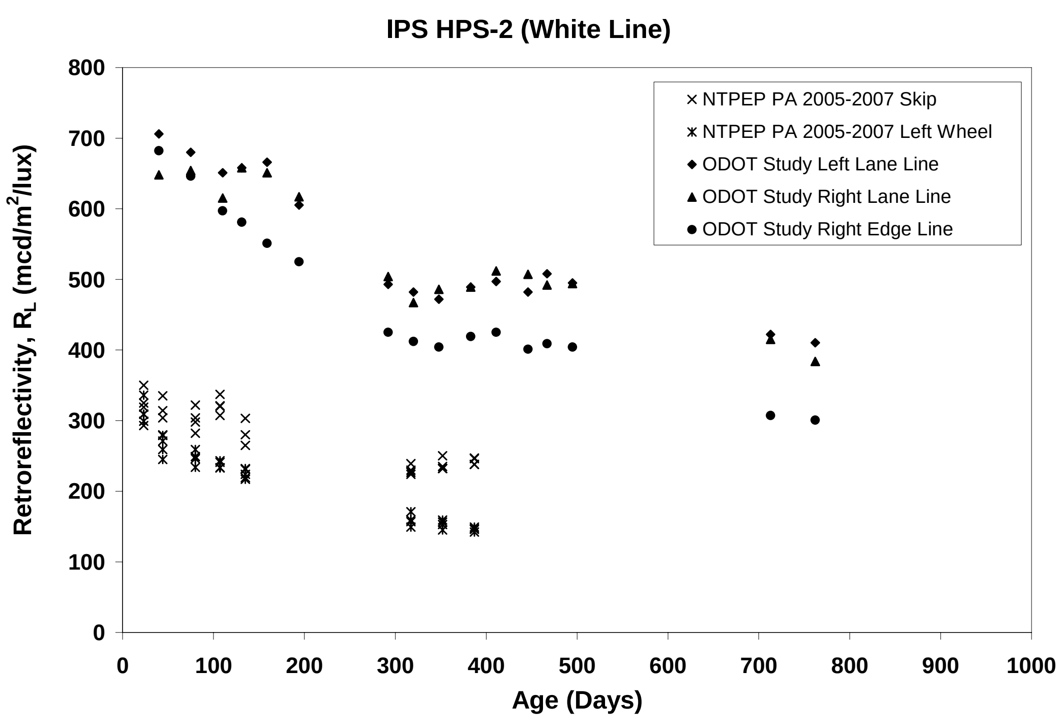

Figure (7.8): Comparison between ODOT District 3 and NTPEP PA 2005-2007 Retroreflectivity Data for White HPS-2.

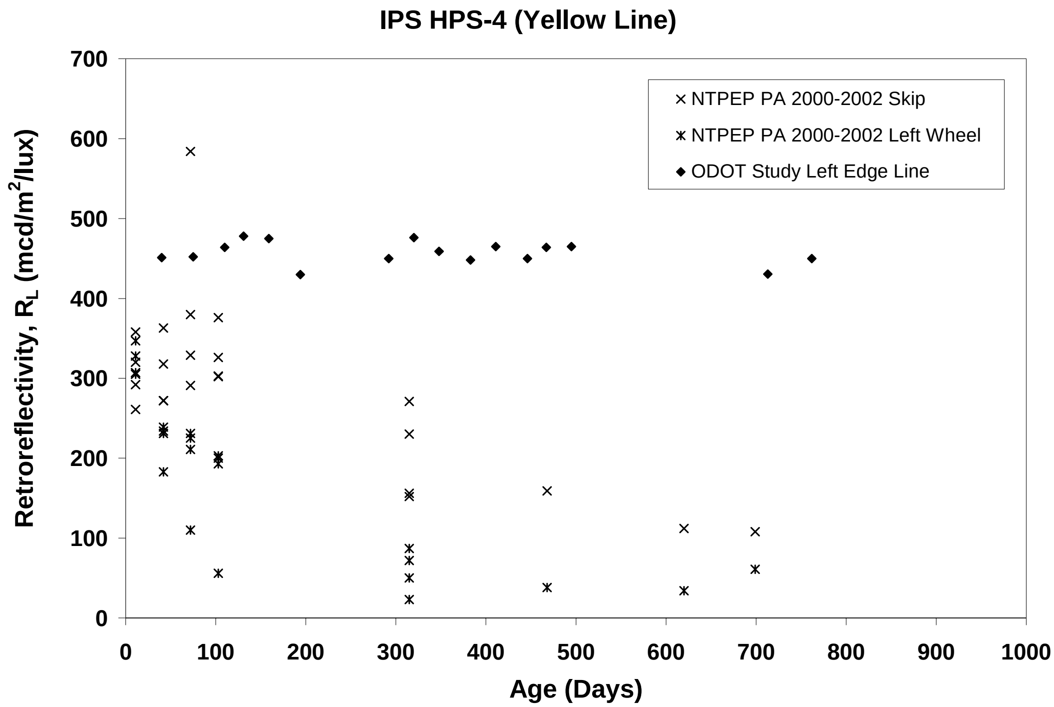

Figure (7.9): Comparison between ODOT District 3 and NTPEP PA 2000-2002 Retroreflectivity Data for Yellow HPS-4.

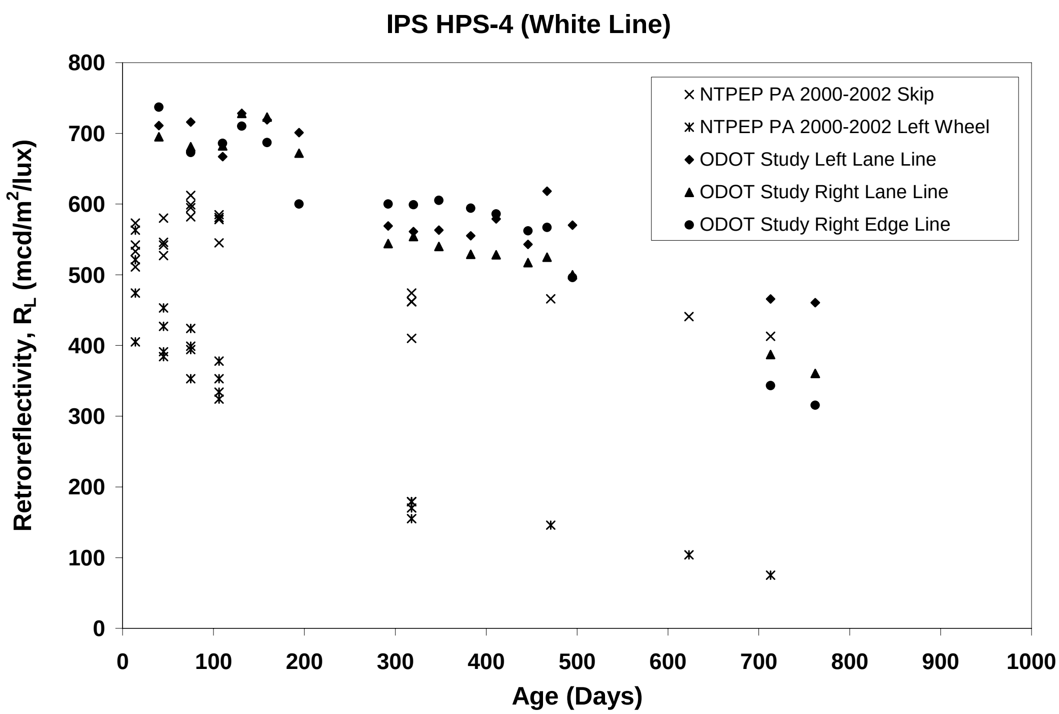

Figure (7.10): Comparison between ODOT District 3 and NTPEP PA 2000-2002 Retroreflectivity Data for White HPS-4.

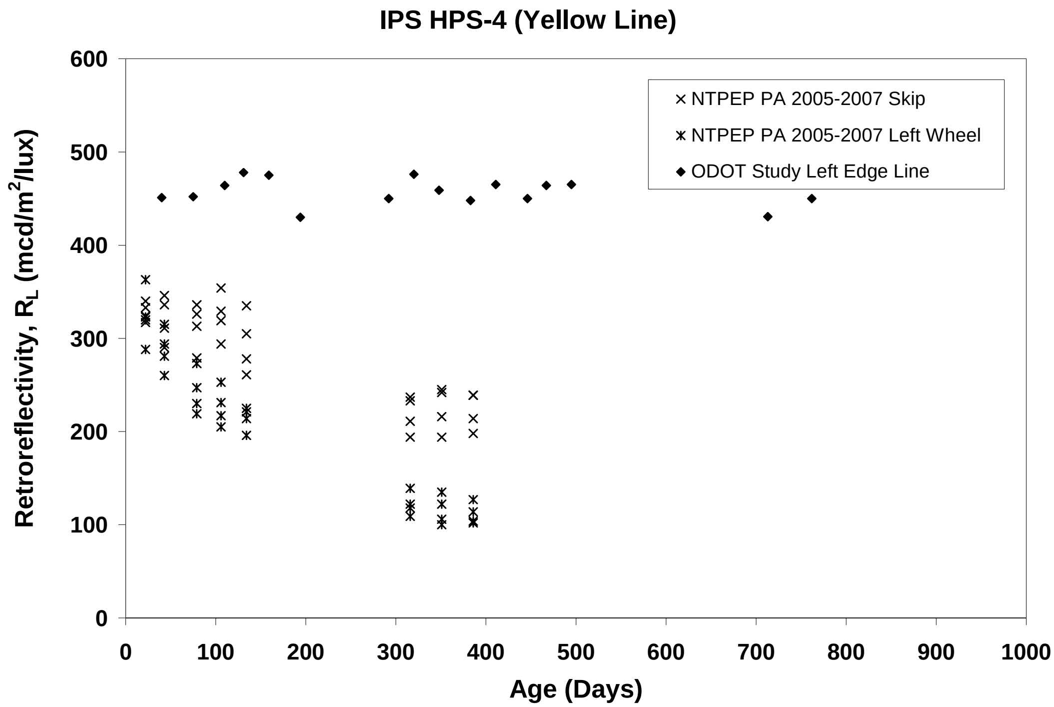

Figure (7.11): Comparison between ODOT District 3 and NTPEP PA 2005-2007 Retroreflectivity Data for Yellow HPS-4.

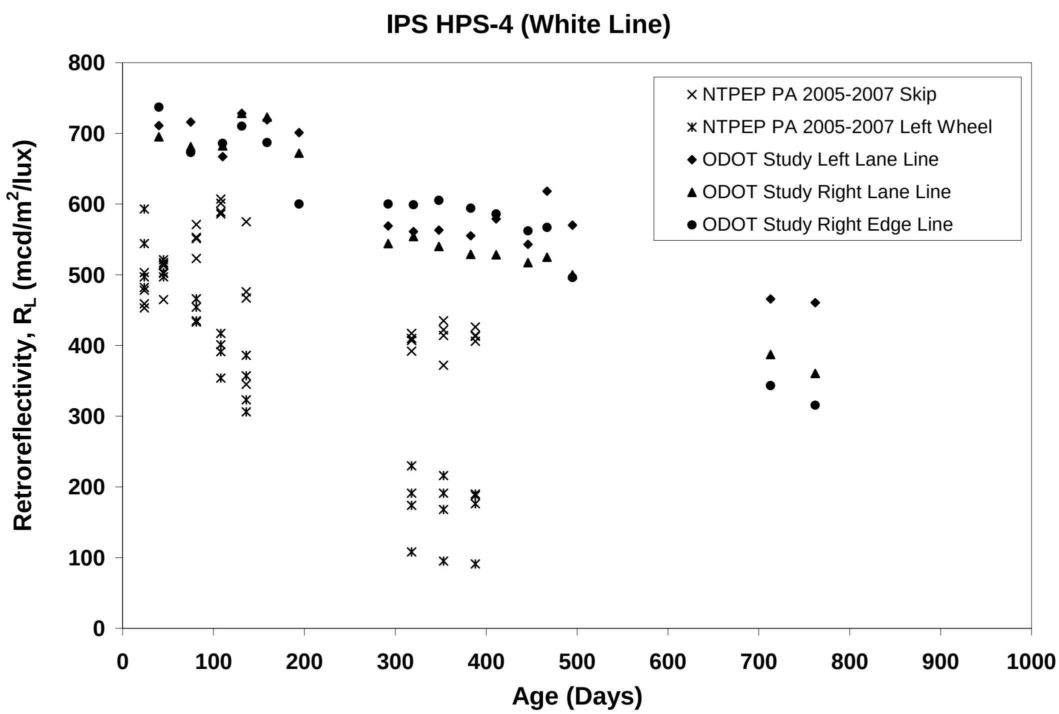

Figure (7.12): Comparison between ODOT District 3 and NTPEP PA 2005-2007 Retroreflectivity Data for White HPS-4.

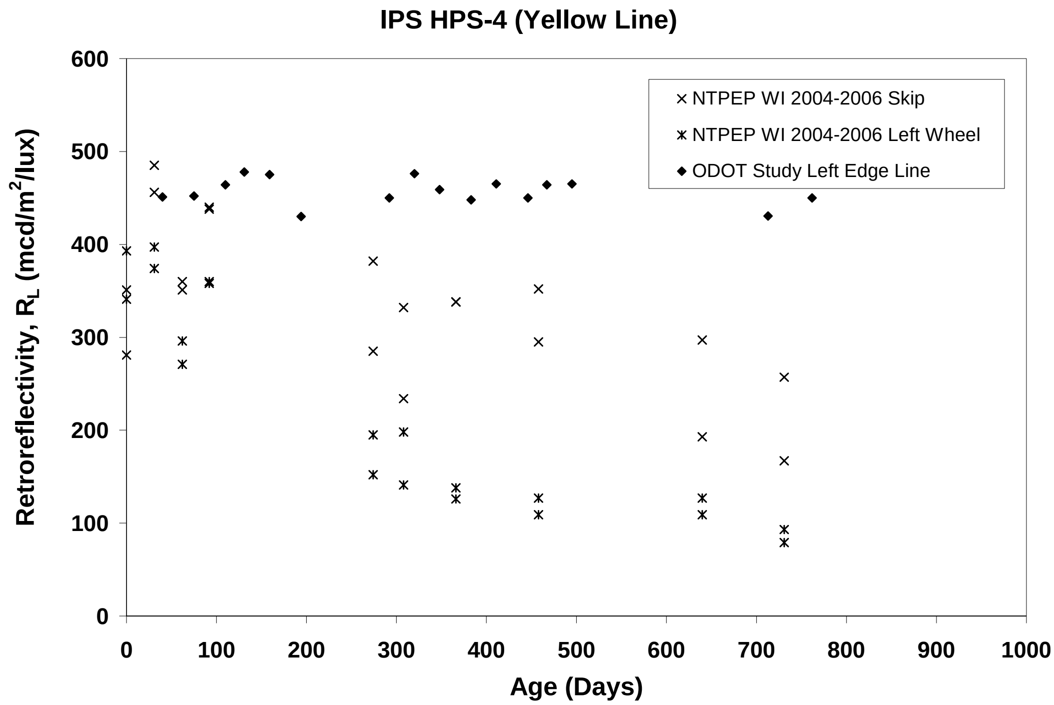

Figure (7.13): Comparison between ODOT District 3 and NTPEP WI 2004-2006 Retroreflectivity Data for Yellow HPS-4.

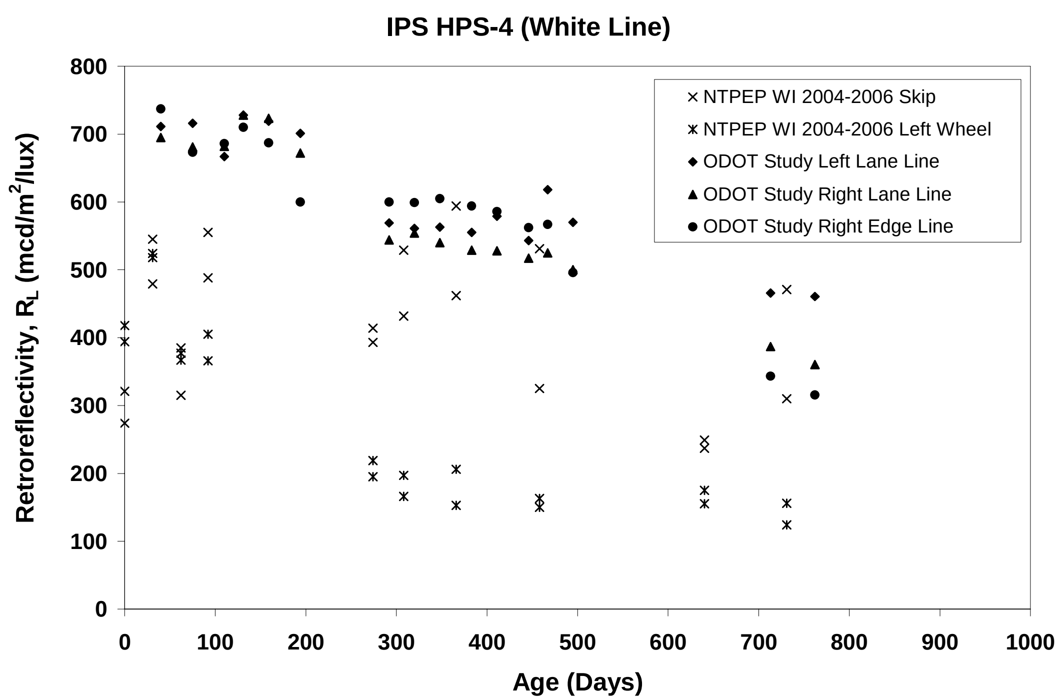

Figure (7.14): Comparison between ODOT District 3 and NTPEP WI 2004-2006 Retroreflectivity Data for White HPS-4.

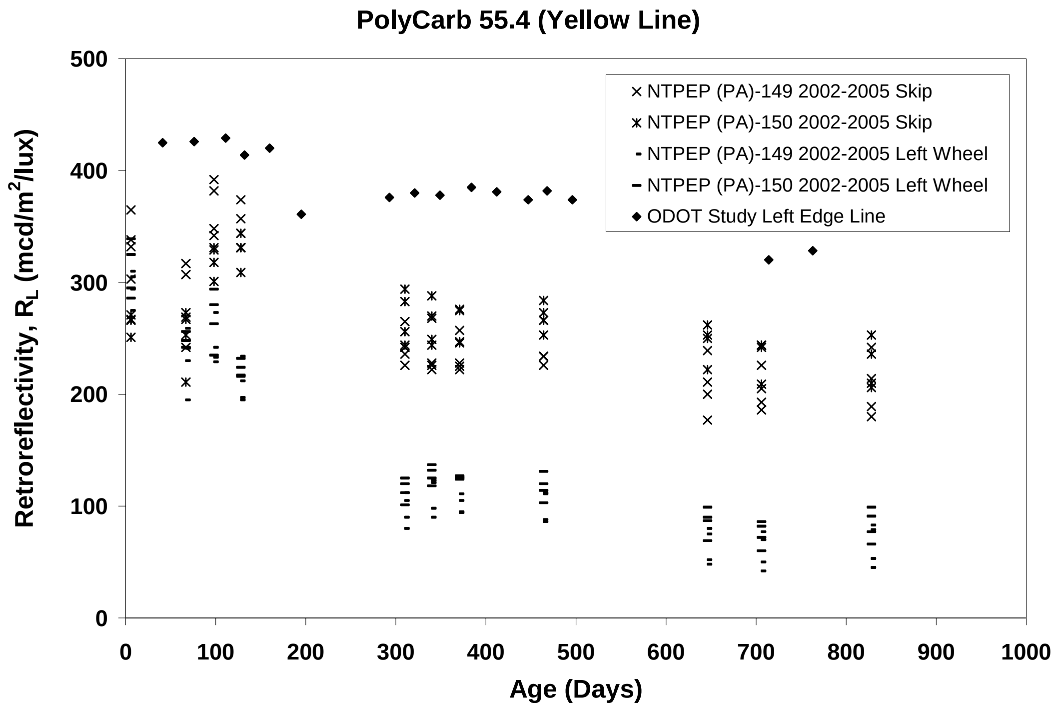

Figure (7.15): Comparison between ODOT District 3 and NTPEP PA 2002-2005 Retroreflectivity Data for Yellow PolyCarb Mark 55.4.

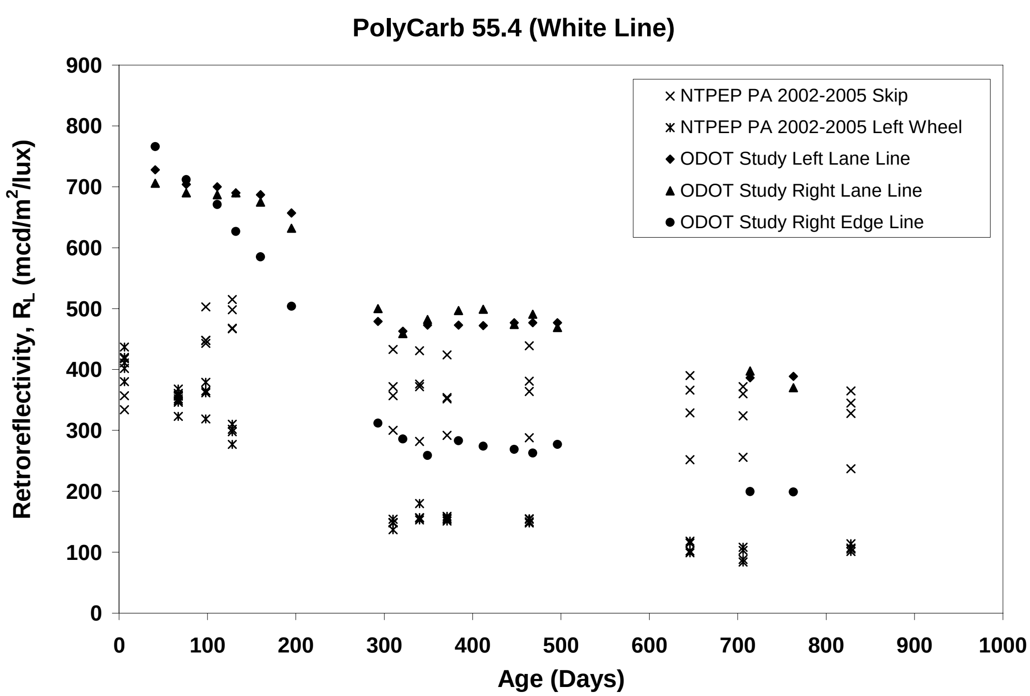

Figure (7.16): Comparison between ODOT District 3 and NTPEP PA 2002-2005 Retroreflectivity Data for White PolyCarb Mark 55.4.

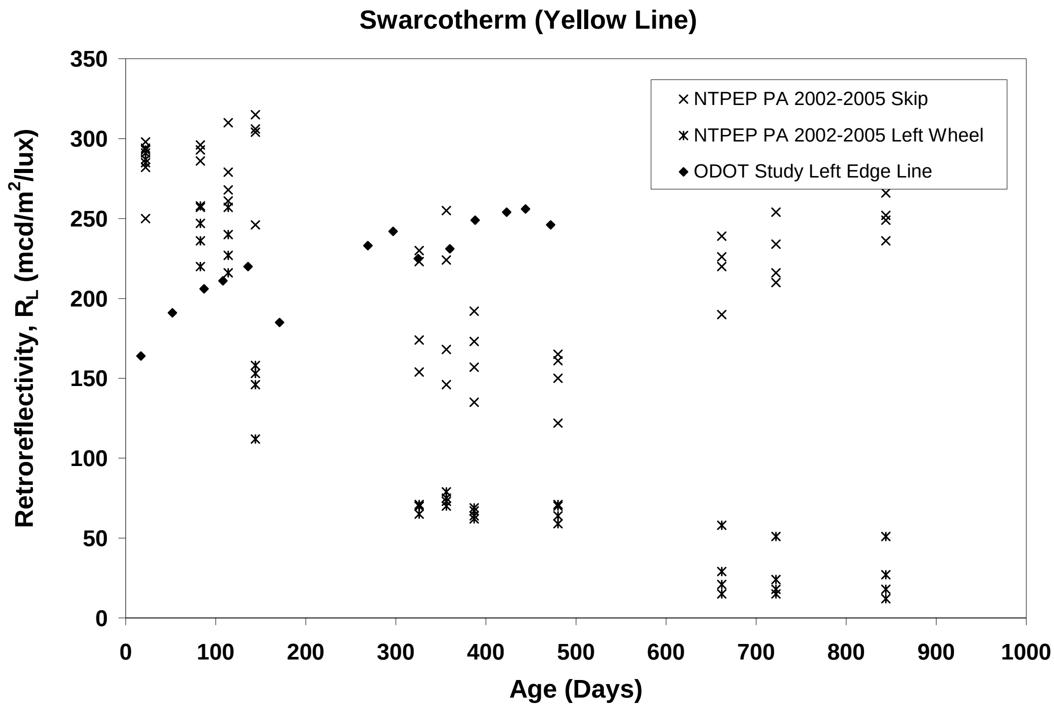

Figure (7.17): Comparison between ODOT District 3 and NTPEP PA 2002-2005 Retroreflectivity Data for Yellow Swarcotherm Alkyd.

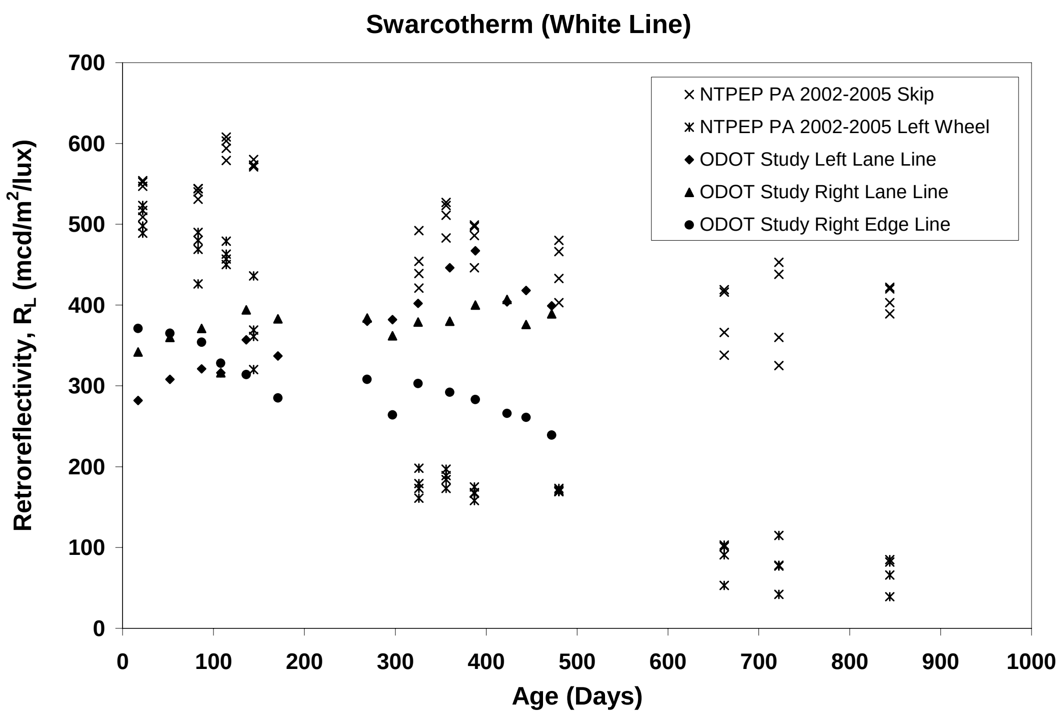

Figure (7.18): Comparison between ODOT District 3 and NTPEP PA 2002-2005 Retroreflectivity Data for White Swarcotherm Alkyd.

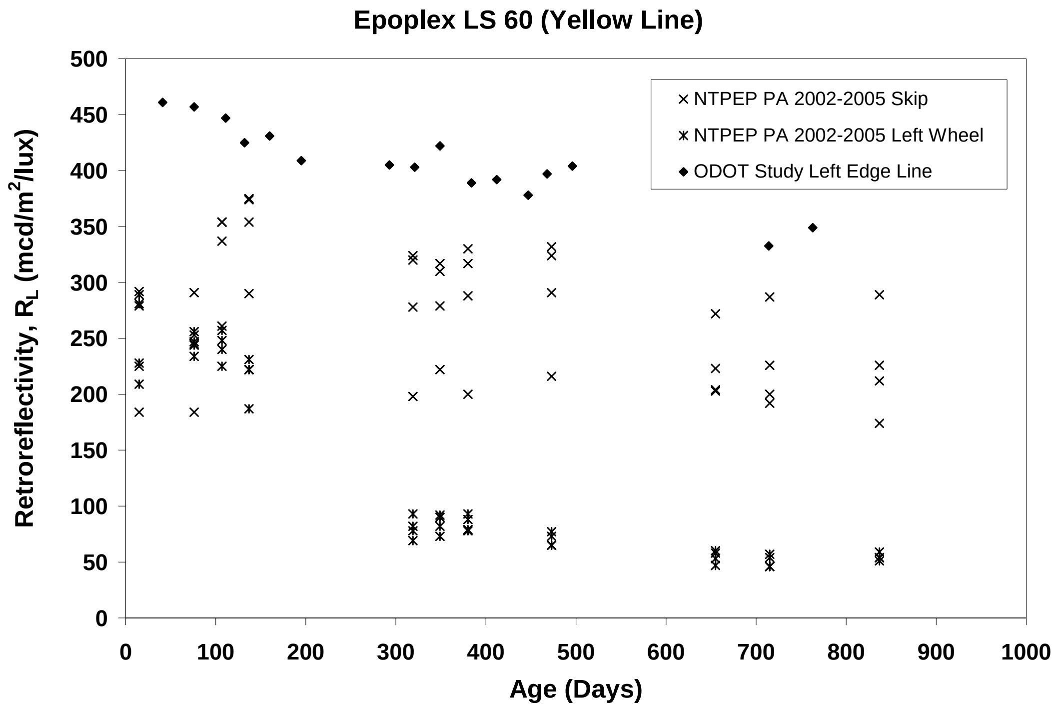

Figure (7.19): Comparison between ODOT District 3 and NTPEP PA 2002-2005 Retroreflectivity Data for Yellow LS 60.

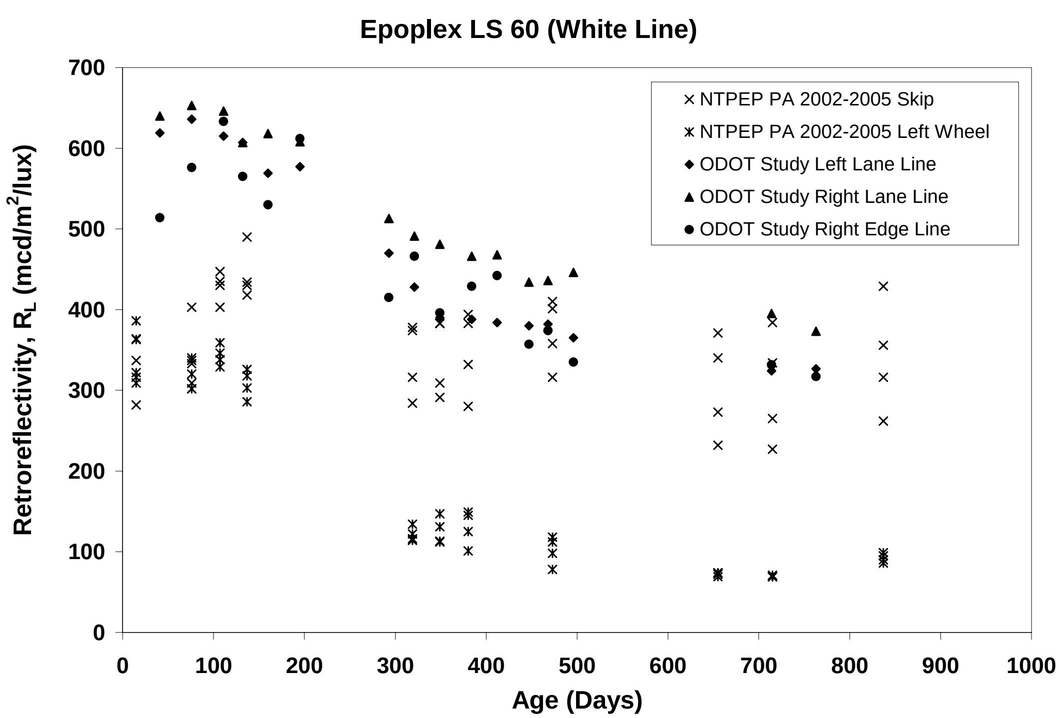

Figure (7.20): Comparison between ODOT District 3 and NTPEP PA 2002-2005 Retroreflectivity Data for White LS 60.

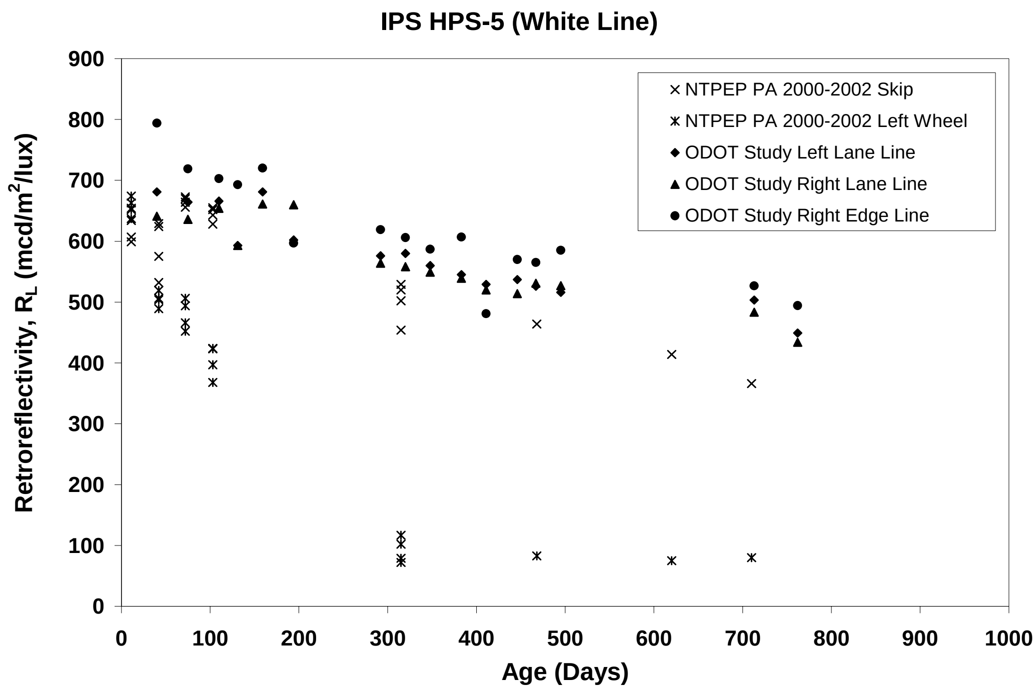

Figure (7.21): Comparison between ODOT District 3 and NTPEP PA 2000-2002 Retroreflectivity Data for White HPS-5.

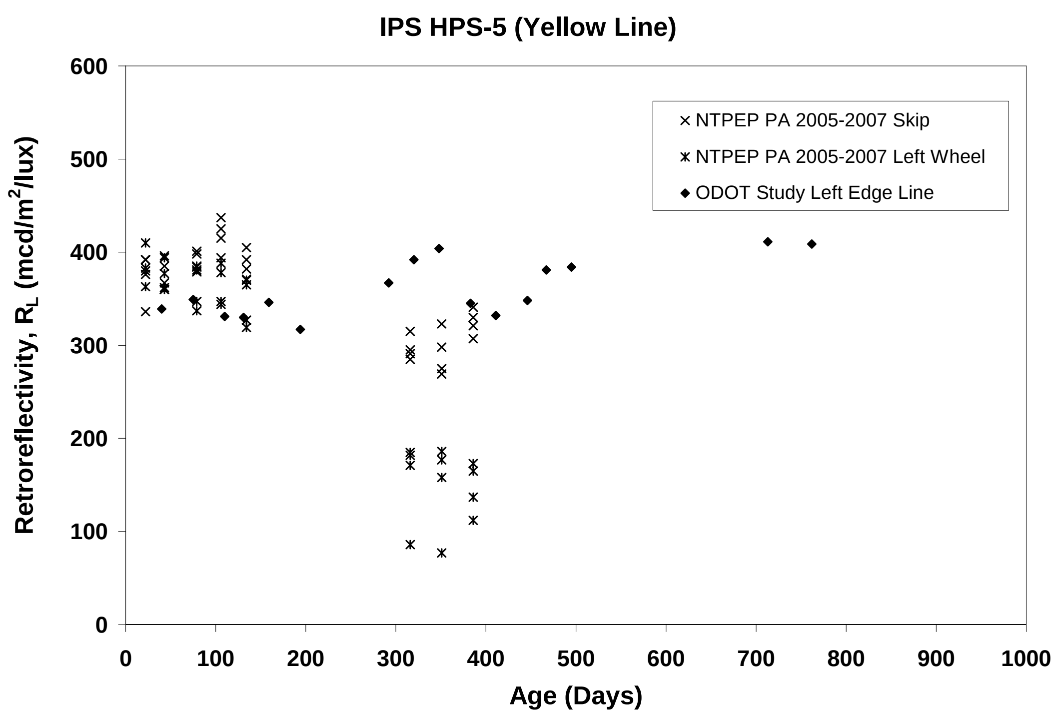

Figure (7.22): Comparison between ODOT District 3 and NTPEP PA 2005-2007 Retroreflectivity Data for Yellow HPS-5.

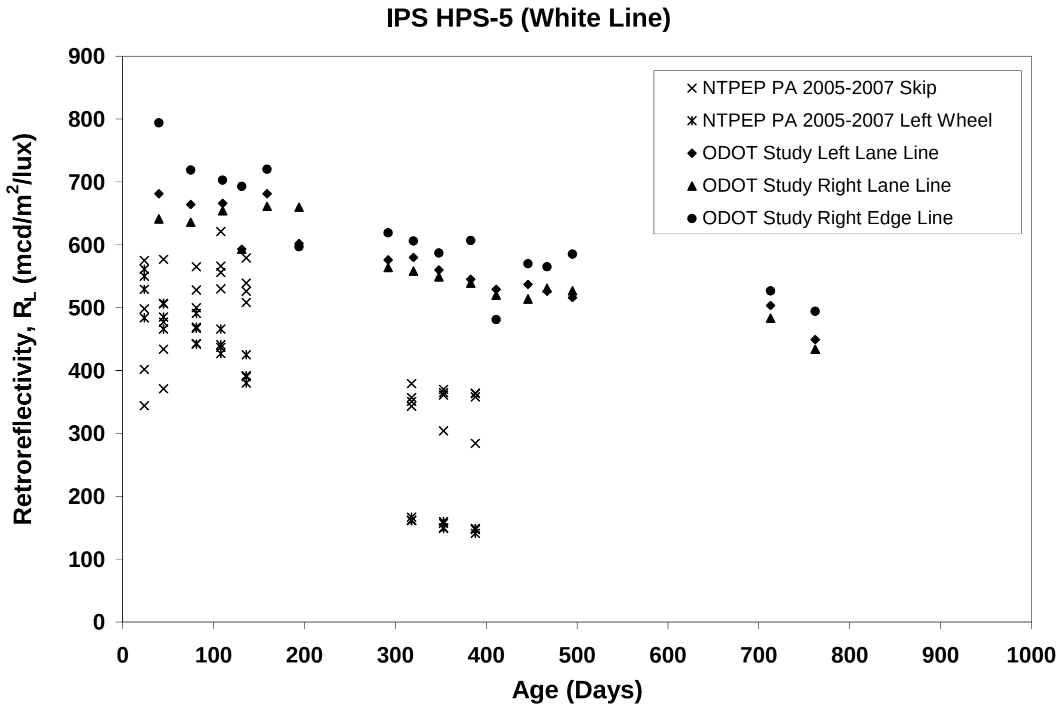

Figure (7.23): Comparison between ODOT District 3 and NTPEP PA 2005-2007 Retroreflectivity Data for White HPS-5.

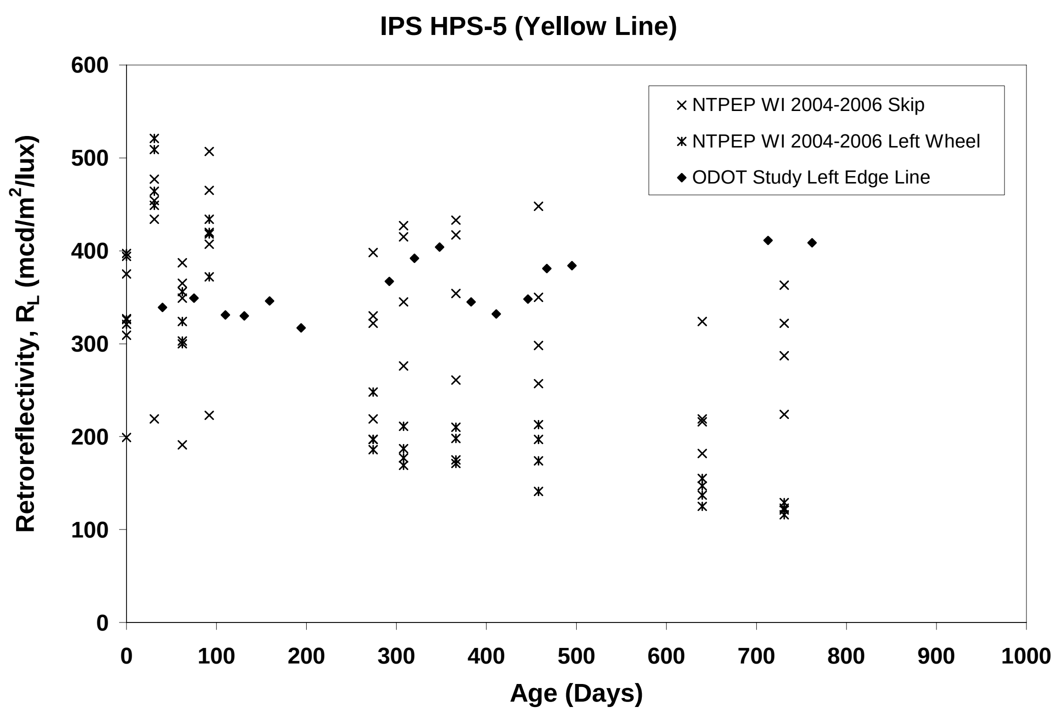

Figure (7.24): Comparison between ODOT District 3 and NTPEP WI 2004-2006 Retroreflectivity Data for Yellow HPS-5.

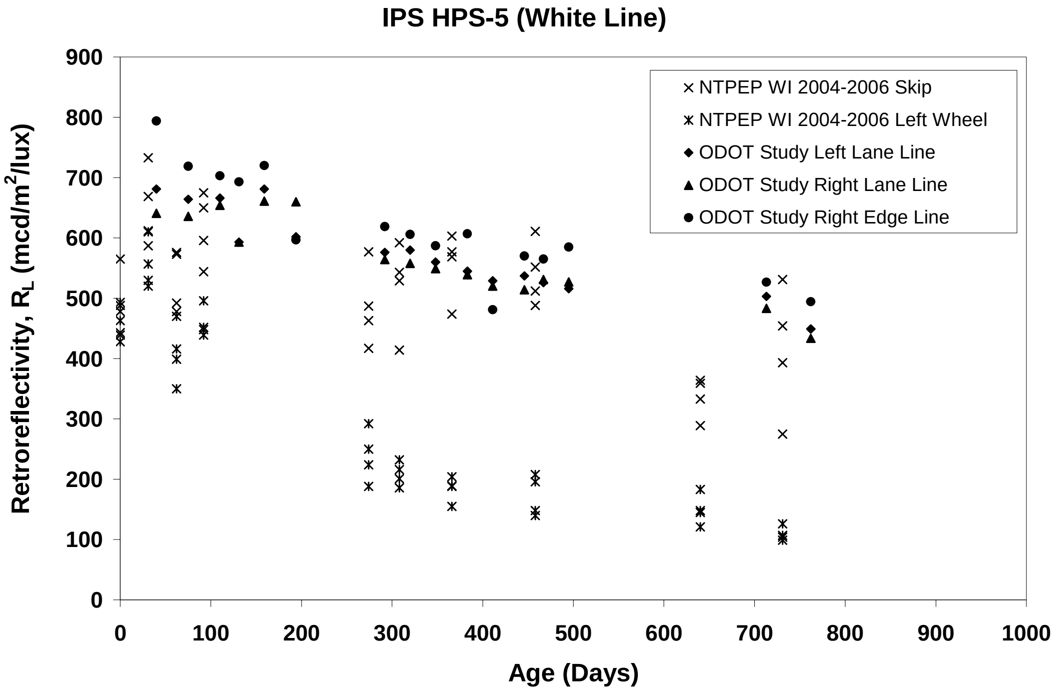

Figure (7.25): Comparison between ODOT District 3 and NTPEP WI 2004-2006 Retroreflectivity Data for White HPS-5.

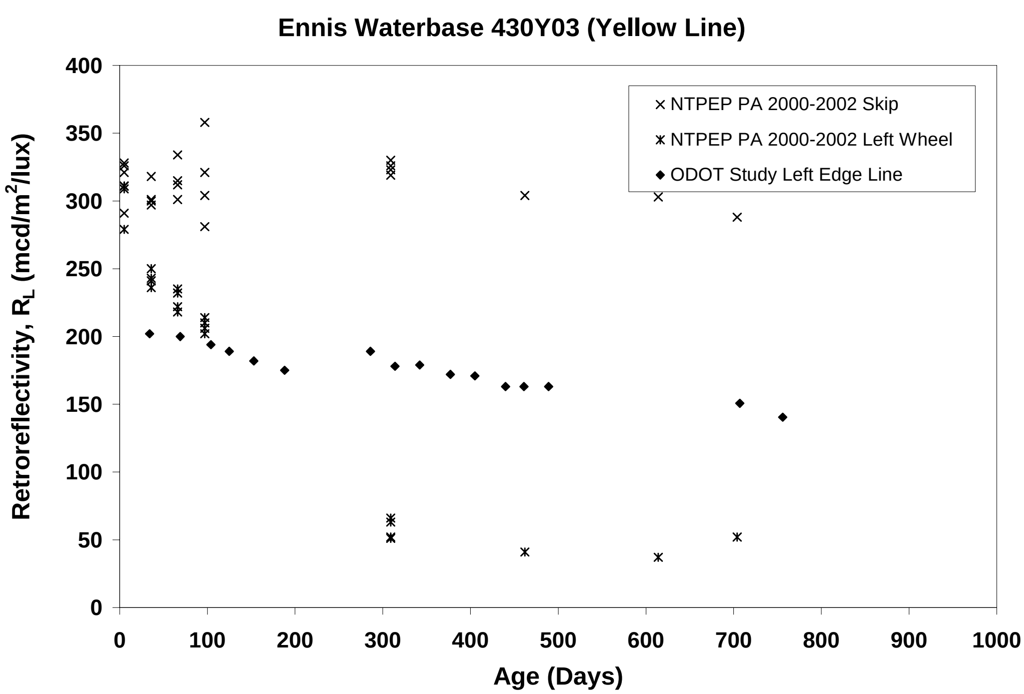

Figure (7.26): Comparison between ODOT District 3 and NTPEP PA 2000-2002 Retroreflectivity Data for Yellow Ennis Paint.

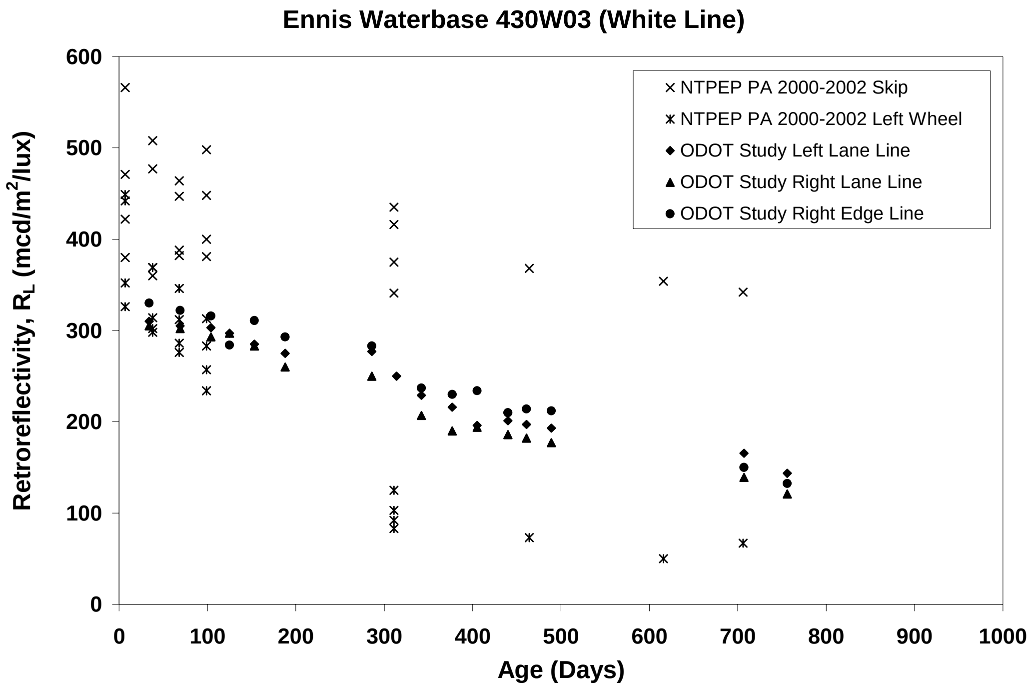

Figure (7.27): Comparison between ODOT District 3 and NTPEP PA 2000-2002 Retroreflectivity Data for White Ennis Paint.

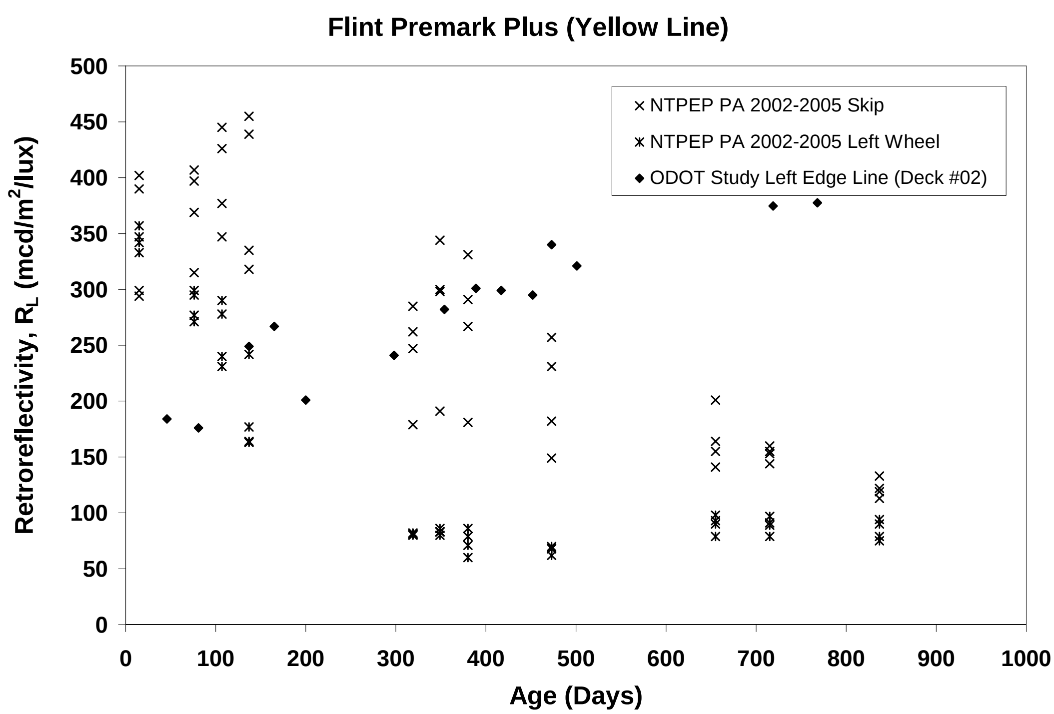

Figure (7.28): Comparison between ODOT District 3 and NTPEP PA 2002-2005 Retroreflectivity Data for Yellow Premark Plus.

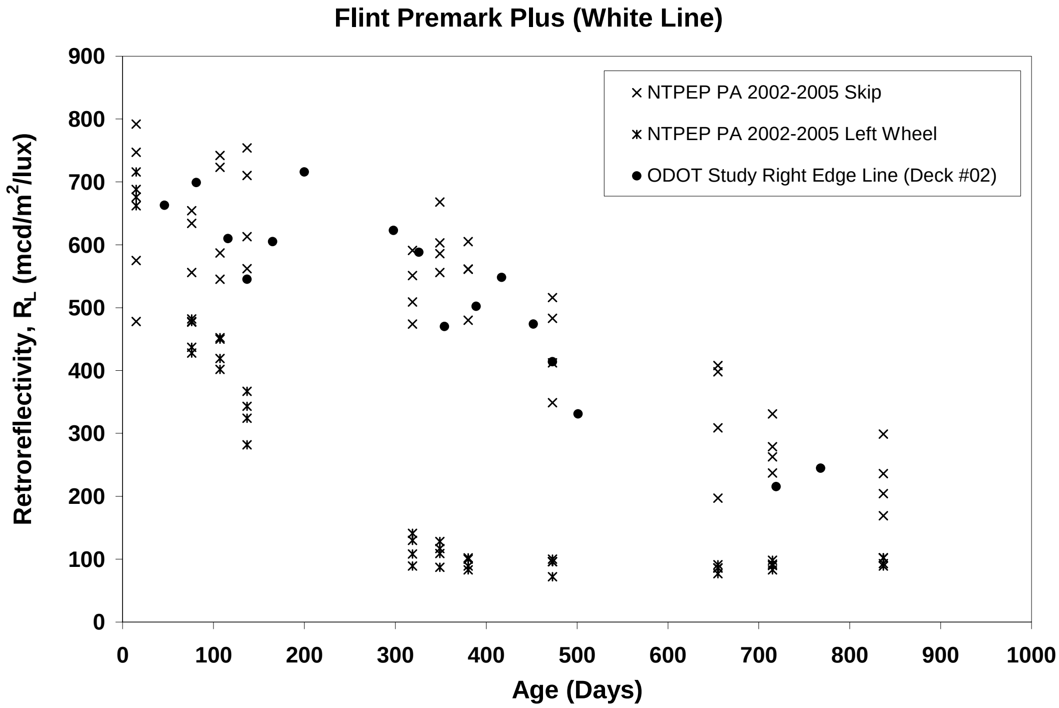

Figure (7.29): Comparison between ODOT District 3 and NTPEP PA 2002-2005 Retroreflectivity Data for White Premark Plus.

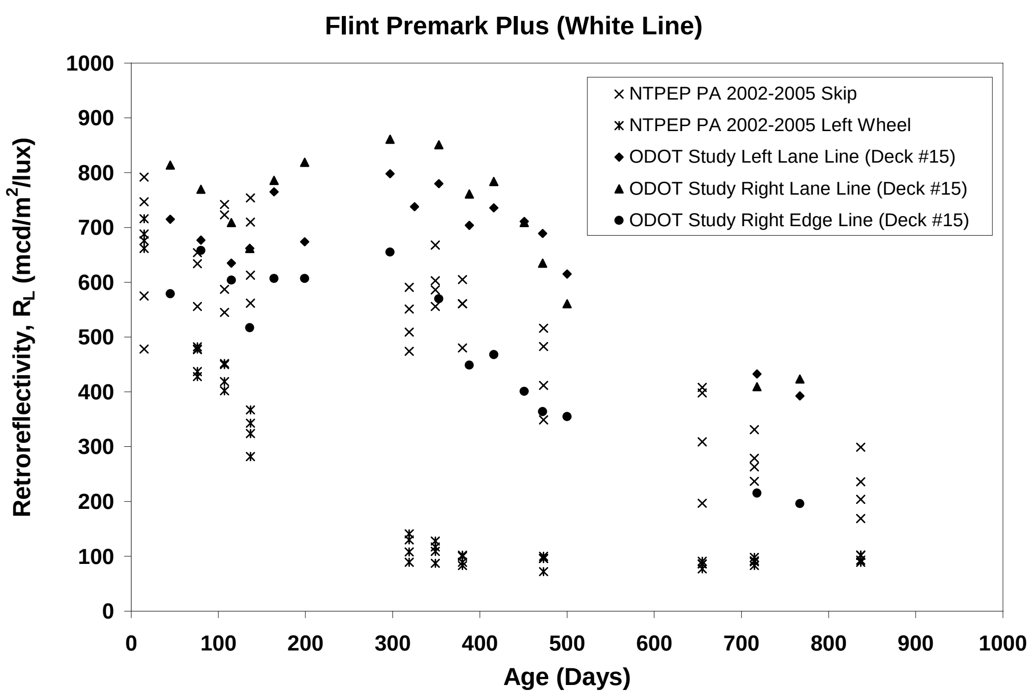

Figure (7.30): Comparison between ODOT District 3 and NTPEP PA 2002-2005 Retroreflectivity Data for White Premark Plus.

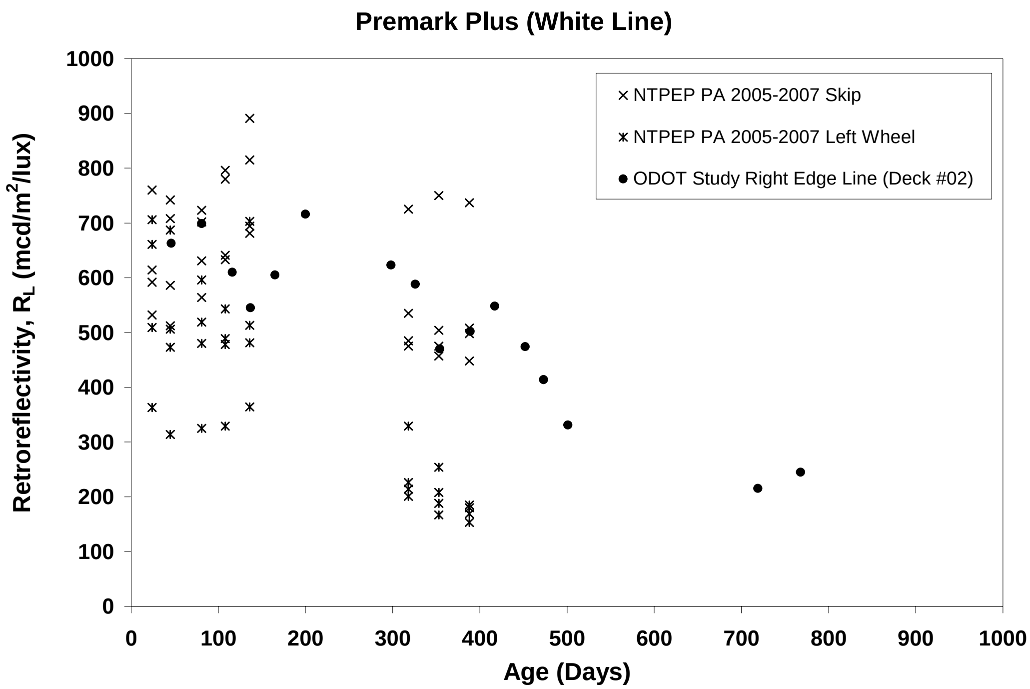

Figure (7.31): Comparison between ODOT District 3 and NTPEP PA 2005-2007 Retroreflectivity Data for White Premark Plus.

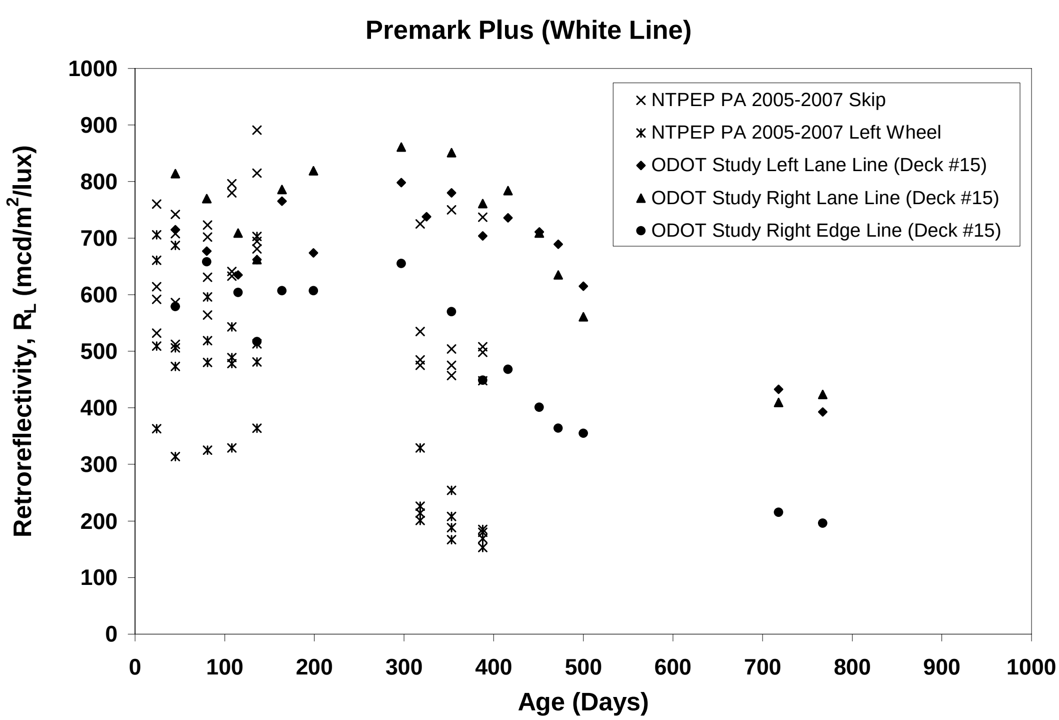

Figure (7.32): Comparison between ODOT District 3 and NTPEP PA 2005-2007 Retroreflectivity Data for White Premark Plus.

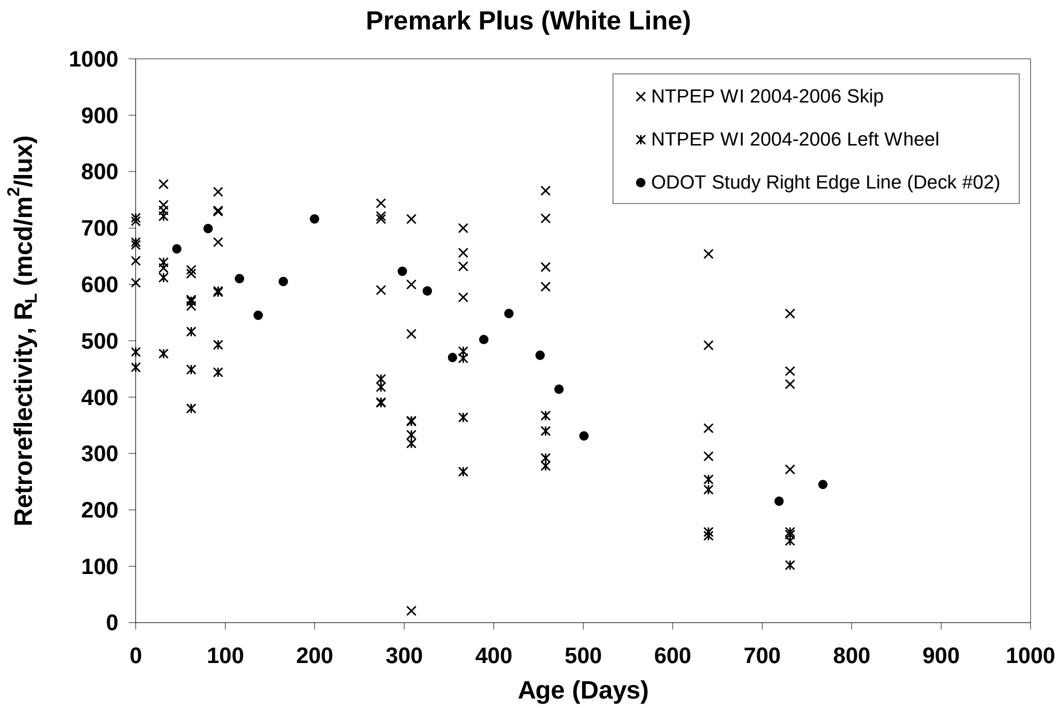

Figure (7.33): Comparison between ODOT District 3 and NTPEP WI 2004-2006 Retroreflectivity Data for White Premark Plus.

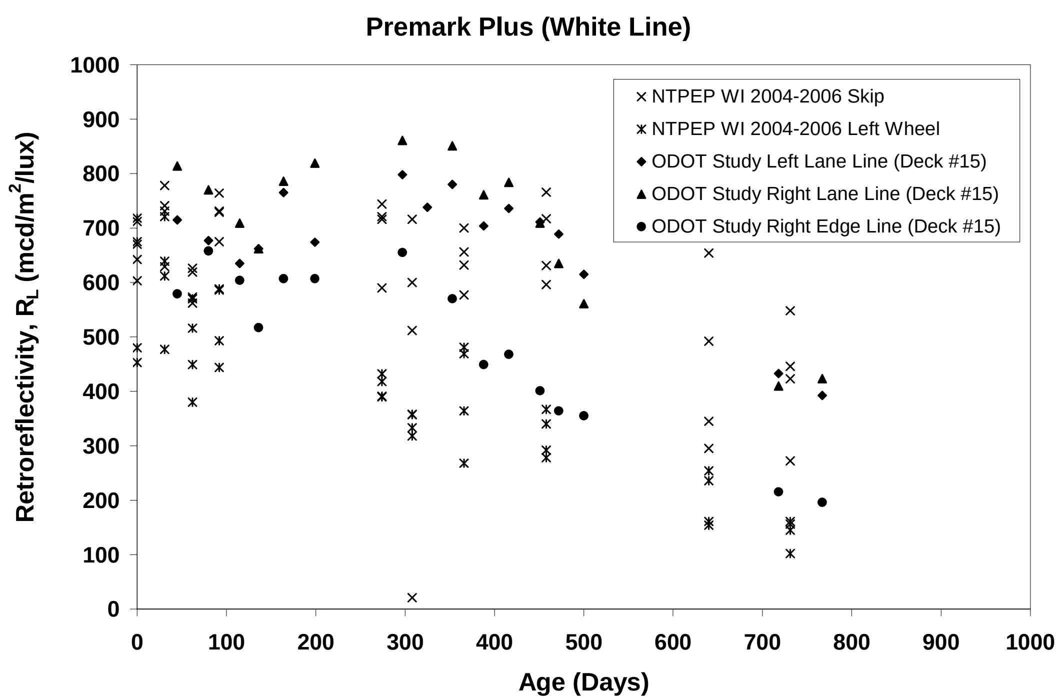

Figure (7.34): Comparison between ODOT District 3 and NTPEP WI 2004-2006 Retroreflectivity Data for White Premark Plus.

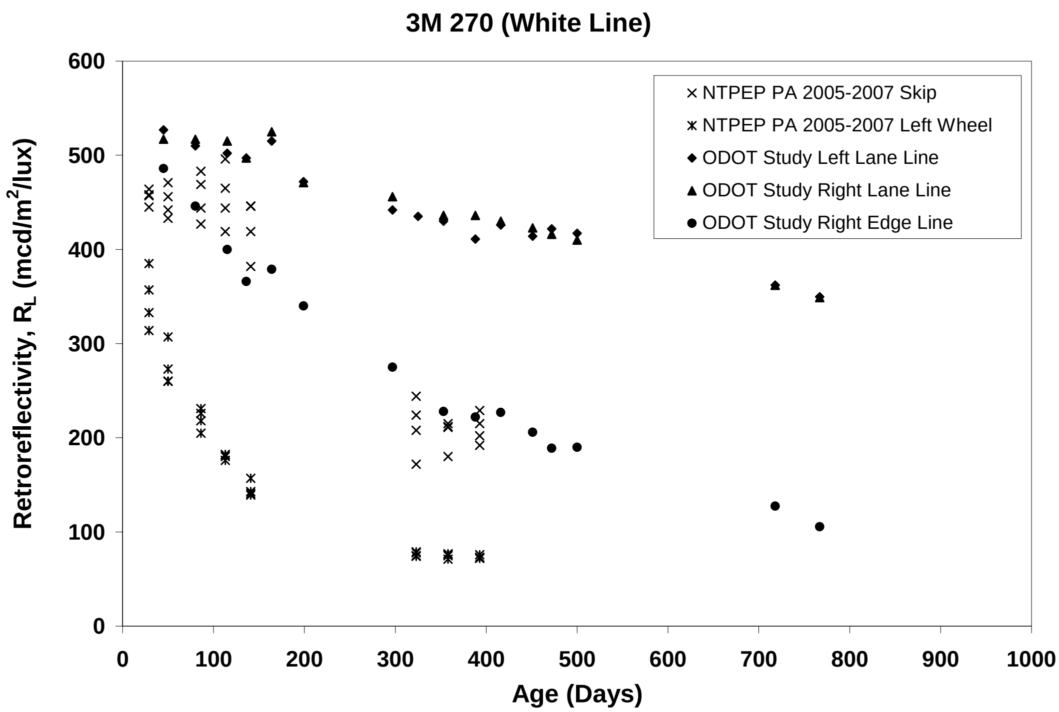

Figure (7.35): Comparison between ODOT District 3 and NTPEP PA 2005-2007 Retroreflectivity Data for White 3M 270 ES.

CHAPTER 8
ESTIMATION OF PAVEMENT MARKING SERVICE LIFE

8.1 Introduction

In the previous chapters, the performance of the evaluated materials was compared to milestone performance criteria. The comparison was based on actual field measurements or ratings collected during the performance evaluation period. This comparison was helpful in characterizing the short and the medium-term performance of these materials, and useful in identifying which materials may perform satisfactorily over the long-term.

In this chapter, future retroreflectivity performance is predicted by fitting various mathematical models to field retroreflectivity data collected during the periodic evaluations. These models along with the corresponding model parameters are then used to estimate the service life of the pavement marking. The latter is defined as the time required for retroreflectivity to drop to a point where the pavement marking is no longer effective as a delineation system. The pavement marking service lives estimated in this chapter are used later in Chapter 9 to calculate the life-cycle cost of the evaluated materials.

8.2 Retroreflectivity Modeling

Five mathematical models were used in this project to describe the deterioration trend of pavement marking retroreflectivity. These models include the linear model, the power model, the exponential model, the natural logarithmic model, and the inverse polynomial model. The mathematical expressions for these models are presented in Table (8.1); in both x-y and R_L versus *Age* forms. For consistency, retroreflectivity, R_L, in these models is defined in mcd/m^2/lux and *Age* is defined in days. As shown in Table (8.2), all five models have been previously used in the literature to model pavement marking retroreflectivity.

Table (8.1): 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	$y = a + b.\ln(x)$	$R_L = a + b.\ln(Age)$
Inverse Polynomial	$y = \frac{1}{a + bx + cx^2}$	$R_L = \frac{1}{a + b.Age + c.Age^2}$

Table (8.2): Selected References that used each Retroreflectivity Model.

Model Type	Reference
Linear	- Lee et al. (1999) - Migletz et al. (2001) - Thamizharasan et al. (2003) - Gates et al. (2003) - Lindly and Wijesundera (2003) - Kobf (2004) - Lindly and Narci (2006)
Power	- Lindly and Wijesundera (2003) - Lindly and Narci (2006)
Exponential	- Martin et al. (1996) - Migletz et al. (2001) - Lindly and Wijesundera (2003) - Gates et al. (2003) - Kobf (2004) - Lindly and Narci (2006)
Natural Logarithmic	- Andrady (1997) - Migletz et al. (2001) - Abboud and Bowman (2002) - Lindly and Wijesundera (2003) - Gates et al. (2003) - Kobf (2004) - Lindly and Narci (2006) - Fitch (2007)
Inverse Polynomial	- Bahar et al. (2006)

To simplify the analysis, the power and the exponential models were linearized using log transformation; the natural logarithmic model was linearized by replacing ln(x) by x'; and the inverse polynomial model was converted into a second-order polynomial model through reciprocal transformation (Table 8.3). In all cases, the original model parameters can be estimated from the transformed model parameters, if necessary.

Table (8.3): Simplification of Retroreflectivity Models.

	Mathematical Form	
Model Type	**Original**	**Transformed**
Linear	$y = a + bx$	$y = a + bx$
Power	$y = ax^b$	$y' = a' + b.x'$ where $y' = \log(y); a' = \log(a); x' = \log(x)$
Exponential	$y = ae^{bx}$	$y' = a' + b.x$ where $y' = \ln(y); a' = \ln(a)$
Natural Logarithmic	$y = a + b.\ln(x)$	$y = a + b.x'$ where $x' = \ln(x)$
Inverse Polynomial	$y = \dfrac{1}{a + bx + cx^2}$	$y' = a + bx + cx^2$ where $y' = 1/y$

The transformed models were then fitted to individual retroreflectivity data collected during the field evaluations. As mentioned previously, an effort was made in this project to collect ten (10) retroreflectivity readings per line per periodic evaluation using two handheld retroreflectometers. In some cases, only five (5) retroreflectivity readings were taken instead of ten (10) due to battery malfunction with one of the devices. In other occasions, no retroreflectivity readings were taken due to rain or due to lane closure for a nearby bridge paint.

Figures (8.1) through (8.4) present example individual retroreflectivity data for 3M 380WR ES installed on Bridge Deck # 1. As discussed in Chapter 4, standard white and yellow 3M 380WR ES tapes were used on the right and left edge lines of Bridge Deck # 1, respectively, and white contrast 3M 380WR-5 ES tape was used on the lane lines of this bridge deck. This material was installed on June 2, 2006. The first periodic evaluation was conducted in July 2006 and the last periodic evaluation was conducted in July 2008. The performance evaluation was limited to dry conditions when the lines were clear of dirt and deicing salt. This restriction limited the ability to conduct the evaluation during the period from November to April. In these figures, it can be noticed that the highest drop in retroreflectivity took place on the white right edge line, followed by the white right and left lane lines, followed by the yellow left edge line. The variability in the retroreflectivity readings was higher for the white and yellow right and left edge lines, respectively (i.e., the standard 3M 380WR ES tape) than that for the white lane lines (i.e., the contrast 3M 380WR-5 ES tape). It can also be noticed that the drop in retroreflectivity during winter – due to snowplowing – was higher than that during summer; and that the drop in retroreflectivity during the second year was higher than that during the first year.

The analysis was repeated for each of the four lines (yellow left edge line, white left lane line, white right lane line, and white right edge line) on every bridge. Therefore, given that sixteen field evaluations were conducted in this project, a relatively large number of retroreflectivity readings were available for the curve fitting.

A Matlab code was developed to handle the large amount of data involved in the analysis. The developed code employed two methods in obtaining the regression model parameters, namely the Ordinary Least Square method and the Weighted Least Square method. Both methods are discussed in detail in the following subsections. In brief, both methods are based on minimizing the sum of the squared difference between the data points and the model predictions in obtaining the model parameters. In the first method, an equal weight is given to all data points, so that all points will contribute equally in estimating the model constants. Whereas in the second method, different weights are given to the data points so that points given higher weights will contribute more than the others in obtaining the model parameters. Since the objective in this chapter is to obtain reasonable estimates of the pavement marking service live, it is more important to accurately predict retroreflectivity performance towards the end of the service life of the pavement marking than its initial retroreflectivity performance. This can be accomplished using the Weighted Least Square method by assigning higher weight factors to retroreflectivity data obtained towards the end of the evaluation period than those obtained initially. As will be discussed in the following subsections, the selection of the weight factors is not arbitrary, but rather is based on the number of field evaluations conducted during each calendar year. Finally, the analysis was repeated by including and excluding individual retroreflectivity readings that varied significantly from the sample mean (i.e., outliers) during each periodic evaluation.

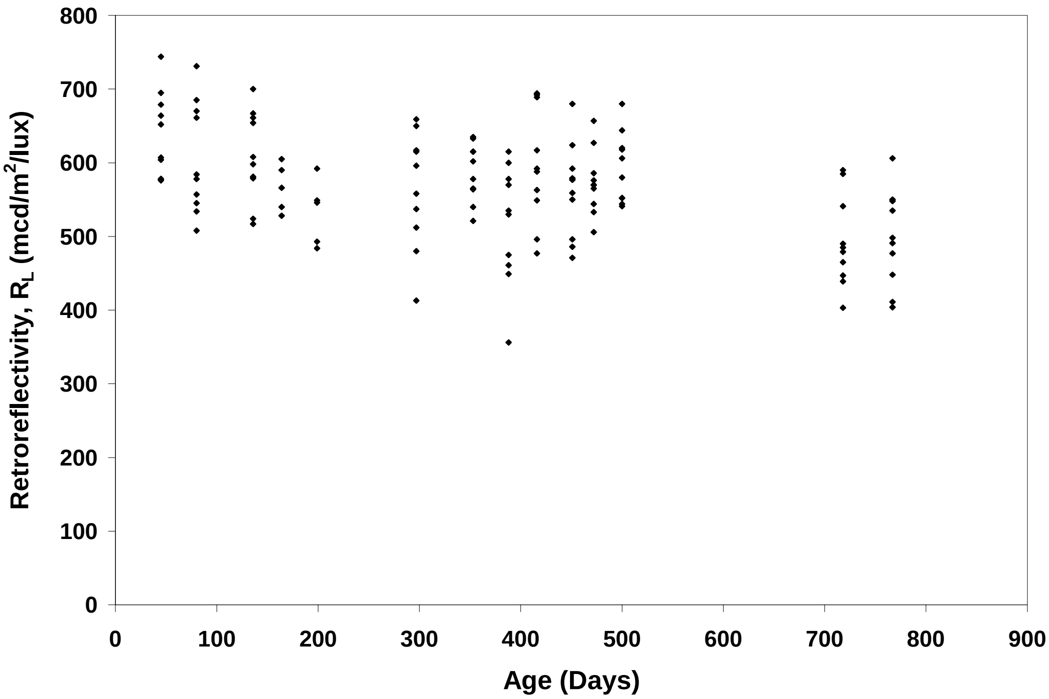

Figure (8.1): Individual Retroreflectivity Readings for Yellow 3M 381WR ES Durable Tape Installed on the Left Edge Line of Bridge Deck # 1.

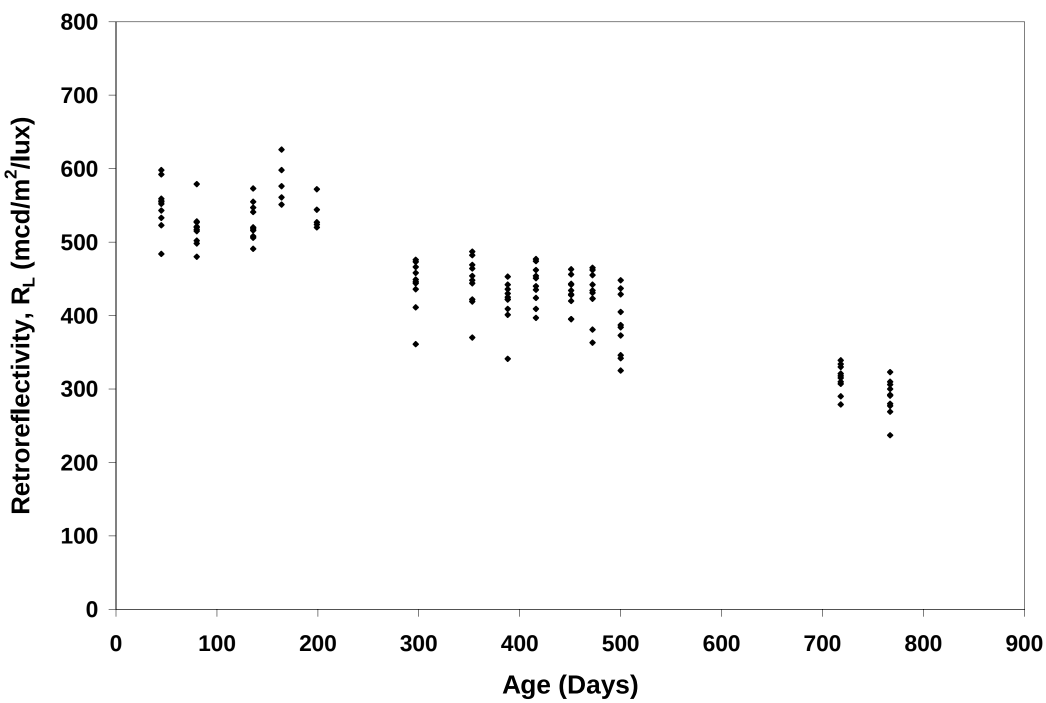

Figure (8.2): Individual Retroreflectivity Readings for White 3M 380WR-5 ES Contrast Tape Installed on the Left Lane Line of Bridge Deck # 1.

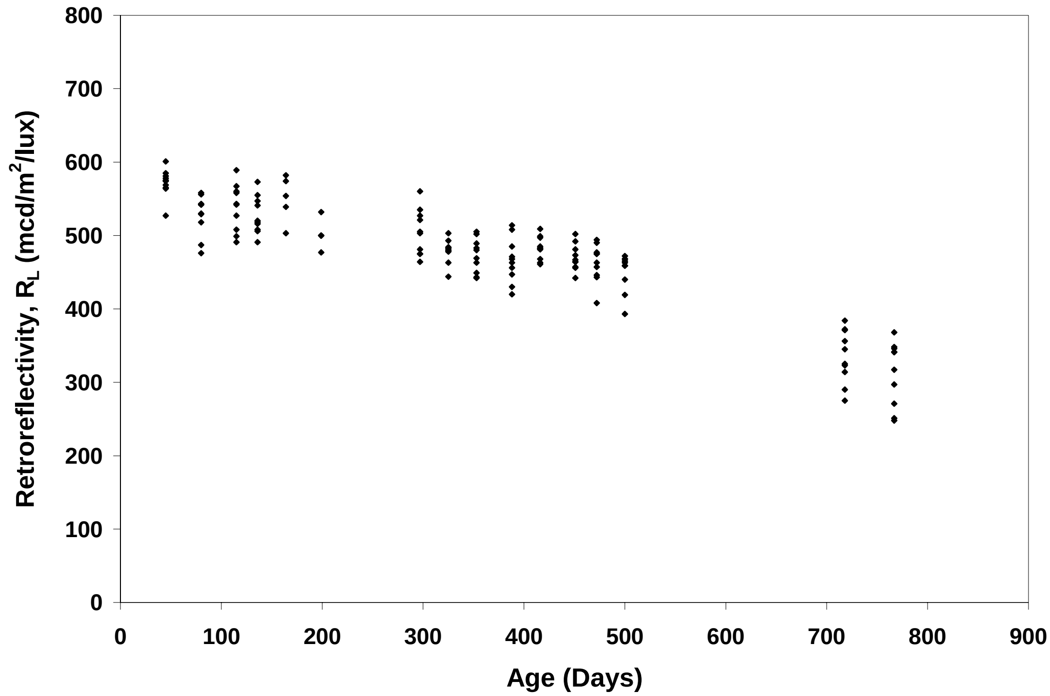

Figure (8.3): Individual Retroreflectivity Readings for White 3M 380WR-5 ES Contrast Tape Installed on the Right Lane Line of Bridge Deck # 1.

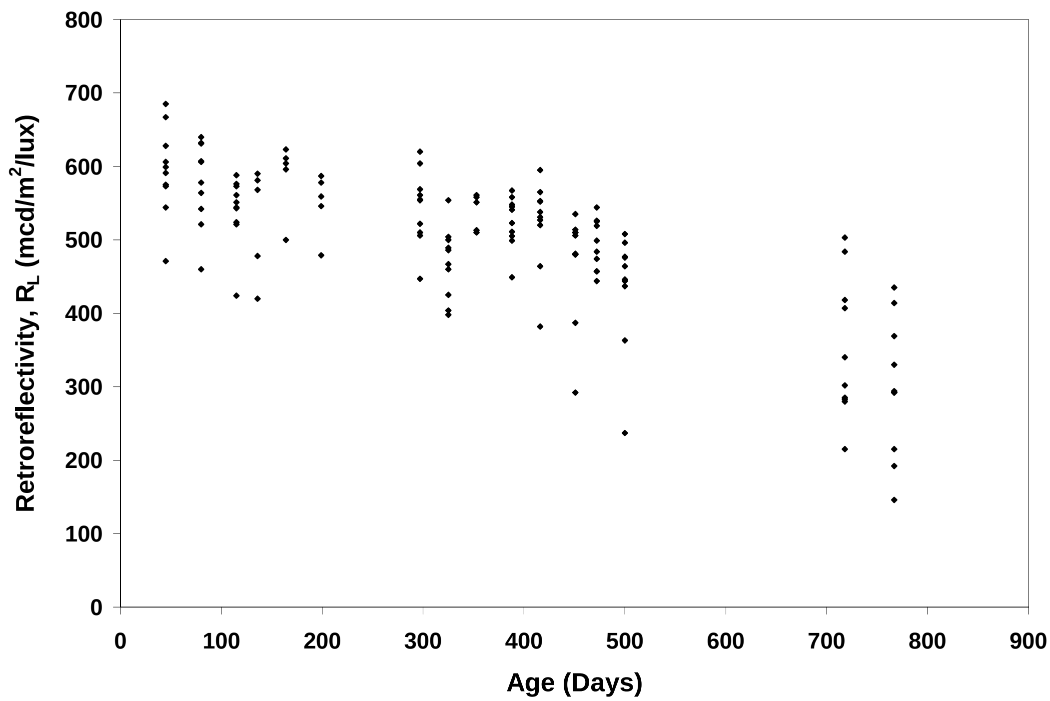

Figure (8.4): Individual Retroreflectivity Readings for White 3M 380WR ES Durable Tape Installed on the Right Edge Line of Bridge Deck # 1.

8.2.1 Ordinary Least Square Method

The formulation in this subsection will be presented first for the simplest form of a mathematical relationship that is the simple linear model first. Then, it will be extended to the second-order polynomial model. The former is applicable to the linear, power, exponential and natural logarithmic models in their linearized forms, while the latter is applicable to the transformed form of the inverse polynomial model.

8.2.1.1 Simple Linear Model

Given sample data consisting of *N* observed pairs of actual $x_{i=1,N}$ and $y_{i=1,N}$ data points, it is assumed that y_i can be reasonably estimated from x_i using the following relationship:

$$\hat{y}_i = \hat{a} + \hat{b} \cdot x_i \tag{8.1}$$

where $\hat{y}_i$ is the estimated value of the dependent variable *y*, x_i is the true value of the independent variable *x*, $\hat{a}$ is the estimated value of the constant *a* (the intercept with the y-axis), and $\hat{b}$ is the estimated value of the constant *b* (the slope of the function y).

The difference between the observed and the estimated value of *y* that cannot be explained by the model is called error, e_i (or residual), and is equal to:

$$e_i = y_i - \hat{y}_i \tag{8.2}$$

In least square methods, the optimal fit is achieved once the sum of square of residuals is minimized. The sum of square of residuals is expressed as:

$$\sum e_i^2 = \sum_{i=1}^{N} (y_i - \hat{y}_i)^2 = \sum_{i=1}^{N} \left(y_i - (\hat{a} + \hat{b}\, x_i)\right)^2 \tag{8.3}$$

The previous equation is dependent on two variables only, $\hat{a}$ and $\hat{b}$. Therefore, it can be minimized by first taking the partial derivative with respect to both variables; equating both partial derivatives to zero; and simultaneously solving the resulting two equations for $\hat{a}$ and $\hat{b}$.

$$\frac{\partial\left(\sum e_i^2\right)}{\partial \hat{a}} = \frac{\partial f\left(\hat{a}, \hat{b}\right)}{\partial \hat{a}} = \frac{\partial}{\partial \hat{a}} \sum_{i=1}^{N} \left[y_i - \hat{a} - \hat{b}\, x_i\right]^2$$

$$= -2\sum y_i + 2N\,\hat{a} + 2\hat{b} \sum x_i = 0 \tag{8.4}$$

$$\frac{\partial\left(\sum e_i^2\right)}{\partial\hat{b}} = \frac{\partial f\left(\hat{a},\hat{b}\right)}{\partial\hat{b}} = \frac{\partial}{\partial\hat{b}}\sum_{i=1}^{N}\left[y_i - \hat{a} - \hat{b}\,x_i\right]^2$$

$$= -2\sum x_i y_i + 2\,\hat{a}\sum x_i + 2\hat{m}\sum x_i^2 = 0 \qquad (8.5)$$

The following are the solutions for $\hat{a}$ and $\hat{b}$ with some rearrangement using $\sum x_i = \bar{x}.N$ and $\sum y_i = \bar{y}.N$:

$$\hat{b} = \frac{\sum x_i y_i - N\,\bar{x}\,\bar{y}}{\sum x_i^2 - N\,\bar{x}^2} \qquad (8.6)$$

$$\hat{a} = \bar{y} - \hat{b}\,\bar{x} \qquad (8.7)$$

where $\bar{y}$ is the mean of y_i, $\bar{x}$ is the mean of x_i, and N is the total number of observations.

In order to utilize the outstanding matrix manipulation capabilities in Matlab, the previous equations were formulated and solved in matrix form. The derivation follows by rewriting Equation (8.1) as a multiplication of an N x 2 matrix by a 2 x 1 array, as follows:

$$\begin{Bmatrix} y_1 \\ y_2 \\ y_3 \\ \vdots \\ y_N \end{Bmatrix} = \begin{bmatrix} 1 & x_1 \\ 1 & x_2 \\ 1 & x_3 \\ \vdots & \vdots \\ 1 & x_N \end{bmatrix} \begin{Bmatrix} \hat{a} \\ \hat{b} \end{Bmatrix} \qquad (8.8)$$

or,

$$\underline{y} = X\,\underline{m} \qquad (8.9)$$

where $\underline{y}$ is an array of N rows that contains the observed y_i values, X is an N x 2 matrix that consists of ones in the first column and the observed x_i values in the second column, and $\underline{m}$ is an array that contains the model constants $\hat{a}$ and $\hat{b}$.

It is clear from the previous equation that the objective is to solve for array $\underline{m}$. This can be accomplished by first multiplying both sides of Equation (8.9) by X^T,

$$X^T\,\underline{y} = X^T X\,\underline{m} \qquad (8.10)$$

Then, multiplying both sides of Equation (8.10) by $\left[X^T X\right]^{-1}$,

$$\left[X^T X\right]^{-1} X^T\,\underline{y} = \left[X^T X\right]^{-1} X^T X\,\underline{m} = I\underline{m} = \underline{m}$$

or,

$$\underline{m} = \left[X^T X\right]^{-1} X^T \underline{y} \tag{8.11}$$

where *I* is a 2 by 2 unity matrix.

In the previous equations,

$$X^T X = \begin{bmatrix} 1 & 1 & 1 & \cdots & 1 \\ x_1 & x_2 & x_3 & \cdots & x_N \end{bmatrix} \begin{bmatrix} 1 & x_1 \\ 1 & x_2 \\ 1 & x_3 \\ \vdots & \vdots \\ 1 & x_N \end{bmatrix}$$

$$= \begin{bmatrix} N & \sum_i x_i \\ \sum_i x_i & \sum_i x_i^2 \end{bmatrix} = \begin{bmatrix} N & \bar{x}.N \\ \bar{x}.N & \sum_i x_i^2 \end{bmatrix} \tag{8.12}$$

and,

$$X^T \underline{y} = \begin{bmatrix} 1 & 1 & 1 & \cdots & 1 \\ x_1 & x_2 & x_3 & \cdots & x_N \end{bmatrix} \begin{Bmatrix} y_1 \\ y_2 \\ y_3 \\ \vdots \\ y_N \end{Bmatrix}$$

$$= \begin{Bmatrix} \sum_i y_i \\ \sum_i x_i y_i \end{Bmatrix} = \begin{Bmatrix} \bar{y}.N \\ \sum_i x_i y_i \end{Bmatrix} \tag{8.13}$$

The similarity between Equations (8.12) and (8.13) and Equations (8.6) and (8.7) is noted.

8.2.1.2 Second-Order Polynomial Model

The formulation for obtaining the second-order polynomial model parameters is similar to that for the linear model. In the revised formulation, the second-order polynomial model, $y = \text{a} + \text{b}x + \text{c}x^2$, is described as a multiplication of an N x 3 matrix by a 3 x 1 array, as follows:

$$\begin{Bmatrix} y_1 \\ y_2 \\ y_3 \\ \vdots \\ y_N \end{Bmatrix} = \begin{bmatrix} 1 & x_1 & x_1^2 \\ 1 & x_2 & x_2^2 \\ 1 & x_3 & x_3^2 \\ \vdots & \vdots & \vdots \\ 1 & x_N & x_N^2 \end{bmatrix} \begin{Bmatrix} \hat{a} \\ \hat{b} \\ \hat{c} \end{Bmatrix} \tag{8.14}$$

or,

$$\underline{y} = X\ \underline{m} \tag{8.15}$$

where $\underline{y}$ is an array of N rows that contains the observed y_i values; X is an N x 3 matrix that consists of ones in the first column, the observed x_i values in the second column, and the square of the observed x_i values in the third column; and $\underline{m}$ is an array that contains the model constants $\hat{a}$, $\hat{b}$, and $\hat{c}$.

Multiplying both sides of Equation (8.15) by X^T, then by $[X^TX]^{-1}$, gives:

$$\underline{m} = \left[X^T X\right]^{-1} X^T \underline{y} \tag{8.16}$$

The previous equation is the same as Equation (8.11). The only difference is that the $\underline{m}$ array in this equation consists of three model parameters, whereas the $\underline{m}$ array in Equation (8.11) consists of two.

8.2.2 Weighted Least Square (WLS) Method

The formulation of the Weighted Least Square method is similar to that of the Ordinary Least Square method. The only difference is that varying weights are assigned to each data point prior to solving for the model parameters. This can be accomplished by multiplying both sides of Equation (8.8), or Equation (8.14) in the case of the second-order polynomial, by a two dimensional square matrix, W, that consists of the weights along its diagonal and zeros elsewhere.

$$\begin{bmatrix} w_1 & 0 & 0 & 0 & 0 \\ 0 & w_2 & 0 & 0 & 0 \\ 0 & 0 & w_3 & 0 & 0 \\ 0 & 0 & 0 & \vdots & 0 \\ 0 & 0 & 0 & 0 & w_N \end{bmatrix} \begin{Bmatrix} y_1 \\ y_2 \\ y_3 \\ \vdots \\ y_N \end{Bmatrix} = \begin{bmatrix} w_1 & 0 & 0 & 0 & 0 \\ 0 & w_2 & 0 & 0 & 0 \\ 0 & 0 & w_3 & 0 & 0 \\ 0 & 0 & 0 & \vdots & 0 \\ 0 & 0 & 0 & 0 & w_N \end{bmatrix} \begin{bmatrix} 1 & x_1 \\ 1 & x_2 \\ 1 & x_3 \\ \vdots & \vdots \\ 1 & x_N \end{bmatrix} \begin{Bmatrix} \hat{a} \\ \hat{b} \end{Bmatrix} \tag{8.17}$$

or,

$$W\ \underline{y} = W\ X\ \underline{m} \tag{8.18}$$

where all parameters have been previously defined.

The $\underline{m}$ array that consists of the model parameters can be obtained by multiplying both sides of Equation (8.18) by X^T; then by $\left[X^T\ W\ X\right]^{-1}$. These two steps will produce:

$$\underline{m} = \left[X^T\ W\ X\right]^{-1}\ X^T\ W\ \underline{y} \tag{8.19}$$

In this project, a weight factor of 4 was used for all retroreflectivity readings collected during the last two field evaluations (May 2008 and July 2008) and a weight factor of 1 for all other retroreflectivity readings. The effect of using these weight factors is the same as repeating the retroreflectivity data set corresponding to the last two field evaluations four times, while keeping the other retroreflectivity data sets unchanged. The underlying reason behind selecting these weight factors is that only two field evaluations were conducted during the year 2008, while five field evaluations were conducted in 2006 and seven field evaluations were conducted in 2007. It is noted that the retroreflectivity performance did not change significantly during the summer as it did during winter, which justifies assigning different weight factors for retroreflectivity readings obtained in 2008 as compared to those obtained in 2006 and 2007.

The effect of using the Weighted Least Square method instead of the Ordinary Least Square method on the estimation of the pavement marking service life depended on whether the rate of retroreflectivity during the second year was higher or lower than that during the first year. If retroreflectivity dropped at a higher rate during the second year as compared to the first year (i.e., the difference between retroreflectivity values in 2008 and 2007 is significantly higher than the difference between retroreflectivity values in 2007 and 2006), lower service life estimates are obtained using the Weighted Least Square method; where if retroreflectivity dropped at a lower rate during the second year as compared to the first year, higher service life estimates are obtained using the Weighted Least Square method.

8.2.3 Outlier Identification and Removal

As mentioned previously, an attempt was made to collect ten retroreflectivity readings per line per periodic evaluation. In few instances, some of the retroreflectivity readings were significantly higher or lower than the sample mean. To this end, if the difference between a retroreflectivity reading and the sample mean was greater than two standard deviations, this data point was considered an outlier. The Matlab code was programmed to include or exclude outliers as prompted by the user. If the user selected to exclude outliers, retroreflectivity data points identified as outliers are replaced with NaN, which stands for "not a number" in Matlab; and the effect of these data points is excluded from the analysis.

8.2.4 Regression Model Parameters

Based on the previous, four types of analyses were conducted in this project:

1- Ordinary Least Square method without excluding outliers
2- Ordinary Least Square method where outliers were excluded
3- Weighted Least Square method without excluding outliers
4- Weighted Least Square method where outliers were excluded

Tables (8.4) through (8.7) summarize the retroreflectivity model parameters resulted from fitting each of the five models discussed earlier to the individual retroreflectivity readings presented in Figures (8.1) through (8.4) for 3M 380WR ES durable tape, using each of the previous four methods. These parameters are depicted in their untransformed form; and hence can be used along with the original retroreflectivity models (middle column in Table 8.1) to predict retroreflectivity at any point in time. For example, the estimated retroreflectivity of 3M 380WR ES white durable tape on the right edge line after one year (365 days) using the exponential model and the Ordinary Least Square method without excluding outliers is equal to $y = a\,e^{b\,x} = 650 \times e^{(-0.000846 \times 365)} = 477$ mcd/m^2/lux. In comparison, the average retroreflectivity value for this material on this line after about one year is about 525 mcd/m^2/lux (May 2007) to 539 mcd/m^2/lux (June 2007).

By comparing the retroreflectivity model parameters in these tables, it can be noticed that there is no difference between the predicted model parameters for yellow left edge line and white right lane line when outliers were included or excluded using either the Ordinary Least Square method (Table 8.4 and 8.5) or the Weighted Least Square method (Table 8.6 and 8.7). This indicates that no outliers were identified for this material on these two lines (i.e., no individual retroreflectivity reading was significantly higher or lower than the sample mean during any periodic evaluation). Meanwhile, a slight difference can be noticed in these tables for white left lane line and white right edge line due to including or excluding outliers. On the other hand, a noticeable difference can be observed between retroreflectivity model parameters obtained using the Ordinary Least Square method and those obtained using the Weighted Least Square method. As will be shown later in this chapter, this difference becomes profound once these models are projected to predict future retroreflectivity performance.

Table (8.4): Retroreflectivity Model Parameters for 3M 380WR ES Durable Tape (Ordinary Least Square Method; Outliers Not Excluded).

		Retroreflectivity Model Parameters			
Retroreflectivity Model	Model Parameter	Yellow Left Edge Line	White Left Lane Line	White Right Lane Line	White Right Edge Line
Linear	a	6.24E+02	5.75E+02	5.84E+02	6.20E+02
	b	-1.51E-01	-3.58E-01	-3.10E-01	-3.53E-01
Exponential	a	6.23E+02	5.96E+02	6.03E+02	6.50E+02
	b	-2.74E-04	-8.60E-04	-7.22E-04	-8.46E-04
Power	a	8.24E+02	1.32E+03	1.15E+03	1.33E+03
	b	-6.73E-02	-1.97E-01	-1.60E-01	-1.81E-01
Natural Logarithmic	a	7.81E+02	9.21E+02	8.76E+02	9.38E+02
	b	-3.76E+01	-8.46E+01	-7.15E+01	-7.90E+01
Inverse Polynomial	a	1.66E-03	1.83E-03	1.90E-03	1.90E-03
	b	1.35E-07	1.92E-07	-7.59E-07	-1.64E-06
	c	4.72E-10	2.46E-09	3.20E-09	4.92E-09

Table (8.5): Retroreflectivity Model Parameters for 3M 380WR ES Durable Tape (Ordinary Least Square Method; Outliers Excluded).

		Retroreflectivity Model Parameters			
Retroreflectivity Model	Model Parameter	Yellow Left Edge Line	White Left Lane Line	White Right Lane Line	White Right Edge Line
Linear	a	6.24E+02	5.78E+02	5.84E+02	6.30E+02
	b	-1.51E-01	-3.62E-01	-3.10E-01	-3.72E-01
Exponential	a	6.23E+02	6.01E+02	6.04E+02	6.65E+02
	b	-2.74E-04	-8.70E-04	-7.22E-04	-8.87E-04
Power	a	8.24E+02	1.36E+03	1.15E+03	1.45E+03
	b	-6.73E-02	-2.01E-01	-1.60E-01	-1.96E-01
Natural Logarithmic	a	7.81E+02	9.35E+02	8.76E+02	9.81E+02
	b	-3.76E+01	-8.67E+01	-7.14E+01	-8.60E+01
Inverse Polynomial	a	1.66E-03	1.83E-03	1.90E-03	1.85E-03
	b	1.35E-07	1.15E-07	-7.82E-07	-1.44E-06
	c	4.72E-10	2.58E-09	3.23E-09	4.74E-09

Table (8.6): Retroreflectivity Model Parameters for 3M 380WR ES Durable Tape (Weighted Least Square Method; Outliers Not Excluded).

		Retroreflectivity Model Parameters			
Retroreflectivity Model	Model Parameter	Yellow Left Edge Line	White Left Lane Line	White Right Lane Line	White Right Edge Line
Linear	a	6.32E+02	5.78E+02	5.97E+02	6.36E+02
	b	-1.85E-01	-3.73E-01	-3.67E-01	-4.18E-01
Exponential	a	6.34E+02	6.10E+02	6.29E+02	6.85E+02
	b	-3.43E-04	-9.52E-04	-9.02E-04	-1.06E-03
Power	a	1.02E+03	2.22E+03	2.17E+03	2.81E+03
	b	-1.10E-01	-3.02E-01	-2.87E-01	-3.32E-01
Natural Logarithmic	a	8.89E+02	1.10E+03	1.11E+03	1.20E+03
	b	-5.95E+01	-1.20E+02	-1.18E+02	-1.32E+02
Inverse Polynomial	a	1.67E-03	1.83E-03	1.91E-03	1.88E-03
	b	3.80E-08	2.08E-07	-8.23E-07	-1.54E-06
	c	6.49E-10	2.46E-09	3.33E-09	4.81E-09

Table (8.7): Retroreflectivity Model Parameters for 3M 380WR ES Durable Tape (Weighted Least Square Method; Outliers Excluded).

		Retroreflectivity Model Parameters			
Retroreflectivity Model	Model Parameter	Yellow Left Edge Line	White Left Lane Line	White Right Lane Line	White Right Edge Line
Linear	a	6.32E+02	5.82E+02	5.97E+02	6.44E+02
	b	-1.85E-01	-3.78E-01	-3.67E-01	-4.30E-01
Exponential	a	6.34E+02	6.15E+02	6.30E+02	6.98E+02
	b	-3.43E-04	-9.64E-04	-9.03E-04	-1.09E-03
Power	a	1.02E+03	2.31E+03	2.16E+03	3.07E+03
	b	-1.10E-01	-3.08E-01	-2.87E-01	-3.46E-01
Natural Logarithmic	a	8.89E+02	1.11E+03	1.11E+03	1.24E+03
	b	-5.95E+01	-1.22E+02	-1.18E+02	-1.38E+02
Inverse Polynomial	a	1.67E-03	1.83E-03	1.91E-03	1.83E-03
	b	3.80E-08	1.35E-07	-8.44E-07	-1.34E-06
	c	6.49E-10	2.56E-09	3.36E-09	4.63E-09

8.2.5 Aptness of the Retroreflectivity Models

Once the retroreflectivity model parameters are obtained using Equations (8.11) or (8.16), the aptness of the resulting retroreflectivity models can be determined using various statistical methods. The following are some of the methods recommended by statisticians that have been used in this project to assess the quality of fit of the regression models:

1. Coefficient of determination, r^2
2. Mean squared error, *MSE*
3. Several diagnostic figures, including:
   a. Measured and predicted retroreflectivity versus age
   b. Predicted versus measured retroreflectivity
   c. Confidence and prediction intervals versus age
   d. Standardized residuals versus age and versus predicted retroreflectivity

Each of the previous quality of fit measures is presented next in detail. Due to the large amount of data generated using the Matlab code, only results for 3M 380WR ES, and in particular the white right edge line, will be presented in the following subsections to demonstrate the concepts.

8.2.5.1 Coefficient of Determination, r^2

The coefficient of determination, r^2, is calculated using the following equation:

$$r^2 = 1 - \frac{SSE}{SST} \tag{8.20}$$

where,

$$SSE = \sum (y_i - \hat{y}_i)^2 \tag{8.21}$$

$$SST = \sum (y_i - \bar{y})^2 \tag{8.22}$$

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

The coefficient of determination is a measure of how much variations in the observed data can be explained by the model. The higher the r^2 value, the better is the fit. If all observed data points (or retroreflectivity readings) fall exactly on the model, the coefficient of determination will be equal to one; meaning that all sample variation can be attributed to the model. Most commonly encountered cases, however, involve observed data points that do not fall exactly on the model. In such cases, the coefficient of determination will be less than one.

Tables (8.8) and (8.9) summarize the r^2 values corresponding to the retroreflectivity model parameters presented in Tables (8.4) and (8.5), respectively. It is noted that the previous equation is only applicable to the Ordinary Least Square method. Therefore, only r^2 values for this method are presented. By comparing the r^2 values in Tables (8.8) and (8.9), it can be noticed that the linear, exponential, and inverse polynomial models had the highest r^2 values, followed by the power and the natural logarithmic models. Furthermore, it can be observed that the r^2 values obtained for the yellow left edge line are lower than those obtained for the remaining lines. These low r^2 values are a consequence of fitting retroreflectivity readings that did not change much over time due to low traffic and probably less aggressive snowplowing activities, which indicates that there is poor correlation between the independent variable (Age) and the dependent variable (retroreflectivity); (i.e., retroreflectivity is independent of Age). Finally, it can also be noticed that the quality of fit slightly improved when outliers were excluded from the analysis as indicated by the slightly higher r^2 values in Table (8.9) in comparison with Table (8.8).

Table (8.8): r^2 Values Obtained by Fitting Various Models to 3M 380WR ES Durable Tape Retroreflectivity Data (Ordinary Least Square Method; Outliers Not Excluded).

	r^2 values			
Retroreflectivity Model	Yellow Left Edge Line	White Left Lane Line	White Right Lane Line	White Right Edge Line
Linear	0.20	0.83	0.80	0.55
Exponential	0.19	0.80	0.75	0.50
Power	0.17	0.60	0.55	0.34
Natural Logarithmic	0.18	0.67	0.61	0.40
Inverse Polynomial	0.19	0.83	0.82	0.55

Table (8.9): r^2 Values Obtained by Fitting Various Models to 3M 380WR ES Durable Tape Retroreflectivity Data (Ordinary Least Square Method; Outliers Excluded).

	r^2 values			
Retroreflectivity Model	Yellow Left Edge Line	White Left Lane Line	White Right Lane Line	White Right Edge Line
Linear	0.20	0.85	0.80	0.59
Exponential	0.19	0.82	0.76	0.54
Power	0.17	0.62	0.55	0.38
Natural Logarithmic	0.18	0.69	0.61	0.45
Inverse Polynomial	0.19	0.85	0.82	0.58

8.2.5.2 Mean Squared Error, MSE

The mean squared error, *MSE*, is another measure that can be used to quantify the quality of fit of a mathematical model. It is calculated using the following equation:

$$MSE = \frac{SSE}{N - (k + 1)} \tag{8.23}$$

where, *SSE* is the error sum of squares, *N* is the number of data points, and k is the number of model parameters (two for linear and three for second-order polynomial).

The mean squared error 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. Therefore, the lower is the *MSE* value, the better is the quality of fit.

Tables (8.10) and (8.11) summarize the *MSE* values corresponding to the retroreflectivity model parameters presented in Tables (8.4) and (8.5), respectively. As was the case with r^2, the previous equation is only applicable to the Ordinary Least Square method. Therefore, only *MSE* values for this method are presented.

The *MSE* values presented in Tables (8.10) and (8.11) confirm the findings made earlier based on the r^2 values regarding the quality of fit of the five models. For example, by comparing the *MSE* values in these two tables, it can be noticed that the linear, exponential, and inverse polynomial models had the lowest *MSE* values. It can also be observed that the *MSE* values obtained for the yellow left edge line are higher than those obtained for the remaining lines; and that the quality of fit slightly improved when outliers were excluded from the analysis.

Table (8.10): *MSE* Values Obtained by Fitting Various Models to 3M 380WR ES Durable Tape Retroreflectivity Data (Ordinary Least Square Method; Outliers Not Excluded).

	MSE values			
Retroreflectivity Model	Yellow Left Edge Line	White Left Lane Line	White Right Lane Line	White Right Edge Line
Linear	4412.02	1264.15	1094.73	4665.71
Exponential	4439.12	1422.71	1322.09	5230.51
Power	4549.97	2919.97	2410.39	6880.15
Natural Logarithmic	4519.93	2427.81	2117.95	6251.91
Inverse Polynomial	4470.80	1240.45	995.13	4639.15

Table (8.11): *MSE* Values Obtained by Fitting Various Models to 3M 380WR ES Durable Tape Retroreflectivity Data (Ordinary Least Square Method; Outliers Excluded).

	MSE values			
Retroreflectivity Model	Yellow Left Edge Line	White Left Lane Line	White Right Lane Line	White Right Edge Line
Linear	4412.02	1123.85	1091.83	4301.64
Exponential	4439.12	1295.70	1323.83	4865.52
Power	4549.97	2816.07	2425.23	6579.20
Natural Logarithmic	4519.93	2303.09	2130.02	5869.74
Inverse Polynomial	4470.80	1096.98	981.33	4416.12

8.2.5.3 Diagnostic Figures

In addition to the previous quantity measures, several diagnostic figures were used in this project to visually assess the aptness of the retroreflectivity models. The following subsections present example diagnostic figures resulted from fitting retroreflectivity data collected from the white right edge line of 3M 380WR ES durable tape using the linear model. It is worth mentioning that the Matlab code produced about one hundred figures for each material using each analysis method. Therefore, it will be impossible to include all figures.

8.2.5.3.1 Measured and Predicted Retroreflectivity versus Age

Figures (8.5) and (8.6) present a comparison between measured and predicted retroreflectivity of 3M 380WR ES white right edge line as they varied with Age. The predicted retroreflectivity values in these figures were obtained by fitting a linear model to the individual retroreflectivity data using the Ordinary Least Square method and the Weighted Least Square method, respectively. It can be noticed that the predicted retroreflectivity values obtained using the Weighted Least Square method (Figure 8.6) were closer to the average retroreflectivity values for the last two field evaluations than those obtained using the Ordinary Least Square method (Figure 8.6) since higher weight factors were assigned in the former to retroreflectivity readings collected during the last two field evaluations. In addition, as discussed earlier and shown in these figures, little difference is observed between the linear model predictions when outliers were included or excluded. Meanwhile, a greater difference is observed between the linear model predictions when the Ordinary and Weighted Least Square methods were used.

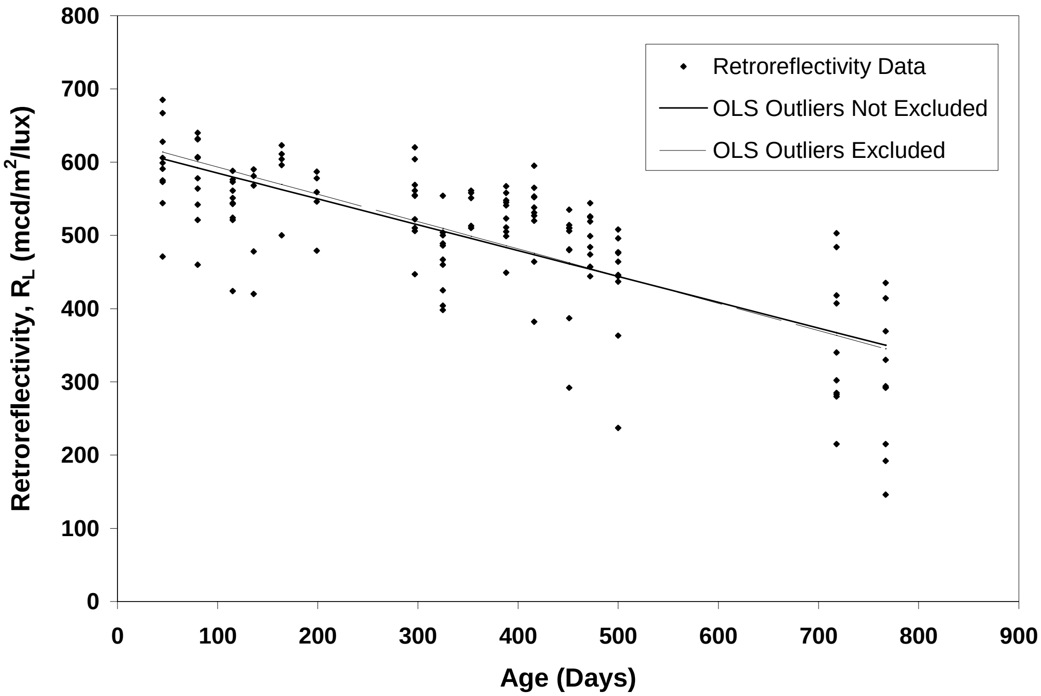

Figure (8.5): Measured and Predicted Retroreflectivity versus Age using the Linear Model (3M 380WR ES; White Right Edge Line; Ordinary Least Square Method).

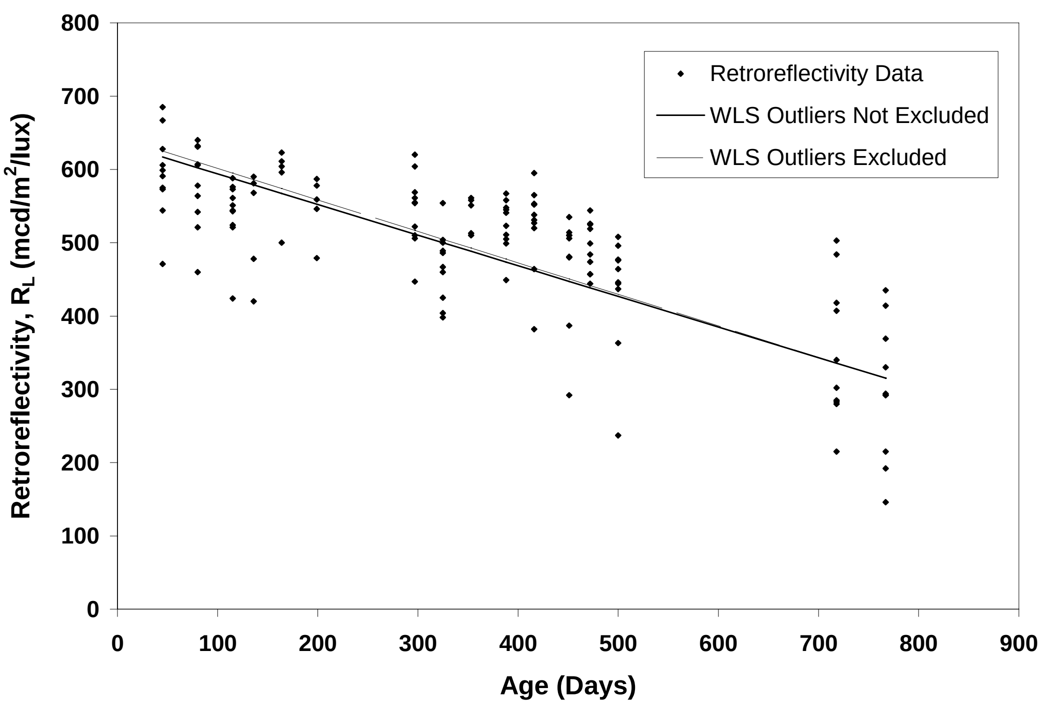

Figure (8.6): Measured and Predicted Retroreflectivity versus Age using the Linear Model (3M 380WR ES; White Right Edge Line; Weighted Least Square Method).

8.2.5.3.2 Predicted versus Measured Retroreflectivity

Figures (8.7) through (8.10) present a comparison between measured and predicted retroreflectivity for 3M 380WR ES white right edge line using the linear model. As shown in these figures, the individual retroreflectivity readings are aligned along the equality line (a linear trend line for which the intercept is constrained to pass through the origin and the slope is constrained to unity), with the average retroreflectivity values being closer to that line. The closer are the individual data points to the equality line, the better is the quality of fit. In these figures, the deviation between the individual retroreflectivity readings and the equality line is probably due to measurement variability that can not be explained by the model. Another measure of the overall model bias is the average error. A concentration of the individual retroreflectivity readings to the right of the equality line is an indication that the regression model underpredicts the dependent variable, while a concentration of the individual retroreflectivity readings to the left of the equality line is an indication that the regression model overpredicts the dependent variable. In these figures, it can be noticed that the individual retroreflectivity readings are equally distributed to the right and left of the equality line. Such distribution is an indication that the regression model produced fairly reasonable retroreflectivity estimates without being biased by the magnitude of retroreflectivity.

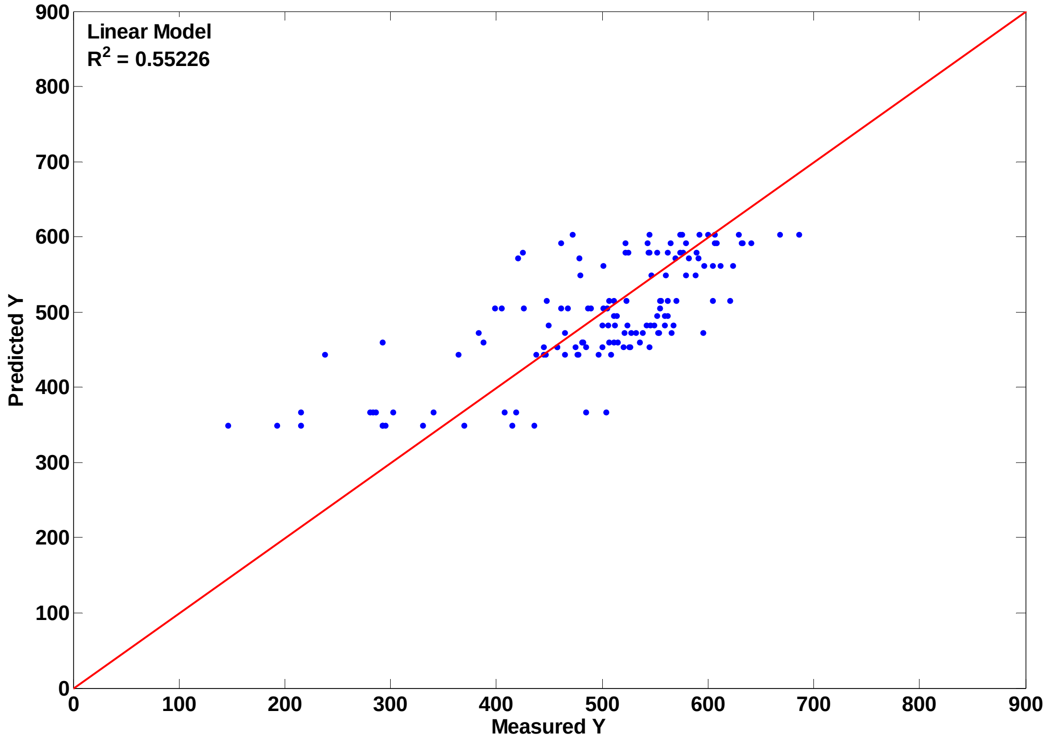

Figure (8.7): Predicted versus Measured Retroreflectivity using the Linear Model (3M 380WR ES; White Right Edge Line; Ordinary Least Square; Outliers Not Excluded).

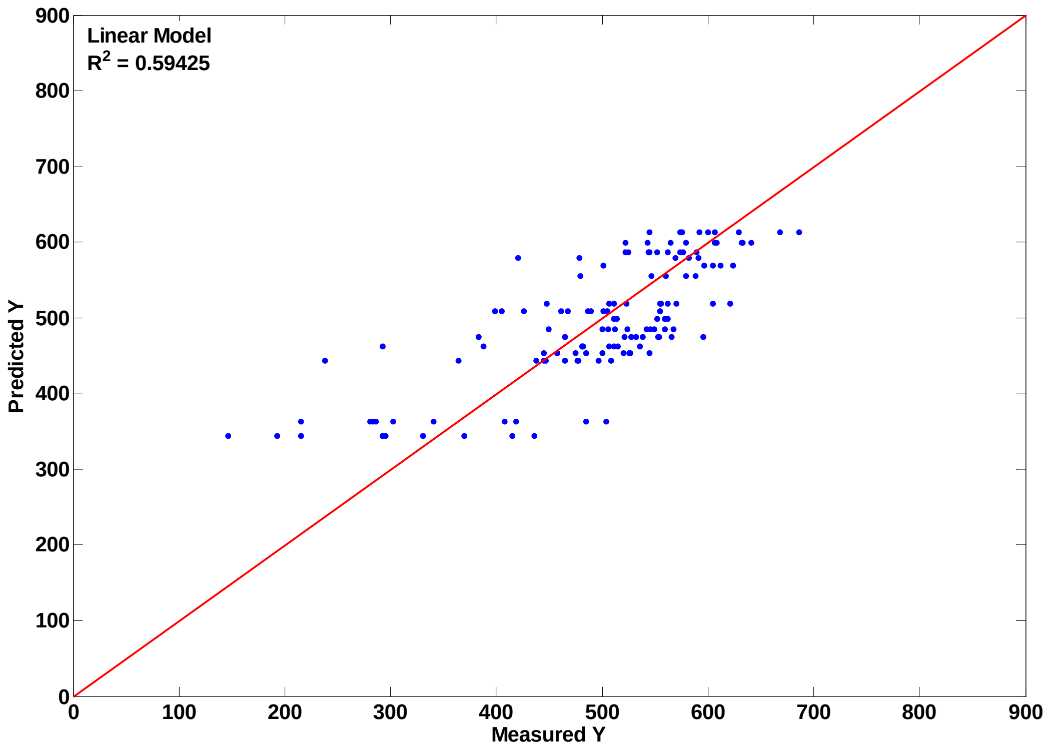

Figure (8.8): Predicted versus Measured Retroreflectivity using the Linear Model (3M 380WR ES; White Right Edge Line; Ordinary Least Square; Outliers Excluded).

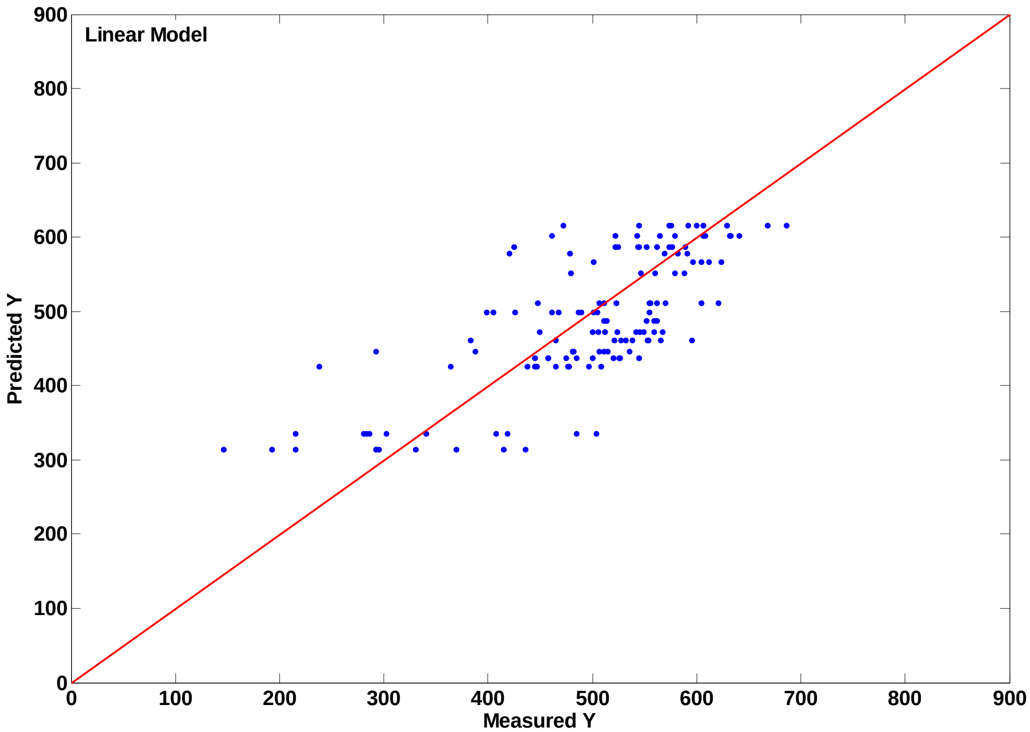

Figure (8.9): Predicted versus Measured Retroreflectivity using the Linear Model (3M 380WR ES; White Right Edge Line; Weighted Least Square; Outliers Not Excluded).

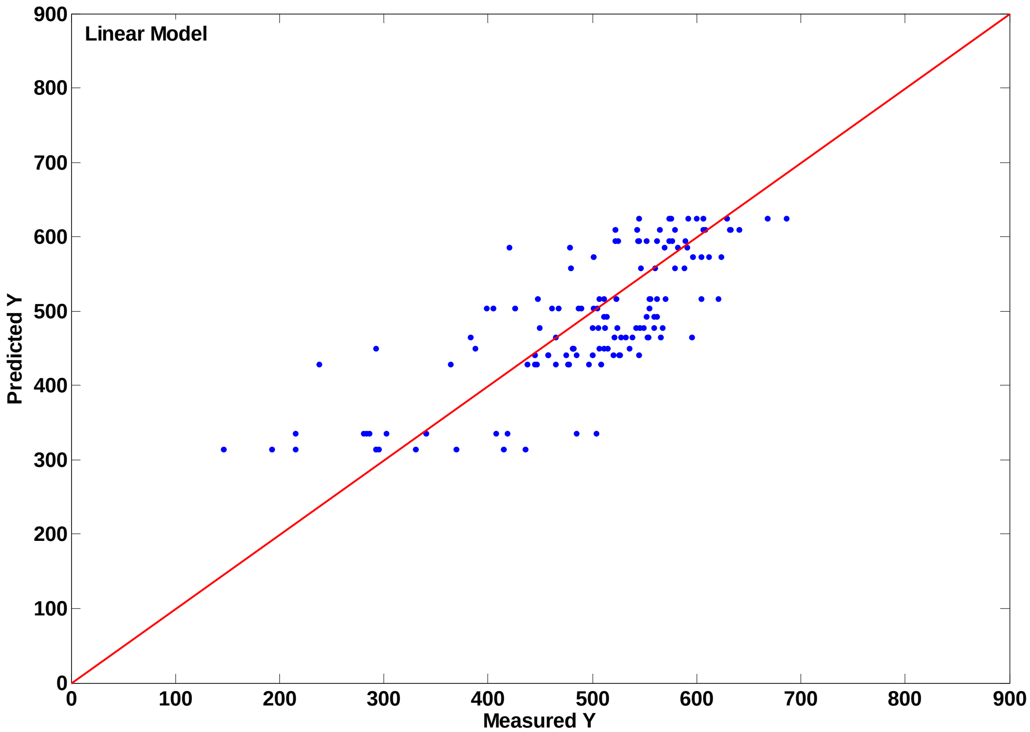

Figure (8.10): Predicted versus Measured Retroreflectivity using the Linear Model (3M 380WR ES; White Right Edge Line; Weighted Least Square; Outliers Not Excluded).

8.2.5.3.3 Confidence and Prediction Intervals versus Age

The true mean of a population (retroreflectivity in this case) is very hard to capture by a sample mean due to sample variation. This is why an entire interval of plausible values for the mean is calculated. This interval is called the confidence interval. It is calculated by first choosing a confidence level, $1-\alpha$, which is the degree of reliability of the interval. The most commonly used confidence level for engineering applications is 95%. Therefore, this confidence level was chosen in this study.

A $100(1-\alpha)\%$ confidence interval, *CI*, for the mean value of *y* when $x = x^*$ is:

$$\begin{aligned}100(1-\alpha)\%\ CI &= \hat{y} \pm t_{\alpha/2,N-k} \bullet s_{\hat{Y}} \\ &= \hat{a} + \hat{b}x^* \pm t_{\alpha/2,N-k} \bullet s_{\hat{Y}} \\ &= \hat{a} + \hat{b}x^* \pm t_{\alpha/2,N-k} \bullet s\sqrt{\frac{1}{N} + \frac{(x^* - \bar{x})^2}{\sum_{j=1}^{N}(x_j - \bar{x})^2}}\end{aligned} \tag{8.24}$$

where $t_{\alpha/2,N-k}$ is the critical value for a *t* distribution with 100(1 – a)% confidence level and $N - k$ degrees of freedom; *N* is the total number of observations; *k* is the number of model parameters; $s_{\hat{Y}}$ is the standard deviation of the predicted value; *s* is the standard deviation of the predicted error; and the rest of the parameters have been previously defined.

The prediction interval is used to predict single observations rather than the sample mean, which is the case in the confidence interval. Therefore, the width of the prediction interval bounds is greater than that of the confidence interval. The prediction interval is approximately three to four times the confidence interval. Similar to the confidence interval, the prediction interval is calculated at a certain confidence level. Again, a confidence level of 95% was chosen for the calculation of the prediction interval bound.

A $100(1-\alpha)\%$ prediction interval, *PI*, for a *y* observation when $x = x^*$ is:

$$100(1-\alpha)\%\ PI = \hat{a} + \hat{b}x^* \pm t_{\alpha/2,N-k} \bullet s\sqrt{1 + \frac{1}{N} + \frac{(x^* - \bar{x})^2}{\sum_{j=1}^{N}(x_j - \bar{x})^2}} \tag{8.25}$$

where all parameters have been previously defined. Note that since α is equal to 5% and a large number of data points are used in the regression analysis, $t_{\alpha/2,N-k}$ is equal to 1.960.

Figures (8.11) and (8.14) present example confidence and prediction intervals resulted from fitting 3M 380WR ES white right edge line retroreflectivity data using the linear model. In these figures, the individual retroreflectivity readings are shown as solid circles, the linear model is depicted as a solid thick line, the confidence interval is depicted as a dashed thin line, and the prediction interval is depicted as a solid thin line. As mentioned earlier, the prediction interval is used to predict single observations rather than the sample mean, which is the case in the confidence interval. Therefore, the width of the prediction interval bounds is greater than that of the confidence interval. As can be seen in Equations (8.24) and (8.25), the width of both intervals is determined by the standard deviation of the predicted error, which is dependent on the variability of the individual measurements as well as the ability of the regression model to produce accurate predictions of the dependent variable.

A regression model is believed to have a good quality of fit if all observations are bound by the prediction interval and all sample means are bound by the confidence interval. In these figures, it can be noticed that the sample means (or the average retroreflectivity values) are close to, but always within, the confidence interval. Meanwhile, most of the observations (or the individual retroreflectivity readings) are within the prediction interval. The latter is not unexpected since the prediction interval was relatively wide due to measurement variability and the inability of the linear model to fully explain the dependency of retroreflectivity on Age.

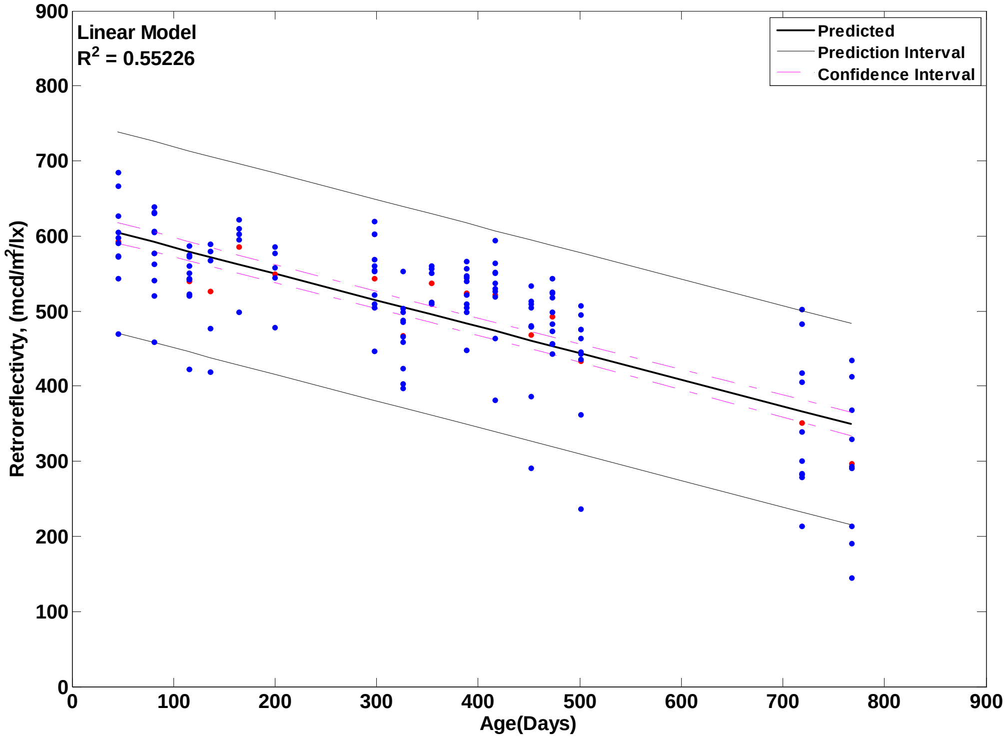

Figure (8.11): Confidence and Prediction Intervals versus Age using the Linear Model (3M 380WR ES; White Right Edge Line; Ordinary Least Square; Outliers Not Excluded).

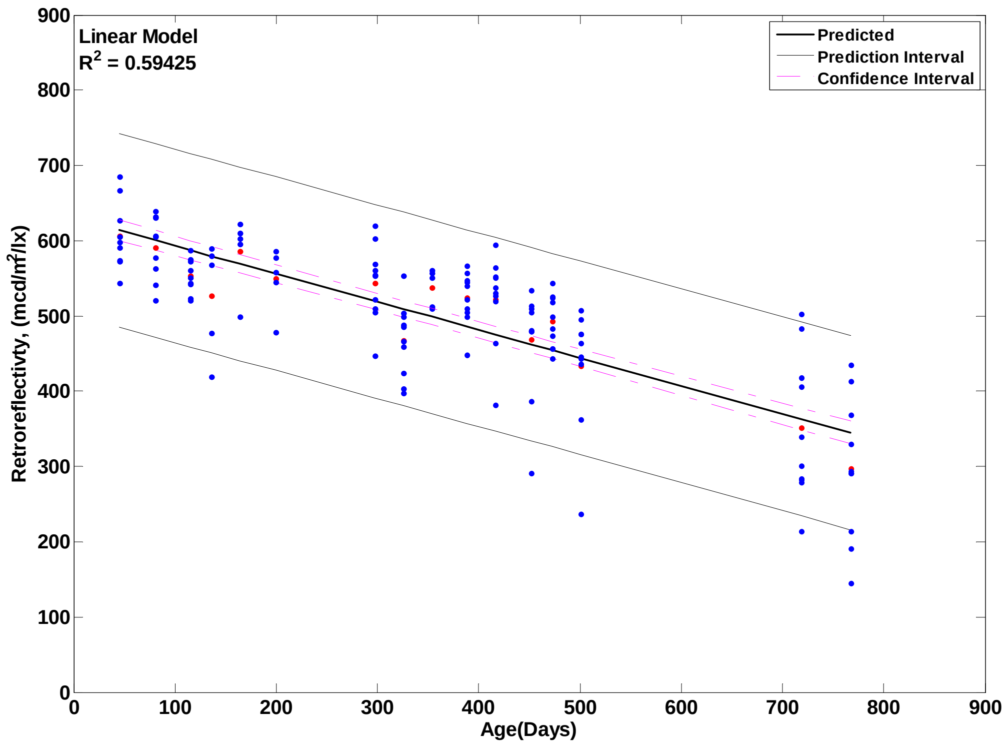

Figure (8.12): Confidence and Prediction Intervals versus Age using the Linear Model (3M 380WR ES; White Right Edge Line; Ordinary Least Square; Outliers Excluded).

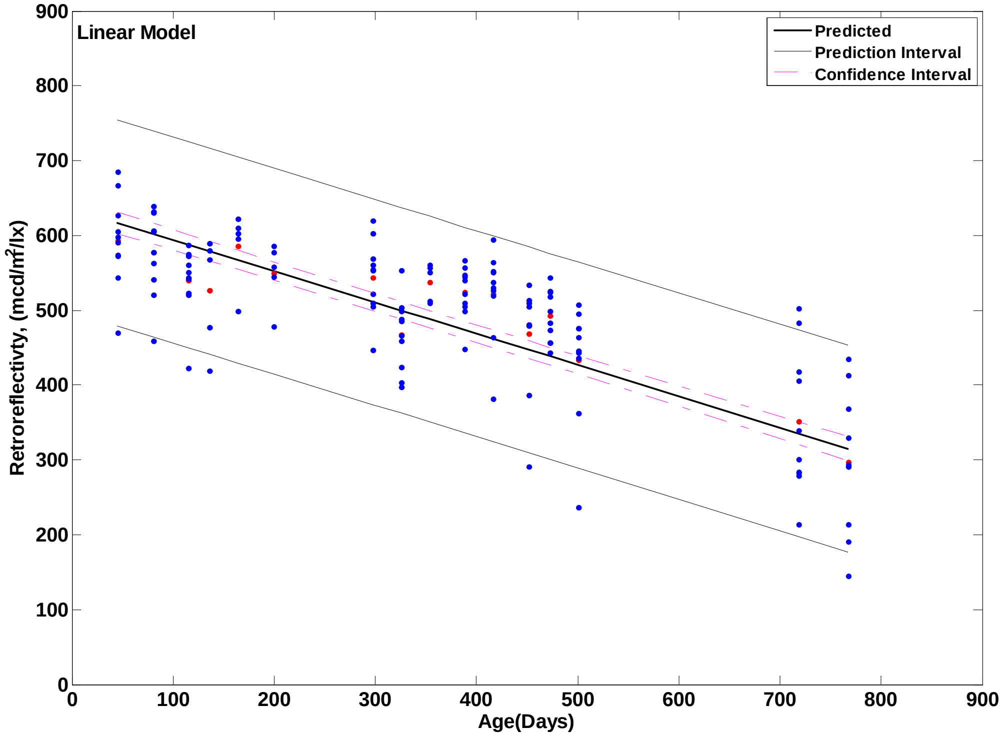

Figure (8.13): Confidence and Prediction Intervals versus Age using the Linear Model (3M 380WR ES; White Right Edge Line; Weighted Least Square; Outliers Not Excluded).

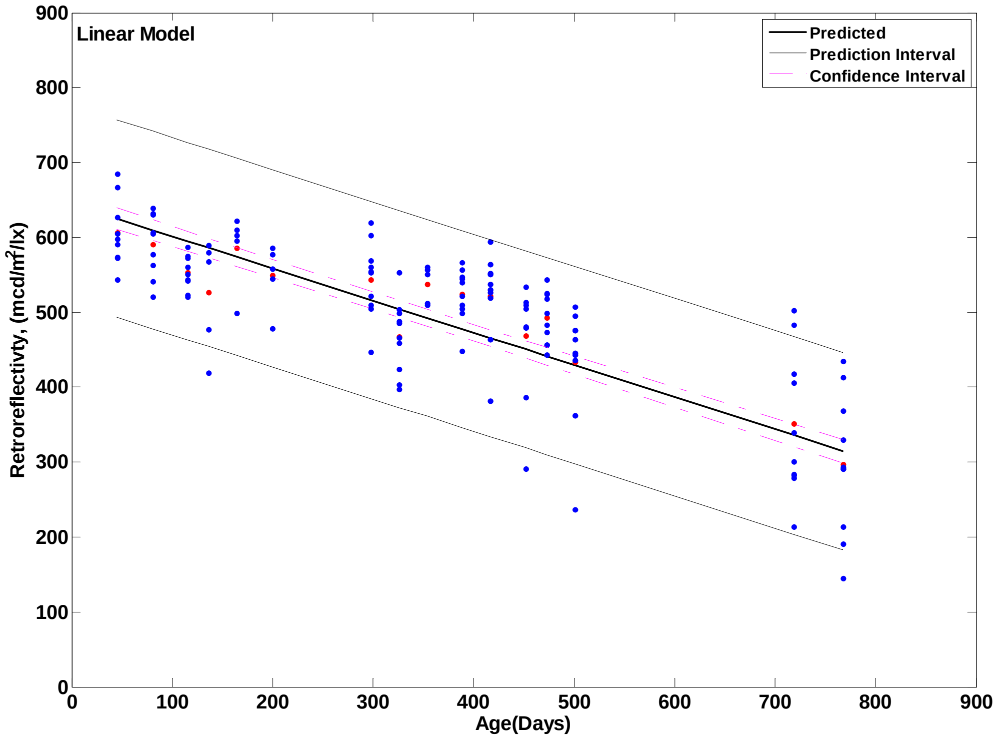

Figure (8.14): Confidence and Prediction Intervals versus Age using the Linear Model (3M 380WR ES; White Right Edge Line; Weighted Least Square; Outliers Excluded).

8.2.5.3.4 Standardized Residuals versus Age and versus Predicted Retroreflectivity

For the regression model of choice to be appropriate, the prediction error must be randomly distributed. To access the plausibility of this assumption, error, or more effectively, the standardized residual, e^*, is plotted versus the independent variable, x (or Age), and versus the estimated dependent variable, $\hat{y}$ (or predicted retroreflectivity). For this assumption to be valid, the standardized residual in these plots should not exhibit any distinct patterns and should be randomly distributed about zero. Otherwise, another regression model should be used in the analysis.

The standardized residual, e^*, is calculated using the following equation:

$$e_i^* = \frac{y_i - \hat{y}_i}{s\sqrt{1 - \frac{1}{N} - \frac{(x_i - \bar{x})^2}{\sum_{j=1}^{N}(x_j - \bar{x})^2}}} \qquad i = 1, \ldots, N \tag{8.26}$$

where all parameters have been previously defined.

Figures (8.15) and (8.22) present example standardized residual plot versus Age and versus predicted retroreflectivity. In these figures, it can be noticed that as desired the standard residual error ranged from -2 to 2 for most points. It can also be observed that the standard residual error is randomly distributed about the zero axis; without showing any distinct patterns of dependency on either the independent variable (Age) or the magnitude of the predicted dependent variable (predicted retroreflectivity). The randomness of the model predictions was not affected by excluding outliers or by using the Weighted Least Square method versus the Ordinary Least Square method. Therefore, it is concluded that the linear model is appropriate for describing the deterioration trend of 3M 380WR ES white right edge line retroreflectivity over the evaluation period during which the retroreflectivity measurements that were used in the analysis were made.

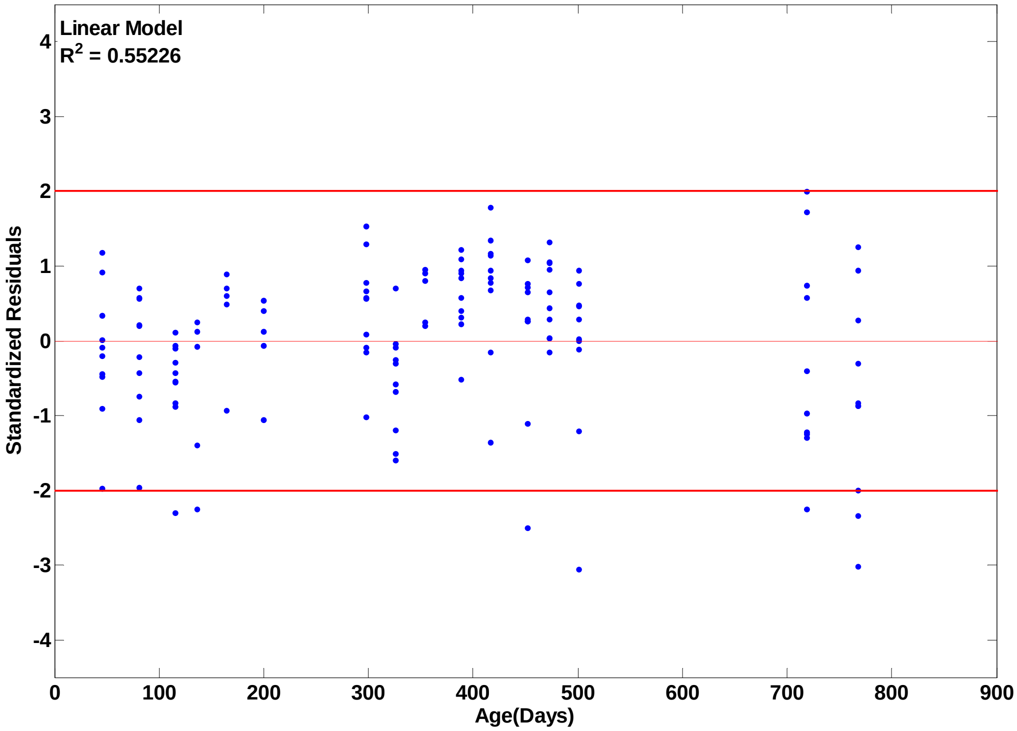

Figure (8.15): Standardized Residual versus Age using the Linear Model (3M 380WR ES; White Right Edge Line; Ordinary Least Square; Outliers Not Excluded).

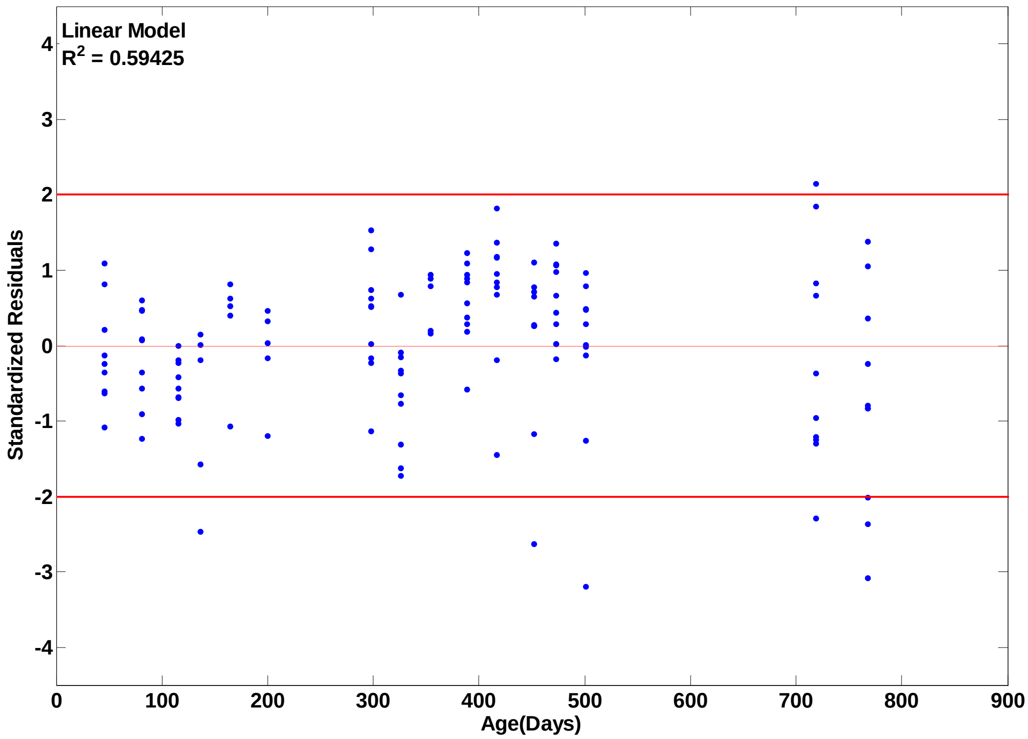

Figure (8.16): Standardized Residual versus Age using the Linear Model (3M 380WR ES; White Right Edge Line; Ordinary Least Square; Outliers Excluded).

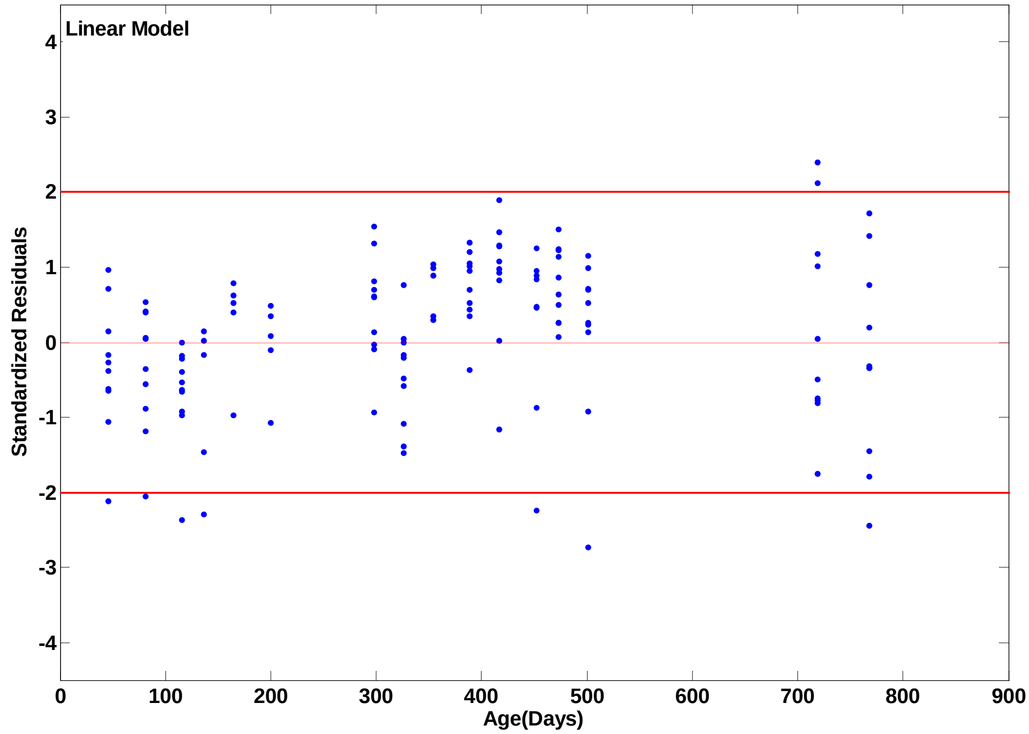

Figure (8.17): Standardized Residual versus Age using the Linear Model (3M 380WR ES; White Right Edge Line; Weighted Least Square; Outliers Not Excluded).

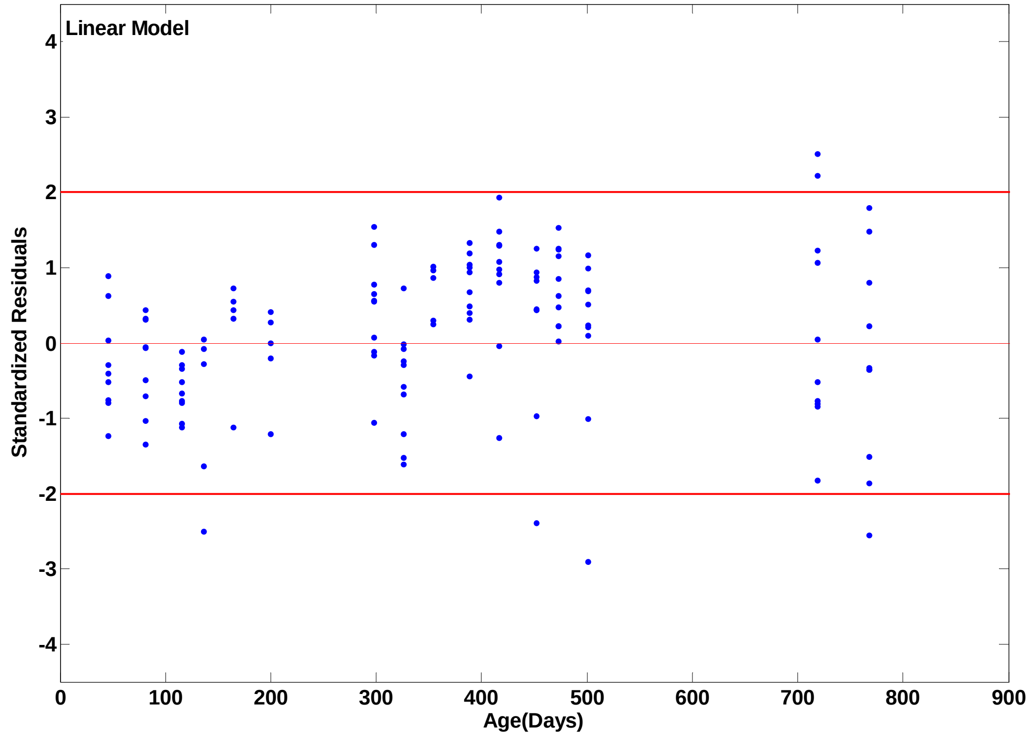

Figure (8.18): Standardized Residual versus Age using the Linear Model (3M 380WR ES; White Right Edge Line; Weighted Least Square; Outliers Excluded).

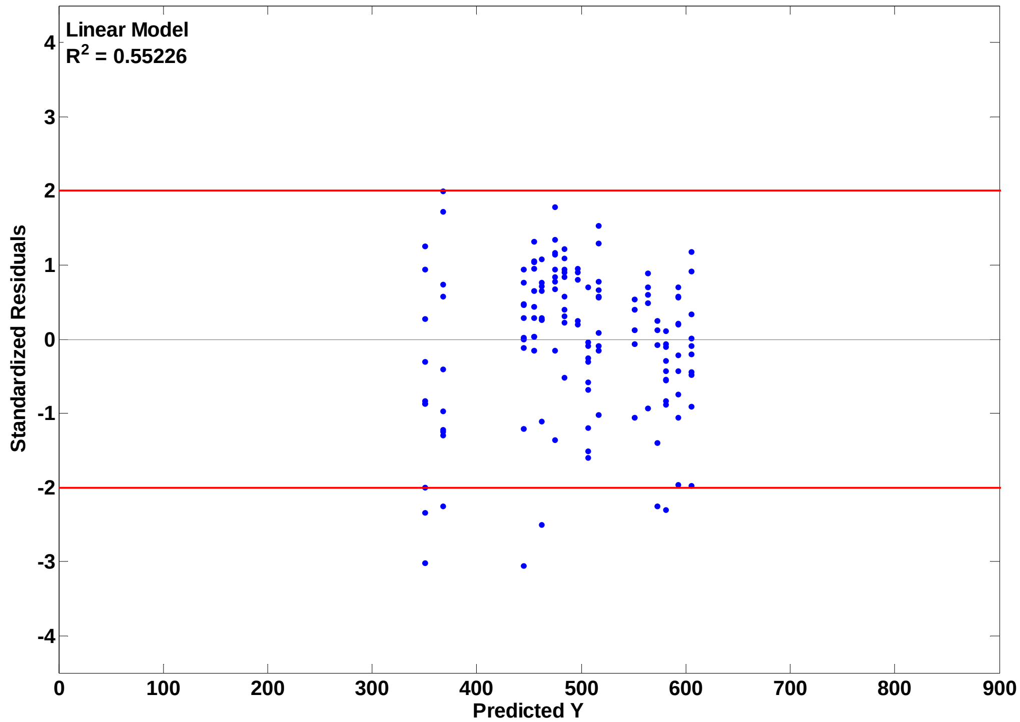

Figure (8.19): Standardized Residual versus Predicted Retroreflectivity (3M 380WR ES; White Right Edge Line; Ordinary Least Square; Outliers Not Excluded).

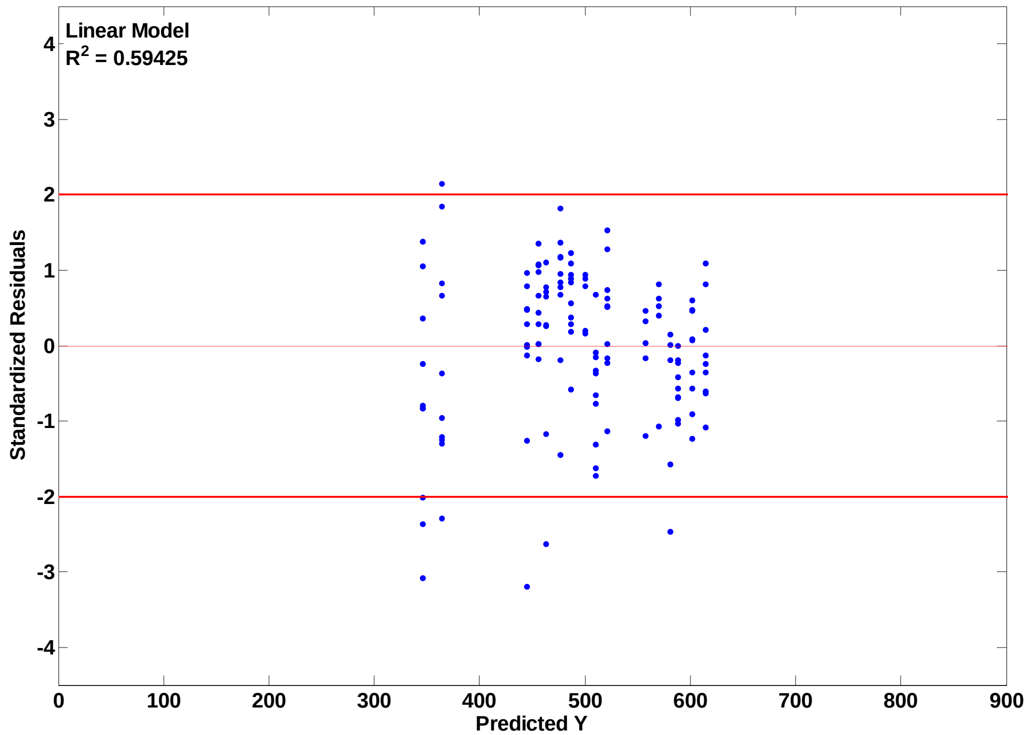

Figure (8.20): Standardized Residual versus Predicted Retroreflectivity (3M 380WR ES; White Right Edge Line; Ordinary Least Square; Outliers Excluded).

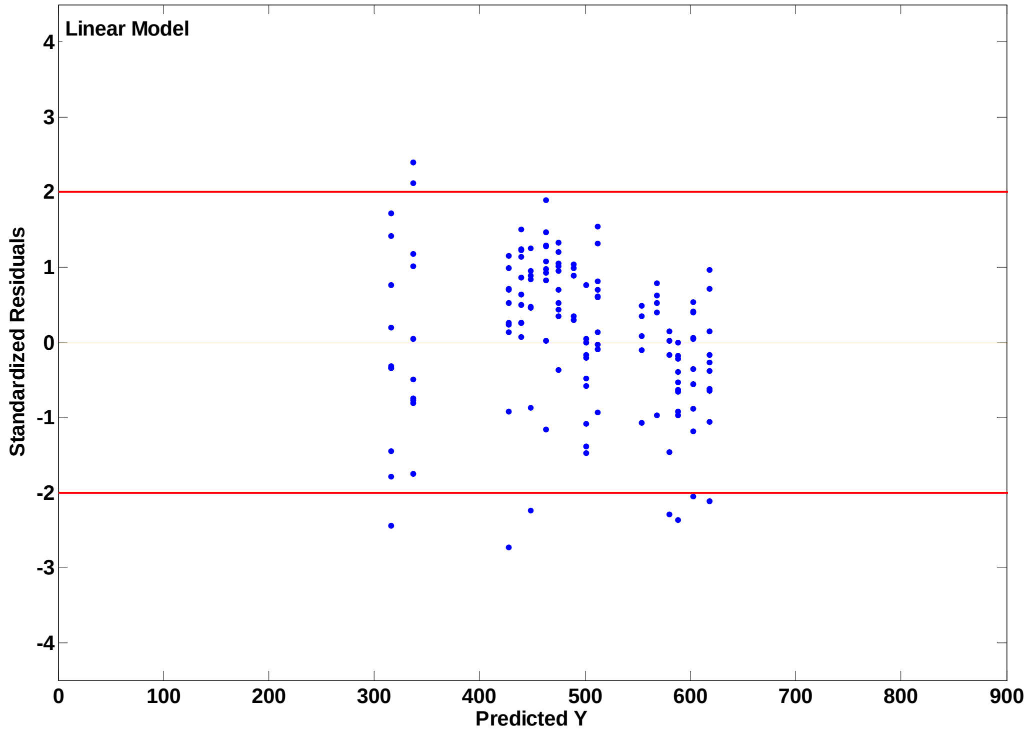

Figure (8.21): Standardized Residual versus Predicted Retroreflectivity (3M 380WR ES; White Right Edge Line; Weighted Least Square; Outliers Not Excluded).

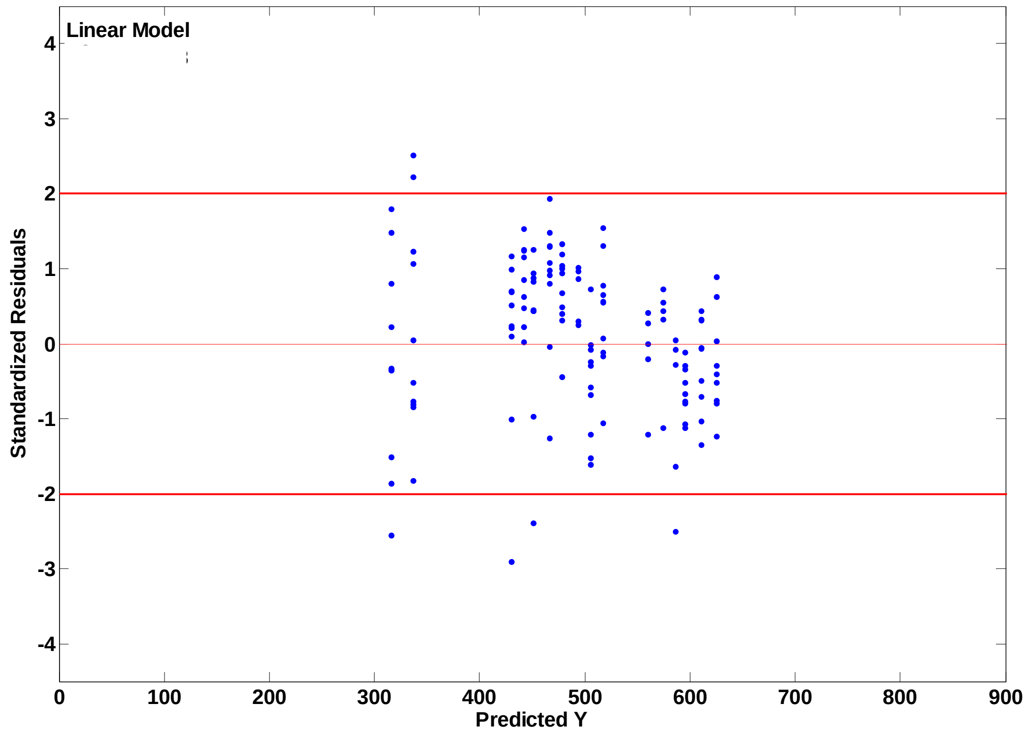

Figure (8.22): Standardized Residual versus Predicted Retroreflectivity (3M 380WR ES; White Right Edge Line; Weighted Least Square; Outliers Excluded).

8.3 Pavement Marking Service Life

In the previous section, five models (linear, exponential, power, natural logarithmic, and inverse polynomial) were used to mathematically describe the deterioration trend of pavement marking retroreflectivity. The aptness of these models was assessed using different statistical methods such as the coefficient of determination, r^2, the mean squared error, *MSE*, and several diagnostic figures. By comparing the r^2 and the *MSE* values, it was concluded the linear, exponential, and inverse polynomial models had the best quality of fit. This conclusion, however, is limited to the period during which the retroreflectivity measurements were made. Therefore, to gain insight regarding the ability of the above-mentioned five models to predict future retroreflectivity, retroreflectivity predictions were plotted versus Age for an extended period of time; and the resulting performance was compared to 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.

Figures (8.23) through (8.26) present example predicted retroreflectivity versus Age figures for 3M 380WR ES white right edge line. In these figures, it can be seen that the power and the natural logarithmic models produced high initial and retained retroreflectivity predictions; the linear and the exponential models produced comparable retroreflectivity during the evaluation period, beyond which the exponential model produced higher predictions; and finally the inverse polynomial model had a Z-shaped curve that slightly increased during the first half year, then rapidly decreased over the next two years and a half to reach a relatively constant retroreflectivity value. The 150 mcd/m^2/lux threshold retroreflectivity criterion for white pavement markings is also depicted in these figures as a horizontal line. The pavement marking service life can be estimated from such figures by identifying the point of intersection between the retroreflectivity model and the threshold criterion. For example, the estimated service life using the linear model is about 3.6 years based on Figure (8.23), 3.5 years based on Figure

(8.24), 3.2 years based on Figure (8.25), and 3.1 years based on Figure (8.25). Based on these values, it can be observed that the exclusion of outliers resulted in slightly lower service life predictions for 3M 380WR ES white right edge line; and that the use of Weighted Least Square method as compared to the Ordinary Least Square method resulted in about 0.4 year lower service life prediction for this line.

The same procedure was followed in estimating the pavement marking service life of the remaining lines and materials. Similar to the conclusions made earlier, the effect of outliers was found to be insignificant. Therefore, there is no need to exclude them. Whereas the difference between the service life predictions using the Weighted Least Square method and the Ordinary Least Square method was found to be significant. For most materials, the Weighted Least Square method produced higher service life predictions than the Ordinary Least Square method, which implies that for these materials the retroreflectivity deterioration rate in the second year was lower than that in the first year.

In general, the linear model produced the most conservative service life predictions, followed by the exponential model, then by the power and the natural logarithmic models. In most cases, the service life predictions using the power and the natural logarithmic models were unrealistic. This was also the case for some materials using the inverse polynomial model, which predicted an initial reduction followed by an unrealistic increase in retroreflectivity that looked like a U shape. Therefore, only results for the linear and the exponential models are presented in this section.

Table (6.12) presents the estimated service lives for all materials using the linear and the exponential models. A maximum service life of six years was assumed in the analysis. This assumption was incorporated to account for the fact that the retroreflectivity of some lines did not drop enough during the evaluation period to predict a reasonable service life using the linear or the exponential model. This was the case for most yellow left edge lines and some of the white lane lines. Therefore, since pavement markings commonly fail in less than six years in one mechanism or another, the pavement marking service life was capped at six years.

The following comments are made regarding the service life predictions in Table (6.12):

- As indicated in this table, the conventional thermoplastic Swarcotherm alkyd, the slow cure epoxy Epoplex LS 70, and the preformed thermoplastic Premark Contast that was applied without sealer on the right lane line of Bridge Deck # 2 failed due to durability in a relatively short period of time.

- The highest service life values were predicted for the yellow left edge lines, followed by the white (right and left) lane lines, followed by the white right edge lines. This pattern is consistent with the retroreflectivity performance on these lines, which has been governed by the traffic distribution in the right, middle, and left lanes on interstate I-71. As such, the performance of the white right edge lines is believed to be representative of the performance of the material under heavy traffic, the performance of the white (right and left) lane lines is believed to be representative of the performance of the material under medium traffic, and the performance of the yellow left edge lines is believed to be representative of the performance of the material under low traffic.
- The estimated service life values presented in this table were obtained by equating the predicted retroreflectivity using the linear or the exponential models to minimum acceptable retroreflectivity criterion depending on the color of the pavement marking. This procedure estimates the time required for average retroreflectivity to drop to that threshold criterion. As expected, some of the individual retroreflectivity readings will fail (drop below threshold) before reaching these service lives.
- The most accurate service life predictions were obtained for the materials (or the lines) that have failed (retroreflectivity dropped below threshold criteria) during the evaluation period such as Ennis fast dry waterbrone traffic paint on the white lane and edge lines and 3M 270 ES tape on the white right edge line since the service life predictions for these materials (or lines) are based on interpolating within the data set that was used in fitting the regression model rather than extrapolating beyond that data set. Meanwhile, the least accurate service life predictions were obtained for the materials (or the lines) that had a relatively low retroreflectivity deterioration rate during the evaluation period since a slight change in the slope of the regression model may result in widely different service life predictions. An example material that had a poor retroreflectivity performance but had a relatively high service life prediction is white Ennis Duraset 1 on Bridge Deck # 13. This material had low initial retroreflectivity. Yet, it had high retained retroreflectivity. Consequently, none of the models seemed to provide reasonable service life estimate for this material. Another example where the regression models were not capable of producing a reasonable service life prediction is that for white Premark Plus preformed thermoplastic on the right edge lines of

Bridge Decks # 2 and 15. The retroreflectivity of this material first increased then decreased over time. This trend cannot be captured by either the linear or the exponential model and hence neither model produced a reasonable service life estimate. A more reasonable estimate of the service life of this material on the white right edge line is about 3.5 years.

- The difference between the service life predictions using the Weighted Least Square method and the Ordinary Least Square method increased with the increase in the difference between the retroreflectivity deterioration rates in the first and the second year. The Weighted Least Square method seemed to produce more reasonable service life predictions (by visually comparing the retroreflectivity deterioration trend and the predicted future retroreflectivity performance) when the retroreflectivity deterioration rate in the second year was higher than that in the first year, while the Ordinary Least Square method seemed to produce more reasonable service life predictions when the retroreflectivity deterioration rate in the first year was higher than that in the second year. In general though, the most reasonable predictions were obtained using the exponential model and the Weighted Least Square method.

Table (6.13) provides a summary of the pavement marking service life predictions. It also offers a comparison between these predictions and the typical service life of the material group on concrete surfaces. Based on these values, it can be noticed that most yellow markings had very high service life predictions since they were not subjected to high traffic. Therefore, the predicted service life values presented in this table for yellow markings do not necessarily reflect how these markings would perform under high traffic. As for the white markings, it can be noticed that HPS-5 and Glomarc 90 polyurea had the highest service life predictions (of more than 5 years) followed by the slow cure epoxies (of about 3.5 to 6 years) and the preformed thermoplastics (of about 3.5 to 6 years). The predicted service life of 3M 380WR ES durable tape was about 3.8 to 4.7 years on all lines, while the predicted service life of 3M 270 ES durable tape was about 4.4 to 4.5 years on the lane lines and about 1.8 years on the right edge line. The predicted service life of the modified urethane HPS-4 was comparable to that of the slow cure epoxies on the lane lines, but slightly lower on the right edge line. The fast cure epoxy Epoplex LS 70 failed due to durability in a relatively short period of time, while the fast cure epoxy PolyCarb Mark 55.4 had a predicted service life of about 5.1 to 5.2 years on the lane lines and about 2.5 years on the right edge line. The methyl methacrylate Duraset 1 installed on the edge lines of Bridge Deck # 14 hardened quickly during the installation, which did not allow the surface applied glass beads to properly embed on its surface. As a result, this material had poor retroreflectivity performance and subsequently low service life predictions. The performance of methyl methacrylate Duraset Pathfinder that was installed on the lane lines of Bridge Deck # 14, on the other hand, resulted in a service life prediction of about 3.9 to 4.9 years, which is comparable to the other durable pavement marking products. The fast dry waterborne traffic paint had a predicted service life of about 1.7 to 2.1 years on the right and left lane lines and about 1.9 years on the right edge line.

From among the previous materials, the following products had a predicted service life on the right edge line that exceeded the typical service life of the material group: HPS-5, Glomarc 90, and Ennis fast dry waterborne traffic paint.

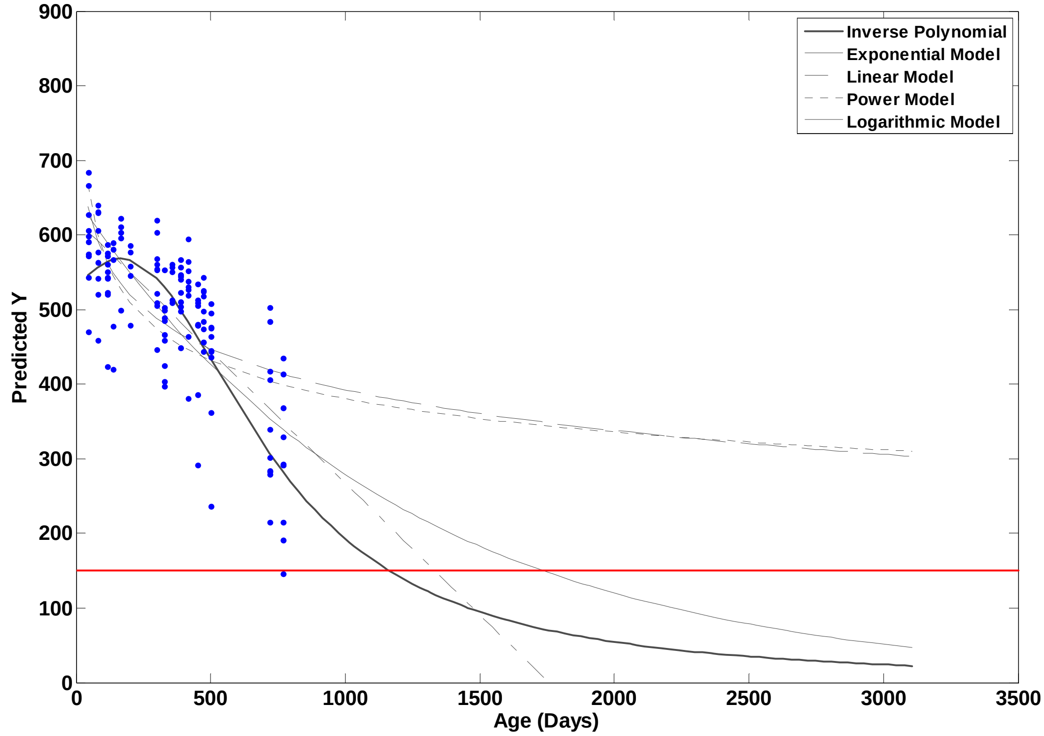

Figure (8.23): Measured and Predicted Retroreflectivity versus Age

(3M 380WR ES; White Right Edge Line; Ordinary Least Square; Outlier Not Excluded).

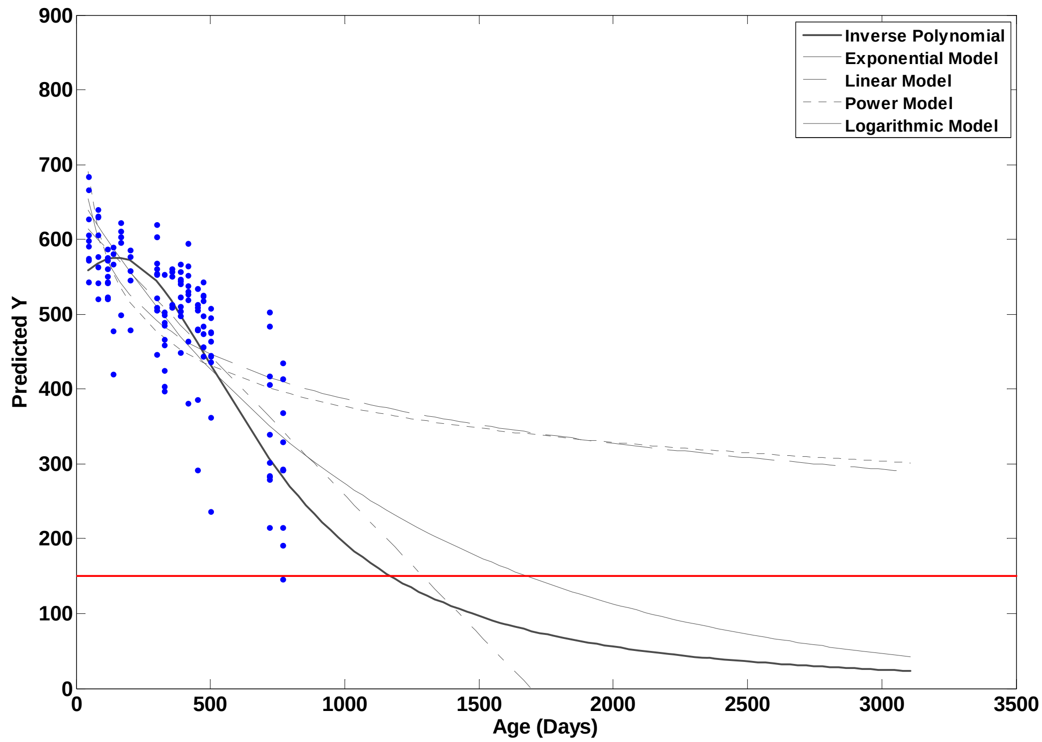

Figure (8.24): Measured and Predicted Retroreflectivity versus Age

(3M 380WR ES; White Right Edge Line; Ordinary Least Square; Outlier Excluded).

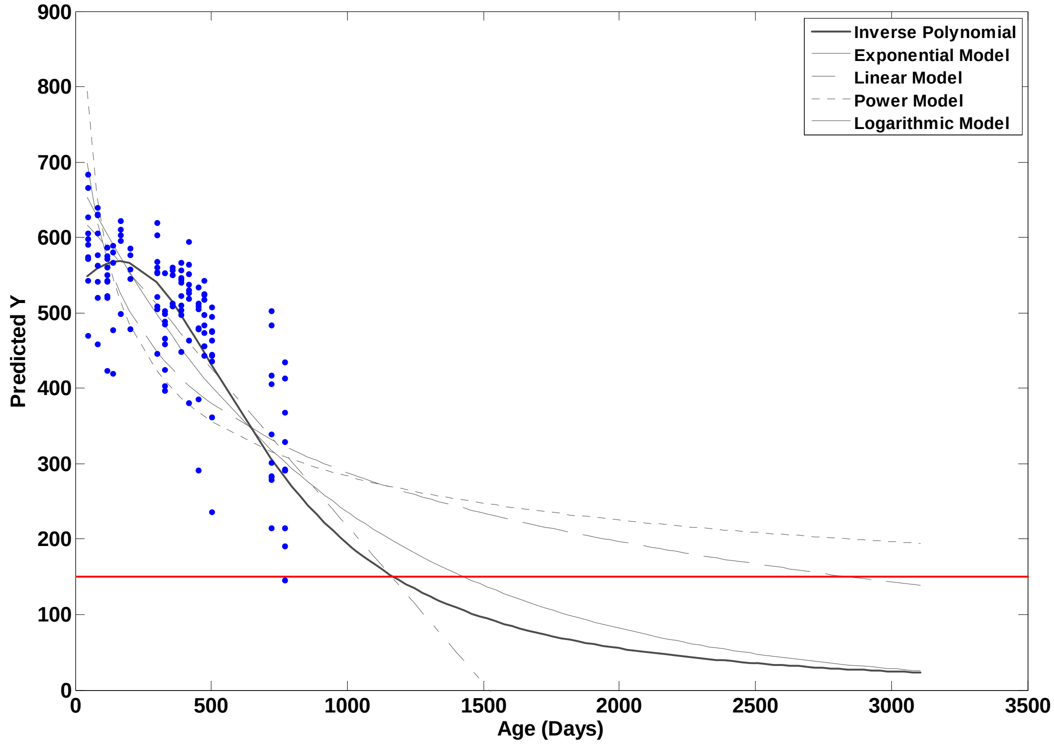

Figure (8.25): Measured and Predicted Retroreflectivity versus Age (3M 380WR ES; White Right Edge Line; Weighted Least Square; Outlier Not Excluded).

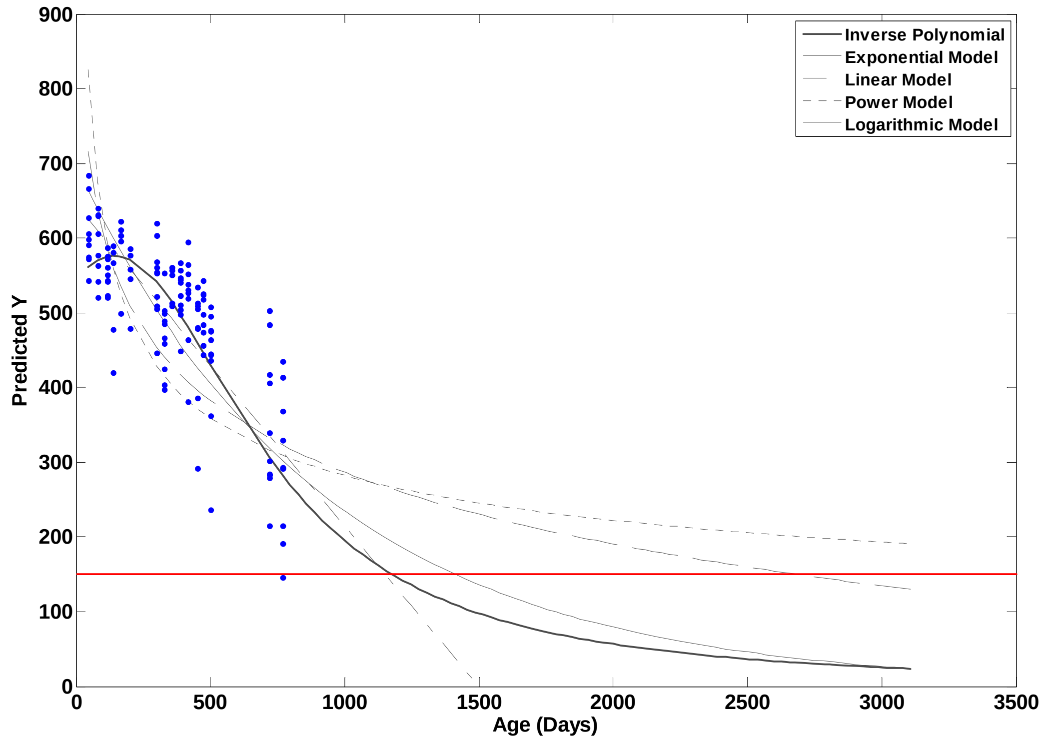

Figure (8.26): Measured and Predicted Retroreflectivity versus Age (3M 380WR ES; White Right Edge Line; Weighted Least Square; Outlier Excluded).

Table (8.12): Estimated Pavement Marking Service Life

(Service Life Predictions Visually Identified as Most Reasonable are Presented in Bold).

Material Type	Estimated Service Life (years)															
	Yellow – Left Edge Line				White – Left Lane Line				White – Right Lane Line				White – Right Edge Line			
	Linear		Exponential		Linear		Exponential		Linear		Exponential		Linear		Exponential	
	OLS	WLS	OLS	WLS	OLS	WLS	OLS	WLS	OLS	WLS	OLS	WLS	OLS	WLS	OLS	WLS
1. 3M 380WR ES	6.0	6.0	6.0	**6.0**	3.2	3.1	4.4	**4.0**	**3.8**	3.3	5.3	4.4	3.6	3.2	**4.7**	3.9
2. Premark Contrast	6.0	6.0	6.0	**6.0**	6.0	6.0	6.0	**6.0**	1.0[1]	1.0[1]	1.0[1]	**1.0**[1]	2.5[2]	2.3[2]	2.9[2]	2.5[2]
3. HPS-2	6.0	6.0	6.0	**6.0**	3.5	4.2	5.5	**6.0**	3.7	4.0	5.7	**5.8**	2.7	3.0	3.6	**3.9**
4. HPS-4	6.0	6.0	6.0	**6.0**	4.3	4.4	6.0	**6.0**	3.2	3.3	4.8	**4.5**	**3.2**	2.8	4.4	3.7
5. Mark 55.2	6.0	6.0	6.0	**6.0**	5.2	5.7	6.0	**6.0**	4.7	**5.5**	6.0	6.0	2.5	2.9	3.3	**3.6**
6. Mark 75	6.0	6.0	6.0	**6.0**	2.5	2.8	3.6	**3.7**	2.1	2.5	2.8	**3.1**	2.1	2.4	2.7	**3.0**
7. Mark 55.4	6.0	6.0	6.0	**6.0**	3.0	3.6	4.6	**5.2**	3.1	3.6	4.7	**5.1**	1.8	2.2	2.1	**2.5**
8. Swarcotherm[1]	1.0	1.0	1.0	**1.0**	1.9	1.9	1.9	**1.9**	0.9	0.9	0.9	**0.9**	0.9	0.9	0.9	**0.9**
9. LS 60	6.0	6.0	6.0	**6.0**	2.7	3.3	3.7	**4.5**	3.3	3.9	4.9	**5.6**	2.9	3.4	4.0	**4.5**
10. Glomarc 90	6.0	6.0	6.0	**6.0**	4.1	4.8	6.0	**6.0**	3.6	4.6	6.0	**6.0**	3.1	3.6	5.1	**5.5**
11. LS 70[1]	1.5	1.5	1.5	**1.5**	1.5	1.5	1.5	**1.5**	0.8	0.8	0.8	**0.8**	0.7	0.7	0.7	**0.7**
12. HPS-5	6.0	6.0	6.0	**6.0**	4.8	5.5	6.0	**6.0**	4.9	5.2	6.0	**6.0**	4.5	5.5	6.0	**6.0**
13. Ennis MMA	0.0	0.0	0.0	**0.0**	3.1	3.7	4.2	**4.9**	2.7	3.2	3.4	**3.9**	6.0[2]	4.2[2]	6.0[2]	4.8[2]
14. Ennis Paint	3.5	3.6	4.2	**4.2**	1.9	2.1	2.0	**2.1**	1.7	1.8	1.7	**1.7**	1.9	1.9	2.0	**1.9**
15. Premark Plus	6.0	6.0	6.0	**6.0**	5.0	3.3	6.0	**4.2**	4.0	3.1	5.5	**4.1**	2.4[2]	2.3[2]	2.8[2]	2.4[2]
16. 3M 270 ES	6.0	6.0	6.0	**6.0**	4.3	**4.5**	6.0	6.0	4.3	**4.4**	6.0	6.0	1.6	**1.8**	1.6	1.7

[1] Material failed due to durability (Durability Rating ≤ 8).
[2] None of the regression models was able to produce reasonable service life predictions for white Ennis Duraset 1 on right edge line of Bridge Deck 13 or white Premark Plus on right edge lines of Bridge Decks # 2 and 15.

Table (8.13): Summary of Pavement Marking Service Life Predictions

Material Group	Material Type	Estimated Service Life (years)				Typical Service Life (years)
		Yellow – Left Edge Line	White – Left Lane Line	White – Right Lane Line	White – Right Edge Line	
Durable Tape	3M 380WR ES	6.0	4.0	3.8	4.7	4 to 8 years[3]
	3M 270 ES	6.0	4.5	4.4	1.8	
Preformed Thermoplastic	Premark Contrast	6.0	6.0	1.0[1]	--[2]	3 to 6 years[4]
	Premark Plus	6.0	4.2	4.1	--[2]	
Slow Cure Epoxy	HPS-2	6.0	6.0	5.8	3.9	3 to 5 years[3]
	Mark 55.2	6.0	6.0	5.5	3.6	
	LS 60	6.0	4.5	5.6	4.5	
Fast Cure Epoxy	Mark 55.4	6.0	5.2	5.1	2.5	3 to 5 years[3]
	LS 70[1]	1.5	1.5	0.8	0.7	
Modified Urethane	HPS-4	6.0	6.0	4.5	3.2	Up to 4 years[3]
Polyurea	Mark 75	6.0	3.7	3.1	3.0	Up to 5 years[3]
	Glomarc 90	6.0	6.0	6.0	5.5	
	HPS-5	6.0	6.0	6.0	6.0	
Thermoplastic	Swarcotherm[1]	1.0	1.9	0.9	0.9	Up to 2 years[3]
Methyl Methacrylate	Ennis MMA	0.0	4.9	3.9	--[2]	Up to 5 years[3]
Fast Dry Waterborne Paint	Ennis Paint	4.2	2.1	1.7	1.9	Up to 1 year[3]

[1] Material failed due to durability (Durability Rating ≤ 8).
[2] None of the regression models was able to produce reasonable service life predictions for white Ennis Duraset 1 on right edge line of Bridge Deck 13 or white Premark Plus on right edge lines of Bridge Decks # 2 and 15.
[3] Typical service life on concrete (after Gates et al. 2003).
[4] After Montebello and Schroeder (2000).

CHAPTER 9
LIFE CYCLE COST OF PAVEMENT MARKINGS

9.1 Introduction

The previous chapters focused on analyzing the performance evaluation results for a number of marking materials on Portland cement concrete surfaces. Materials that failed to meet preselected milestone performance criteria were highlighted and materials that performed satisfactorily with the potential of lasting for an extended period of time were identified. In this chapter, the life cycle cost analysis method is used to determine the cost effectiveness of these materials by accounting for the costs involved in using each material.

9.2 Life Cycle Cost Analysis Inputs

The life cycle cost analysis method is an economic evaluation technique that can be used to determine the feasibility of different pavement markings over a period of time. This method accounts for the total discounted dollar cost of initial material installation, removal at the end of service life (if necessary), and maintaining the lines throughout the analysis period by restriping or replacement.

The cost effectiveness of each material can be determined by calculating its present value using the following equation:

$$PV = A_o + \sum A_t \left(\frac{1}{1+i} \right)^t \tag{9.1}$$

where, PV is the present value; A_o is the initial material and installation cost (often called the contracted cost); A_t is the maintenance cost incurred at time t; and i is the discount rate.

The present value is the equivalent of present and future cash flows at the beginning of the analysis period. This quantity accounts for the initial and future costs incurred during the analysis period through a discount rate that reflects the annual change in the money value. A discount rate of 4% is typical in life cycle cost analyses. In order to be consistent, the same analysis period must be used for all materials. In this study, an analysis period of eight years (the typical service life of an asphalt overlay) is used (Lindly and Wijesundera 2003).

Striping practices in Ohio vary from one district to another. Common striping practices for multilane roadways in ODOT District 3, for example, involve using extruded thermoplastic for new asphalt surfaces, restriping with polyester after about 4 to 5 years, then restriping with fast dry waterborne paint after about 3 years. In addition, ODOT is currently experimenting with sprayed thermoplastic as an alternative restriping material on thermoplastics. However, no decision has been made yet regarding this issue. As for new concrete surfaces, it is more common to use epoxy markings for initial application, followed by restriping with fast dry waterborne traffic paint after about 3 to 4 years, and every two years thereafter.

In this project, two alternative maintenance strategies were considered. The first involves using the pavement marking until the end of its service life, followed by restriping with fast dry waterborne traffic paint every year until the end of the eighth year. The second involves using the pavement marking until the end of its service life, followed by restriping with fast dry waterborne traffic paint every other year until the end of the eighth year. According to Table (9.1), all materials used in this project are compatible with waterborne traffic paint as a restriping material except durable tapes. Therefore, these tapes have to be removed at the end of their service life prior to restriping with waterborne traffic paint.

Table (9.1): Material Compatibility Matrix (after TxDOT 2004).

Existing (Old) Material	Restripe (New) Material							
	Thermo	WB Paint	Tape	Epoxy	Polyurea	Mod. Ureth.	MMA	Buttons
Thermo	Y	Y	N	N	N	N	N	Y
WB Paint	Y	Y	N	N	N	N	N	Y
Tape	N	N	N	N	N	N	N	N
Epoxy	Y	Y	N	Y	–	–	–	Y
Polyurea	Y	Y	N	–	Y	–	–	Y
Mod. Ureth.	Y	Y	N	–	–	Y	–	Y
MMA	Y	Y	N	–	–	–	Y	Y
Buttons	N	N	N	N	N	N	N	N

Table (9.2) outlines the average material installation, grooving, and removal costs involved in the using each marking material group. These figures are based on average contracted costs reported in the literature. Actual contracted costs though may vary depending on the size of the project, the type of the pavement surface (whether asphalt or concrete), and the type of the line (whether it is edge line, lane line, or centerline). In this table, it can be noticed that waterborne traffic paint is the least expensive, followed by extruded thermoplastic, then epoxies, then modified urethane, then polyurea, then methyl methacrylate and durable tapes. No data was available in the literature for preformed thermoplastic. This material has been previously used in Ohio as a transverse marking, but not as a longitudinal marking. All materials evaluated in this project were installed in grooves. Therefore, the additional cost of grooving should be added. The average grooving cost on Portland cement concrete pavements ranges from 0.85 to 1.00 $/LF. A grooving cost of 0.90 $/LF was used in this project. As for the removal cost, this cost was only included for durable tapes since, as discussed earlier, durable tapes are not compatible with any other restriping material. Therefore, they have to be removed at the end of their service life. A removal cost of 0.75 $/LF was used in this project.

Table (9.2) also presents the predicted service life values for each material group. These values are based on the performance of the individual materials in each group on the highly trafficked white right edge lines, and the subsequent service life predictions obtained in Chapter 8. As shown in this table, no reasonable service life estimates were obtained for Premark Plus preformed thermoplastic on Bridge Decks # 2 and 15 or for Ennis Duraset 1 methyl methacrylate on Bridge Deck # 13. Therefore, these two materials were excluded from the analysis.

Table (9.2): Average Costs and Service Life Values in the Analysis.

Material Group	Average Contracted Cost ($/LF)	Average Grooving Cost ($/LF)[3]	Average Removal Cost ($/LF)	Service Life (years)[4]
Durable Tape	2.57[1]	0.90	0.75	4 to 5 years
Preformed Thermoplastic	--[2]	0.90	--	--[5]
Slow Cure Epoxy	0.40[1]	0.90	--	3 to 5 years
Modified Urethane	0.63[1]	0.90	--	3 to 4 years
Polyurea	1.00[1]	0.90	--	3 to 6 years
Thermoplastic	0.35[1]	0.90	--	Up to 1 year
Methyl Methacrylate	2.50[1]	0.90	--	--[5]
Fast Dry Waterborne Paint	0.08[1]	0.90	--	Up to 2 years

[1] After TxDOT (2004).
[2] No data was available for this material in the literature.
[3] Average grooving cost on concrete is 0.85 to 1.00 $/LF.
[4] Based on values obtained in Chapter 8.
[5] None of the regression models used in Chapter 8 was able to produce reasonable service life predictions for white Ennis Duraset 1 on right edge line of Bridge Deck 13 or white Premark Plus on right edge lines of Bridge Decks # 2 and 15.

9.3 Life Cycle Cost Analysis Results and Limitations

The life cycle cost analysis results for maintenance strategies 1 and 2 are presented in Table (9.3). In this table, the present worth value was calculated for each material over a range of possible service life values. As discussed earlier, maintenance strategy 1 involves using the pavement marking until the end of its service life, followed by restriping with fast dry waterborne traffic paint every year until the end of the eighth year, while maintenance strategy 2 involves using the pavement marking until the end of its service life, followed by restriping with fast dry waterborne traffic paint every other year until the end of the eighth year. As such, the first maintenance strategy is expected to result in higher present worth values than the second maintenance strategy.

As shown in this table, waterborne traffic paint had the lowest present worth value for both maintenance strategies 1 and 2, followed by epoxy, then thermoplastic, then modified urethane, then polyurea, then durable tapes. The analysis results did not seem to be influenced by the assumed pavement marking service life or by whether maintenance strategy 1 or 2 was used, which is probably due to the relatively low cost of waterborne traffic paint used in restriping and the large differences in average contracted costs between the marking materials.

While the previous analysis results show a clear cost advantage for using less durable marking materials such as waterborne traffic paint, the following factors should be taken into consideration when deciding which material to use:

- The life cycle cost analysis results presented herein did not account for the retroreflectivity of the pavement marking during its service life. It is generally believed that higher retroreflectivity entails better nighttime visibility and subsequently safer roads with potentially fewer accidents. Some of the more expensive pavement markings evaluated in this study provided much higher retroreflectivity values than waterborne traffic paint; and therefore, are considered advantageous from that perspective.
- The life cycle cost analysis method did not address the impact of frequent striping using less durable pavement markings on traffic flow and the potential risk to maintenance crew. Besides, the life cycle cost analysis did not account for the additional administrative cost from initiating such striping projects.
- Results presented in this report are limited to the performance of the pavement markings under dry conditions, which is not necessarily indicative of the performance of these

materials under wet conditions. The 3M 380WR ES wet reflective durable tape for example is designed to improve retroreflectivity under wet conditions. However, this factor was not taken into consideration in the life cycle cost analysis.

- Finally, several factors affect the performance of pavement markings including the pavement marking material type and color, type and size of glass beads, quality of installation, type of pavement surface, type of application (on surface or in groove), traffic volume, percentage of heavy vehicles, roadway geometry, weather conditions, and snow removal practices and activities. Results presented in this project are limited to the conditions under which data was obtained. Different results are expected under different prevailing conditions.

Table (9.3): Life Cycle Cost Analysis Results.

Material Group	Assumed Service Life (years)	Maintenance Strategy 1 Present Value ($/LF)[2]	Maintenance Strategy 2 Present Value ($/LF)[3]
Durable Tape	4	4.43	4.25
	5	4.33	4.19
Preformed Thermoplastic	--[1]	--[1]	--[1]
Slow Cure Epoxy	3	1.69	1.47
	4	1.62	1.43
	5	1.55	1.40
Modified Urethane	3	1.92	1.70
	4	1.85	1.66
Polyurea	3	2.29	2.07
	4	2.22	2.03
	5	2.15	2.00
	6	2.08	1.97
Thermoplastic	1	1.79	1.50
Methyl Methacrylate	--[1]	--[1]	--[1]
Fast Dry Waterborne Paint	1	1.52	1.23
	2	1.44	1.19

[1] None of the regression models used in Chapter 8 was able to provide reasonable service life predictions for preformed thermoplastic or methyl methacrylate. Therefore, these materials were excluded from the analysis.
[2] Maintenance Strategy 1 involves using the pavement marking until the end of its service life, followed by restriping with fast dry waterborne traffic paint every year until the end of the eighth year.
[3] Maintenance Strategy 2 involves using the pavement marking until the end of its service life, followed by restriping with fast dry waterborne traffic paint every other year until the end of the eighth year.

CHAPTER 10
SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

10.1 Project Summary

The performance of several pavement markings, including waterborne traffic paint (Ennis fast dry waterborne traffic paint), thermoplastic (Swarcotherm alkyd), preformed thermoplastic (Premark Plus and Premark Contrast), slow cure epoxy (HPS-2, Mark 55.2, and LS 60), fast cure epoxy (Mark 55.4 and LS 70), polyurea (HPS-5, Mark 75, and Glomarc 90), modified urethane (HPS-4), methyl methacrylate (Duraset 1 and Duraset Pathfinder), and high performance durable tapes (3M 380WR ES, 3M 380WR-5 ES, and 3M 270 ES), was evaluated on sixteen concrete bridge decks located in Ashland and Richland counties in ODOT District 3 along interstate I-71. All bridges are connected to mainline asphalt pavement where the interstate has three lanes per direction, with an average daily traffic (ADT) of about 42,000 vehicles per day.

Each material was installed in four locations along the three lanes of the interstate. Yellow was installed on the left edge line and white was installed on the two lane lines and the right edge line. All materials were installed in 150-mil (3.8 mm) grooves. The groove depth selected was the same as the transverse tines depth on the bridge decks in order to ensure that all traces of the old thermoplastic have been completely removed; and thus, eliminate its effect on the newly installed products.

The performance evaluation period lasted for slightly over two years. The performance evaluation plan included measuring retroreflectivity using two handheld LTL-X retroreflectometers and color using a MiniScan XE Plus colorimeter. It also included rating daytime color, nighttime visibility, and durability according to Supplemental 1047 (dated April 18, 2008). In addition, a pocket magnifier was used to examine glass bead retention as it varied over time.

The performance evaluation results obtained during the periodic evaluations were compared to preselected milestone performance criteria and augmented with NTPEP data from the Pennsylvania and Wisconsin test decks. The service life of each marking material was predicted using different mathematical models that estimated the time required for retroreflectivity to drop to a threshold value of 150 mcd/m^2/lux for white markings and 100 mcd/m^2/lux for yellow markings. The service life predictions were then used to calculate the life cycle costs of the marking materials in order to determine their cost effectiveness.

10.2 Conclusions

Based on the performance evaluation results and the subsequent analysis findings, the following conclusions can be made:

- <u>Performance Evaluation Results</u>
  - *Retroreflectivity:*
    - Ennis fast dry waterborne traffic paint had poor initial retroreflectivity. However, its performance was fairly acceptable throughout this project (i.e., for almost two years). It seems that installing this material in-groove protected it from traffic and significantly extended its service life.
    - The conventional thermoplastic Swarcotherm alkyd had acceptable retroreflectivity performance. However, it failed due to durability in less than a year.
    - Comparable retroreflectivity performance was obtained from HPS-2, Mark 55.2, and LS 60 slow cure epoxies. The initial retroreflectivity of these materials was in the 500 to 700 mcd/m^2/lux range, and their 2-yr retroreflectivity ranged from 290 to 340 mcd/m^2/lux. On the other hand, unsatisfactory performance was obtained for LS 70 and Mark 55.4 slow cure epoxies. The former failed due to durability in less than eight months, while the latter had very high retroreflectivity deterioration rate.
    - The performance of HPS-4 modified urethane was comparable to the less expensive slow cure epoxies.
    - Two durable tapes were evaluated in this study, namely 3M 380WR ES and 3M 270 ES. The more expensive 3M 380WR ES tape performed much better than the less expensive 3M 270 ES tape especially on the highly trafficked white right edge line. The initial retroreflectivity of 3M 380WR ES on the right edge line was about 600 mcd/m^2/lux, and its 2-yr retroreflectivity was about 350 mcd/m^2/lux. These values are comparable to those obtained for some of the less expensive slow cure epoxies.
    - The preformed thermoplastic Premark Plus had an initial retroreflectivity of 663 mcd/m^2/lux and 579 mcd/m^2/lux on the right lane lines of Bridge Decks # 2 and 15, respectively, and a 2-yr retroreflectivity of 215 mcd/m^2/lux on both bridge decks.

While this material had high initial retroreflectivity, its 2-yr retroreflectivity was lower than the less expensive slow cure epoxies.

- The performance of the three polyurea products (Glomarc 90, Mark 75, and HPS-5) widely varied. As mentioned earlier, Glomarc 90 had the highest initial, 1-yr, and 2-yr retroreflectivity, with all retroreflectivity measurements exceeding 500 mcd/m^2/lux at all times. Mark 75 had acceptable initial retroreflectivity for yellow and very high initial retroreflectivity for white. However, its 1-yr and 2-yr retroreflectivity performance was comparable, if not lower, to the less expensive slow cure epoxy products. Finally, HPS-5 had acceptable initial retroreflectivity for yellow and very high initial retroreflectivity for white. It also had very high retained retroreflectivity for both white and yellow markings.
- Duraset 1 methyl methacrylate had the lowest initial retroreflectivity for both yellow and white markings, which was attributed to poor installation. Meanwhile, the performance of Duraset Pathfinder methyl methacrylate, which was applied using the splatter method instead of extrusion, was satisfactory.

- *Color:*
  - All materials met ODOT specifications for white color. However, several materials (Premark Plus, HPS-2, HPS-4, Mark 75, LS 60, Glomarc 90, LS 70, HPS-5, and Ennis Fast Dry Waterborne Traffic Paint) did not meet the specifications for yellow. Among these materials HPS-2, Mark 75, Glomarc 90, HPS-5, LS 70, and Ennis Fast Dry Waterborne Traffic Paint failed to meet ODOT yellow color specifications towards the end of the second year, but were acceptable before that time.
- *Durability:*
  - The durability of most materials did not drop below a rating of ten over the duration of this project, which is probably due to installing all materials in 150-mil (3.8 mm) grooves. As mentioned earlier, this groove depth was selected in order to ensure that all traces of the old thermoplastic have been completely removed; and thus, eliminate its effect on the newly installed products.
  - Among the materials that failed due to durability are: Swarcotherm alkyd, Epoplex LS 70, and Premark Contrast when a sealer was not used.

- *Daytime Color:*
  - The three polyurea products (Mark 75, Glomarc 90, and HPS-5) had the highest daytime color ratings over the duration of this study; followed by the epoxies (excluding LS 70), the modified urethane, the methyl methacrylate, the waterborne traffic paint, and the durable tapes; then the conventional and preformed thermoplastics.
  - One advantage of the polyurea products in terms of color is that they had a dirt repellent glossy surface, which provided them with better contrast with the underlying gray concrete surface and improved their color during winter when other lines were full of dirt and deicing salt.
  - The daytime color ratings were not always consistent with the color measurements obtained using the MiniScan XE Plus colorimeter. Some of the evaluated materials such as HPS-2, HPS-4, Mark 55.2, and Mark 55.4 had acceptable yellow color even though their color readings were very close to the bottom corner of ODOT yellow color specification box. On the other hand, some of the evaluated materials had white color readings well within ODOT white color specification box, but did not have acceptable color contrast. This calls into question the applicability of ODOT color specifications to determine pavement marking daytime color acceptability.
- *Nighttime Visibility:*
  - The nighttime visibility evaluation consisted of rating three attributes of the pavement markings: uniformity (on a scale of 0 to 4), retroreflectivity (on a scale of 0 to 3), and nighttime color (on a scale of 0 to 3). The nighttime visibility rating was calculated as the sum of the three ratings for these three attributes.
  - Based on the previous, it is not expected that there will be high correlation between retroreflectivity readings measured using an LTL-X retroreflectometer and nighttime visibility ratings since the latter accounts for retroreflectivity uniformity and nighttime color.
  - Among the materials that received low nighttime visibility ratings (less than seven) are: Premark Plus and Premark Contrast; Swarcotherm alkyd; Ennis Duraset 1 methyl methacrylate; and Ennis fast dry waterborne paint.

- *Glass Bead Retention:*
    - The polyurea products had the best glass bead retention followed by epoxies. Still, both materials had satisfactory glass bead retention.
    - On the other hand, HPS-4 modified urethane had very poor ability to retain large glass beads especially on the highly trafficked white right edge line where 60 to 70% of the large glass beads were lost after two years. This fact did not seem to have a significant effect on the retroreflectivity performance of this material.

- <u>Comparison with NTPEP Data</u>
    - Different deterioration trends were noticed for white and yellow markings in ODOT District 3 than in the NTPEP. In ODOT District 3, the white right edge lines deteriorated at the highest rate, followed by the white (left and right) lane lines, then the yellow left edge lines. In the NTPEP, white and yellow markings are applied transversely to ensure that both markings are subjected to the same traffic. Still, for most materials, yellow markings deteriorated at a higher rate than white markings.
    - The deterioration rate of yellow markings in ODOT District 3 was modest compared to that in the NTPEP PA and WI test decks due to grooving and low traffic level.
    - The 2-yr white markings retroreflectivity in ODOT District 3 was in general consistent (especially on the right edge line) with the NTPEP PA test deck skip retroreflectivity, but slightly higher than the skip retroreflectivity in NTPEP WI test deck. This implies that the deterioration rate in NTPEP WI is slightly lower than the deterioration rate in NTPEP PA for the same material. This difference should be taken into consideration by product prequalification specifications that utilize data from both NTPEP test decks such as ODOT Supplemental 1047.
    - The following materials performed better on the NTPEP test decks than in ODOT District 3: Mark 55.4, Swarcotherm alkyd, and Ennis fast dry waterborne paint. The following materials performed somewhat the same in both studies: 3M 380WR ES, HPS-2 (NTPEP PA 2000-2002), HPS-4, LS 60, Premark Plus, and 3M 270 ES. The only material that performed better in ODOT District 3 was HPS 5. Still, this material had high retroreflectivity values on the NTPEP test decks even after two years. The rest of the materials have not been tested on the NTPEP test decks.

- Pavement Marking Service Life
  - Yellow markings in this study were subjected to low traffic. Therefore, their performance is not necessarily representative of how these materials would perform under high traffic.
  - As for the white markings on the highly trafficked right edge line, the estimated service lives were as follows:
    - Traffic paint: 1.9 years for Ennis fast dry waterborne paint.
    - Thermoplastic: 0.9 years for Swarcotherm alkyd.
    - Slow cure epoxies: 3.9 years for HPS-2, 3.6 years for Mark 55.2, and 4.5 years for LS 60.
    - Fast cure epoxies: 2.5 years for Mark 55.4 and 0.7 years for LS 70.
    - Modified urethane: 3.2 years for HPS-4.
    - Durable tapes: 4.7 years for 3M 380WR ES and 1.8 years for 3M 270 ES.
    - Polyurea: 3.0 years for Mark 75, 5.5 years for Glomarc 90, and 6.0 years for HPS-5.
    - None of the mathematical models used in this study were able to provide reasonable service life predictions for Duraset 1 methyl methacrylate or Premark Plus preformed thermoplastic.

- Life Cycle Cost Analysis
  - Based on the life cycle cost analysis results, it was concluded that waterborne traffic paint is the most cost effective marking material, followed by slow cure epoxies, then modified urethane, then polyurea, then durable tapes. The rest of the materials were not included in the analysis due to premature failure or due to unreasonable service life predictions.
  - The main limitation of the life cycle cost analysis procedure employed in this study is that it did not account for the retroreflectivity of the pavement marking during its service life, which disadvantaged some of the more expensive pavement markings that had high retroreflectivity. In addition, it did not address the impact of frequent striping using less durable pavement markings on traffic flow and the potential risk to maintenance crew.

10.3 Recommendations

Based on the performance evaluation results and the subsequent analysis findings, the following conclusions and recommendations were made:

- Three slow cure epoxies were evaluated in this study, namely IPS HPS-2, PolyCarb Mark 55.2, and Epoplex LS 60. All three products performed satisfactorily over the two-year performance evaluation period, with an expected service life of about 3 to 5 years. From among these products, only LS 60 is currently included in ODOT "Approved List" of pavement markings. Hence, it is recommended to add both HPS-2 and Mark 55.2 to this list.
- Two pavement marking materials showed the potential of lasting for more than five years under high traffic, namely IPS HPS-5 polyurea and Epoplex Glomarc 90 polyurea. These products, however, did not compare favorably with the less expensive slow cure epoxies based on the life cycle cost analysis results. Therefore, it will not be cost effective to use them on a large scale. Another concern regarding Glomarc 90 is that Epoplex has recently changed the bead systems used in this product. Therefore, additional evaluation may be necessary for this material with the new bead systems. Still, it is recommended to include HPS-5 polyurea in ODOT "Approved List" on a conditional basis by limiting its use to a number of projects per year that involve Portland cement concrete surfaces subjected to high traffic.
- The third polyurea product PolyCarb Mark 75 did not perform as satisfactorily as the other two polyurea products. Therefore, it is not recommended to include this material in ODOT "Approved List."
- Given their very high initial cost, durable tapes did not seem to offer clear advantage over the less expensive slow cure epoxies under dry conditions. One of the durable tapes, 3M 380WR ES series, contains specially designed optics to improve its performance under wet night conditions. Additional research is needed to evaluate the performance of this tape under such conditions.
- The performance of HPS-4 modified urethane was comparable to that of slow cure epoxies. This material is slightly more expensive. Yet, it dries much faster, which makes it desirable for areas with high traffic volumes since it requires less traffic control. Therefore, it is recommended to conditionally approve this material.

- Epoplex LS 70 slow cure epoxy failed due to durability in less than eight months. Therefore, it is not recommended to approve using this material.
- Even though PolyCarb Mark 55.4 fast cure epoxy is currently included in ODOT "Approved List," this product had one of the highest retroreflectivity deterioration rates. Therefore, it is recommended to review recent projects striped with this material to determine whether to keep it or remove it from the "Approved List."
- The performance of the preformed thermoplastic Premark Plus and Premark Contrast was comparable to the performance of the less expensive slow cure epoxies over the two-year performance evaluation period. Therefore, it is not recommended to use these materials for longitudinal applications on Portland cement concrete bridge decks.
- Poor installation of Duraset 1 methyl methacrylate resulted in poor performance. Additional evaluation may be required to assess the performance of this material. At the present, it is not recommended to include it in ODOT "Approved List".
- The performance of Duraset Pathfinder methyl methacrylate was comparable to that of the less expensive slow cure epoxies. Therefore, it is not recommended to include it in ODOT "Approved List."
- Interestingly, even though Ennis fast dry waterborne traffic paint did not meet most milestone retroreflectivity criteria set forth for the more durable products, its performance was reasonably acceptable (retroreflectivity is greater than 150 mcd/m^2/lux for white markings and 100 mcd/m^2/lux for yellow markings) even after two years from installation. This material is typically applied on the surface rather than in groove. However, in this study, it was installed in 150-mil (3.8 mm) grooves similar to the rest of the materials. One disadvantage of doing so is that the lines became completely invisible under wet night conditions once the grooves were filled with water. This was not necessarily the case for thicker materials and materials that had patterned structures.
- Some of the evaluated materials such as HPS-2, HPS-4, Mark 55.2, and Mark 55.4 had acceptable yellow color even though their color readings were very close to the bottom corner of ODOT yellow color specification box. On the other hand, some of the evaluated materials had white color readings well within ODOT white color specification box, but did not have acceptable color contrast. This calls into question the applicability of ODOT color specifications to determine pavement marking daytime color acceptability.

- Finally, grooving has been shown to improve the performance of some of the pavement markings such as Ennis fast dry waterborne traffic paint. Therefore, it is recommended to consider this surface preparation technique in the installation of pavement markings on Portland cement concrete bridge decks that are subjected to high traffic.

In summary, it is recommended to use the following products on Portland cement concrete bridge decks: Ennis fast dry waterborne traffic paint (for bridges with low to medium traffic volumes or as part of a mainline asphalt pavement striping project), LS 60, HPS-2, Mark 55.2, Mark 55.4, HPS-4, and HPS-5. Grooving has been shown to improve the performance of some of these materials such as Ennis fast dry waterborne traffic paint. Therefore, it is recommended to consider this surface preparation technique in the installation of pavement markings on Portland cement concrete bridge decks that are subjected to high traffic. To this end, it is recommended to add the following products to ODOT "Approved List" of pavement markings: IPS HPS-2, PolyCarb Mark 55.2, IPS HPS-4, and IPS HPS-5.

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